March 30, 2009

University of California
Office of Campus Planning & Design
c/o Vision2025
Santa Barbara, CA 93106-1030

RE: Comments on the Recirculated Draft Environmental Impact Report for the Proposed 2008 Long Range Development Plan for the University of California at Santa Barbara

Submitted electronically to info@UCSBVision2025.com, ***with hard copy to follow***

Dear Ms. Hummer:

On behalf of my client, the Sustainable University Now Coalition ("SUN"), I hereby submit these comments regarding the Recirculated Draft Environmental Impact Report ("RDEIR") for the proposed 2008 Long Range Development Plan ("LRDP") for the University of California at Santa Barbara ("UCSB"). SUN is a coalition of 12 local community non-profit organizations who are committed to advancing the proposition that UCSB should be the leader in sustainability, not just within its "four walls," but in the community as a whole. SUN's members include: Associated Students- Legislative Council (USCB), Citizen's Planning Association (CPA), Coalition for Sustainable Transportation (COAST), Chilla Vista (UCSB), Community Environmental Council, League of Women Voters of Santa Barbara, Santa Barbara Audubon Society, Santa Barbara County Action Network (SB *CAN*), Sierra Club Los Padres Chapter - Santa Barbara Group, PUEBLO Education Fund, Santa Barbara Channelkeeper, Santa Barbara Urban Creeks Council and Heal the Ocean.

SUN has committed substantial resources to participating in the public review process of UCSB's proposed 2008 LRDP. SUN's Principles, set forth in Attachment A, express its support and appreciation for the contribution UCSB students, faculty, staff and administration make to our community. SUN believes that it is essential that the entire Santa Barbara County community be involved in the LRDP process given UCSB's development impacts on the future of the region.

As the only coastal campus, UCSB's development plans have far reaching implications on the public's access to, and safe use of, the ocean and beaches. Impacts include limitations on access due to traffic and lack of parking, plus increased pollution resulting from both runoff and inadequate wastewater treatment.

The RDEIR identifies **18 significant and unavoidable impacts** that would result from the proposed LRDP **in just five impact areas**. In addition to all of the significant, Class I impacts identified in the RDEIR, however, the LRDP will result in even more – and more severe – impacts to our community and to the Environment, as identified below.

The RDEIR fails to meet the basic requirements of the California Environmental Quality Act ("CEQA"), Public Resources Code, § 21000 *et seq.*, in the following ways:

- Is missing critical information in the Project Description;
- Underestimates impacts to Air Quality, Housing, Traffic, Water and Wastewater;
- Still fails to accurately disclose and address emissions of greenhouse gases;
- Contains ineffective, unenforceable mitigation measures that are not based on substantial evidence in the record;
- Failed to revise the Alternatives analysis despite addition of significant new information in Air Quality, Housing, Traffic, Water and Wastewater impacts;
- Failed to provide and consider meaningful alternatives that would lessen environmental impacts;
- Omitted critical information from the Cumulative Impacts analysis

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Correction of these and other deficiencies that are discussed below will result in "significant new information" that must be added to the RDEIR. Accordingly, as required by section 15088.5 of the CEQA Guidelines, the RDEIR must be revised and re-circulated, again. A failure to do so will result in a legally deficient FEIR that cannot be certified.

I. Summary of SUN's Key Comments

UCSB's own goals for sustainability on campus appear unattainable, given the growth they project and the mitigations they propose. SUN's response to the LRDP and RDEIR are based on the following key points:

1. ***Traffic and parking impact caused by the LRDP will have a significant, detrimental effect on access to and use of California public beaches in the South Coast of Santa Barbara.***
As the LRDP and RDEIR currently stand, the Coastal Commission should be concerned that access to oceans and beaches throughout the South Coast would be severely limited by an excess of traffic and a severe shortage of parking for the public.

2. ***The proposed LRDP is overly private automobile centric, continuing to use a 20th Century circulation model for a 21st Century world.***
For example, this plan

- Provides many new parking spaces but not even one more bus stop on campus through 2025.
- No specific programs or timetables or funding for "carrots and sticks" to significantly shift transportation to carpooling, mass transit, biking, telecommuting, non-peak commuting, etc. When combined with UCSB's poor track record of

achieving the reduction of automobile use, there is little reason for optimism that the mitigations stated in the current LRDP and RDEIR will be effective in reducing traffic.

- Most of UCSB's mitigations are about increasing capacity of surrounding roads and intersections, which history has shown will invite more traffic by private automobile. In contrast, many of these road expansion mitigations would be unnecessary in a less car-centric plan.

3. *UCSB has a responsibility to mitigate impacts resulting from the traffic it has already created and not just the incremental effects of the proposed new growth.*
One of the RDEIR's main contentions is that traffic is already bad and if the RDEIR changes are implemented, traffic will be no worse. This ignores the fact that current local traffic congestion is significantly due to UCSB's past growth whose impacts were either underestimated or unmitigated. Also, UCSB's past traffic projections and mitigations make current projections highly suspect.

UCSB must be strongly committed to facilitating pedestrian, bicycle, and public transit while actively discouraging the use of private cars, and provide resources and incentives to achieving this shift. This would not only mitigate traffic, parking and air quality concerns but would also help meet national goals of reducing use of fossil fuels and their effects on climate change. *Accordingly, a final RDEIR should embody a systematic and detailed transportation plan toward this end.*

4. *The Housing Plan creates a housing deficit in two ways.*
First, it provides less housing than the demand it will create in our community. Second, it has a built in "lag" of several years between the time additional people arrive and the time incremental housing is available to them. The plan exacerbates what is already a jobs/housing imbalance that is at critical levels in our community. UCSB must reverse this trend by building the housing proposed in the RDEIR while reducing the number of students and concomitant faculty and staff it proposes adding.

It is imperative that housing built as part of the LRDP is maintained for the use of the UCSB faculty, student and staff population.

5. *There is a lack of congruence between the proposed LRDP and the Isla Vista Master Plan.*
The result is to create considerable public uncertainty about the future of the area. Instead, UCSB's RDEIR must explicitly integrate IV development with its own plans with respect to housing, traffic, and services.

6. *UCSB underestimates South Coast Santa Barbara County water needs resulting from UCSB expansion under the LRDP while overestimating the region's water supply.* According to the Goleta Water District ("GWD"), the RDEIR's assessment of water supply is inaccurate and an overestimate of water available to support the LRDP. The GWD also concludes that the University's water demand figures are underestimates. As a result, the RDEIR fails to accurately disclose the impacts to water, the impacts are underestimated and the mitigation measures are not sufficient to lessen the impact to the maximum extent feasible.

7. *While the LRDP and its mitigations depend entirely on a stated cap in the number of student "headcount" by 2025, it lacks clarity and specificity on exactly how that headcount is to be determined, when and by whom.*
Nor is there specificity on the limit on the number of students to be added in any given year, or what "penalty" will apply if the cap number is exceeded in any given year or at the end. As long as the RDEIR lacks definitions of and limitations on its key benchmark of growth, the headcount cap, the RDEIR is fundamentally flawed, and so is the RDEIR.

We call on UCSB to demonstrate leadership in creating sustainable communities starting right here, right now in a revised LRDP and RDEIR.

II. The DEIR Omits Critical Information from the Project Description.

An accurate, complete and sufficiently detailed project description sets the stage for the impact analysis and review necessary to properly inform decision-makers – a review that is the cornerstone of CEQA. An accurate project description is the "*sine qua non* of an informative and legally sufficient EIR."[1]

One of the primary components of the proposed LRDP is the number of faculty, staff and students it proposes to add – which is identified as 5000 additional students, 336 additional faculty, and 1400 staff. (DEIR 3.0-1.) Yet, the DEIR fails to disclose how the student head count will be determined. For example, there is no statement of when counts are taken, whether part time students count as a full, single headcount or if students studying abroad are included in the headcount for purposes of the cap.

This is a necessary component of the proposed LRDP that should have been disclosed in the Project Description and will significantly affect the RDEIR's impact analysis. The primary impacts caused by the proposed 2008 LRDP stem from the increased number of students and faculty. Most, if not all, of the significant impacts to air quality, population and housing, transportation and circulation and water identified in the RDEIR are a result of this significant increase in students and faculty. In fact, the only distinguishing component of the environmentally superior alternative identified in the DEIR to lessen impacts, the Reduced Enrollment alternative, is that it has 1/3 fewer students and faculty. As such, it is critical that the RDEIR disclose how student head count is determined.

Although the University appears to use certain criteria for determining head count, these criteria must be made explicit and public. The RDEIR must be revised to disclose how students will be counted for purposes of calculating the enrollment cap. Moreover, there must be some predetermined way of calculating a "penalty" or way to make up the difference if the cap is exceeded.

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[1] *Berkeley Jets Over the Bay v. Board v. Board of Port Cmrs.* (2001) 91 Cal. App.4th 1344, 1358, citing *Sacramento Old City Assn. v. City Council* (1991) 229 Cal.App.3d 1011, 1023; *Stanislaus Natural Heritage Project v. County of Stanislaus* (1996) 48 Cal.App.4th 182, 201.

In addition, it appears that UCSB intends to increase its population by a specific percentage, yet the RDEIR does not specify the population that will not be exceeded in each year. The LRDP and the RDEIR must specify the *pace* at which UCSB will add students in order to assure that mitigations will keep pace with the resulting impacts.

The following information must be disclosed in the RDEIR.
Students who must be counted as part of the cap total:

- Students who are undergraduates or graduates taking any courses for credit at UCSB's Santa Barbara Campus.
- Students in the above category, regardless of any additional teaching or staff duties they may have, as Teaching Assistants or Administrative Assistants, for example.
- Students in the above category measured by an average of the 3 non-summer quarter and determined within 6 weeks if the start of each quarter. This is not a "rolling average." Instead, the average is determined beginning with the fall quarter and continues until the summer quarter. The average of those 3 quarters shall not exceed the cap for the year ending with the start of the summer quarter. For example, if there are 20,000 students in the Fall of 2008, 19,500 in the Winter quarter of 2008, and 20,500 in the Spring quarter of 2009, the average for 2009 will be 20,000 students.
- Students auditing classes.
- Students who are in enrolled in any other school such as high school or SB City College, but taking courses at UCSB's Santa Barbara Campus.

Students who should not be counted:

- Those studying abroad or at another campus.
- Those on leave of absence, as long as they do not live in campus housing.
- Those who are studying in the summer, as long as the total summer enrollment does not exceed the average attendance of the other 3 quarters.
- Those people who are doing research but not for credit or auditing.
- Students living outside of Santa Barbara County doing "remote learning," meaning they do not attend classes at UCSB's Santa Barbara Campus or related facilities.

Penalty for exceeding the cap:
There must be a penalty that is automatically imposed if UCSB either grows at a pace faster than it committed to or if it exceeds its cap.

III. The RDEIR Fails to Adequately Assess and Mitigate Impacts as Required by CEQA.

An EIR must describe feasible mitigation measures which will avoid or substantially lessen each significant environmental effect to the maximum extent feasible.[2] A lead agency cannot approve a project if there are feasible alternatives or mitigation measures that would avoid or substantially lessen significant impacts.[3]

The lead agency's decision with regards to the feasibility of mitigation measures must be based on substantial evidence in the record.[4] Decisions regarding whether or not alternatives and mitigation measures substantially lessen or avoid significant impacts must also be based on substantial evidence in the record.

Moreover, mitigation may not be deferred. As a matter of law, an agency cannot defer consideration or adoption of mitigation measures to a later date.[5] Deferral may only be allowed where there is a reasonable expectation of effectiveness and compliance based on a requirement that the measure meet specific performance standards that are identified in the EIR.[6] The impacts of proposed mitigation measures must also be discussed in the RDEIR.[7]

As identified below, the RDEIR fails to comply with the mandates for CEQA with respect to the analysis of the environmental impacts, and proposed mitigation measures.

A. <u>Air Quality</u>

The RDEIR's proposed mitigation measures are defective because they lack sufficient detail and are not enforceable.

TRANS-8. *Mesa Road may be widened west of Ocean Road to accommodate bike-lanes and pedestrian paths.*
Comment: This should be a commitment. Additional dense campus housing is planned west of Mesa Road, and the bike lanes and pedestrian paths will be needed to improve safety and encourage alternative transportation between housing and the main campus.

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[2] CEQA Guidelines §15126.4(a)(1); *Save Our Peninsula Committee v. Monterey board of County Supervisors* (2001) 87 Cal.App.4th 99.

[3] Pub. Res. Code §§21002 and 21081(a)(3); CEQA Guidelines §§ 15002(a)(3) and 15021(a)(2); *Mountain Lion Foundation* v. Fish and Game Commission (1997) 16 Cal.App.4th 105.

[4] *Citizens for Goleta Valley v. Board of Supervisors* (1988) 197 Cal.App.3d 1167 [243 Cal.Rptr. 39] ("Goleta I").

[5] CEQA Guidelines §15126.4(a)(1)(B); *Kings County Bureau v. City of Hanford* (1990) 221 Cal.App.3d 692 [270 Cal.Rptr. 650]; *Sundstrom v. County of Mendocino* (1988) 202 Cal.App.3d 296 [248 Cal.Rptr. 352].

[6] *Endangered Habitats League, Inc. v. County of Orange* (2005) 131 Cal. App.4th 777 [32 Cal. Rptr.3d 177.

[7] CEQA Guidelines §15126.4(a)(1).

Note: At the time of widening of Mesa Road, the University sewer lines should be relocated out of Storke Wetland, and coordination with Goleta West Sanitary District for re-location of their sewer lines to Mesa Road. These actions will allow for restoration of tidal circulation of Storke Wetland.[8]

TRANS-9. *The campus shall continue to maintain and improve bicycle and pedestrian access way to the beach as necessary to protect sensitive habitat areas and public safely.*
Comment. No commitment or goals are provided. Suggested are specific benchmarks, such as a new stairway to the beach from West Campus Bluffs when the first campus housing is constructed at the Devereux School site.

ACC-3. *The University, in cooperation with Metropolitan Transit District, shall ensure that regular bus and/or shuttle service is provided between all University housing and the Main Campus.*
Comment. This is crucial to the reduction in emissions from transportation. This is a significant component of a Transit Plan that UCSB should develop. A funding mechanism should be explored, and adaptation of measures such as frequency of service to meet benchmarks of shuttle utilization and reduced auto use from campus housing to the main campus.

ACC-4. *The University shall work with MTD to provide transit service to campus neighborhoods and shall provide new bus or shuttle stops in each housing development to maximize convenience and increase transit ridership.*
Comment. The University *must* work in partnership with MTD *and provide funding for new routes/frequency of service* so that the alternative transportation system is convenient and time-efficient, and thus utilized. Construction of bus stops is insufficient.

Feasible Mitigation Measures that must be considered in the RDEIR.

According to the RDEIR, campus growth under the proposed LRDP will cause significant air quality impacts that currently remain unavoidable even with the proposed mitigation. The RDEIR discloses that the LRDP would not be consistent with the 2007 Clean Air Plan, which is in place to prevent further degradation of the state's ozone and PM10 air quality standards.

Thus, SUN recommends that the following mitigation measures to reduce air quality impacts be explored and developed:

1) **A Reduced Enrollment Alternative**, based on less than the University's LRDP planned growth rate. This alternative would reduce impacts to air quality, transportation, water, housing and aesthetics. Services to students could be enhanced with incorporation of aspects of the Virtual University Alternative. Some reductions in the expected academic space, faculty and staff would result.

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[8] See Attachment B, see letter from Santa Barbara Audubon Society, Inc. re DEIR for the LRDP, March 28, 2008.

2) **Transportation Plan** The final RDEIR must embody a systematic and detailed transportation plan.. This would not only address air quality concerns, but also mitigate traffic and parking and would also help meet national goals of reducing use of fossil fuels and their effects on climate change.

3) **Green building policy.** Maximum energy efficiency is needed due to the significant residual impacts. The LEED certification goals should be Gold and Silver, not the lowest level of "certified."

The RDEIR fails to disclose the proposed LRDP's GHG Emissions and resulting impacts on climate change.

It appears that Table 4.2-20 attempts to disclose the GHG emissions from the proposed LRDP; however, the Table is misleading, inaccurate and fatally flawed in several respects.

First, the RDEIR provides a confusing GHG inventory in Table 4.2-20.
The RDEIR states that the GHG emissions disclosed do not reflect "business as usual emissions" because they "already incorporate reductions associated with transportation demand management measures, water conservation, energy conservation, and solid waste reduction." (RDEIR 4.2-59.) What "measures" is the RDEIR referring to and how did they quantify the emission offsets from these measures? How were the GHG emissions calculated? The RDEIR fails to provide sufficient detail as to how the values in this Table were derived and calculated, rendering it useless as a tool to inform decision makers and evaluate impacts.

Second, the RDEIR uses an incorrect and preposterous baseline to assess GHG impacts.
Under CEQA, the baseline against which impacts are to be measured is the physical environmental condition at the time of the Notice of Preparation.[9] Table 4.2-20 compares GHG emissions from the LRDP with housing against the LRDP without housing, and then erroneously concludes that by including housing the LRDP has reduced its potential GHG emissions by 43%, thus "GHG emissions are reduced to levels which are less than the significance thresholds." RDEIR 4.2-59. This is an unfounded conclusion that is based on a false baseline. The LRDP GHG emissions impacts must be calculated and compared against the current environmental setting that exists today in the air basin – the same way the RDEIR assessed the rest of the impacts in the RDEIR as required by CEQA.[10] It is disingenuous for the RDEIR to attempt to compare the LRDP's GHG emissions against an "imaginary" project alternative where housing is not provided. Thus, the true impact of GHG emissions on the current environmental setting is still not disclosed in the RDEIR, does not meet the requirements of a sufficient EIR under CEQA and will require revision and recirculation, again.

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[9] CEQA Guidelines §15125.
[10] CEQA Guidelines §15125.

Third, the RDEIR uses an incorrect significance threshold for GHG emissions.
The RDEIR incorrectly uses three thresholds for significance, described on p. 4.2-55, which include: 1) a 30% reduction from BAU which corresponds to the AB-32 goal; 2) Residential Transportation Performance Standard; and, 3) consistency with CARB's 2008 Scoping Plan.

Recent scientific reports confirm that human activities are a major cause of climate change and that global warming poses a serious threat to the health, natural resources, economic well being and environment of California.[11] In response, Assembly Bill 32 (AB 32), the California Global Warming Solutions Act, was passed in 2006 to require the State to reduce greenhouse gas emissions to 1990 levels by 2020.[12] This mandate is equivalent to a 25% emissions reduction from current levels. Therefore, any new project under CEQA would need to be carefully scrutinized to assess whether or not it would comply with this mandate.[13]

Any new GHG emissions must be considered significant. This is consistent with the "zero emission threshold" identified by CAPCOA (*CEQA & Climate Change: Evaluating and Addressing Greenhouse Gas Emissions from Projects Subject to the California Environmental Quality Act*, CAPCOA, January 2008). A zero emissions threshold is also used by the California State Lands Commission.[14]

Moreover, several recent scientific reports now reveal that the AB-32 targets are already out of date and that we need to reduce our GHG emissions even further, thus providing clear scientific evidence to support a zero emissions significance threshold as necessary.[15]

The RDEIR fails to disclose the proposed LRDP's impact on climate change.

The RDEIR must disclose specific impacts of adding to global climate change, including rising temperatures, increased droughts, shifting habitats, loss of species and biodiversity, increased severity and frequency of storms and extreme weather events, famine, increases in pests and diseases, sea level rise, flooding, etc.

An EIR must contain a "detailed statement" of all significant effects on the environment of the proposed project.[16] In addition, an EIR must analyze and disclose any irreversible

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[11] The California Global Warming Solutions Act of 2006, Health and Safety Code § 38501.

[12] Health and Safety Code § 38500 et seq.

[13] Technical Advisory: CEQA and Climate Change, Governor's Office of Planning and Research (June 17, 2008).

[14] See, Draft EIR for the Expansion of Offshore Oil and Gas Devlopment and Onshore Pipeline) Full Field Devlopment Project) Santa Barbara County (Venoco Inc.) ; and Venoco Ellwood Marine Terminal Lease Recirculated DEIR.

[15] Attachment C, see Hansen, James, et al, Target Atmospheric CO2:Where Should Humanity Aim? ,The Open Atmospheric Science Journal , 2008 2, 217-231; and Mathews, Damon H. and Caldeira, Ken, Stabilizing Climate Requires Near-Zero Emissions, GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L04705, doi:10.1029/2007GLO32388, 2008.

[16] Cal. Pub. Res. Code §21100(b)(1).

effects.[17] The emission of greenhouse gases and resulting climate change will cause irreversible harm in California and around the world.[18] The IPCC, Union of Concerned Scientists, and the California Climate Change Center have published several studies that identify how climate change will affect the environment.[19] These impacts include an increase in water temperatures, rise in sea level, reduction of the Sierra snowpack, increase in intensity of storms, changes in ecosystems, and increase in heat waves, ozone formation, and the potential for wildfires. These impacts must be disclosed in the RDEIR.

The RDEIR fails to analyze the LRDP's cumulative impacts on climate change

The RDEIR must evaluate the cumulative impacts relating to the Project's greenhouse gas emissions and the resulting contribution to climate change. In a case such as this, where the existing environmental problems are severe, the threshold for determining that a project's contribution to a cumulative impact is significant is that much lower.[20] Therefore, the RDEIR must fully disclose and analyze the Project's cumulative impact on global climate change.

The RDEIR failed to evaluate the impacts of global climate change on the LRDP.

The RDEIR must also analyze the potential effects of increased climate change on the Projects, in terms of sea level rise, increased coastal erosion and blufftop retreat, and other potential impacts. Scientific data reveals that sea levels will rise from a fairly modest sea level rise.[21] According to this data, UCSB is part of a vulnerable population to a 100-year coastal flood with a 1.4 meter sea level rise.[22]

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[17] Cal. Pub. Res. Code §21100(b)(2)(B).

[18] Baer, Paul and Michael Mastrandrea (Institute for Public Policy Research). 2006. High Stakes: Designing Emissions Pathways to Reduce the Risk of Dangerous Climate Change. Available at www.ippr.org; Cayan et al. 2006. Our Changing Climate – Assessing the Risks to California. Available at http://www.climatechange.ca.gov/biennial_reports/2006report/index.html.

[19] Union of Concerned Scientists. 2006. California Global Warming Impacts and Solutions, available at http://www.ucsusa.org/clean_california/ca-global-warming-impacts.html. California Climate Change Center reports include: Baldocchi and Wong, 2006; Battles et al., 2006; Cavagnaro et al., 2006; Cayan et al., 2006a; Cayan et al., 2006b; Cayan et al., 2006c; Drechsler et al., 2006; Franco and Sanstad, 2006; Fried et al., 2006; Gutierrez et al., 2006; Joyce et al., 2006; Lenihan et al., 2006; Luers et al., 2006; Luers and Moser, 2006; Medellin et al., 2006; Miller and Schlegel, 2006; Moritz and Stephens, 2006; Vicuña, 2006; Vicuña et al., 2006; Westerling and Bryant, 2006.

[20] *Kings County Farm Bureau v. City of Hanford* (1990) 221 Cal.App.3d 692, 721 [270 Cal.Rptr. 650]; *Communities for a Better Environment v. California Resources Agency* (2002) 103 Cal.App.4th 98, 120 [126 Cal.Rptr. 2d 441].

[21] Attachment D, California Climate Change Center, The Impacts of Sea-Level Rise on the California Coast, March 2009.

[22] Attachment E, *Id*. maps found at http://www.pacinst.org/reports/sea_level_rise/tmap.html.

B. Population and Housing

The RDEIR underestimates impacts to Population and Housing

Indirect growth resulting from the LRDP is underestimated. Indirect growth in the region is derived from the ripple effects of increased campus population and University expenditures on the job market in the region. Indirect growth resulting from the LRDP will produce housing demand greater than supply. This indirect growth derives from the need to replace retiring faculty and staff with new hires, many of whom will come from outside the region and with families. This effect must be analyzed in the RDEIR.

The RDEIR fails to adequately mitigate impacts to housing

The RDEIR discloses that housing development may not keep pace with enrollment and that this is a significant impact. The mitigation proposed to decrease this impact proposes to provide housing for new students with a "lag" as much as 4 years after the students arrive. Further components of the "mitigations" identified in POP-3A provide for crowding and substandard accommodations for students if there is a significant lag between enrollment increases and provision of new housing for those increases. The proposed LRDP as currently crafted will guarantee that there will be a lag time between enrollment and housing.

Moreover, the language used to bind the University to provide for these mitigation measures is weak and effectively unenforceable, in violation of CEQA. For example, POP-3A states only that the University "shall work toward achieving the following housing development goals" of decreasing the lag time to 4 years. The only binding "mitigation" identified in POP-3A in the certain event of a housing shortfall allows the University to :1) increase per room occupancy in the existing residential facilities; 2) "seek" off campus housing opportunities in motels and apartment complexes; and/or 3) temporarily convert lounges to bedrooms. Not only do these mitigation measures fail to lessen the impacts to housing, but they promise to cause additional impacts. These mitigation measures have the potential to cause significant environmental impacts to air quality, water, and traffic that have not been disclosed in the RDEIR – as required by CEQA Guideline §15126.4(a)(1).

The RDEIR fails to consider effective measures that will avoid or lessen impacts to housing.

The RDEIR fails to propose and examine the one mitigation measure that will feasibly reduce impacts to housing and population - to **pace enrollment growth to follow rather than precede development.** UCSB should develop housing prior to growth increases.

A reduced growth plan should have been examined with respect to housing. Indeed, it would appear evident that a reduced enrollment target coupled with fulfillment of the LRDP's housing projects would make a substantial positive impact on the area's housing supply. If UCSB made housing available to its existing and replacement faculty and staff, and a student population that was smaller than that projected in the LRDP, it would be significantly reducing pressure on the regional housing supply, and reducing its impact on transportation and circulation as well.

Another measure that should be explored would be to add no new enrollment but to add housing to meet requirements and mitigation goals of the 1990 LRDP in reducing current impacts such as those on the environment, water use, road capacity and air pollution.

The RDEIR is required by CEQA to propose mitigation measures that lessen impacts and has clearly failed to do so for impacts to housing and population.

C. Transportation and Circulation

The RDEIR's assessment of impacts to Traffic and Circulation is deficient and inaccurate because it omits critical information.

- There seems to be no discussion about traffic impacts of students, employees and spouses commuting *from* UCSB Housing to school, work, or play *away* from UCSB, especially at roads and intersections that were not studied in the RDEIR. The RDEIR states that, "Providing on campus housing for all LRDP enrollees…would greatly reduce if not eliminate "trips to campus" which we feel is grossly inaccurate, especially in light of the fact that a large proportion of the new enrollees will be graduate students, who often have families.

- There seems to be no discussion about assumptions regarding traffic increases due to large number of people added to the community to serve new students, faculty and staff – nurses, plumbers, dry cleaners, etc.. These additional people will be either living in the South Coast or commuting from North and South. What "multiplier effect" – the ratio of people required in the community to serve UCSB incremental students, faculty and other employees – is the RDEIR based on?

The mitigation proposed in the LRDP lacks sufficient detail, is unenforceable and ineffective in lessening impacts to Transportation and Circulation.

- Under mitigation measures, the RDEIR switches to using the passive voice, with no clarity about who would be doing the monitoring, the timetable, the funding, etc. lacking necessary information and rendering it unenforceable.

- Many of the mitigations require funding. Given that California is currently facing current and future budgetary deficits and balancing its budget through massive borrowing from future revenue sources – lottery, bonds, etc. – there seem to be no guarantees that there will be funding for the mitigations.

Without funding the mitigation proposed is merely speculative and will fail to lessen impacts.

- Similarly, some of the mitigations depend on actions of others such as MTD, which also has budget challenges. History suggests that mitigations have not been fulfilled in the past. For example, conditions of approval for the Costco Shopping centers, shuttles to Old Town Goleta and UCSB, never took place.

The following are feasible mitigation measures that can lessen impacts to parking and traffic and must be analyzed in the RDEIR.

a. Parking
  - Create an ongoing program to give cash "rebates" to students and faculty who do NOT request a parking space.
  - Lease/create remote parking space away from Campus, such as near otherwise unbuildable freeway areas or underutilized parking lots, with shuttles to and from campus.
  - Make parking free for faculty and staff willing to share a single space.
  - Make parking free for motorcycles, as it is for bikes.
  - Create an IV Residential parking permit program in a way that does not conflict with the Coastal Act and impede access to coast.

b. Public Transit
  - Use scanners on buses to record who is using them. Give "frequent flier" miles with some rewards for reaching certain levels of use. Same for Van Pools.
  - Create a UCSB Shuttle for campus and outlying UCSB housing.
  - Increase number of bus stops on campus (both Shuttle and MTD).
  - Cover bus stops from sun and rain.
  - Provide MTD passes to faculty/staff (currently discounted) as 59% of faculty/staff living on campus commute by SOV.
  - Expansion of TAP services to include increased car share service both on the main campus and at strategic University housing locations.
  - Provide shuttle service to Calle Real shopping to help reduce trip generation from campus

c. Actions to Better Manage Peak Hour Traffic
  - Change class schedules away from peak traffic hours.
  - Offer Faculty and staff flex time away from peak traffic hours
  - Encourage Telecommuting for Faculty and Staff
  - Create greater incentives for students to attend summer quarter
  - Offer more classes on weekends, away from peak days.

d. Encourage Biking
  - Cover Bike racks from the rain.

- Implement Bike station on campus to provide facilities like showers, secure locking facilities and tools for those with a longer commute to campus.
- Have locking racks on the racks themselves that better reduce bike theft.
- Provide more bike lockers for those who are interested in having a more secure place to store their bike as faculty and some students may have more valuable bikes
- Lease bikes to students, faculty and staff for nominal charge (with a deposit so they are returned). This reduces the barriers of buying and selling bikes and storing them between terms.
- The 5 new connections to campus through Ocean Road should be implemented for bikes, pedestrians, public transit and emergency vehicles

e. Reduce Use of Private Cars

- Restrict cars for freshmen and sophomores (at a minimum) living on campus; and increase enforcement of existing program. Numerous campuses (including UCSC, UCD, and UCB) have found success in these programs
- Explore pricing mechanisms/regulations to reduce car use. e.g. If one parking space is provided for each faculty/staff housing unit, any second space will be significantly more expensive, and cost alternatives are provided such as Zip car/transit option.

D. <u>Water</u>

The RDEIR's impact analysis is flawed because it overestimates the amount of water available to support the proposed LRDP, and underestimates the amount of water that will be required by the LRDP.

- According to the GWD, the RDEIR's assessment of water supply is inaccurate and an overestimate of water available to support the LRDP.[23] The RDEIR must accurately describe the environmental setting, which in this case includes the amount of water available to support the project. This provides the baseline for which impacts are assessed. This error will skew the impact analysis and effectiveness of proposed mitigation. The RDEIR must revise its water supply data, and disclose the true impacts of the LRDP on water supply.

- The GWD also concludes that the University's water demand figures are underestimates.[24] As a result, the RDEIR fails to accurately disclose the impacts to water, the impacts are underestimated and the mitigation measures are not sufficient to lessen the impact to the maximum extent feasible. The RDEIR must correct this error, which is significant new information and must trigger recirculation as required by CEQA.

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[23] Attachment F. Letter from Goleta Water District, re Comments on RDEIR for 2008 UCSB LRDP, March 30, 2009.

[24] *Id.*

- It is does not appear that the RDEIR sufficiently takes into account the possibility of a long drought in this area.

- The RDEIR does not take into account foreseeable future projects that would require water. For example, projects currently seeking or having received partial approvals include Bacara Expansion, Haskell's Beach Housing and Shelby Ranch and are not considered in the RDEIR. Also not considered in the RDEIR are Bishop Ranch and the Glen Annie Golf Course, both of which could be rezoned for massive housing by 2025.

The RDEIR fails to disclose impacts caused from mitigation measures.

The RDEIR states in proposed mitigation measure W-3G that if sufficient water supplies cannot be acquired then the University shall halt development. If development is halted before sufficient housing can be built on campus to accommodate the enrollment increases, then significant impacts to Air Quality, GHG emissions, Housing, and Traffic will result from this mitigation measure. CEQA Guidelines § 15126.4(a)(1)(D) require the RDEIR to analyze and disclose significant impacts created from mitigation measures.

The RDEIR must discuss feasible measures to mitigate impacts to water.

These include the following:

- Add fewer students, faculty and staff

- Undertake significant water conservation measures within UCSB, beyond those mentioned in the RDEIR's Mitigations including Recycled water use expansion at all campus sites. Water conservation can save substantial amounts of water. For example, a report for the Massachusetts Executive Office of Energy and Environmental Affairs calculated that an office with 1,000 men equipped with waterless urinals could save 1.56 million gallons of water annually. One acre-foot of water is 325,850 gallons, thus almost 4.8 AFY. Some calculations are needed for water savings with "state of the art" technology. Certainly this technology can improve during the build-out of the LRDP.
  1) Looping of "dead end reclaimed water lines to improve reliability. This was mentioned in the DEIR as a means of improving reliability but was not proposed as part of the LRDP. It should be.
  2) Extend recycled water lines to all campus sites; probably lines are not in place to the Devereux School site, the Storke Family Housing or North Campus housing. The 90% landscaping use of recycled water can be expanded to 100%.
  3) Use of recycled water for toilets should be re-evaluated, and the offset of potable water use calculated.

- Fund water conservation measures on the south coast, particularly, but not limited to, efforts of the Goleta Water District.

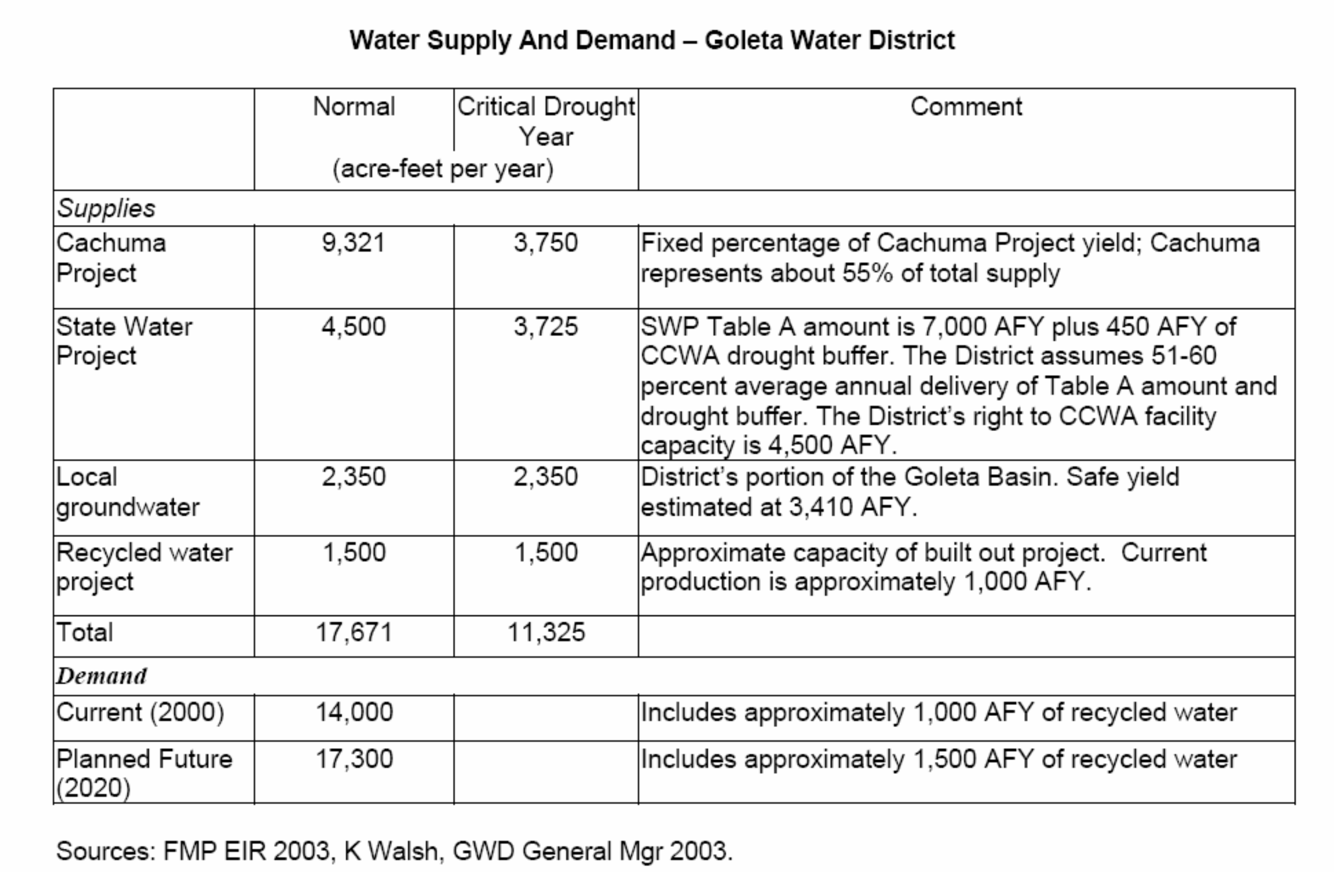
- Fund new water sources such as rain runoff cisterns for use on campus

- Fund a water reclamation/re-use facility that would recycle virtually all water used on campus

- Employ aggressive water efficiency efforts for all new construction, and retrofit of existing buildings. Examples would be waterless urinals, which have been installed in some locations on campus.

Additional Comments

- The RDEIR contains an inadequate assessment of the impact of a drought year on surface water supplies. The average surface water supply buffer from 1994 to present is not necessarily the buffer that would actually be available from a not-so-average critical drought year. A more accurate prediction of available water supply is from a table created by Steve Mack, Water Supply Manager, City of Santa Barbara on October 30, 2003, using information provided by the then General Manager of the Goleta water District, Kevin Walsh. Steve Mack's data shows that only 11,325 AF would be available to the Goleta Water District in a critical drought year, not ~17,000 AF stated in the DEIR.



Water Supply And Demand – Goleta Water District

	Normal (acre-feet per year)	Critical Drought Year (acre-feet per year)	Comment
Supplies			
Cachuma Project	9,321	3,750	Fixed percentage of Cachuma Project yield; Cachuma represents about 55% of total supply
State Water Project	4,500	3,725	SWP Table A amount is 7,000 AFY plus 450 AFY of CCWA drought buffer. The District assumes 51-60 percent average annual delivery of Table A amount and drought buffer. The District's right to CCWA facility capacity is 4,500 AFY.
Local groundwater	2,350	2,350	District's portion of the Goleta Basin. Safe yield estimated at 3,410 AFY.
Recycled water project	1,500	1,500	Approximate capacity of built out project. Current production is approximately 1,000 AFY.
Total	17,671	11,325	
Demand			
Current (2000)	14,000		Includes approximately 1,000 AFY of recycled water
Planned Future (2020)	17,300		Includes approximately 1,500 AFY of recycled water

Sources: FMP EIR 2003, K Walsh, GWD General Mgr 2003.

- Regarding recycled water consumer, the Glen Annie Golf Course currently uses about 20% of the recycled water produced locally. They are considering plans to dismantle the gold course to build housing or other non-golf course uses. This could *decrease* demand for recycled water and increase demand for potable water.

- The Sustainability Plan for Water (SP-9: Water, page 4.2-51) has goals that include:
  1) Creating a water management plan
  2) Reducing potable water use from off campus by 15% (1-3 yrs) and 25% (3-5 yrs).
  3) Increasing reclaimed water use by 15% (1-3 yrs) and 25% (3-5 yrs)
  4) Implementing water efficiency strategies for the campus based on a new water management plan.

  These are very ambitious goals, and meeting them would require following the recommendations outlined above.

- The Long-term goals depend on "on-site generation" of potable water. The mechanism is not mentioned, but desalinization comes to mind as the only likely mechanism. Given environmental and cost issues associated with desalinization, SUN opposes desalination.

E. Stormwater

General Comments

UCSB Campus Planning and Design is proposing an immense program of infrastructure upgrades. Campus wastewater is treated at the Goleta Wastewater Treatment Plant, which is operated by the Goleta Sanitary District ("GSD"). Heal the Ocean, a member of SUN, was instrumental in the campaign for the upgrade of the Goleta Sanitary District Wastewater Treatment Plant to full secondary levels, and GSD is in the process of engineering and construction to be completed five years from now, by 2014. We are familiar with GSD's designed capacity, as well as the relationship of GSD to Goleta West Sanitary District ("GWSD"), which uses GSD's facility and ocean outfall for wastewater discharge.

The RDEIR cites dramatically increased wastewater flows from both GWSD and GSD, yet maintains that no mitigation is necessary, and further engineering work or Environmental Impact Report (EIR) is not required. SUN strongly disagrees. The RDEIR (4.14-25 Clean Water Act) states, "The University is responsible for compliance with regulations associated with the Clean Water Act and any other applicable federal environmental laws regarding location, type, planning, and funding of facilities." The Clean Water Act sets forth federal water quality standards that apply to sanitary sewer service, and the expected population increase at the University is guaranteed to have a profound impact on the sanitary sewer collection system. The LRDP exceeds wastewater treatment requirements of the applicable Regional Water Quality Control Board ("RWQCB"), and is considered significant under CEQA's Guidelines.

The RDEIR Underestimates Impacts to Wastewater by Relying upon Inadequate Mitigation Measures that are Uncertain, Not Under the Control of the University and Uneenforceable.

The RDEIR (4.15-11) states, "The Goleta Sanitary District and Goleta West Sanitary District Land Use Survey/Wastewater Generation Projections Study 2006 Update (Dudek and Associates, Inc., 2006) quantifies future wastewater flow through both the GSD and GWSD systems associated with buildout of land uses within their service areas **other than** the University." Based on the Dudek study the RDEIR (4.15-13 and Table 4.15-5) states the following:

- "Cumulative wastewater flows for the GSD will fall within the treatment plant's designcapacity, but **will exceed** the remaining National Pollutant Discharge Elimination System (NPDES) capacity at buildout of other land as well as buildout of that portion of the 2008 LRDP that falls within the District;
- "Cumulative wastewater flows associated with UCSB **will exceed** the University's remaining share of the treatment plant design capacity and remaining share of NPDES permit capacity at buildout of the 2008 LRDP."

The LRDP Impact WW-1 (4.15.2.3 2008 LRDP Impacts and Mitigation Measures) states that the "implementation of the 2008 LRDP will increase wastewater flows to the Goleta Wastewater Treatment Plan via conveyance systems owned by the University, GSD and GWSD. Buildout of the 2008 LRDP, along with the buildout of projected development within the service areas of the three agencies would result in the following:

- "The total design capacity of the treatment plant would not be exceeded;
- "The portion of the total design capacity of the treatment plant owned by the University **would be exceeded**;
- "The permitted capacity owned by the University under GSD's NPDES permit **would be exceeded**;
- "The portion of the total design capacity of the treatment plant owned by the GSD would not be exceeded;
- "The permitted capacity owned by GSD under GSD's NPDES permit **would be exceeded**;
- "Neither the treatment plant design capacity nor the permitted capacity owned by the GWSD under the GSD's NPDES permit would be exceeded."

The LRDP Mitigation WW-1A (4.15.2.3 2008 LRDP Impacts and Mitigation Measures) states:

- **"**The University will request that the GSD and GWSD apply to the RWQCB to modify or re-issue each District's National Pollution Discharge Elimination Permit for the wastewater treatment plant as necessary to accommodate the average annual enrollment growth rate for the University."

The LRDP Mitigation WW-1B (4.15.2.3 2008 LRDP Impacts and Mitigation Measures) states:

- "The University will negotiate the acquisition of additional design capacity in the GSD wastewater treatment plant as necessary to accommodate the average annual enrollment growth rate."

The GSD and GWSD must acquire a re-issued NPDES permit for the wastewater treatment plants to accommodate for the population growth of the University **before** the LRDP is approved. The RDEIR states that the GSD commented on the Draft EIR which states (4.15-14), "*(GSD) does not believe that it is prudent to sell any of its remaining treatment plant capacity based on the projection of future capacity in the January 2006 Dudek and Associates report."* The RDEIR does not state if GWSD intends to sell treatment plant capacity to the University. The University cannot assume GSD and/or GWSD will sell additional treatment plant capacity to the University to accommodate the population growth. It is the responsibility of the University to finalize negotiations with GSD and/or GWSD to buy additional treatment plant capacity **before** the LRDP is approved and to follow CEQA guidelines as it pertains to the environmental impact the LRDP is initiating.

IV. The Alternatives Analysis is Flawed and Fails to Meet the Criteria Set Forth in CEQA.

The Alternatives analysis is essential to ensure compliance with the substantive requirement of CEQA, which is to avoid or lessen the environmental impacts of a proposed project. "The core of an EIR is the mitigation and alternatives sections"; alternatives should "offer substantial environmental advantages over the project proposal." [25]

The Alternatives analysis is flawed in two critical respects, discussed below: 1) the RDEIR added significant new information to the DEIR's impacts yet failed to revise the Alternatives analysis; and, 2) it fails to identify an adequate range of alternatives that would lessen environmental impacts in a meaningful way;

The RDEIR failed to revise the Alternatives analysis to reflect the significant new information added for five new impact areas.

The RDEIR added significant new information to the DEIR's impacts in five critical impact areas, yet failed to revise the Alternatives section and disclose the impact of that new information on the comparison of alternatives. Thus, the Alternatives section in the DEIR is inadequate because it is based on incorrect and outdated information for impacts to Air Quality, Population and Housing, Traffic and Circulation, and Water and Wastewater, and the resulting analysis and conclusions are therefore incorrect.

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[25] CEQA Guidelines §15126.6, emphasis added.

The RDEIR failed to identify an adequate range of alternatives that could lessen the environmental impacts of the LRDP.

The DEIR offers an inadequate range of alternatives, and fails to have any alternatives that offer "substantial environmental advantages over the project proposal." For example, although the Reduced Enrollment Alternative was deemed the environmentally superior alternative in the DEIR, it still had significant impacts to air quality, population and housing, and many of the same impacts to water quality, biology, land use, traffic and circulation that rely upon the same inadequate mitigation measures that are attributed to the proposed LRDP.

The RDEIR must consider alternatives that would reduce impacts.

In order to provide a meaningful alternative that would reduce many of the significant impacts of identified as a result of increased growth at UCSB, the RDEIR should consider the following suggestions and either include them in an alternative or provide an analysis as to why they are not feasible under CEQA.

1. Any growth planned by UCSB must be conditioned on the following:

- UCSB must audit and make available its findings as to the mitigations required in the 1990 LRDP and whether they were completed or not, plus whether they achieved the mitigation they were designed to accomplish.
- UCSB must complete any 1990 mitigations that were not completed. In addition, UCSB must mitigate any impacts that were either underestimated or for which the mitigations were not fully effective in accomplishing what they were designed to do.
- Mitigations must be made before growth and its impacts occur. Mitigations must not trail the impacts they are designed to mitigate.

2. UCSB's future mitigations should result in <u>improving</u> the situation and <u>reducing</u> impacts in the community – many of which it is responsible for creating – not just march in place.

Whatever growth alternative is proposed, UCSB must include mitigations greater than the amount that would merely offset the impacts of that growth. If there are insufficient funds for actions required to mitigate the growth UCSB proposes, the only alternatives to be explored are those that <u>reduce</u> growth and not reduce funding for required mitigations.

Three key examples in this regard are:

a) Housing: UCSB must develop housing that helps reduce its existing as well as future impact on the regional housing supply and to improve the region's jobs/housing balance.

b) Transportation: UCSB must plan from the outset to reduce private automobile use by students and staff. This goal should be intrinsic to the LRDP.

c) Water: UCSB must take actions to significantly reduce water consumption and increase conservation. Water – a very precious, shared and finite resource - is already in short supply and will not support UCSB's current proposal. In addition, our water supply is subject to rather severe fluctuations when droughts occur and any alternative must anticipate the eventuality of drought.

3. RDEIR should examine the alterative that enrollment growth be planned to follow rather than precede development.

4. A reduced growth plan should have been examined with respect to housing.
Indeed, it would appear evident that a reduced enrollment target coupled with fulfillment of the LRDP's housing projects would make a substantial positive impact on the area's housing supply. If UCSB made housing available to its existing and replacement faculty and staff, and a student population that was smaller than that projected in the LRDP, it would be significantly reducing pressure on the regional housing supply, and reducing its impact on transportation and circulation as well.

5. Another alternative that should be explored would be to add no new enrollment but to add housing to meet requirements and mitigation goals of the 1990 LRDP in reducing current impacts such as those on the environment, water use, road capacity and air pollution.

6. Another alternative is to increase "remote learning", requiring fewer people to come to campus.

V. The RDEIR Fails to Consider Cumulative Impacts.

CEQA section 21083 states: "the incremental effects of an individual project are considerable when viewed in connection with the effects of past projects, the effects of other current projects, and the effects of probably future projects."

Section 15355 of the CEQA Guidelines states:

> The cumulative impact from several projects is the change in the environment which results from the incremental impact of the project when added to other closely related past, present, and reasonably foreseeable probable future projects. Cumulative impacts can result from individually minor but collectively significant projects taking place over a period of time.

The RDEIR fails to consider the impacts of the Isla Vista Master Plan.
Each plan is enormous in its scope. The timing of the construction and phasing of each is critical. The cumulative impacts of the noise, air and water pollution, water use and

traffic during the construction phase varies a great deal depending on whether they proceed in series or in parallel time frames.

There is a very strong inter-relationship between developments in these two areas, as acknowledged, but not fully fleshed out by UCSB. For example, UCSB has repeatedly and publicly stated that it would implement a policy to bar freshman and possibly sophomores from owning a car, but only if IV had a permit parking program. Without such a program, UCSB alleges that people barred from car ownership would simply park their car in IV.

Similarly, if a parking permit program is instituted in IV, UCSB has not taken into account potential impacts in the surrounding areas. For example, people currently living in IV or on campus may park their cars in non-IV and non-campus locations, increasing traffic and parking burden in the surrounding Goleta Valley.

Though UCSB states that their RDEIR takes into account all the development outlined in the IV Master Plan, this is at odds with reality. There are major decisions still to be made on the amount, timing and location of development in IV. Since much IV redevelopment depends on private funding, it is impossible to know at this time when and to what extent IV redevelopment will occur. Similarly UCSB has acknowledged that it is unsure when it will receive funding for the development contained in the LRDP. Without knowing the timing and extent of the build out of each development plan, the cumulative impacts and the required mitigations cannot be adequately addressed.

The LRDP contains at least 50,000 square feet of commercial development on UCSB campus at Ocean Road alone, right on the campus border with Isla Vista. The RDEIR grossly underestimates the effects on current and future businesses in IV and the resulting impacts both from IV residents traveling to campus businesses and vice versa.

The LRDP carries impacts on IV and campus that have not fully been assessed, such as: the elimination of the Pardall Tunnel, the opening of numerous IV roads to car traffic, access points that today carry only bike and pedestrian traffic and end at Ocean Road.

The cumulative of impacts of housing supply, water use, wastewater, traffic, public safety and parking resulting from massive development in these two contiguous, densely populated areas can only be determined if their development plans and schedules are carefully studied and integrated. This information must be fully addressed under cumulative impacts in the RDEIR.

The RDEIR must account for development and its impacts from other jurisdictions.

- Isla Vista (County)
- County of Santa Barbara for its own building or facilities
- The City of Santa Barbara projects for its own building/facilities, such as those related to the airport.

- The City of Santa Barbara owned land (developed by developers) in areas around UCSB or even farther away. For example, some Santa Barbara City development may require water and MTD, resources shared with UCSB.
- The Federal Government facilities – military or post office or other.
- California State Government – National Guard or other
- CalTrans

Several projects in Goleta have not been accounted for in this RDEIR.
These include: Bacara expansion, Haskell's Landing, Glen Annie Housing, and Shelby. Also, when the Goleta General Plan is redone around 2020, there is a good chance that some or all of Bishop Ranch will be re-zoned for significant commercial or residential development.

VI. Conclusion

The RDEIR concludes that the proposed LRDP will result in ***eighteen significant and unmitigated impacts to air and water quality, housing, transportation and wastewater.*** These impacts will degrade our environment and negatively impact our coastal economy. In addition, the proposed LRDP will result in unmitigated levels of greenhouse gas emissions that will contribute to global warming and interfere with UCSB's goals for sustainability.

In summary, the RDEIR fails to meet CEQA's basic requirements for a legally sufficient EIR. The DEIR and RDEIR must be revised and recirculated again to include new and significant information about the project description, impacts, mitigation measures, and alternatives, as described above, for public review and comment.

Thank you for this opportunity to comment on the RDEIR. Please do not hesitate to contact me at (805) 698-5164 with any questions or for clarifications.

Respectfully submitted,

Alicia Roessler

Alicia Roessler
Attorney

Attachment A

SUSTAINABLE UNIVERSITY NOW
COALITION PRINCIPLES

UCSB is an integral part of the greater Santa Barbara County community.

The University's current Long Range Development Plan (LRDP) efforts will set the stage for its expansion over the next twenty years. Decisions made by and about the University will have far reaching and long lasting consequences for residents of the campus, Isla Vista, the Cities of Santa Barbara and Goleta and throughout Santa Barbara County.

The LRDP should fully acknowledge the relationship and impact of the University's development plans on other constituencies and jurisdictions. UCSB must ensure that the cumulative impacts on the resources it shares with its neighbors – roads and intersections, water supply, watersheds and sensitive habitats, etc. – are understood and specifically addressed.

We believe that the following principles should guide this process:

- The LRDP must be based on principles of **sustainability** and UCSB should demonstrate **leadership** in such areas as transportation, protection of natural resources, water, affordable housing, traffic, parking, energy conservation, climate change concerns, recycling, etc. UCSB development should seek to promote and include modern sustainability planning principles.

- Any UCSB growth plans should be warranted by broad social benefits as well as institutional needs. UCSB's development must be at a level that maintains and enhances the quality of life of its surrounding communities.

- Concerns and impacts raised in the draft Environmental Impact Report should be addressed fully, openly, and inclusively, providing specific mitigations, timetables and detailed planning as part of the final plan.

- The final LRDP will benefit from and should be the result of substantial community involvement and local public hearings and meetings on the proposed EIR. UCSB should seek participation from all South Coast jurisdictions and constituencies, including, but not limited to, the City of Goleta, the City and County of Santa Barbara, agencies such as the Isla Vista Redevelopment Agency, the Isla Vista Recreation and Park District, the Goleta Water

District, the Goleta West Sanitary District, the Goleta Sanitary District, neighborhood associations and individuals.

MEMBERS OF SUSTAINABLE UNIVERSITY NOW COALITION

March 17, 2009

Associated Students- Legislative Council (USCB)

Citizen's Planning Association (CPA)

Coalition for Sustainable Transportation (COAST)

Chilla Vista (UCSB)

Community Environmental Council

League of Women Voters of Santa Barbara

Santa Barbara Audubon Society

Santa Barbara County Action Network (SB CAN)

Sierra Club Los Padres Chapter - Santa Barbara Group

PUEBLO Education Fund

Santa Barbara Channelkeeper

Santa Barbara Urban Creeks Council

Attachment B

Santa Barbara Audubon Society, Inc.
A Chapter of the National Audubon Society

5679 Hollister Avenue, Suite 5B, Goleta, CA 93117 (805) 964-1468

March 29, 2009

Alissa Hummer
Campus Planning and Design
Facilities Management
c/o Vision 2025
UC Santa Barbara. CA 93106-1030
alissa.hummer@planning.ucsb.edu

RE: Comments on LRDP 2008 & Draft EIR

Dear Ms. Hummer:

Santa Barbara Audubon (Audubon) is commenting primarily on the draft EIR for the 2008 Long Range Development Plan (LRDP) of the University of California at California. Audubon is concerned about community sustainability, protection of the Devereux & Goleta Sloughs, and protection of the Coal Oil Point Reserve (COPR). A few comments are included on the proposed LRDP.

Water supply

University's current water allotment from Goleta Water District (GWD) is 944.5 acre-feet per year (AFY), but currently plans for needing 1,442 AFY for full development of the LRDP by 2025, on the main campus alone. While a minor water supply deficit is projected for Santa Catalina Residence (28 AFY deficit), North/West campus and Devereux Campus have projected surpluses (37 AFY and 25 AFY balances, respectively). As stated in the EIR introduction on water supply**, "The 2008 LRDP at full development requires more water than GWD projects will be available when all development is built and served." Impact W-3 is a Class I impact under CEQA, since it requires remedy by an outside agency, the Goleta Water District, to address.**

The draft EIR states that the LRDP development might need to be reduced 24% in order to fit with available GWD supplies (194 AFY). However, that presumes that all unallocated GWD would be allocated to UCSB. Until the projected need of potable water is reduced, and or the permits are renegotiated with GWD, the ***actual reduction in projected growth is 62%*** --for the 498 AFY needed beyond the current allocation.

It seems evident that measures must be taken to reduce the projected water deficit, and that the LRDP should not be approved for development beyond secured water supply.

The EIR should evaluate what Audubon believes is the most promising and sustainable water source for UCSB: working with GWD, funding upgraded treatment and expanded facilities for reclaimed (recycled)water, and reclaimed water lines to irrigated agricultural users. This is consistent with the Goleta Water District comments (draft letter 6-16-2008). This would free up potable water that could be utilized by UCSB, with negotiated agreements.

Vice-Chancellor John Weimann sated that the University is in negotiations with the City of Carpinteria to purchase a portion of their unutilized State Water allotment. Audubon considers this to be an unreliable source of water, especially during drought years. With climate change, California is predicted to have greater weather extremes, with more severe dry and wet years. This would result in some years of having a pipeline but no available water.

The EIR should evaluate the impacts of these water sources for state and local impacts; we believe that the local expansion of reclaimed water will be more reliable and have fewer environmental impacts.

Investment in the highest water conservation technology is also critical to a positive water balance--in new construction and expanded retrofit in existing buildings.

In discussion of the recycled water supply (reclaimed water), the EIR states that over 90% of irrigation at UCSB is now reclaimed water. This is supplied with “dead end lines”. It states that “looping” of dead end reclaimed water lines would improve reliability of the system, but is not proposed as part of the LRDP. It furthermore states that “approved redundant supply from the potable water system for each branch” would also enhance the reliability of the recycled water system. An evaluation of plumbing toilets with recycled water in all new construction, and possibly as a retrofit, should be done to determine the amount of potable water that could be freed up for water uses requiring potable water. Apparently this was tried in one campus building, possibly the Bren School, but the possibility of poor reliability was too risky. Rather than abandoning this approach, options of “double plumbing” or an ”approved redundant supply of potable water” should be explored. This approach can be compared/ combined in the EIR with funding other GWD users of reclaimed water. **These measures would be consistent with Mitigation W-3b “use of recycled water to the maximum extent feasible”.**

Audubon has noted that the new facilities proposed for Santa Catalina (formerly Francisco Torres) will result in a water deficit relative to current allocations. Does this facility have recycled water lines? This would be a relatively easy fix for freeing up potable water. Lines could then easily be extended to the other campuses west of Isla Vista, if they are not already installed.

Innovative water conservation measures, such as super-conservative appliances and equipment in new construction, and retrofitted in existing structures, could reduce the projected future water demand of the LRDP at build-out, by reducing the “water duty factor” for each building. If the water use declined in current UCSB buildings, even those under differ water permits, it would be strong position for re-negotiating water permits to request transfer of unused allocations to the permit areas in need of more water. If these measures were insufficient, the University might offer to fund extension of recycled water lines to other water district users who could use non-potable water for landscaping and agricultural needs. According to the LRDP, UCSB currently used 143 AFY of recycled water, and has a “right of first refusal” to 280 AFY. Full utilization of this recycled water to preserve potable water for “higher” uses should be a high priority in water use planning. In addition, expansion of the Goleta Sanitary District recycled water capacity is feasible, we understand, if demand is present.

These conservation measures would likely be much less expensive and more reliable than purchasing State Water, desalinization of sea water, or filtration of recycled water to drinking water standards. Given the recent restraints on water deliveries of state water due to environmental concerns, and the likelihood of global climate change impacts on the water supply (reduced snow pack, more variability in weather patterns so more dry years and more very wet years), State Water should not be relied on for expanded water needs.

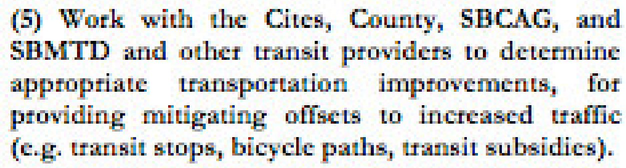
Transportation

The LRDP plans to house all additional students, faculty and staff on campus. This is commendable, and reduces the impact of additional people in the community, but by no means to zero. The EIR demonstrates that some intersections would be at unacceptable levels of service at full build-out of the LRDP. A comprehensive alternative transportation system should be evaluated in the EIR to determine if such a program would reduce adverse impacts to an acceptable level.

Several components of an alternative transportation system could include:

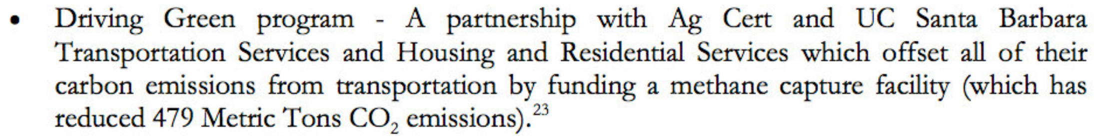
1) Comprehensive bicycle routes and parking on and between all UCSB campuses. Given the high usage of bicycles now, this is crucial to the program. Ensuring that bicyclists can safely and efficiently cross the modified Ocean Road is a major requirement of the program.
2) An electric shuttle between all housing clusters and academic facilities. This could be operated separately by campus or by MTD, if negotiated.
3) MTD-coordinated service to campus and to middle school, high school, shopping and recreational destinations. High levels of service will encourage usage. This will require long-term operational funding for MTD.
4) Expansion of the Zip Car service, with cars available at all housing clusters and on the main campus.
5) Improved connection to the Goleta train station.

The reluctance of the University to commit to expensive mitigations such as an electric shuttle among all housing clusters is understandable. However, given the unacceptable impacts of the proposed expansion, Audubon believes that these impacts must be mitigated to the maximum extent feasible, and that the Vision 2025 should not be approved until these mitigations are spelled out. The Transportation Mitigation stated below is inadequate, that the University will work with other agencies to address transportation impacts.



(5) Work with the Cites, County, SBCAG, and SBMTD and other transit providers to determine appropriate transportation improvements, for providing mitigating offsets to increased traffic (e.g. transit stops, bicycle paths, transit subsidies).

The current Driving Green program is exemplary, but there is no information if the program could be expanded to cover additional greenhouse emissions.

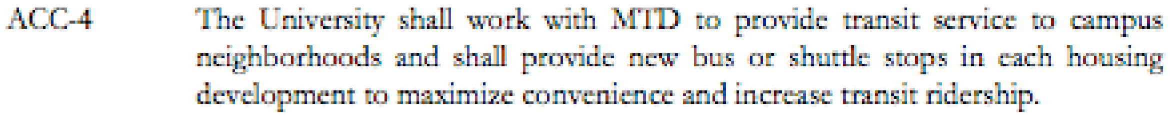


- Driving Green program - A partnership with Ag Cert and UC Santa Barbara Transportation Services and Housing and Residential Services which offset all of their carbon emissions from transportation by funding a methane capture facility (which has reduced 479 Metric Tons CO_2 emissions).[23]

How will the TAP program be expanded to reduce the impact of LRDP expansion? The documents describe what it is and the level of use in 2007. No plans for expanding the program to address additional impacts is provided in the document.

The dense clustering of housing makes shuttle service to campus and expansion of Zipcars to provide alternatives to private automobile ownership more feasible, and these alternatives should be emphasized. Coordination with the City of Goleta, the City of Santa Barbara, and the County of Santa Barbara could make a vibrant Zipcar program in our community. Audubon understands the University currently has *two Zipcars* available, which is a start but hardly sufficient to reduce car ownership and usage.

Shuttle bus service can be offered by the University or in partnership with MTD. The latter is probably preferable, as it can be better integrated with transportation to work, shopping, K-12 schools, and recreation in the community at large. The LRDP does include the following policy, which is very desirable:



ACC-4 The University shall work with MTD to provide transit service to campus neighborhoods and shall provide new bus or shuttle stops in each housing development to maximize convenience and increase transit ridership.

Undergraduates have free bus passes on MTD as part of their registration. Do graduate students? As a higher proportion of graduate students than undergraduates are proposed in the 5000-student expansion, this would encourage bus use and alternative transportation. Would staff and faculty use bus passes if provided?

Audubon has heard that the campus has a policy that parking permits are not issued if one lives within one mile of campus, but that it is not enforced. Is this policy applicable to students only? Evaluation of enforcement of this policy, and the effect on bicycle and shuttle use to campus should be included in the EIR.

The EIR describes the parking problem at Goleta Beach and Isla Vista, where students and staff park in order to avoid paying for parking on campus. However, so strategies to address this problem are proposed.

Commuter Rail Service.

The LRDP supports commuter rail service, should it come to pass. However, no effort is made to make current rail service practical for UCSB students/staff, particularly those without a private vehicle. Many students and staff could use the train for out-of-town visits, and the Goleta train depot is not far from campus. However, one student reported that she took the train back to Isla Vista from her home in San Luis Obispo, and it took *two hours by bus* from the depot to her Isla Vista home. Partnership with MTD and publicity of new service, eg. in the *Nexus* and Transportation Services, could make UCSB students, faculty and staff aware of the service. By the way, the student ended up riding her bicycle to and from the train station, but it limits the luggage one can take on a week-end excursion! Most people will decide they need a car for week-end trips given such inconvenience.

Utilities--Energy Use

The draft LRDP and draft EIR describe the energy efficiency of the plan and of individual buildings, and having new students, faculty and staff living close to (on) campus, and need for electricity and natural gas. It also describes the efforts to improve energy efficiency in existing buildings. However, **the draft EIR fails to estimate the future energy needs of the campus at full build-out of the 2008 LRDP.** This is a significant deficiency in the plan and EIR.

The dEIR describes the Facilities Energy Program, which has invested $4.4 million in energy efficiency, and declines in energy in some buildings, such as the UCEN. However, there are discrepancies: on page 4.16-6 the document states that "due to physical growth over the past 10 years, total usage of electricity has increased. However, there has been a decrease in energy consumption on a per-building level as a result of the implementation of energy conservation programs." However, two pages later the document claims "Reduction is energy usage has been maintained through 2006, despite ongoing building expansion and increased facilities." This is misleading, as it reflects the time period only from the peak usage in 1998.

While the energy conservation efforts to date are laudable**, the energy usage must be calculated for the proposed LRDP construction.** There seems to be a disconnect with the stated sustainability goals, and the proposed expansion of the campus. The LRDP Draft sustainability Plan--said to be in Appendix 4.16-1, but not provided--has these stated goals:

- "Develop a Campus climate Neutral Plan by 2008
- "By 2010, reduce greenhouse gas emissions to 2000 levels
- "By 2020, reduce greenhouse gas emissions to 1990 levels….."

While the 2010 goal might be achievable, there is nothing to demonstrate that the 2020 is conceivably possible if full build out proceeds per the 2008 LRDP proposal. The UCSB Sustainability Plan is available on the web, but there appears to be no mention of how the sustainability goals could be achieved under a scenario of LRDP 2008 implementation.

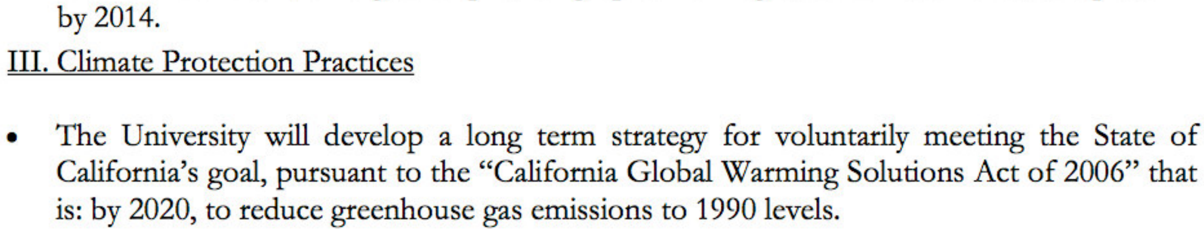
The impact evaluation of increased energy demand under the LRDP 2008 is totally inadequate. UTIL-3 states there will be an increase in energy use--without any calculations-- and somehow that is less than significant and no mitigation is required.

Global Climate Change (listed under "other CEQA considerations")

The dEIR states that despite implementation of energy reducing strategies over the past years (number of years not stated!)" the campus's total greenhouse gas emissions have risen approximately 5%." While the University is to be commended for the progress to date, the increase in greenhouse emissions with the recent construction demonstrated the immense task to reduce emissions given the planned expansion.

This level of commitment to LEED building standards, etc. will clearly not be sufficient to meet the climate protection standards that the University system and this campus have agreed to meet. For example:

II. Clean Energy Standard



- The University will develop a strategic plan for siting renewable power projects in existing and new facilities with a goal of providing up to 10 megawatts of local renewable power by 2014.

III. Climate Protection Practices

- The University will develop a long term strategy for voluntarily meeting the State of California's goal, pursuant to the "California Global Warming Solutions Act of 2006" that is: by 2020, to reduce greenhouse gas emissions to 1990 levels.

Given the timeframe of the LRDP and the Clean Energy Standard commitment of a renewable power project providing 10 mw of renewable energy by 2014, this plan should be part of the LRDP. There is *no* plan presented to reduce greenhouse gas emission to the 1990 level. This would be ambitious for UCSB with the current level of development, but feasible with retrofitting of older, inefficient buildings. With the addition of 1.8 million ASF of academic space plus additional housing for the proposed new 5000 students, 336 faculty and 1400 staff, it seems impossible.

No attempt is made to demonstrate how these goals will be met, other than very nonspecific statements such as cogeneration and/or on-site renewable energy (page 6.0-14). The LRDP, to be credible, should have specific proposals for alternative energy. Such as a potential site for a wind turbine, or specific buildings or campuses planned for photovoltaic, or solar hot water for a specific swimming pool. What buildings might be good candidates for cogeneration? --with a commitment to construct with implementation of that portion of the LRDP.

The LRDP and dEIR are deficient in that they do not present mechanisms by which the stated goals can be met. See comments on the transportation impacts as related the climate change, in the Transportation Section comments.

Expansion, Commitment to House added students, faculty and staff

The plan states that all the added 5000 students, 340 faculty and 1,400 staff will be housed on campus. That is excellent for efficiency in transportation and land use. However, it is also stated that there could be "lag time" of up to four years where housing lags behind the addition of new students, staff or faculty. The **impact of this lag is not evaluated.** The mitigation that should be included is a **commitment that additional students, faculty and staff will not be added until housing is available to accommodate the additional people.**

Comments Biology 4.3

Wildlife Resources

"Common vertebrate species documented in riparian/wetland communities of the campus include…. California quail (*Callipepla californica*)…. " (pg Bio 4.3-12) While California quail are generally a common species, according to Paul Lehman (*The Birds of Santa Barbraa County, California, 1994*), California quail disappeared from the UCSB campus in 1985 or 1986 and from Coal Oil Point Reserve (COPR) in 1988. Paul Lehman attributed declines in the coastal areas to development, drought and increased predation. In the past few years, breeding has resumed on the North Bluff and COPR, possibly associated with habitat restoration of these areas.

Increased human activity associated with LRDP 2008 could jeopardize these gains and general wildlife habitat of adjacent natural areas. It is recommended that enhancement of campus natural areas be a goal of the LRDP. Where no direct impacts require mitigation measures, these enhancements can be funded with grants.

Sensitive Species--UCSB Campus

Table 4.3-1 lists Special-status habitats, plants and vertebrates at Coal Oil Point Reserve (COPR). Missing is Santa Barbara honeysuckle, which is listed for the North Campus. Figure 4.3-2 is missing sites for several sensitive species at COPR: Tidewater goby shown only at the northern boundary where Devereux Creek enters the slough, while the species is prevalent in other parts of the slough. Santa Barbara honeysuckle and Ventura milk vetch are not shown on the map. California Least Tern nesting/ roosting sites (endangered species) are not shown. The text/tables and figures should be consistent.

Parish's glasswort is a Species of Local Concern, located at COPR, and is not mentioned. The only populations are disturbed by trails; proposed trail improvements should reduce impacts to these populations.

Increased recreational use as campus human populations increased exert pressure on the sensitive wildlife species. Even without direct impacts to wetlands such as Francisco Torres (Santa Catalina) wetlands and the Devereux Slough fingers, these areas should be restored to enhance their wildlife habitat values as adjacent open space is developed. Again, where no direct impacts occur, these restoration efforts can be grant funded. However, restoration plans should be included in LRDP goals, with timetables associated with development of adjacent areas.

Sensitive Plant Communities

Old Gym wetlands would be an example of coastal freshwater marsh, even though a constructed wetland. This should be listed.

Southern Coastal Bluff Scrub

"Southern coastal bluff scrub habitat is considered sensitive by the CNDDB and the CCC" states the draft LRDP (pg 4.3-10). See ESHA section.

Environmentally Sensitive Habitat Areas (ESHA)

Figure 4.3-3 shows the Proposed ESHA overlay--all areas proposed for ESHA designation as part of the LRDP 2008. The Old Gym wetlands are not shown as ESHA, and likely qualify for this designation. This should be evaluated.

100-foot Setback from wetlands

The current LRDP retains 100-foot setbacks from wetland resources. The only exception has been North Campus faculty housing where the South parcel has been set aside as open space with a conservation easement and specified restoration acreage in compensation. **Policies 302400(b).9 and 30240(b).10 in the 1990 LRDP are not proposed for retention in the 2008 LRDP.** These policies establish building setbacks around the Storke wetlands, protect transition habitats surrounding wetlands, and protect raptor and wildlife habitat and trees surrounding the Storke Wetland in areas directly adjacent to Goleta Slough. **Audubon asserts that it is essential that these policies be retained in their entirety in the 2008 LRDP.**

LRDP Mitigation BIO-1D: "Project plans for any development under the 2008 LRDP Mitigation BIO-1D: Project plans for any development under the 2008 LRDP within 100 feet of aquatic resources shall include design features to minimize the effects of increased noise, lighting, and automotive and foot traffic density on the adjacent aquatic resource.

There should not be encroachment in the 100-foot setback. Some existing encroachments cannot be remedied, e.g. the Slough Road along the edge of Devereux Slough, which is built on fill within the wetland. However, all improvements must take place within the existing development.

An example is the redevelopment of Santa Ynez Apartments. From the map it appears that existing development is within the 100-foot wetland buffer in some areas. This should be pulled back to provide for the appropriate buffer, which should be restored, during redevelopment.

Coal Oil Point Reserve Protection

COP Parking

There are conflicting statements regarding Coastal Access parking at Coal Oil Point Reserve. Audubon opposes public access parking at COP, in order to protect natural resources in the reserve. TRANS 4 lists COP as one of the options for providing 80 public access parking sites for North and West campus. Elsewhere (PE.9) it states that parking will be restricted at COP. Audubon supports handicapped parking only for the public at this location.

Slough Road Improvements

PE.5 suggests that to reduce traffic on Devereux road (Slough Road), one way traffic may be instituted with return traffic through the Devereux School site. Also stated, this would provide space for an adjacent walkway/bikeway. This may be an excellent idea, and increase safety on this narrow road. Audubon encourages further evaluation of this circulation improvement. The EIR must evaluate this proposal: given the wetland on both sides of Slough Road for a significant portion, the combined roadway and walkway can be no wider than the current road. Restoration of the road berm along the North and South Fingers should be part of this project. This would be the appropriate time for modification of the culverts under the road, to enhance hydrologic connection of the Fingers with the slough. These modifications would be enhancements that could be grant funded, unless the transportation project has impacts requiring mitigation.

Hydrology

The hydrologic impacts are inadequately assessed, and not adequately mitigated**. Impact HYD-3 states there will be an increase in impermeable surfaces, but the impact is not significant, and no mitigation measures are proposed**. Significant portion of the main campus drain into Goleta Slough, an impaired water body. Measures to limit impervious surfaces, to retain infiltration to the maximum extent feasible are needed. This can be achieved by permeable surfaces, such as parking areas, walkways and patios, and retention areas to encourage groundwater infiltration.

Goleta Slough Impacts

Impacts to Goleta Slough are not well identified. However, there is an intensification of development adjacent to and within the Goleta Slough. In addition to BMPs to reduce run-of and filter pollutants, Audubon recommends that UCSB commit to removing University sewer lines from Storke Wetlands, and work with the Goleta West Sanitary District to have all lines relocated to University Road. The SB Airport is nearing completion of the Tidal Circulation Study with bird use evaluations. Should this provide no evidence of an *increase* in bird strike hazard, re-establishment of tidal circulation will be feasible. If direct impacts are identified, re-establishment if tidal circulation would be the optimal mitigation for hydrologic, water quality and biological resource impacts to Goleta Slough wetlands. Without direct impacts to the slough from University, this can be grant-funded. However, it would compensate for indirect impacts and be a community amenity. **Policy 30240(a).14 appears to be excluded from the proposed 2008 LRDP.** This policy was contained in the previous 1980 and 1990 LRDPs This policy requires the University to work with the City of Santa Barbara to allow tidal influx from Goleta Slough into the Storke Wetlands through the Airport's tidal gates.

Summary

The LRDP and draft EIR provide very detailed information in some areas, but are deficient in evaluating the impacts of some major issues. Further analysis is needed before certification of the EIR. If significant impacts cannot be mitigated, the scale of the LRDP must be reduced.

Thank you for the opportunity to comment on the LRDP 2008 and the draft EIR.

Sincerely,

Darlene Chirman

Darlene Chirman, President
Santa Barbara Audubon

Attachment C

The Open Atmospheric Science Journal, **2008**, *2*, **217-231**

Open Access

Target Atmospheric CO_2: Where Should Humanity Aim?

James Hansen[*,1,2], Makiko Sato[1,2], Pushker Kharecha[1,2], David Beerling[3], Robert Berner[4], Valerie Masson-Delmotte[5], Mark Pagani[4], Maureen Raymo[6], Dana L. Royer[7] and James C. Zachos[8]

[1]*NASA/Goddard Institute for Space Studies, New York, NY 10025, USA*

[2]*Columbia University Earth Institute, New York, NY 10027, USA*

[3]*Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK*

[4]*Department of Geology and Geophysics, Yale University, New Haven, CT 06520-8109, USA*

[5]*Lab. Des Sciences du Climat et l'Environnement/Institut Pierre Simon Laplace, CEA-CNRS-Universite de Versailles Saint-Quentin en Yvelines, CE Saclay, 91191, Gif-sur-Yvette, France*

[6]*Department of Earth Sciences, Boston University, Boston, MA 02215, USA*

[7]*Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459-0139, USA*

[8]*Earth & Planetary Sciences Dept., University of California, Santa Cruz, Santa Cruz, CA 95064, USA*

Abstract: Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica. Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.

Keywords: Climate change, climate sensitivity, global warming.

1. INTRODUCTION

Human activities are altering Earth's atmospheric composition. Concern about global warming due to long-lived human-made greenhouse gases (GHGs) led to the United Nations Framework Convention on Climate Change [1] with the objective of stabilizing GHGs in the atmosphere at a level preventing "dangerous anthropogenic interference with the climate system."

The Intergovernmental Panel on Climate Change [IPCC, [2]] and others [3] used several "reasons for concern" to estimate that global warming of more than 2-3°C may be dangerous. The European Union adopted 2°C above pre-industrial global temperature as a goal to limit human-made warming [4]. Hansen *et al*. [5] argued for a limit of 1°C global warming (relative to 2000, 1.7°C relative to pre-industrial time), aiming to avoid practically irreversible ice sheet and species loss. This 1°C limit, with nominal climate sensitivity of ¾°C per W/m^2 and plausible control of other GHGs [6], implies maximum CO_2 ~ 450 ppm [5].

Our current analysis suggests that humanity must aim for an even lower level of GHGs. Paleoclimate data and ongoing global changes indicate that 'slow' climate feedback processes not included in most climate models, such as ice sheet disintegration, vegetation migration, and GHG release from soils, tundra or ocean sediments, may begin to come into play on time scales as short as centuries or less [7]. Rapid on-going climate changes and realization that Earth is out of energy balance, implying that more warming is 'in the pipeline' [8], add urgency to investigation of the dangerous level of GHGs.

A probabilistic analysis [9] concluded that the long-term CO_2 limit is in the range 300-500 ppm for 25 percent risk tolerance, depending on climate sensitivity and non-CO_2 forcings. Stabilizing atmospheric CO_2 and climate requires that net CO_2 emissions approach zero, because of the long lifetime of CO_2 [10, 11].

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*Address correspondence to this author at the NASA/Goddard Institute for Space Studies, New York, NY 10025, USA; E-mail: jhansen@giss.nasa.gov

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We use paleoclimate data to show that long-term climate has high sensitivity to climate forcings and that the present global mean CO_2, 385 ppm, is already in the dangerous zone. Despite rapid current CO_2 growth, ~2 ppm/year, we show that it is conceivable to reduce CO_2 this century to less than the current amount, but only *via* prompt policy changes.

1.1. Climate Sensitivity

A global climate forcing, measured in W/m^2 averaged over the planet, is an imposed perturbation of the planet's energy balance. Increase of solar irradiance (So) by 2% and doubling of atmospheric CO_2 are each forcings of about 4 W/m^2 [12].

Charney [13] defined an idealized climate sensitivity problem, asking how much global surface temperature would increase if atmospheric CO_2 were instantly doubled, assuming that slowly-changing planetary surface conditions, such as ice sheets and forest cover, were fixed. Long-lived GHGs, except for the specified CO_2 change, were also fixed, not responding to climate change. The Charney problem thus provides a measure of climate sensitivity including only the effect of 'fast' feedback processes, such as changes of water vapor, clouds and sea ice.

Classification of climate change mechanisms into fast and slow feedbacks is useful, even though time scales of these changes may overlap. We include as fast feedbacks aerosol changes, e.g., of desert dust and marine dimethylsulfide, that occur in response to climate change [7].

Charney [13] used climate models to estimate fast-feedback doubled CO_2 sensitivity of 3 ± 1.5°C. Water vapor increase and sea ice decrease in response to global warming were both found to be strong positive feedbacks, amplifying the surface temperature response. Climate models in the current IPCC [2] assessment still agree with Charney's estimate.

Climate models alone are unable to define climate sensitivity more precisely, because it is difficult to prove that models realistically incorporate all feedback processes. The Earth's history, however, allows empirical inference of both fast feedback climate sensitivity and long-term sensitivity to specified GHG change including the slow ice sheet feedback.

2. PLEISTOCENE EPOCH

Atmospheric composition and surface properties in the late Pleistocene are known well enough for accurate assessment of the fast-feedback (Charney) climate sensitivity. We first compare the pre-industrial Holocene with the last glacial maximum [LGM, 20 ky BP (before present)]. The planet was in energy balance in both periods within a small fraction of 1 W/m^2, as shown by considering the contrary: an imbalance of 1 W/m^2 maintained a few millennia would melt all ice on the planet or change ocean temperature an amount far outside measured variations [Table **S1** of 8]. The approximate equilibrium characterizing most of Earth's history is unlike the current situation, in which GHGs are rising at a rate much faster than the coupled climate system can respond.

Climate forcing in the LGM equilibrium state due to the ice age surface properties, i.e., increased ice area, different vegetation distribution, and continental shelf exposure, was -3.5 ± 1 W/m^2 [14] relative to the Holocene. Additional forcing due to reduced amounts of long-lived GHGs (CO_2, CH_4, N_2O), including the indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor (Fig. **S1**) was -3 ± 0.5 W/m^2. Global forcing due to slight changes in the Earth's orbit is a negligible fraction of 1 W/m^2 (Fig. **S3**). The total 6.5 W/m^2 forcing and global surface temperature change of 5 ± 1°C relative to the Holocene [15, 16] yield an empirical sensitivity ~¾ ± ¼ °C per W/m^2 forcing, i.e., a Charney sensitivity of 3 ± 1 °C for the 4 W/m^2 forcing of doubled CO_2. This empirical fast-feedback climate sensitivity allows water vapor, clouds, aerosols, sea ice, and all other fast feedbacks that exist in the real world to respond naturally to global climate change.

Climate sensitivity varies as Earth becomes warmer or cooler. Toward colder extremes, as the area of sea ice grows, the planet approaches runaway snowball-Earth conditions, and at high temperatures it can approach a runaway greenhouse effect [12]. At its present temperature Earth is on a flat portion of its fast-feedback climate sensitivity curve (Fig. **S2**). Thus our empirical sensitivity, although strictly the mean fast-feedback sensitivity for climate states ranging from the ice age to the current interglacial period, is also today's fast-feedback climate sensitivity.

2.1. Verification

Our empirical fast-feedback climate sensitivity, derived by comparing conditions at two points in time, can be checked over the longer period of ice core data. Fig. (**1a**) shows CO_2 and CH_4 data from the Antarctic Vostok ice core [17, 18] and sea level based on Red Sea sediment cores [18]. Gases are from the same ice core and have a consistent time scale, but dating with respect to sea level may have errors up to several thousand years.

We use the GHG and sea level data to calculate climate forcing by GHGs and surface albedo change as in prior calculations [7], but with two refinements. First, we specify the N_2O climate forcing as 12 percent of the sum of the CO_2 and CH_4 forcings, rather than the 15 percent estimated earlier [7] Because N_2O data are not available for the entire record, and its forcing is small and highly correlated with CO_2 and CH_4, we take the GHG effective forcing as

$$Fe\ (GHGs) = 1.12\ [Fa(CO_2) + 1.4\ Fa(CH_4)], \qquad (1)$$

using published formulae for Fa of each gas [20]. The factor 1.4 accounts for the higher efficacy of CH_4 relative to CO_2, which is due mainly to the indirect effect of CH_4 on tropospheric ozone and stratospheric water vapor [12]. The resulting GHG forcing between the LGM and late Holocene is 3 W/m^2, apportioned as 75% CO_2, 14% CH_4 and 11% N_2O.

The second refinement in our calculations is to surface albedo. Based on models of ice sheet shape, we take the horizontal area of the ice sheet as proportional to the 4/5 power of volume. Fig. (**S4**) compares our present albedo forcing with prior use [7] of exponent 2/3, showing that this

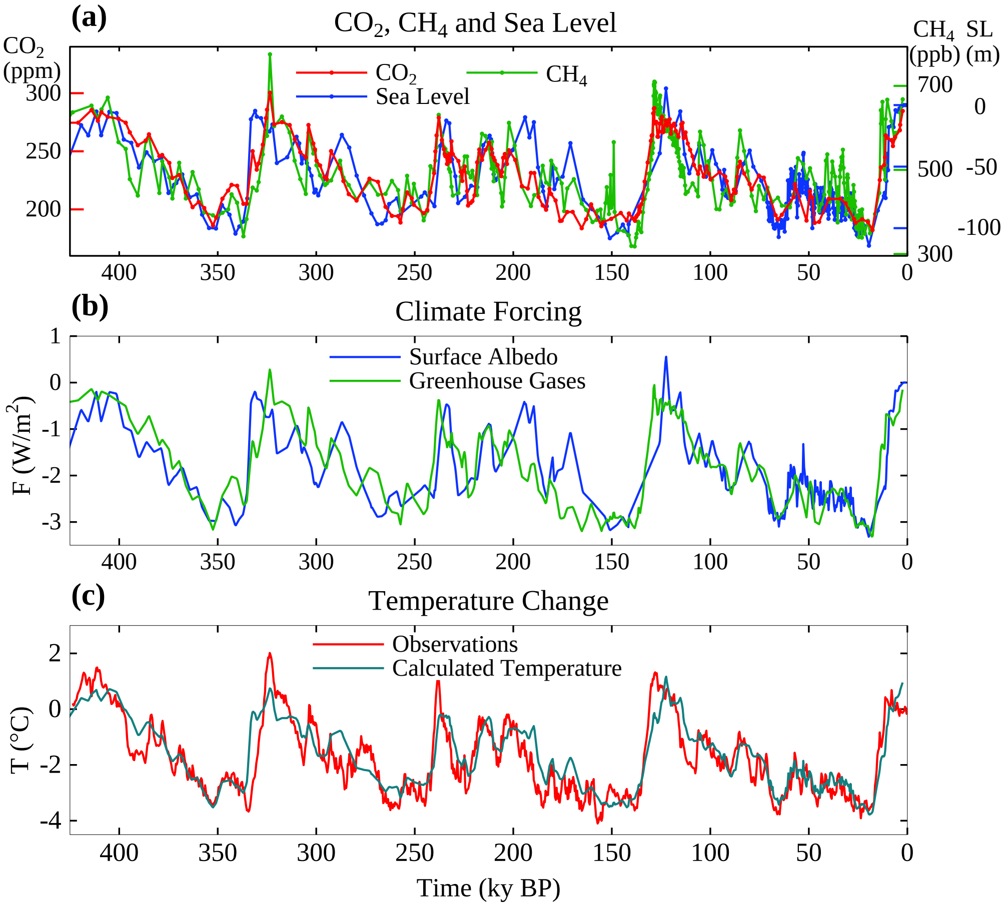

Fig. (1). (**a**) CO$_2$, CH$_4$ [17] and sea level [19] for past 425 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from sea level change. (**c**) Calculated global temperature change based on climate sensitivity of ¾°C per W/m^2. Observations are Antarctic temperature change [18] divided by two.

choice and division of the ice into multiple ice sheets has only a minor effect.

Multiplying the sum of GHG and surface albedo forcings by climate sensitivity ¾°C per W/m^2 yields the blue curve in Fig. (**1c**). Vostok temperature change [17] divided by two (red curve) is used to crudely estimate global temperature change, as typical glacial-interglacial global annual-mean temperature change is ~5°C and is associated with ~10°C change on Antarctica [21]. Fig. (**1c**) shows that fast-feedback climate sensitivity ¾°C per W/m^2 (3°C for doubled CO$_2$) is a good approximation for the entire period.

2.2. Slow Feedbacks

Let us consider climate change averaged over a few thousand years – long enough to assure energy balance and minimize effects of ocean thermal response time and climate change leads/lags between hemispheres [22]. At such temporal resolution the temperature variations in Fig. (**1**) are global, with high latitude amplification, being present in polar ice cores and sea surface temperature derived from ocean sediment cores (Fig. **S5**).

GHG and surface albedo changes are mechanisms causing the large global climate changes in Fig. (**1**), but they do not initiate these climate swings. Instead changes of GHGs and sea level (a measure of ice sheet size) lag temperature change by several hundred years [6, 7, 23, 24].

GHG and surface albedo changes are positive climate feedbacks. Major glacial-interglacial climate swings are instigated by slow changes of Earth's orbit, especially the tilt of Earth's spin-axis relative to the orbital plane and the precession of the equinoxes that influences the intensity of summer insolation [25, 26]. Global radiative forcing due to orbital changes is small, but ice sheet size is affected by changes of geographical and seasonal insolation (e.g., ice melts at both poles when the spin-axis tilt increases, and ice melts at one pole when perihelion, the closest approach to the sun, occurs in late spring [7]. Also a warming climate causes net release of GHGs. The most effective GHG feedback is release of CO$_2$ by the ocean, due partly to temperature dependence of CO$_2$ solubility but mostly to increased ocean mixing in a warmer climate, which acts to flush out

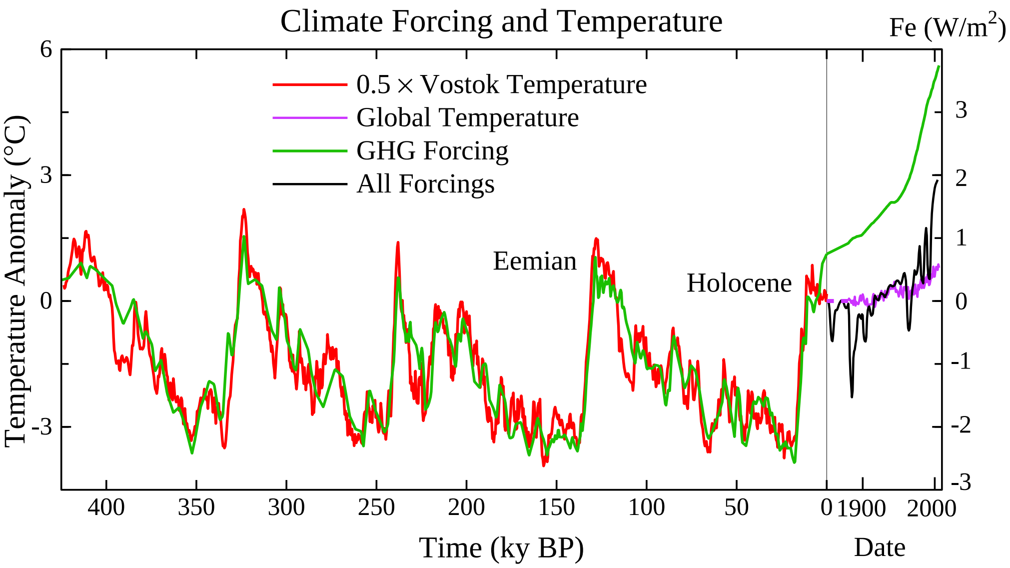

Fig. (2). Global temperature (left scale) and GHG forcing (right scale) due to CO_2, CH_4 and N_2O from the Vostok ice core [17, 18]. Time scale is expanded for the industrial era. Ratio of temperature and forcing scales is 1.5°C per W/m^2, i.e., the temperature scale gives the expected equilibrium response to GHG change including (slow feedback) surface albedo change. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky BP (Fig. **S6**). Zero point of modern temperature and net climate forcing was set at 1850 [5], but this is also the zero point for 10-8 ky BP, as shown by the absence of a trend in Fig. (**S6**) and by the discussion of that figure.

deep ocean CO_2 and alters ocean biological productivity [27].

GHG and surface albedo feedbacks respond and contribute to temperature change caused by any climate forcing, natural or human-made, given sufficient time. The GHG feedback is nearly linear in global temperature during the late Pleistocene (Fig. **7** of [6, 28]). Surface albedo feedback increases as Earth becomes colder and the area of ice increases. Climate sensitivity on

Pleistocene time scales includes slow feedbacks, and is larger than the Charney sensitivity, because the dominant slow feedbacks are positive. Other feedbacks, e.g., the negative feedback of increased weathering as CO_2 increases, become important on longer geologic time scales.

Paleoclimate data permit evaluation of long-term sensitivity to specified GHG change. We assume only that, to first order, the area of ice is a function of global temperature. Plotting GHG forcing [7] from ice core data [18] against temperature shows that global climate sensitivity including the slow surface albedo feedback is 1.5°C per W/m^2 or 6°C for doubled CO_2 (Fig. **2**), twice as large as the Charney fast-feedback sensitivity. Note that we assume the area of ice and snow on the planet to be predominately dependent on global temperature, but some changes of regional ice sheet properties occur as part of the Earth orbital climate forcing (see Supplementary Material).

This equilibrium sensitivity of 6°C for doubled CO_2 is valid for specified GHG amount, as in studies that employ emission scenarios and coupled carbon cycle/climate models to determine GHG amount. If GHGs are included as a feedback (with say solar irradiance as forcing) sensitivity is still larger on Pleistocene time scales (see Supplementary Material), but the sensitivity may be reduced by negative feedbacks on geologic time scales [29, 30]. The 6°C sensitivity reduces to 3°C when the planet has become warm enough to lose its ice sheets.

This long-term climate sensitivity is relevant to GHGs that remain airborne for centuries-to-millennia. The human-caused atmospheric GHG increase will decline slowly if anthropogenic emissions from fossil fuel burning decrease enough, as we illustrate below using a simplified carbon cycle model. On the other hand, if the globe warms much further, carbon cycle models [2] and empirical data [6, 28] reveal a positive GHG feedback on century-millennia time scales. This amplification of GHG amount is moderate if warming is kept within the range of recent interglacial periods [6], but larger warming would risk greater release of CH_4 and CO_2 from methane hydrates in tundra and ocean sediments [29]. On still longer, geological, time scales weathering of rocks causes a negative feedback on atmospheric CO_2 amount [30], as discussed in section 3, but this feedback is too slow to alleviate climate change of concern to humanity.

2.3. Time Scales

How long does it take to reach equilibrium temperature with specified GHG change? Response is slowed by ocean thermal inertia and the time needed for ice sheets to disintegrate.

Ocean-caused delay is estimated in Fig. (**S7**) using a coupled atmosphere-ocean model. One-third of the response occurs in the first few years, in part because of rapid response over land, one-half in ~25 years, three-quarters in 250 years, and nearly full response in a millennium. The ocean-caused delay is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of surface water and deep water [31], as discussed in the Supplementary Material Section.

Ice sheet response time is often assumed to be several millennia, based on the broad sweep of paleo sea level change (Fig. **1a**) and primitive ice sheet models designed to capture that change. However, this long time scale may reflect the slowly changing orbital forcing, rather than inherent inertia, as there is no discernable lag between maximum ice sheet melt rate and local insolation that favors melt [7]. Paleo sea level data with high time resolution reveal frequent 'suborbital' sea level changes at rates of 1 m/century or more [32-34].

Present-day observations of Greenland and Antarctica show increasing surface melt [35], loss of buttressing ice shelves [36], accelerating ice streams [37], and increasing overall mass loss [38]. These rapid changes do not occur in existing ice sheet models, which are missing critical physics of ice sheet disintegration [39]. Sea level changes of several meters per century occur in the paleoclimate record [32, 33], in response to forcings slower and weaker than the present human-made forcing. It seems likely that large ice sheet response will occur within centuries, if human-made forcings continue to increase. Once ice sheet disintegration is underway, decadal changes of sea level may be substantial.

2.4. Warming "in the Pipeline"

The expanded time scale for the industrial era (Fig. **2**) reveals a growing gap between actual global temperature (purple curve) and equilibrium (long-term) temperature response based on the net estimated climate forcing (black curve). Ocean and ice sheet response times together account for this gap, which is now 2.0°C.

The forcing in Fig. (**2**) (black curve, Fe scale), when used to drive a global climate model [5], yields global temperature change that agrees closely (Fig. **3** in [5]) with observations (purple curve, Fig. **2**). That climate model, which includes only fast feedbacks, has additional warming of ~0.6°C in the pipeline today because of ocean thermal inertia [5, 8].

The remaining gap between equilibrium temperature for current atmospheric composition and actual global temperature is ~1.4°C. This further 1.4°C warming still to come is due to the slow surface albedo feedback, specifically ice sheet disintegration and vegetation change.

One may ask whether the climate system, as the Earth warms from its present 'interglacial' state, still has the capacity to supply slow feedbacks that double the fast-feedback sensitivity. This issue can be addressed by considering longer time scales including periods with no ice.

3. CENOZOIC ERA

Pleistocene atmospheric CO_2 variations occur as a climate feedback, as carbon is exchanged among surface reservoirs: the ocean, atmosphere, soils and biosphere. The most effective feedback is increase of atmospheric CO_2 as climate warms, the CO_2 transfer being mainly from ocean to atmosphere [27, 28]. On longer time scales the total amount of CO_2 in the surface reservoirs varies due to exchange of carbon with the solid earth. CO_2 thus becomes a primary agent of long-term climate change, leaving orbital effects as 'noise' on larger climate swings.

The Cenozoic era, the past 65.5 My, provides a valuable complement to the Pleistocene for exploring climate sensitivity. Cenozoic data on climate and atmospheric composition are not as precise, but larger climate variations occur, including an ice-free planet, thus putting glacial-interglacial changes in a wider perspective.

Oxygen isotopic composition of benthic (deep ocean dwelling) foraminifera shells in a global compilation of ocean sediment cores [26] provides a starting point for analyzing Cenozoic climate change (Fig. **3a**). At times with negligible ice sheets, oxygen isotope change, $\delta^{18}O$, provides a direct measure of deep ocean temperature (T_{do}). Thus T_{do} (°C) ~ -4 $\delta^{18}O$ + 12 between 65.5 and 35 My BP.

Rapid increase of $\delta^{18}O$ at about 34 My is associated with glaciation of Antarctica [26, 40] and global cooling, as evidenced by data from North America [41] and Asia [42]. From then until the present, ^{18}O in deep ocean foraminifera is affected by both ice volume and T_{do}, lighter ^{16}O evaporating preferentially from the ocean and accumulating in ice sheets. Between 35 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3‰, change of T_{do} was ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Given that a 1.5‰ change of $\delta^{18}O$ is associated with a 6°C T_{do} change, we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75). Equal division of $\delta^{18}O$ between temperature and sea level yields sea level change in the late Pleistocene in reasonable accord with available sea level data (Fig. **S8**). Subtracting the ice volume portion of $\delta^{18}O$ yields deep ocean temperature T_{do} (°C) = -2 ($\delta^{18}O$ -4.25‰) after 35 My, as in Fig. (**3b**).

The large (~14°C) Cenozoic temperature change between 50 My and the ice age at 20 ky must have been forced by changes of atmospheric composition. Alternative drives could come from outside (solar irradiance) or the Earth's surface (continental locations). But solar brightness increased ~0.4% in the Cenozoic [43], a linear forcing change of only +1 W/m^2 and of the wrong sign to contribute to the cooling trend. Climate forcing due to continental locations was < 1 W/m^2, because continents 65 My ago were already close to present latitudes (Fig. **S9**). Opening or closing of oceanic gateways might affect the timing of glaciation, but it would not provide the climate forcing needed for global cooling.

CO_2 concentration, in contrast, varied from ~180 ppm in glacial times to 1500 ± 500 ppm in the early Cenozoic [44]. This change is a forcing of more than 10 W/m^2 (Table **1** in [16]), an order of magnitude larger than other known forcings. CH_4 and N_2O, positively correlated with CO_2 and global temperature in the period with accurate data (ice cores), likely increase the total GHG forcing, but their forcings are much smaller than that of CO_2 [45, 46].

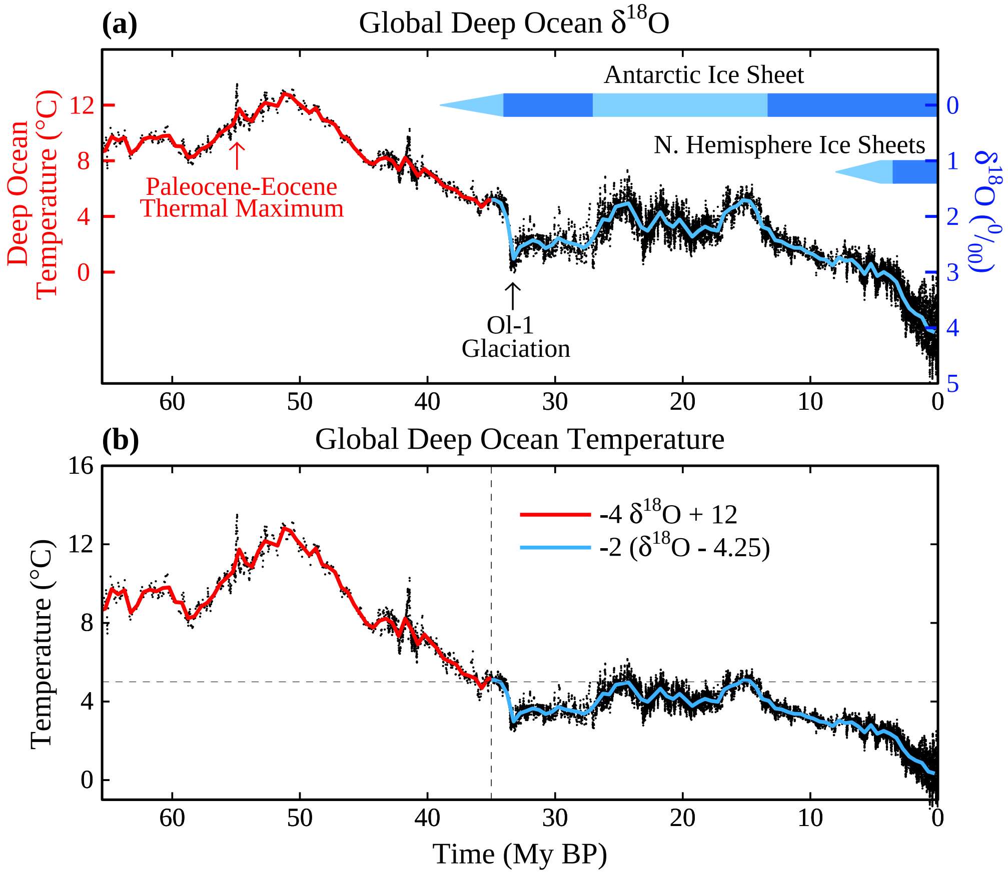

Fig. (3). Global deep ocean (**a**) $\delta^{18}O$ [26] and (**b**) temperature. Black curve is 5-point running mean of $\delta^{18}O$ original temporal resolution, while red and blue curves have 500 ky resolution.

3.1. Cenozoic Carbon Cycle

Solid Earth sources and sinks of CO_2 are not, in general, balanced at any given time [30, 47]. CO_2 is removed from surface reservoirs by: (1) chemical weathering of rocks with deposition of carbonates on the ocean floor, and (2) burial of organic matter; weathering is the dominant process [30]. CO_2 returns primarily *via* metamorphism and volcanic outgassing at locations where carbonate-rich oceanic crust is being subducted beneath moving continental plates.

Outgassing and burial of CO_2 are each typically 10^{12}-10^{13} mol C/year [30, 47-48]. At times of unusual plate tectonic activity, such as rapid subduction of carbon-rich ocean crust or strong orogeny, the imbalance between outgassing and burial can be a significant fraction of the one-way carbon flux. Although negative feedbacks in the geochemical carbon cycle reduce the rate of surface reservoir perturbation [49], a net imbalance ~10^{12} mol C/year can be maintained over thousands of years. Such an imbalance, if confined to the atmosphere, would be ~0.005 ppm/year, but as CO_2 is distributed among surface reservoirs, this is only ~0.0001 ppm/year. This rate is negligible compared to the present human-made atmospheric CO_2 increase of ~2 ppm/year, yet over a million years such a crustal imbalance alters atmospheric CO_2 by 100 ppm.

Between 60 and 50 My ago India moved north rapidly, 18-20 cm/year [50], through a region that long had been a depocenter for carbonate and organic sediments. Subduction of carbon-rich crust was surely a large source of CO_2 outgassing and a prime cause of global warming, which peaked 50 My ago (Fig. **3b**) with the Indo-Asian collision. CO_2 must have then decreased due to a reduced subduction source and enhanced weathering with uplift of the Himalayas/Tibetan Plateau [51]. Since then, the Indian and Atlantic Oceans have been major depocenters for carbon, but subduction of carbon-rich crust has been limited mainly to small regions near Indonesia and Central America [47].

Thus atmospheric CO_2 declined following the Indo-Asian collision [44] and climate cooled (Fig. **3b**) leading to Antarctic glaciation by ~34 My. Antarctica has been more or less glaciated ever since. The rate of CO_2 drawdown declines as atmospheric CO_2 decreases due to negative feedbacks, including the effect of declining atmospheric temperature and plant growth rates on weathering [30]. These negative feedbacks tend to create a balance between crustal outgassing and drawdown of CO_2, which have been equal within 1-2 percent over the past 700 ky [52]. Large fluctuations in the size of the Antarctic ice sheet have occurred in the past 34 My, possibly related to temporal variations of plate tectonics [53] and outgassing rates. The relatively constant atmospheric CO_2 amount of the past 20 My (Fig. **S10**) implies a near balance of outgassing and weathering rates over that period.

Knowledge of Cenozoic CO_2 is limited to imprecise proxy measures except for recent ice core data. There are discrepancies among different proxy measures, and even between different investigators using the same proxy method, as discussed in conjunction with Fig. (**S10**). Nevertheless, the proxy data indicate that CO_2 was of the order of 1000 ppm in the early Cenozoic but <500 ppm in the last 20 My [2, 44].

3.2. Cenozoic Forcing and CO_2

The entire Cenozoic climate forcing history (Fig. **4a**) is implied by the temperature reconstruction (Fig. **3b**), assuming a fast-feedback sensitivity of ¾°C per W/m^2. Subtracting the solar and surface albedo forcings (Fig. **4b**), the latter from Eq. S2 with ice sheet area *vs* time from $\delta^{18}O$, we obtain the GHG forcing history (Fig. **4c**).

We hinge our calculations at 35 My for several reasons. Between 65 and 35 My ago there was little ice on the planet, so climate sensitivity is defined mainly by fast feedbacks. Second, we want to estimate the CO_2 amount that precipitated Antarctic glaciation. Finally, the relation between global surface air temperature change (ΔT_s) and deep ocean temperature change (ΔT_{do}) differs for ice-free and glaciated worlds.

Climate models show that global temperature change is tied closely to ocean temperature change [54]. Deep ocean temperature is a function of high latitude ocean surface temperature, which tends to be amplified relative to global mean ocean surface temperature. However, land temperature change exceeds that of the ocean, with an effect on global temperature that tends to offset the latitudinal variation of ocean temperature. Thus in the ice-free world (65-35 My) we take $\Delta T_s \sim \Delta T_{do}$ with generous (50%) uncertainty. In the glaciated world ΔT_{do} is limited by the freezing point in the deep ocean. ΔT_s between the last ice age (20 ky) and the present

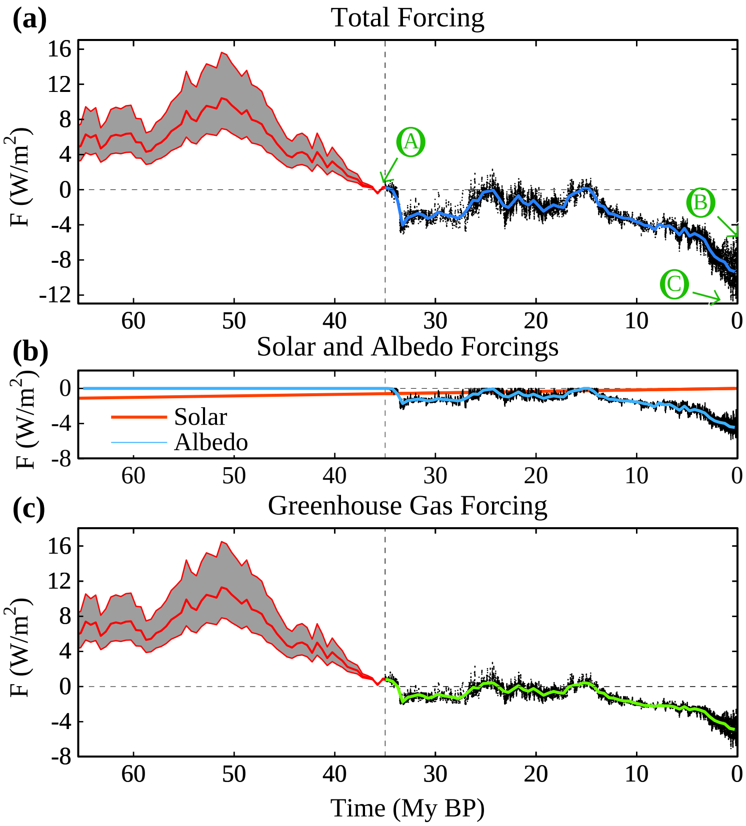

Fig. (4). (**a**) Total climate forcing, (**b**) solar and surface albedo forcings, and (**c**) GHG forcing in the Cenozoic, based on T_{do} history of Fig. (**3b**) and assumed fast-feedback climate sensitivity ¾°C per W/m^2. Ratio of T_s change and T_{do} change is assumed to be near unity in the minimal ice world between 65 and 35 My, but the gray area allows for 50% uncertainty in the ratio. In the later era with large ice sheets we take $\Delta T_s/\Delta T_{do} = 1.5$, in accord with Pleistocene data.

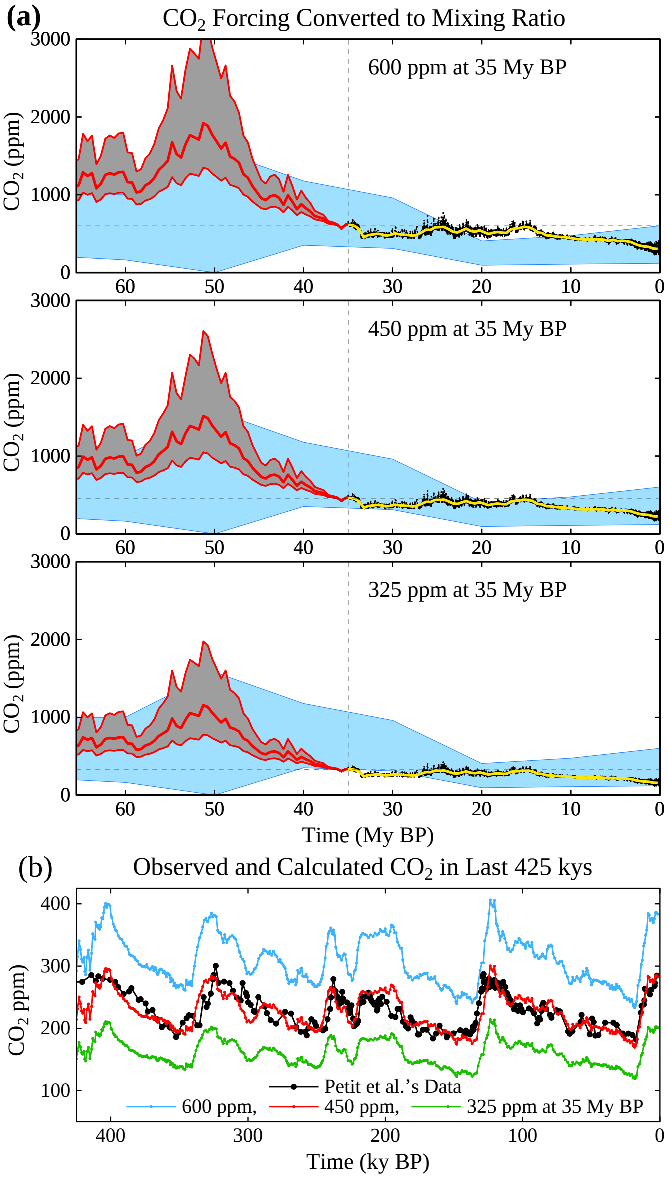

Fig. (5). (**a**) Simulated CO_2 amounts in the Cenozoic for three choices of CO_2 amount at 35 My (temporal resolution of black and colored curves as in Fig. (**3**); blue region: multiple CO_2 proxy data, discussed with Fig. (**S10**); gray region allows 50 percent uncertainty in ratio of global surface and deep ocean temperatures). (**b**) Expanded view of late Pleistocene, including precise ice core CO_2 measurements (black curve).

interglacial period (~5°C) was ~1.5 times larger than ΔT_{do}. In Fig. (**S5**) we show that this relationship fits well throughout the period of ice core data.

If we specify CO_2 at 35 My, the GHG forcing defines CO_2 at other times, assuming CO_2 provides 75% of the GHG forcing, as in the late Pleistocene. CO_2 ~450 ppm at 35 My keeps CO_2 in the range of early Cenozoic proxies (Fig. **5a**) and yields a good fit to the amplitude and mean CO_2 amount in the late Pleistocene (Fig. **5b**). A CO_2 threshold for Antarctic glaciation of ~500 ppm was previously inferred from proxy CO_2 data and a carbon cycle model [55].

Individual CO_2 proxies (Fig. **S10**) clarify limitations due to scatter among the measurements. Low CO_2 of some early Cenozoic proxies, if valid, would suggest higher climate sensitivity. However, in general the sensitivities inferred from the Cenozoic and Phanerozoic [56, 57, 58] agree well with our analysis, if we account for the ways in which sensitivity is defined and the periods emphasized in each empirical derivation (Table **S1**).

Our CO_2 estimate of ~450 ppm at 35 My (Fig. **5**) serves as a prediction to compare with new data on CO_2 amount. Model uncertainties (Fig. **S10**) include possible changes of non-CO_2 GHGs and the relation of ΔT_s to ΔT_{do}. The model fails to account for cooling in the past 15 My if CO_2 increased, as several proxies suggest (Fig. **S10**). Changing ocean currents, such as the closing of the Isthmus of Panama, may have contributed to climate evolution, but models find little effect on temperature [59]. Non-CO_2 GHGs also could have played a role, because little forcing would have been needed to cause cooling due to the magnitude of late Cenozoic albedo feedback.

3.3. Implication

We infer from Cenozoic data that CO_2 was the dominant Cenozoic forcing, that CO_2 was ~450 ± 100 ppm when Antarctica glaciated, and that glaciation is reversible. Together these inferences have profound implications.

Consider three points marked in Fig. (**4**): point A at 35 My, just before Antarctica glaciated; point B at recent interglacial periods; point C at the depth of recent ice ages. Point B is about half way between A and C in global temperature (Fig. **3b**) and climate forcings (Fig. **4**). The GHG forcing from the deepest recent ice age to current interglacial warmth is ~3.5 W/m^2. Additional 4 W/m^2 forcing carries the planet, at equilibrium, to the ice-free state. Thus equilibrium climate sensitivity to GHG change, including the surface albedo change as a slow feedback, is almost as large between today and an ice-free world as between today and the ice ages.

The implication is that global climate sensitivity of 3°C for doubled CO_2, although valid for the idealized Charney definition of climate sensitivity, is a considerable understatement of expected equilibrium global warming in response to imposed doubled CO_2. Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity.

Equilibrium sensitivity 6°C for doubled CO_2 is relevant to the case in which GHG changes are specified. That is appropriate to the anthropogenic case, provided the GHG amounts are estimated from carbon cycle models including climate feedbacks such as methane release from tundra and ocean sediments. The equilibrium sensitivity is even higher if the GHG feedback is included as part of the climate response, as is appropriate for analysis of the climate response to Earth orbital perturbations. The very high sensitivity with both albedo and GHG slow feedbacks included accounts for the huge magnitude of glacial-interglacial fluctuations in the Pleistocene (Fig. **3**) in response to small forcings (section 3 of Supplementary Material).

Equilibrium climate response would not be reached in decades or even in a century, because surface warming is slowed by the inertia of the ocean (Fig. **S7**) and ice sheets. However, Earth's history suggests that positive feedbacks, especially surface albedo changes, can spur rapid global warmings, including sea level rise as fast as several meters per century [7]. Thus if humans push the climate system sufficiently far into disequilibrium, positive climate feedbacks may set in motion dramatic climate change and climate impacts that cannot be controlled.

4. ANTHROPOCENE ERA

Human-made global climate forcings now prevail over natural forcings (Fig. **2**). Earth may have entered the Anthropocene era [60, 61] 6-8 ky ago [62], but the net human-made forcing was small, perhaps slightly negative [7], prior to the industrial era. GHG forcing overwhelmed natural and negative human-made forcings only in the past quarter century (Fig. **2**).

Human-made climate change is delayed by ocean (Fig. **S7**) and ice sheet response times. Warming 'in the pipeline', mostly attributable to slow feedbacks, is now about 2°C (Fig. **2**). No additional forcing is required to raise global temperature to at least the level of the Pliocene, 2-3 million years ago, a degree of warming that would surely yield 'dangerous' climate impacts [5].

4.1. Tipping Points

Realization that today's climate is far out of equilibrium with current climate forcings raises the specter of 'tipping points', the concept that climate can reach a point where, without additional forcing, rapid changes proceed practically out of our control [2, 7, 63, 64]. Arctic sea ice and the West Antarctic Ice Sheet are examples of potential tipping points. Arctic sea ice loss is magnified by the positive feedback of increased absorption of sunlight as global warming initiates sea ice retreat [65]. West Antarctic ice loss can be accelerated by several feedbacks, once ice loss is substantial [39].

We define: (1) the *tipping level*, the global climate forcing that, if long maintained, gives rise to a specific consequence, and (2) the *point of no return*, a climate state beyond which the consequence is inevitable, even if climate forcings are reduced. A point of no return can be avoided, even if the tipping level is temporarily exceeded. Ocean and ice sheet inertia permit overshoot, provided the climate forcing is returned below the tipping level before initiating irreversible dynamic change.

Points of no return are inherently difficult to define, because the dynamical problems are nonlinear. Existing models are more lethargic than the real world for phenomena now unfolding, including changes of sea ice [65], ice streams [66], ice shelves [36], and expansion of the subtropics [67, 68].

The tipping level is easier to assess, because the paleoclimate quasi-equilibrium response to known climate forcing is relevant. The tipping level is a measure of the long-term climate forcing that humanity must aim to stay beneath to avoid large climate impacts. The tipping level does not define the magnitude or period of tolerable overshoot. However, if overshoot is in place for centuries, the thermal perturbation will so penetrate the ocean [10] that recovery without dramatic effects, such as ice sheet disintegration, becomes unlikely.

4.2. Target CO_2

Combined, GHGs other than CO_2 cause climate forcing comparable to that of CO_2 [2, 6], but growth of non-CO_2 GHGs is falling below IPCC [2] scenarios. Thus total GHG climate forcing change is now determined mainly by CO_2 [69]. Coincidentally, CO_2 forcing is similar to the net human-made forcing, because non-CO_2 GHGs tend to offset negative aerosol forcing [2, 5].

Thus we take future CO_2 change as approximating the net human-made forcing change, with two caveats. First, special effort to reduce non-CO_2 GHGs could alleviate the CO_2 requirement, allowing up to about +25 ppm CO_2 for the same climate effect, while resurgent growth of non-CO_2 GHGs could reduce allowed CO_2 a similar amount [6]. Second, reduction of human-made aerosols, which have a net cooling effect, could force stricter GHG requirements. However, an emphasis on reducing black soot could largely off-set reductions of high albedo aerosols [20].

Our estimated history of CO_2 through the Cenozoic Era provides a sobering perspective for assessing an appropriate target for future CO_2 levels. A CO_2 amount of order 450 ppm or larger, if long maintained, would push Earth toward the ice-free state. Although ocean and ice sheet inertia limit the rate of climate change, such a CO_2 level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity's control.

The climate system, because of its inertia, has not yet fully responded to the recent increase of human-made climate forcings [5]. Yet climate impacts are already occurring that allow us to make an initial estimate for a target atmospheric CO_2 level. No doubt the target will need to be adjusted as climate data and knowledge improve, but the urgency and difficulty of reducing the human-made forcing will be less, and more likely manageable, if excess forcing is limited soon.

Civilization is adapted to climate zones of the Holocene. Theory and models indicate that subtropical regions expand poleward with global warming [2, 67]. Data reveal a 4-degree latitudinal shift already [68], larger than model predictions, yielding increased aridity in southern United States [70, 71], the Mediterranean region, Australia and parts of Africa. Impacts of this climate shift [72] support the conclusion that 385 ppm CO_2 is already deleterious.

Alpine glaciers are in near-global retreat [72, 73]. After a one-time added flush of fresh water, glacier demise will yield summers and autumns of frequently dry rivers, including rivers originating in the Himalayas, Andes and Rocky Mountains that now supply water to hundreds of millions of people. Present glacier retreat, and warming in the pipeline, indicate that 385 ppm CO_2 is already a threat.

Equilibrium sea level rise for today's 385 ppm CO_2 is at least several meters, judging from paleoclimate history [19, 32-34]. Accelerating mass losses from Greenland [74] and West Antarctica [75] heighten concerns about ice sheet stability. An initial CO_2 target of 350 ppm, to be reassessed as effects on ice sheet mass balance are observed, is suggested.

Stabilization of Arctic sea ice cover requires, to first approximation, restoration of planetary energy balance. Climate models driven by known forcings yield a present planetary energy imbalance of +0.5-1 W/m^2 [5]. Observed heat increase in the upper 700 m of the ocean [76] confirms the planetary energy imbalance, but observations of the entire ocean are needed for quantification. CO_2 amount must be reduced to 325-355 ppm to increase outgoing flux 0.5-1 W/m^2, if other forcings are unchanged. A further imbalance reduction, and thus CO_2 ~300-325 ppm, may be needed to restore sea ice to its area of 25 years ago.

Coral reefs are suffering from multiple stresses, with ocean acidification and ocean warming principal among them [77]. Given additional warming 'in-the-pipeline', 385 ppm CO_2 is already deleterious. A 300-350 ppm CO_2 target would significantly relieve both of these stresses.

4.3. CO_2 Scenarios

A large fraction of fossil fuel CO_2 emissions stays in the air a long time, one-quarter remaining airborne for several centuries [11, 78, 79]. Thus moderate delay of fossil fuel use will not appreciably reduce long-term human-made climate change. Preservation of a climate resembling that to which humanity is accustomed, the climate of the Holocene, requires that most remaining fossil fuel carbon is never emitted to the atmosphere.

Coal is the largest reservoir of conventional fossil fuels (Fig. **S12**), exceeding combined reserves of oil and gas [2, 79]. The only realistic way to sharply curtail CO_2 emissions is to phase out coal use except where CO_2 is captured and sequestered.

Phase-out of coal emissions by 2030 (Fig. **6**) keeps maximum CO_2 close to 400 ppm, depending on oil and gas reserves and reserve growth. IPCC reserves assume that half of readily extractable oil has already been used (Figs. **6**, **S12**). EIA [80] estimates (Fig. **S12**) have larger reserves and reserve growth. Even if EIA estimates are accurate, the IPCC case remains valid if the most difficult to extract oil and gas is left in the ground, *via* a rising price on carbon emissions that discourages remote exploration and environmental regulations that place some areas off-limit. If IPCC gas reserves (Fig. **S12**) are underestimated, the IPCC case in Fig. (**6**) remains valid if the additional gas reserves are used at facilities where CO_2 is captured.

However, even with phase-out of coal emissions and assuming IPCC oil and gas reserves, CO_2 would remain above 350 ppm for more than two centuries. Ongoing Arctic and ice sheet changes, examples of rapid paleoclimate change, and other criteria cited above all drive us to consider scenarios that bring CO_2 more rapidly back to 350 ppm or less.

4.4. Policy Relevance

Desire to reduce airborne CO_2 raises the question of whether CO_2 could be drawn from the air artificially. There are no large-scale technologies for CO_2 air capture now, but

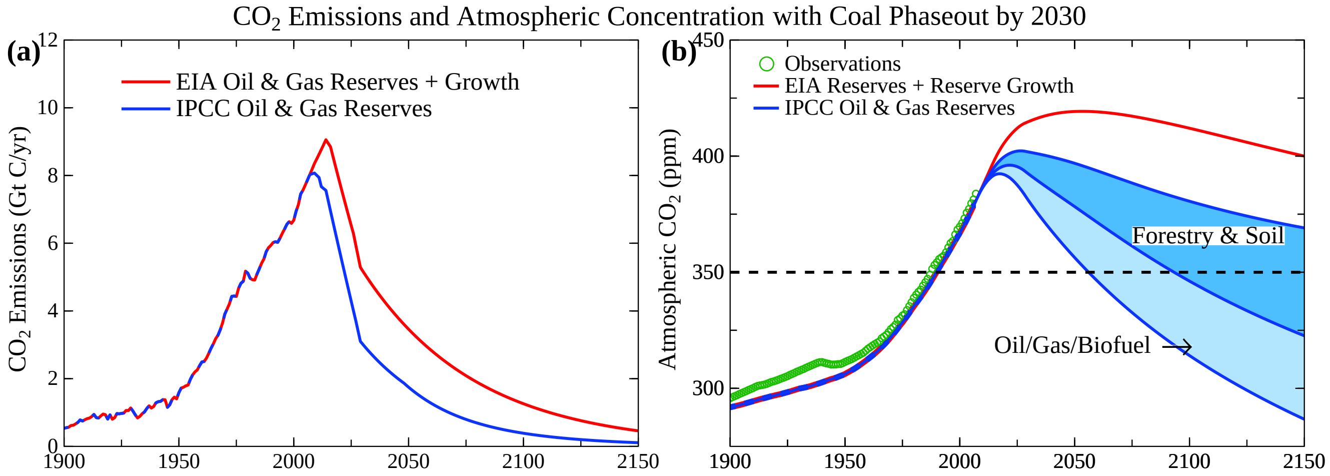

Fig. (6). (**a**) Fossil fuel CO_2 emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. (**b**) Resulting atmospheric CO_2 based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

with strong research and development support and industrial-scale pilot projects sustained over decades it may be possible to achieve costs ~$200/tC [81] or perhaps less [82]. At $200/tC, the cost of removing 50 ppm of CO_2 is ~$20 trillion.

Improved agricultural and forestry practices offer a more natural way to draw down CO_2. Deforestation contributed a net emission of 60±30 ppm over the past few hundred years, of which ~20 ppm CO_2 remains in the air today [2, 83] (Figs. (**S12**, **S14**). Reforestation could absorb a substantial fraction of the 60±30 ppm net deforestation emission.

Carbon sequestration in soil also has significant potential. Biochar, produced in pyrolysis of residues from crops, forestry, and animal wastes, can be used to restore soil fertility while storing carbon for centuries to millennia [84]. Biochar helps soil retain nutrients and fertilizers, reducing emissions of GHGs such as N_2O [85]. Replacing slash-and-burn agriculture with slash-and-char and use of agricultural and forestry wastes for biochar production could provide a CO_2 drawdown of ~8 ppm or more in half a century [85].

In the Supplementary Material Section we define a forest/soil drawdown scenario that reaches 50 ppm by 2150 (Fig. **6b**). This scenario returns CO_2 below 350 ppm late this century, after about 100 years above that level.

More rapid drawdown could be provided by CO_2 capture at power plants fueled by gas and biofuels [86]. Low-input high-diversity biofuels grown on degraded or marginal lands, with associated biochar production, could accelerate CO_2 drawdown, but the nature of a biofuel approach must be carefully designed [85, 87-89].

A rising price on carbon emissions and payment for carbon sequestration is surely needed to make drawdown of airborne CO_2 a reality. A 50 ppm drawdown *via* agricultural and forestry practices seems plausible. But if most of the CO_2 in coal is put into the air, no such "natural" drawdown of CO_2 to 350 ppm is feasible. Indeed, if the world continues on a business-as-usual path for even another decade without initiating phase-out of unconstrained coal use, prospects for avoiding a dangerously large, extended overshoot of the 350 ppm level will be dim.

4.5. Caveats: Climate Variability, Climate Models, and Uncertainties

Climate has great variability, much of which is unforced and unpredictable [2, 90]. This fact raises a practical issue: what is the chance that climate variations, e.g., a temporary cooling trend, will affect public recognition of climate change, making it difficult to implement mitigation policies? Also what are the greatest uncertainties in the expectation of a continued global warming trend? And what are the impacts of climate model limitations, given the inability of models to realistically simulate many aspects of climate change and climate processes?

The atmosphere and ocean exhibit coupled nonlinear chaotic variability that cascades to all time scales [91]. Variability is so large that the significance of recent decadal global temperature change (Fig. **7a**) would be very limited, if the data were considered simply as a time series, without further information. However, other knowledge includes information on the causes of some of the temperature variability, the planet's energy imbalance, and global climate forcings.

The El Nino Southern Oscillation (ENSO) [94] accounts for most low latitude temperature variability and much of the global variability. The global impact of ENSO is coherent from month to month, as shown by the global-ocean-mean SST (Fig. **7b**), for which the ocean's thermal inertia minimizes the effect of weather noise. The cool anomaly of 2008 coincides with an ENSO minimum and does not imply a change of decadal temperature trend.

Decadal time scale variability, such as predicted weakening of the Atlantic overturning circulation [95], could interrupt global warming, as discussed in section 18 of the Supplementary Material. But the impact of regional dynamical effects on global temperature is opposed by the planet's energy imbalance [96], a product of the climate system's thermal inertia, which is confirmed by increasing ocean heat

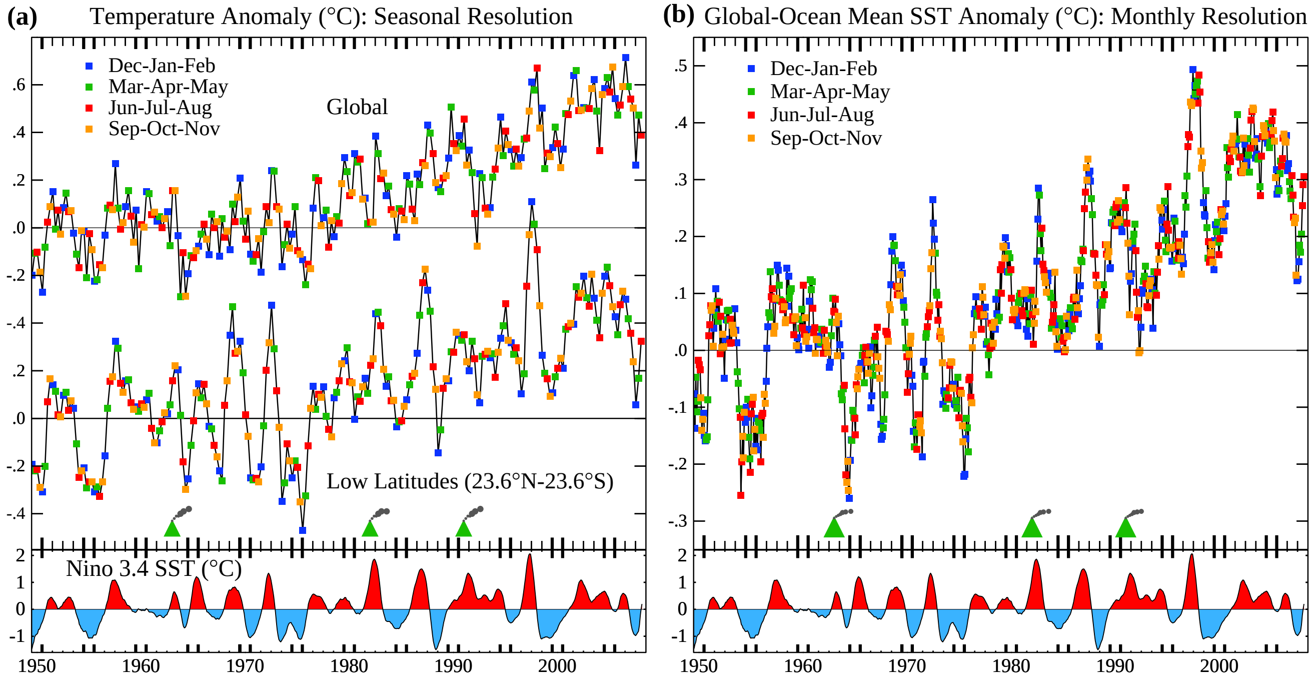

Fig. (7). (**a**) Seasonal-mean global and low-latitude surface temperature anomalies relative to 1951-1980, an update of [92], (**b**) global-ocean-mean sea surface temperature anomaly at monthly resolution. The Nino 3.4 Index, the temperature anomaly (12-month running mean) in a small part of the tropical Pacific Ocean [93], is a measure of ENSO, a basin-wide sloshing of the tropical Pacific Ocean [94]. Green triangles show major volcanic eruptions.

storage [97]. This energy imbalance makes decadal interruption of global warming, in the absence of a negative climate forcing, improbable [96].

Volcanoes and the sun can cause significant negative forcings. However, even if the solar irradiance remained at its value in the current solar minimum, this reduced forcing would be offset by increasing CO_2 within seven years (Supplementary Material section 18). Human-made aerosols cause a greater negative forcing, both directly and through their effects on clouds. The first satellite observations of aerosols and clouds with accuracy sufficient to quantify this forcing are planned to begin in 2009 [98], but most analysts anticipate that human-made aerosols will decrease in the future, rather than increase further.

Climate models have many deficiencies in their abilities to simulate climate change [2]. However, model uncertainties cut both ways: it is at least as likely that models underestimate effects of human-made GHGs as overestimate them (Supplementary Material section 18). Model deficiencies in evaluating tipping points, the possibility that rapid changes can occur without additional climate forcing [63, 64], are of special concern. Loss of Arctic sea ice, for example, has proceeded more rapidly than predicted by climate models [99]. There are reasons to expect that other nonlinear problems, such as ice sheet disintegration and extinction of interdependent species and ecosystems, also have the potential for rapid change [39, 63, 64].

5. SUMMARY

Humanity today, collectively, must face the uncomfortable fact that industrial civilization itself has become the principal driver of global climate. If we stay our present course, using fossil fuels to feed a growing appetite for energy-intensive life styles, we will soon leave the climate of the Holocene, the world of prior human history. The eventual response to doubling pre-industrial atmospheric CO_2 likely would be a nearly ice-free planet, preceded by a period of chaotic change with continually changing shorelines.

Humanity's task of moderating human-caused global climate change is urgent. Ocean and ice sheet inertias provide a buffer delaying full response by centuries, but there is a danger that human-made forcings could drive the climate system beyond tipping points such that change proceeds out of our control. The time available to reduce the human-made forcing is uncertain, because models of the global system and critical components such as ice sheets are inadequate. However, climate response time is surely less than the atmospheric lifetime of the human-caused perturbation of CO_2. Thus remaining fossil fuel reserves should not be exploited without a plan for retrieval and disposal of resulting atmospheric CO_2.

Paleoclimate evidence and ongoing global changes imply that today's CO_2, about 385 ppm, is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted. Realization that we must reduce the current CO_2 amount has a bright side: effects that had begun to seem inevitable, including impacts of ocean acidification, loss of fresh water supplies, and shifting of climatic zones, may be averted by the necessity of finding an energy course beyond fossil fuels sooner than would otherwise have occurred.

We suggest an initial objective of reducing atmospheric CO_2 to 350 ppm, with the target to be adjusted as scientific understanding and empirical evidence of climate effects accumulate. Although a case already could be made that the eventual target probably needs to be lower, the 350 ppm target is sufficient to qualitatively change the discussion and drive fundamental changes in energy policy. Limited opportunities for reduction of non-CO_2 human-caused forcings are important to pursue but do not alter the initial 350 ppm CO_2 target. This target must be pursued on a timescale of decades, as paleoclimate and ongoing changes, and the ocean response time, suggest that it would be foolhardy to allow CO_2 to stay in the dangerous zone for centuries.

A practical global strategy almost surely requires a rising global price on CO_2 emissions and phase-out of coal use except for cases where the CO_2 is captured and sequestered. The carbon price should eliminate use of unconventional fossil fuels, unless, as is unlikely, the CO_2 can be captured. A reward system for improved agricultural and forestry practices that sequester carbon could remove the current CO_2 overshoot. With simultaneous policies to reduce non-CO_2 greenhouse gases, it appears still feasible to avert catastrophic climate change.

Present policies, with continued construction of coal-fired power plants without CO_2 capture, suggest that decision-makers do not appreciate the gravity of the situation. We must begin to move now toward the era beyond fossil fuels. Continued growth of greenhouse gas emissions, for just another decade, practically eliminates the possibility of near-term return of atmospheric composition beneath the tipping level for catastrophic effects.

The most difficult task, phase-out over the next 20-25 years of coal use that does not capture CO_2, is Herculean, yet feasible when compared with the efforts that went into World War II. The stakes, for all life on the planet, surpass those of any previous crisis. The greatest danger is continued ignorance and denial, which could make tragic consequences unavoidable.

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Supplementary Material

1. ICE AGE CLIMATE FORCINGS

Fig. (**S1**) shows the climate forcings during the depth of the last ice age, 20 ky BP, relative to the Holocene [14]. The largest contribution to the uncertainty in the calculated 3.5 W/m^2 forcing due to surface changes (ice sheet area, vegetation distribution, shoreline movements) is due to uncertainty in the ice sheet sizes [14, S1]. Formulae for the GHG forcings [20] yield 2.25 W/m^2 for CO_2 (185 ppm → 275 ppm), 0.43 W/m^2 for CH_4 (350 → 675 ppb) and 0.32 W/m^2 for N_2O (200 → 270 ppb). The CH_4 forcing includes a factor 1.4 to account for indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor [12].

The climate sensitivity inferred from the ice age climate change (~¾°C per W/m^2) includes only fast feedbacks, such as water vapor, clouds, aerosols (including dust) and sea ice. Ice sheet size and greenhouse gas amounts are specified boundary conditions in this derivation of the fast-feedback climate sensitivity.

It is permissible, alternatively, to specify aerosol changes as part of the forcing and thus derive a climate sensitivity that excludes the effect of aerosol feedbacks. That approach was used in the initial empirical derivation of climate sensitivity from Pleistocene climate change [14]. The difficulty with that approach is that, unlike long-lived GHGs, aerosols are distributed heterogeneously, so it is difficult to specify aerosol changes accurately. Also the forcing is a sensitive function of aerosol single scatter albedo and the vertical distribution of aerosols in the atmosphere, which are not measured. Furthermore, the aerosol indirect effect on clouds also depends upon all of these poorly known aerosol properties.

One recent study [S2] specified an arbitrary glacial-interglacial aerosol forcing slightly larger than the GHG glacial-interglacial forcing. As a result, because temperature, GHGs, and aerosol amount, overall, are positively correlated in glacial-interglacial changes, this study inferred a climate sensitivity of only ~2°C for doubled CO_2. This study used the correlation of aerosol and temperature in the Vostok ice core at two specific times to infer an aerosol forcing for a given aerosol amount. The conclusions of the study are immediately falsified by considering the full Vostok aerosol record (Fig. **2** of [17]), which reveals numerous large aerosol fluctuations without any corresponding temperature change. In contrast, the role of GHGs in climate change is confirmed when this same check is made for GHGs (Fig. **2**), and the fast-feedback climate sensitivity of 3°C for doubled CO_2 is confirmed (Fig. **1**).

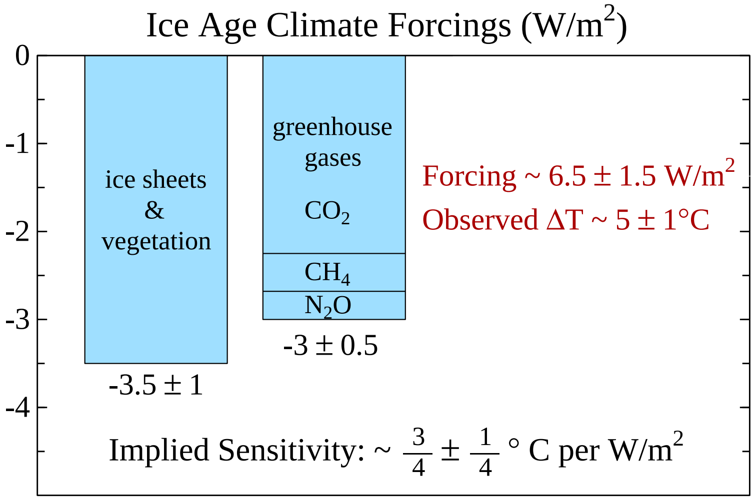


Fig. (S1). Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

All the problems associated with imprecise knowledge of aerosol properties become moot if, as is appropriate, aerosols are included in the fast feedback category. Indeed, soil dust, sea salt, dimethylsulfide, and other aerosols are expected to vary (in regional, inhomogeneous ways) as climate changes. Unlike long-lived GHGs, global aerosol amounts cannot be inferred from ice cores. But the effect of aerosol changes is fully included in observed global temperature change. The climate sensitivity that we derive in Fig. (**S1**) includes the aerosol effect accurately, because both the climate forcings and the global climate response are known. The indirect effect of aerosol change on clouds is, of course, also included precisely.

2. CLIMATE FORCINGS AND CLIMATE FEEDBACKS

The Earth's temperature at equilibrium is such that the planet radiates to space (as heat, i.e., infrared radiation) the same amount of energy that it absorbs from the sun, which is ~240 W/m^2. A blackbody temperature of ~255°K yields a heat flux of 240 W/m^2. Indeed, 255°K is the temperature in the mid-troposphere, the mean level of infrared emission to space.

A climate forcing is a perturbation to the planet's energy balance, which causes the Earth's temperature to change as needed to restore energy balance. Doubling atmospheric CO_2 causes a planetary energy imbalance of ~4 W/m^2, with more energy coming in than going out. Earth's temperature would need to increase by ΔT_O = 1.2-1.3°C to restore planetary energy balance, if the temperature change were uniform throughout the atmosphere and if nothing else changed.

Actual equilibrium temperature change in response to any forcing is altered by feedbacks that can amplify or diminish the response, thus the mean surface temperature change is [14]

$$\begin{aligned}\Delta T_{eq} &= f\ \Delta T_O\\ &= \Delta T_O + \Delta T_{feedbacks}\\ &= \Delta T_O + \Delta T_1 + \Delta T_2 + \ldots,\end{aligned}$$

where f is the net feedback factor and the ΔT_i are increments due to specific feedbacks.

The role of feedback processes is clarified by defining the gain, g,

$$\begin{aligned}g &= \Delta T_{feedbacks}/\Delta T_{eq}\\ &= (\Delta T_1 + \Delta T_2 + \ldots)/\Delta T_{eq}\\ &= g_1 + g_2 + \ldots\end{aligned}$$

g_i is positive for an amplifying feedback and negative for a feedback that diminishes the response. The additive nature of the g_i, unlike f_i, is a useful characteristic of the gain. Evidently

$$f = 1/(1 - g)$$

The value of g (or f) depends upon the climate state, especially the planetary temperature. For example, as the planet becomes so warm that land ice disappears, the land ice albedo feedback diminishes, i.e. $g_{\text{land ice albedo}} \rightarrow 0$.

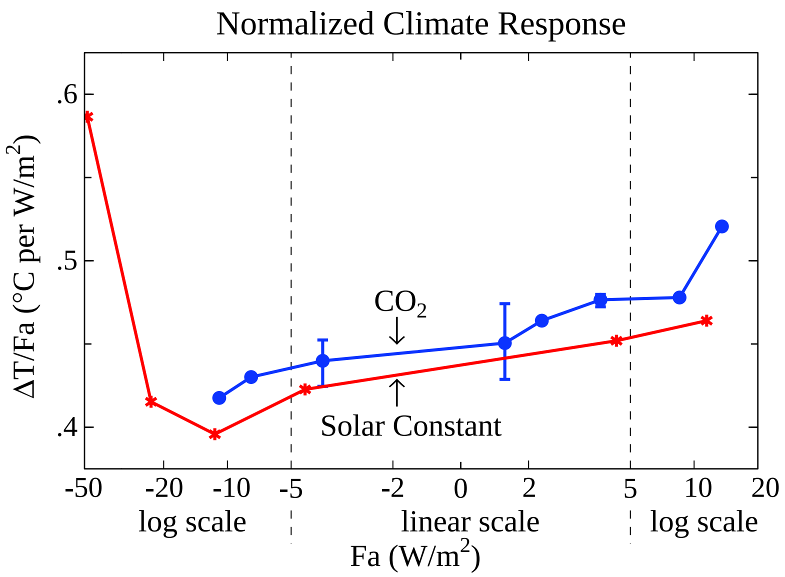


Fig. (S2). Global surface air temperature change [12] after 100 years in simulations with the Goddard Institute for Space Studies modelE [S3, 5] as a function of climate forcing for changes of solar irradiance and atmospheric CO_2. Fa is the standard adjusted climate forcing [12]. Results are extracted from Fig. (**25a**) of [12]. Curves terminate because the climate model 'bombs' at the next increment of forcing due to failure of one or more of the parameterizations of processes in the model as extreme conditions are approached.

'Fast feedbacks', such as water vapor, clouds and sea ice, are the mechanisms usually included in the 'Charney' [13] climate sensitivity. Climate models yield a Charney (fast feedback) sensitivity of about 3°C for doubled CO_2 [2, 12], a conclusion that is confirmed and tightened by empirical evidence from the Pleistocene (Section 2.1). This sensitivity implies

$$g_{\text{fast feedbacks}} \sim 0.5\text{-}0.6.$$

This fast feedback gain and climate sensitivity apply to the present climate and climate states with global temperatures that are not too different than at present.

If g approaches unity, $f \rightarrow \infty$, implying a runaway climate instability. The possibility of such instability is anticipated for either a very warm climate (runaway greenhouse effect [S4]) or a very cold climate (snowball Earth [S5]). We can investigate how large a climate forcing is needed to cause $g \rightarrow 1$ using a global climate model that includes the fast feedback processes, because both of these instabilities are a result of the temperature dependence of 'fast feedbacks' (the water vapor and ice/snow albedo feedbacks, respectively).

Fig. (**S2**) suggests that climate forcings ~10-25 W/m^2 are needed to approach either runaway snowball-Earth conditions or the runaway greenhouse effect. More precise quantification requires longer simulations and improved parameterizations of physical processes as extreme climates are approached. The processes should include slow feedbacks that can either amplify or diminish the climate change.

Earth has experienced snowball conditions [S5], or at least a 'slushball' state [S6] with ice reaching sea level in the tropics, on at least two occasions, the most recent ~640 My BP, aided by reduced solar irradiance [43] and favorable continental locations. The mechanism that allowed Earth to escape the snowball state was probably reduced weathering in a glaciated world, which allowed CO$_2$ to accumulate in the atmosphere [S5]. Venus, but not Earth, has experienced the runaway greenhouse effect, a state from which there is no escape.

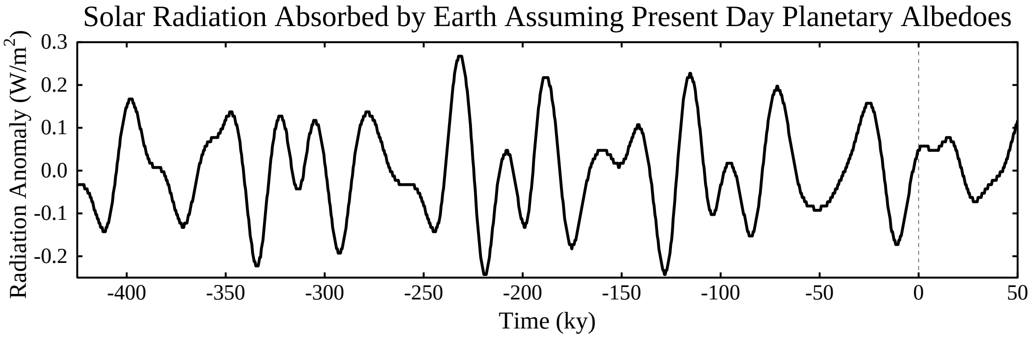


Fig. (S3). Annual-mean global-mean perturbation of the amount of solar radiation absorbed by the Earth, calculated by assuming present-day seasonal and geographical distribution of albedo.

3. PLEISTOCENE FORCINGS AND FEEDBACKS

Fig. (**S3**) shows the perturbation of solar radiation absorbed by the Earth due to changes in Earth orbital elements, i.e., the tilt of the Earth's spin axis relative to the orbital plane, the eccentricity of the Earth's orbit, and the time of year at which the Earth is closest to the sun (precession of equinoxes). This perturbation is calculated using fixed (present day) seasonal and geographical distribution of planetary albedo.

The global-mean annual-mean orbital (Milankovitch) forcing is very weak, at most a few tenths of 1 W/m^2. Our procedure in calculating the forcing, keeping ice sheet properties (size and albedo) fixed, is appropriate for 'instantaneous' and 'adjusted' radiative forcings [12].

Further, successive, definitions of the orbital 'forcing', e.g., allowing some regional response to the seasonal insolation perturbations, may be useful for the purpose of understanding glacial-interglacial climate change. For example, it may be informative to calculate the 'forcing' due to insolation-induced changes of ice-she*et al*bedo, because increased insolation can 'age' (increase snow crystal size and thus darken) an ice surface and also spur the date of first snow-melt [7]. However, one merit of the standard forcing definition is the insight that glacial-interglacial climate swings are almost entirely due to feedbacks.

Indeed, the gain during the Pleistocene is close to unity. Climate models and empirical evaluation from the climate change between the last ice age (Section 2.1 above) yield $g_{\text{fast feedbacks}}$ ~0.5-0.6 (the gain corresponding to fast feedback climate sensitivity 3°C for doubled CO$_2$). GHGs and surface albedo contribute about equally to glacial-interglacial 'forcings' and temperature change, with each having gain ~0.2 [14]. Thus

$$\begin{aligned} g &= g_{\text{fast feedbacks}} + g_{\text{surface albedo}} + g_{\text{GHG}} \\ &= \sim 0.5\text{-}0.6 + \sim 0.2 + \sim 0.2. \end{aligned}$$

Thus climate gain in the Pleistocene was greater than or of the order of 0.9. It is no wonder that late Cenozoic climate fluctuated so greatly (Fig. **3b**). When substantial ice is present on the planet, g is close to unity, climate is sensitive, and large climate swings occur in response to small orbital forcings. Indeed, with g near unity any forcing or climate noise can cause large climate change, consistent with the conclusion that much of climate variability is not due to orbital forcings [S7]. In the early Cenozoic there was little ice, $g_{\text{surface albedo}}$ was small, and thus climate oscillations due to insolation perturbations were smaller.

It may be useful to divide inferences from Pleistocene climate change into two categories: (1) well-defined conclusions about the nature of the climate change, (2) less certain suggestions about the nature and causes of the climate change. The merit of identifying well-defined conclusions is that they help us predict likely consequences of human-made climate forcings. Less certain aspects of Pleistocene climate change mainly concern the small forcings that instigated climate swings. The small forcings are of great interest to paleoclimatologists, but they need not prevent extraction of practical implications from Pleistocene climate change.

Two fundamental characteristics of Pleistocene climate change are clear. First, there is the high gain, at least of the order of 0.9, i.e., the high sensitivity to a climate forcing, when the planet is in the range of climates that existed during the Pleistocene. Second, we have a good knowledge of the amplifying feedbacks that produce this high gain. Fast feedbacks, including water vapor, clouds, aerosols, sea ice and snow, contribute at least half of this gain. The remainder of the amplification is provided almost entirely by two factors: surface albedo (mainly ice sheets) and GHGs (mainly CO_2).

Details beyond these basic conclusions are less certain. The large glacial-interglacial surface albedo and GHG changes should lag global temperature, because they are feedbacks on global temperature on the global spatial scale and millennial time scale. The lag of GHGs after temperature change is several hundred years (Fig. **6** of [6]), perhaps determined by the ocean overturning time. Ice sheet changes may lag temperature by a few millennia [24], but it has been argued that there is no discernible lag between insolation forcing and the maximum rate of change of ice sheet volume [7].

A complication arises from the fact that some instigating factors (forcing mechanisms) for Pleistocene climate change also involve surface albedo and GHG changes. Regional anomalies of seasonal insolation are as much as many tens of W/m^2. The global forcing is small (Fig. **S3**) because the local anomalies are nearly balanced by anomalies of the opposite sign in either the opposite hemisphere or the opposite season. However, one can readily imagine climate change mechanisms that operate in such a way that cancellation does not occur.

For example, it has been argued [7] that a positive insolation anomaly in late spring is most effective for causing ice sheet disintegration because early ‘albedo flip’, as the ice becomes wet, yields maximum extension of the melt season. It is unlikely that the strong effect of albedo flip on absorbed solar energy could be offset by a negative insolation anomaly at other times of year.

A second example is non-cancellation of hemispheric insolation anomalies. A hemispheric asymmetry occurs when Earth is cold enough that ice sheets extend to Northern Hemisphere middle latitudes, due to absence of similar Southern Hemisphere land. It has been argued [7] that this hemispheric asymmetry is the reason that the orbital periodicities associated with precession of the equinoxes and orbit eccentricity became substantial about 1 million years ago.

Insolation anomalies also may directly affect GHG amounts, as well as surface albedo. One can readily imagine ways in which insolation anomalies affect methane release from wetlands or carbon uptake through biological processes.

Surface albedo and GHG changes that result immediately from insolation anomalies can be defined as climate forcings, as indirect forcings due to insolation anomalies. The question then becomes: what fractions of the known paleo albedo and GHG changes are immediate indirect forcings due to insolation anomalies and what fractions are feedbacks due to global temperature change?

It is our presumption that most of the Pleistocene GHG changes are a slow feedback in response to climate change. This interpretation is supported by the lag of several hundred years between temperature change and greenhouse gas amount (Fig. **6** of [6]). The conclusion that most of the ice area and surface albedo change is also a feedback in response to global temperature change is supported by the fact that the large climate swings are global (Section 5 of Appendix).

Note that our inferred climate sensitivity is not dependent on detailed workings of Pleistocene climate fluctuations. The fast feedback sensitivity of 3°C for doubled CO_2, derived by comparing glacial and interglacial states, is independent of the cause and dynamics of glacial/interglacial transitions.

Climate sensitivity including surface albedo feedback (~6°C for doubled CO_2) is the average sensitivity for the climate range from 35 My ago to the present and is independent of the glacial-interglacial ‘wiggles’ in Fig. (**3**). Note that climate and albedo changes occurred mainly at points with ‘ready’ [63] feedbacks: at Antarctic glaciation and (in the past three million years) with expansion of Northern Hemisphere glaciation, which are thus times of high climate sensitivity.

The entire ice albedo feedback from snowball-Earth to ice-free planet (or vice versa) can be viewed as a response to changing global temperature, with wiggles introduced by Milankovitch (orbital) forcings. The average $g_{\text{surface albedo}}$ for the range from today’s climate through Antarctic deglaciation is close to $g_{\text{surface albedo}} \sim 0.2$, almost as large as in the Pleistocene. Beyond Antarctic deglaciation (i.e., for an ice-free planet) $g_{\text{surface albedo}} \rightarrow 0$, except for vegetation effects.

For the sake of specificity, let us estimate the effect of slow feedbacks on climate sensitivity. If we round ΔT_O to 1.2°C for doubled CO_2 and the fast feedback gain to $g_{\text{fast feedbacks}} = 0.6$, then for fast feedbacks alone $f = 2.5$ and the equilibrium warming is $\Delta T_{eq} = 3°C$. Inclusion of $g_{\text{surface albedo}} = 0.2$ makes $f = 5$ and $\Delta T_{eq} = 6°C$, which is the sensitivity if the GHG amount is specified from observations or from a carbon cycle model.

The feedback factor f can approach infinity, i.e., the climate can become unstable. However, instabilities are limited except at the snowball Earth and runaway greenhouse extremes. Some feedbacks have a finite supply, e.g., as when Antarctica becomes fully deglaciated. Also climate change can cause positive feedbacks to decrease or negative feedbacks to come into play.

For example, Fig. (**S2**) suggests that a cooling climate from the present state first reduces the fast feedback gain. This and reduced weathering with glaciation may be reasons that most ice ages did not reach closer to the iceball state. Also there may be limitations on the ranges of GHG (CO_2, CH_4, N_2O) feedbacks. Empirical values g_{GHG} ~ 0.2 and $g_{surface\ albedo}$ ~ 0.2 were derived as averages relevant to the range of climates that existed in the past several hundred thousand years, and they may not be valid outside that range.

On the other hand, if the forcing becomes large enough, global instabilities are possible. Earth did become cold enough in the past for the snowball-Earth instability. Although the runaway greenhouse effect has not occurred on Earth, solar irradiance is now at its highest level so far, and Fig. (**S2**) suggests that the required forcing for runaway may be only 10-20 W/m^2. If all conventional and unconventional fossil fuels were burned, with the CO_2 emitted to the atmosphere, it is possible that a runaway greenhouse effect could occur, with incineration of life and creation of a permanent Venus-like hothouse Earth. It would take time for the ice sheets to melt, but the melt rate may accelerate as ice sheet disintegration proceeds.

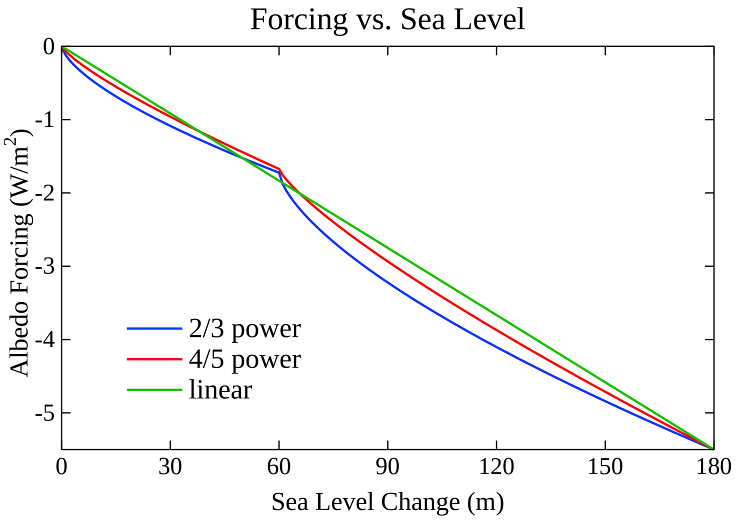


Fig. (S4). Surface albedo climate forcing as a function of sea level for three approximations of the ice sheet area as a function of sea level change, from an ice free planet to the last glacial maximum. For sea level between 0 and 60 m only Antarctica contributes to the albedo change. At the last glacial maximum Antarctica contains 75 m of sea level and the Northern Hemisphere contains 105 m.

4. ICE SHEET ALBEDO

In the present paper we take the surface area covered by an ice sheet to be proportional to the 4/5 power of the volume of the ice sheet, based on ice sheet modeling of one of us (VM-D). We extend the formulation all the way to zero ice on the planet, with separate terms for each hemisphere. At 20 ky ago, when the ice sheets were at or near their maximum size in the Cenozoic era, the forcing by the Northern Hemisphere ice sheet was -3.5 W/m^2 and the forcing by the Southern Hemisphere ice sheet was -2 W/m^2, relative to the ice-free planet [14]. It is assumed that the first 60 m of sea level fall went entirely into growth of the Southern Hemisphere ice sheet. The water from further sea level fall is divided proportionately between hemispheres such that when sea level fall reaches -180 m there is 75 m in the ice sheet of the Southern Hemisphere and 105 m in the Northern Hemisphere.

The climate forcing due to sea level changes in the two hemispheres, SL_S and SL_N, is

$$F_{Albedo}\ (W/m^2) = -\ 2\ (SL_S/75\ m)^{4/5}\ -\ 3.5\ (SL_N/105\ m)^{4/5}, \qquad (S1)$$

where the climate forcings due to fully glaciated Antarctica (-2 W/m^2) and Northern Hemisphere glaciation during the last glacial maximum (-3.5 W/m^2) were derived from global climate model simulations [14].

Fig. (**S4**) compares results from the present approach with results from the same approach using exponent 2/3 rather than 4/5, and with a simple linear relationship between the total forcing and sea level change. Use of exponent 4/5 brings the results close to the linear case, suggesting that the simple linear relationship is a reasonably good approximation. The similarity of Fig. (**1c**) in our present paper and Fig. (**2c**) in [7] indicates that change of exponent from 2/3 to 4/5 did not have a large effect.

5. GLOBAL NATURE OF MAJOR CLIMATE CHANGES

Climate changes often begin in a specific hemisphere, but the large climate changes are invariably global, in part because of the global GHG feedback. Even without the GHG feedback, forcings that are located predominately in one hemisphere, such as ice sheet changes or human-made aerosols, still evoke a global response [12], albeit with the response being larger in the hemisphere of the forcing. Both the atmosphere and ocean transmit climate response between hemispheres. The deep ocean can carry a temperature change between hemispheres with little loss, but because of the ocean's thermal inertia there can be a hemispheric lag of up to a millennium (see Ocean Response Time, below).

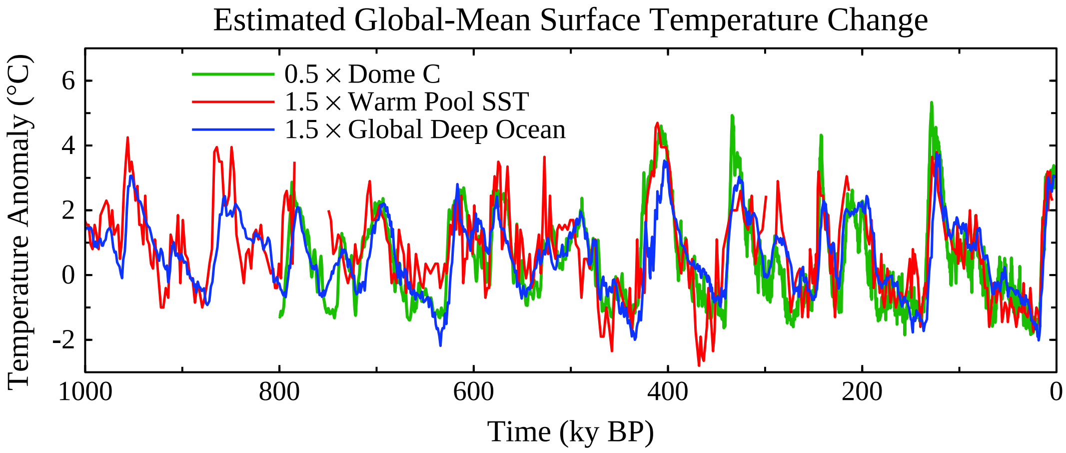


Fig. (S5). Estimated global temperature change based on measurements at a single point or, in the case of the deep ocean, a near-global stack of ocean drilling sites: Antarctica Dome C [S8], Warm Pool [S9], deep ocean [26].

Fig. (**S5**) compares temperature change in Antarctica [S8], the tropical sea surface [S9], and the global deep ocean [26]. Temperature records are multiplied by factors that convert the temperature record to an estimate of global temperature change. Based on paleoclimate records, polar temperature change is typically twice the global average temperature change, and tropical temperature change is about two-thirds of the global mean change. This polar amplification of the temperature change is an expected consequence of feedbacks [14], especially the snow-ice albedo feedback. The empirical result that deep ocean temperature changes are only about two-thirds as large as global temperature change is obtained from data for the Pleistocene epoch, when deep ocean temperature change is limited by its approach to the freezing point.

6. HOLOCENE CLIMATE FORCINGS

The GHG zero-point for the paleo portion of Fig. (**2**) is the mean for 10-8 ky BP, a time that should precede any significant anthropogenic effect on GHG amount. It has been suggested that the increase of CO_2 that began 8000 years ago is due to deforestation and the increase of CH_4 that began 6000 years ago is caused by rice agriculture [62]. This suggestion has proven to be controversial, but regardless of whether late Holocene CO_2 and CH_4 changes are human-made, the GHG forcing is anomalous in that period relative to global temperature change estimated from ocean and ice cores. As discussed elsewhere [7], the late Holocene is the only time in the ice core record in which there is a clear deviation of temperature from that expected due to GHG and surface albedo forcings.

The GHG forcing increase in the second half of the Holocene is ~3/4 W/m^2. Such a large forcing, by itself, would create a planetary energy imbalance that could not be sustained for millennia without causing a large global temperature increase, the expected global warming being about 1°C. Actual global temperature change in this period was small, perhaps a slight cooling. Fig. (**S6**) shows estimates of global temperature change obtained by dividing polar temperature change by two or multiplying tropical and deep ocean temperatures by 1.5. Clearly the Earth has not been warming rapidly in the latter half of the Holocene. Thus a substantial (negative) forcing must have been operating along with the positive GHG forcing.

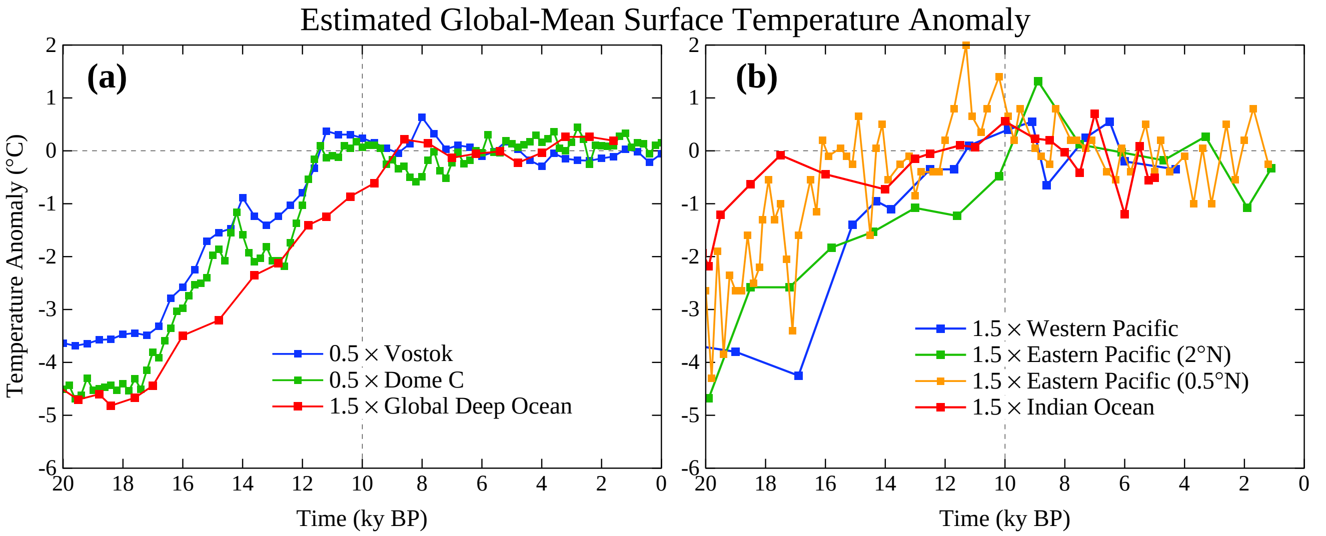


Fig. (S6). Estimates of global temperature change inferred from Antarctic ice cores [18, S8] and ocean sediment cores [S9-S13], as in Fig. (**S5**) but for a period allowing Holocene temperature to be apparent.

Deforestation causes a negative climate forcing [12], but an order of magnitude too small to balance GHG positive forcing. A much larger negative forcing is expected from human-made aerosols. Aerosol forcing is non-linear, especially the indirect effect on clouds, with aerosols added to a pristine atmosphere being more effective than those added to the current highly polluted atmosphere. Given estimates of a negative forcing of 1-2 W/m^2 for today's anthropogenic aerosols [2, 5, 12], a negative aerosol forcing at least of the order of 0.5 W/m^2 in 1850 is expected. We conclude that aerosols probably were the predominant negative forcing that opposed the rapid increase of positive GHG forcing in the late Holocene.

7. OCEAN RESPONSE TIME

Fig. (**S7**) shows the climate response function, defined as the fraction of equilibrium global warming that is obtained as a function of time. This response function was obtained [7] from a 3000-year simulation after instant doubling of atmospheric CO_2, using GISS modelE [S3, 12] coupled to the Russell ocean model [S14]. Note that although 40% of the equilibrium solution is obtained within several years, only 60% is achieved after a century, and nearly full response requires a millennium. The long response time is caused by slow uptake of heat by the deep ocean, which occurs primarily in the Southern Ocean.

This delay of the surface temperature response to a forcing, caused by ocean thermal inertia, is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of water into the deep ocean [31]. The ocean model used for Fig. (**S7**) may mix somewhat too rapidly in the waters around Antarctica, as judged by transient tracers [S14], reducing the simulated surface response on the century time scale. However, this uncertainty does not qualitatively alter the shape of the response function (Fig. **S7**).

When the climate model used to produce Fig. (**S7**) is driven by observed changes of GHGs and other forcings it yields good agreement with observed global temperature and ocean heat storage [5]. The model has climate sensitivity ~3°C for doubled CO_2, in good agreement with the fast-feedback sensitivity inferred from paleoclimate data.

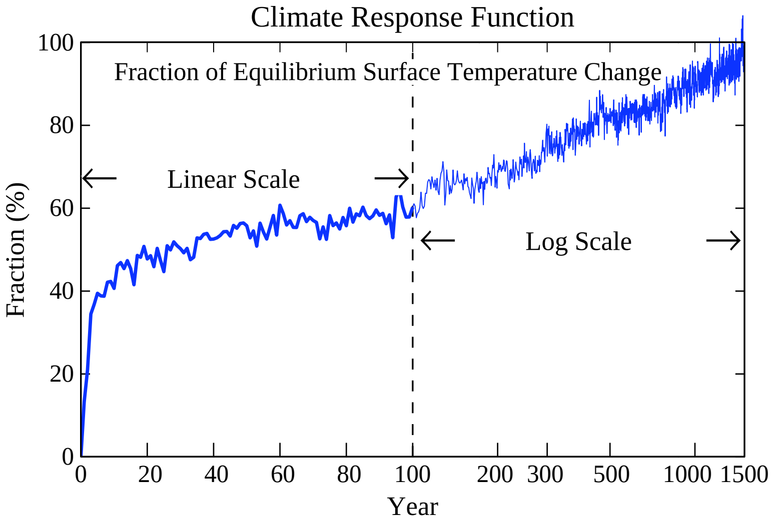


Fig. (S7). Fraction of equilibrium surface temperature response versus time in the GISS climate model [7, 12, S3] with the Russell [S14] ocean. The forcing was doubled atmospheric CO_2. The ice sheets, vegetation distribution and other long-lived GHGs were fixed.

8. SEPARATION OF Δ^{18}O INTO ICE VOLUME AND TEMPERATURE

δ^{18}O of benthic (deep ocean dwelling) foraminifera is affected by both deep ocean temperature and continental ice volume. Between 34 My and the last ice age (20 ky) the change of δ^{18}O was ~ 3, with T_{do} change ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Based on the rate of change of δ^{18}O with deep ocean temperature in the prior period without land ice, ~ 1.5 of δ^{18}O is associated with the T_{do} change of ~ 6°C, and we assign the remaining δ^{18}O change to ice volume linearly at the rate 60 msl per mil δ^{18}O change (thus 180 msl for δ^{18}O between 1.75 and 4.75).

Thus we assume that ice sheets were absent when $\delta^{18}O < 1.75$ with sea level 75 msl higher than today. Sea level at smaller values of δ^{18}O is given by

$$SL\ (m) = 75 - 60 \times (\delta^{18}O - 1.75). \qquad (S2)$$

Fig. (**S8**) shows that the division of δ^{18}O equally into sea level change and deep ocean temperature captures well the magnitude of the major glacial to interglacial changes.

9. CONTINENTAL DRIFT AND ATMOSPHERIC CO_2

At the beginning of the Cenozoic era 65 My ago the continents were already close to their present latitudes, so the effect of continental location on surface albedo had little direct effect on the planet's energy balance (Fig. **S9**). However, continental drift has a major effect on the balance, or imbalance, of outgassing and uptake of CO_2 by the solid Earth and thus a major effect on atmospheric composition and climate. We refer to the carbon in the air, ocean, soil and biosphere as the combined surface reservoir of carbon, and carbon in ocean sediments and the rest of the crust as the carbon in the 'solid' Earth. Sloshing of CO_2 among the surface reservoirs, as we have shown, is a primary mechanism for glacial-interglacial climate fluctuations. On longer time scales the total amount of carbon in the surface reservoirs can change as a result of any imbalance between outgassing and uptake by the solid Earth.

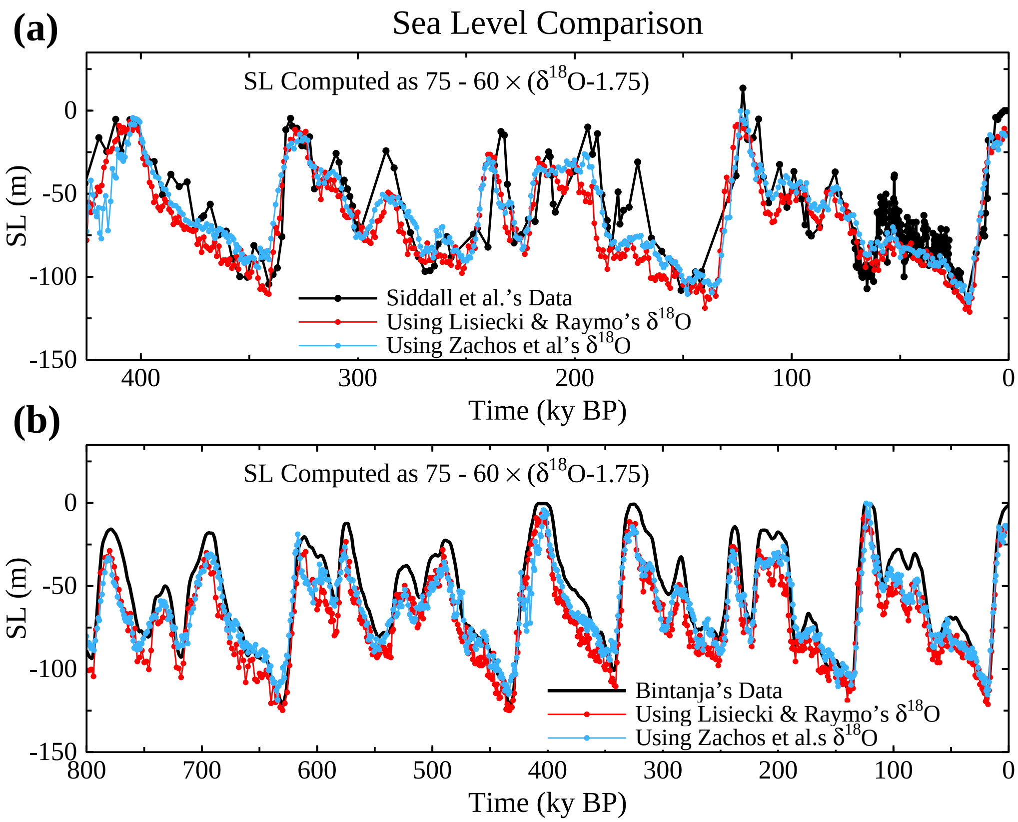
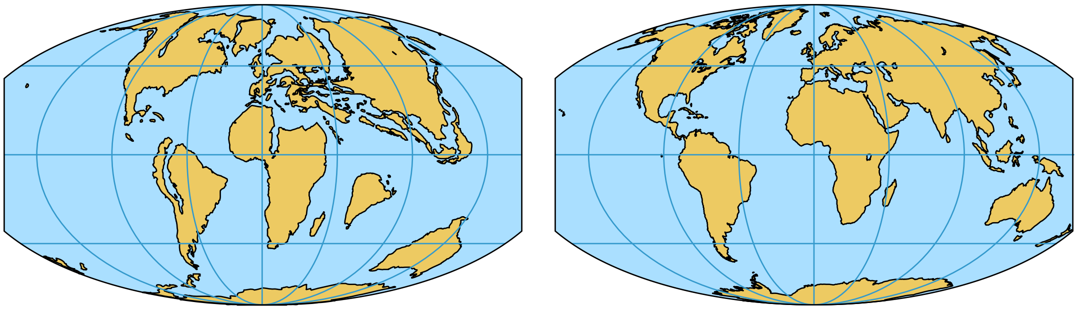


Fig. (S8). (**a**) Comparison of Siddall *et al.* [19] sea level record with sea level computed from $\delta^{18}O$ *via* Eq. S2 using two alternative global benthic stacks [26, S15]. (**b**) Comparison of Bintanja *et al*. [S16] sea level reconstruction with the same global benthic stacks as in (**a**).



End of Cretaceous (65 My BP) Present Day

Fig. (S9). Continental locations at the beginning and end of the Cenozoic era [S17].

Outgassing, which occurs mainly in regions of volcanic activity, depends upon the rate at which carbon-rich oceanic crust is subducted beneath moving continental plates [30, 47]. Drawdown of CO_2 from the surface reservoir occurs with weathering of rocks exposed by uplift, with the weathering products carried by rivers to the ocean and eventually deposited as carbonates on the ocean floor [30] and by burial of organic matter. Both outgassing and drawdown of CO_2 are affected by changes in plate tectonics, which thus can alter the amount of carbon in the surface reservoir. The magnitude of the changes of carbon in the surface reservoir, and thus in the atmosphere, is constrained by a negative weathering feedback on the time scale of hundreds of thousands of years [30, 52], but plate tectonics can evoke changes of the surface carbon reservoir by altering the rates of outgassing and weathering.

At the beginning of the Cenozoic the African plate was already in collision with Eurasia, pushing up the Alps. India was still south of the equator, but moving north rapidly through a region with fresh carbonate deposits. It is likely that subduction of carbon rich crust of the Tethys Ocean, long a depocenter for sediments, caused an increase of atmospheric CO_2 and the early Cenozoic warming that peaked ~50 My ago. The period of rapid subduction terminated with the collision of India with Eurasia, whereupon uplift of the Himalayas and the Tibetan Plateau increased weathering rates and drawdown of atmospheric CO_2 [51].

Since 50 My ago the world's major rivers have emptied into the Indian and Atlantic Oceans, but there is little subduction of oceanic crust of these regions that are accumulating sediments [47]. Thus the collision of India with Asia was effective in both reducing a large source of outgassing of CO_2 as well as exposing rock for weathering and drawdown of atmospheric CO_2. The rate of CO_2 drawdown decreases as the CO_2 amount declines because of negative feedbacks, including the effects of temperature and plant growth rate on weathering [30].

10. PROXY CO_2 DATA

There are inconsistencies among the several proxy measures of atmospheric CO_2, including differences between results of investigators using nominally the same reconstruction method. We briefly describe strengths and weaknesses of the four paleo-CO_2 reconstruction methods included in the IPCC report [2], which are shown in Fig. (**S10**) and discussed in detail elsewhere [S18]. The inconsistencies among the different proxies constrain their utility for rigorously evaluating our CO_2 predictions. We also include a comparison of our calculated CO_2 history with results from a version of the Berner [30] geochemical carbon cycle model, as well as a comparison with an emerging CO_2 proxy based on carbon-isotope analyses of nonvascular plant (bryophyte) fossils [S19].

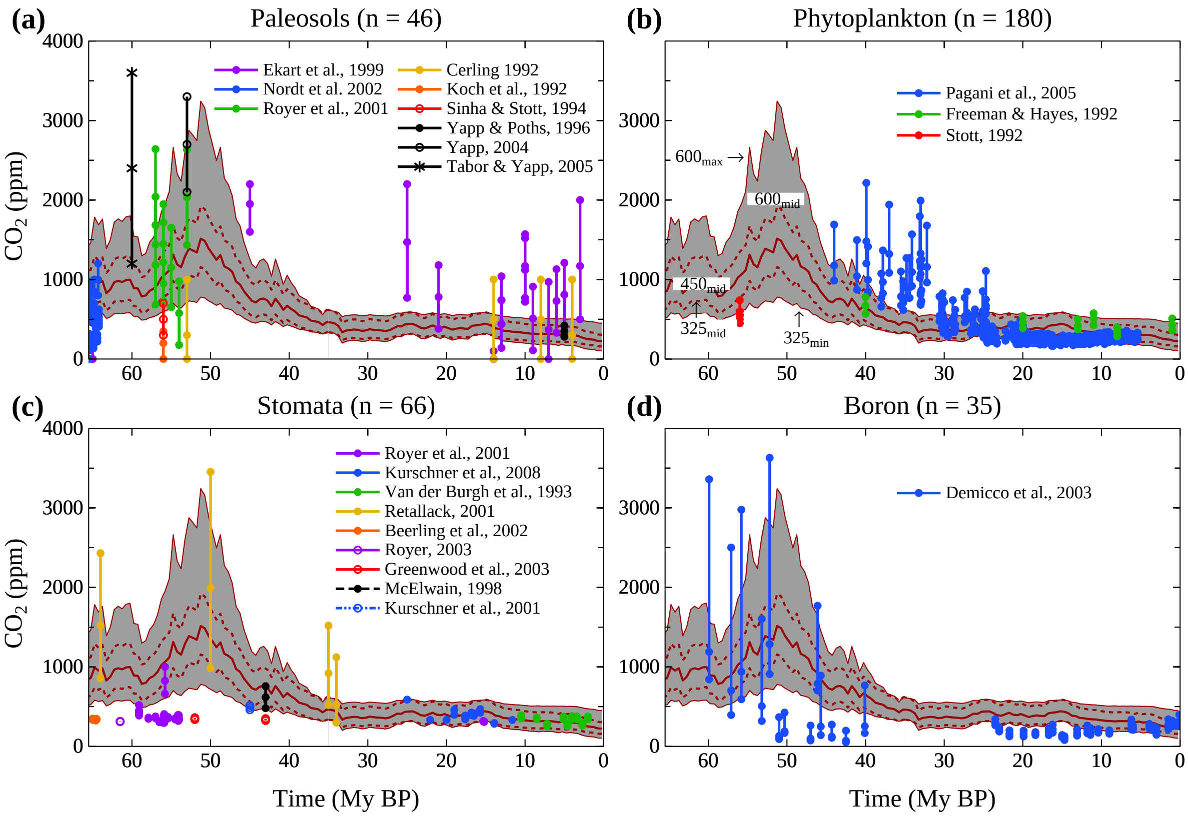


Fig. (S10). Comparison of proxy CO_2 measurements with CO_2 predictions based on deep-ocean temperature, the latter inferred from benthic $\delta^{18}O$. The shaded range of model results is intended mainly to guide the eye in comparing different proxies. The dark central line is for the standard case with CO_2 = 450 ppm at 35 My ago, and the dashed lines are the standard cases for CO_2 = 325 and 600 ppm at 35 My ago. The extremes of the shaded area correspond to the maximum range including a 50% uncertainty in the relation of ΔT_s and ΔT_{do}. Our assumption that CO_2 provides 75% of the GHG throughout the Cenozoic adds additional uncertainty to the predicted CO_2 amount. References for data sources in the legends are provided by Royer [55], except Kurshner *et al.* [S20].

The paleosol method is based on the $\delta^{13}C$ of pedogenic carbonate nodules, whose formation can be represented by a two end-member mixing model between atmospheric CO_2 and soil-derived carbon [S21]. Variables that need to be constrained or assumed include an estimation of nodule depth from the surface of the original soil, the respiration rate of the ecosystem that inhabits the soil, the porosity/diffusivity of the original soil, and the isotopic composition of the vegetation contribution of respired CO_2. The uncertainties in CO_2 estimates with this proxy are substantial at high CO_2 (±500-1000 ppm when CO_2 > 1000 ppm) and somewhat less in the lower CO_2 range (±400-500 ppm when CO_2 < 1000 ppm).

The stomatal method is based on the genetically-controlled relationship [S22] between the proportion of leaf surface cells that are stomata and atmospheric CO_2 concentrations [S23]. The error terms with this method are comparatively small at low CO_2 (< ±50 ppm), but the method rapidly loses sensitivity at high CO_2 (> 500-1000 ppm). Because stomatal-CO_2 relationships are often species-specific, only extant taxa with long fossil records can be used [S24]. Also, because the fundamental response of stomata is to the partial pressure of CO_2 [S25], constraints on paleoelevation are required.

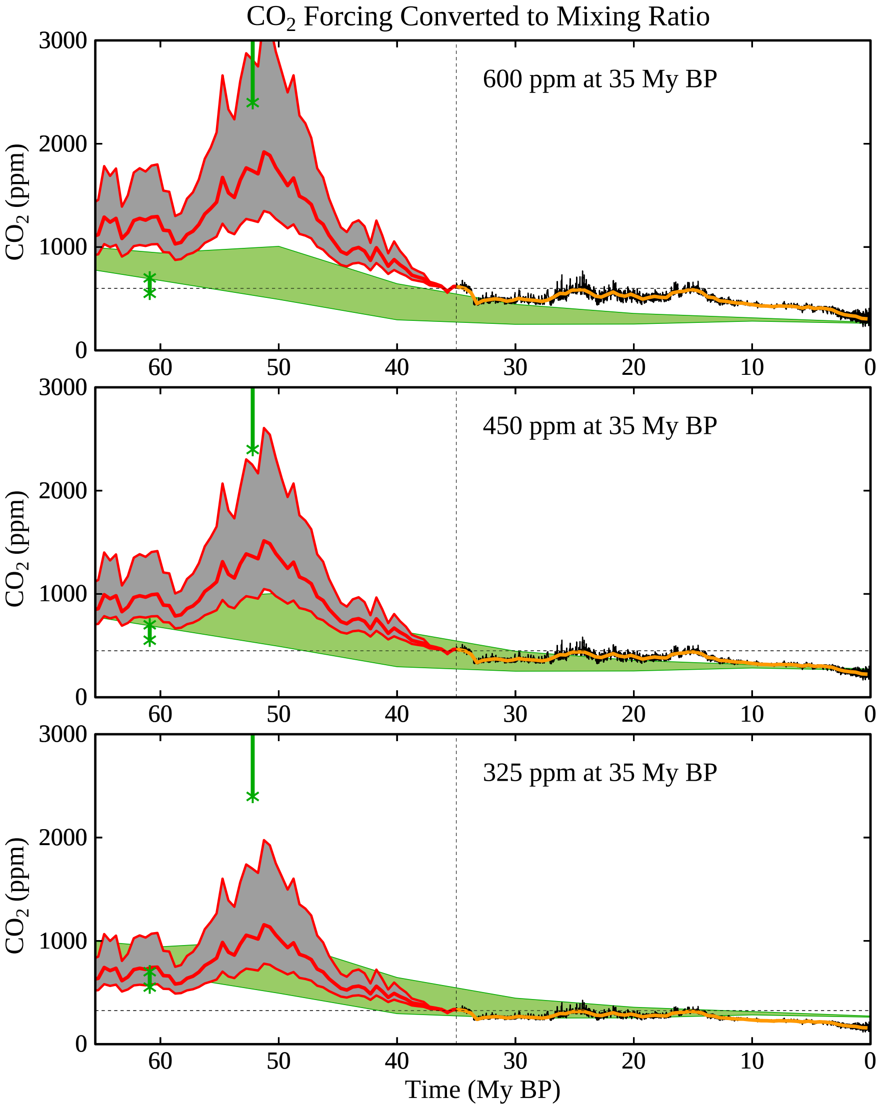


Fig. (S11). Simulated CO_2 in the Cenozoic for three choices of CO_2 amount at 35 My, as in Fig. (**5**), compared with the CO_2 history in a geochemical model [30], specifically the model version described by Fletcher *et al.* [S19]. The green vertical bars are a proxy CO_2 measure [S19] obtained from fossils of non-vascular plants (bryophytes) that is not included among the proxies shown in Fig. (**S10**).

The phytoplankton method is based on the Rayleigh distillation process of fractionating stable carbon isotopes during photosynthesis [S26]. In a high CO_2 environment, for example, there is a higher diffusion rate of CO_2 through phytoplankton cell membranes, leading to a larger available intercellular pool of $CO_{2[aq]}$ and more depleted $\delta^{13}C$ values in photosynthate. Cellular growth rate and cell size also impact the fractionation of carbon isotopes in phytoplankton and thus fossil studies must take these factors into account [S27]. This approach to reconstructing CO_2 assumes that the diffusional transport of CO_2 into the cell dominates, and that any portion of carbon actively transported into the cell remains constant with time. Error terms are typically small at low CO_2 (< ±50 ppm) and increase substantially under higher CO_2 concentrations [S27].

The boron-isotope approach is based on the pH-dependency of the $\delta^{11}B$ of marine carbonate [S28]. This current method assumes that only borate is incorporated in the carbonate lattice and that the fractionation factor for isotope exchange between boric acid and borate in solution is well-constrained. Additional factors that must be taken into account include test dissolution and size, species-specific physiological effects on carbonate $\delta^{11}B$, and ocean alkalinity [S29-S31]. As with the stomatal and phytoplankton methods, error terms are comparatively small at low CO_2 (< ±50 ppm) and the method loses sensitivity at higher CO_2 (> 1000 ppm). Uncertainty is unconstrained for extinct foraminiferal species.

Fig. (**S10**) illustrates the scatter among proxy data sources, which limits inferences about atmospheric CO_2 history. Given the large inconsistency among different data sets in the early Cenozoic, at least some of the data or their interpretations must be flawed. In the range of proxy data shown in Fig. (**5**) we took all data sources as being of equal significance. It seems likely that the low CO_2 values in the early Cenozoic are faulty, but we avoid omission of any data until the matter is clarified, and thus the range of proxy data shown in Fig. (**5**) is based on all data. Reviews of the proxy data [S19, 55] conclude that atmospheric CO_2 amount in the early Cenozoic reached values of at least 500-1000 ppm.

Fig. (**S11**) shows that geochemical carbon cycle modeling [30, S19] is reasonably consistent with our calculated long-term trend of atmospheric CO_2 for the cases with CO_2 at 34 My ago being in the range from about 325 to 450 ppm. The geochemical modeling does not yield a strong maximum of CO_2 at 50 My ago, but the temporal resolution of the modeling (10 My) and the absence of high resolution input data for outgassing due to variations in plate motions tends to mitigate against sharp features in the simulated CO_2.

Fig. (**S11**) also shows (vertical green bars) an emerging CO_2 proxy based on the isotopic composition of fossil liverworts. These non-vascular plants, lacking stomatal pores, have a carbon isotopic fractionation that is strongly CO_2 dependent, reflecting the balance between CO_2 uptake by photosynthesis and inward CO_2 diffusion [S19].

11. CLIMATE SENSITIVITY COMPARISONS

Other empirical or semi-empirical derivations of climate sensitivity from paleoclimate data (Table **S1**) are in reasonable accord with our results, when account is taken of differences in definitions of sensitivity and the periods considered.

Royer *et al.* [56] use a carbon cycle model, including temperature dependence of weathering rates, to find a best-fit doubled CO_2 sensitivity of 2.8°C based on comparison with Phanerozoic CO_2 proxy amounts. Best-fit in their comparison of model and proxy CO_2 data is dominated by the times of large CO_2 in the Phanerozoic, when ice sheets would be absent, not by the times of small CO_2 in the late Cenozoic. Their inferred sensitivity is consistent with our inference of ~3°C for doubled CO_2 at times of little or no ice on the planet.

Higgins and Schrag [57] infer climate sensitivity of ~4°C for doubled CO_2 from the temperature change during the Paleocene-Eocene Thermal Maximum (PETM) ~55 My ago (Fig. **3**), based on the magnitude of the carbon isotope excursion at that time. Their climate sensitivity for an ice-free planet is consistent with ours within uncertainty ranges. Furthermore, recalling that we assume non-CO_2 to provide 25% of the GHG forcing, if one assumes that part of the PETM warming was a direct of effect of methane, then their inferred climate sensitivity is in even closer agreement with ours.

Pagani *et al.* [58] also use the magnitude of the PETM warming and the associated carbon isotopic excursion to discuss implications for climate sensitivity, providing a graphical relationship to help assess alternative assumptions about the origin and magnitude of carbon release. They conclude that the observed PETM warming of about 5°C implies a high climate sensitivity, but with large uncertainty due to imprecise knowledge of the carbon release.

Table S1. Climate Sensitivity Inferred Semi-Empirically from Cenozoic or Phanerozoic Climate Change

Reference	Period	Doubled CO_2 Sensitivity
Royer *et al.* [56]	0-420 My	~ 2.8°C
Higgins and Schrag [57]	PETM	~4°C
Pagani *et al.* [58]	PETM	High

12. GREENHOUSE GAS GROWTH RATES

Fossil fuel CO_2 emissions have been increasing at a rate close to the highest IPCC [S34] scenario (Fig. **S12b**). Increase of CO_2 in the air, however, appears to be in the middle of the IPCC scenarios (Fig. **S12c**, **d**), but as yet the scenarios are too close and interannual variability too large, for assessment. CO_2 growth is well above the "alternative scenario", which was defined with the objective of keeping added GHG forcing in the 21st century at about 1.5 W/m^2 and 21st century global warming less than 1°C [20].

Non-CO_2 greenhouse gases are increasing more slowly than in IPCC scenarios, overall at approximately the rate of the "alternative scenario", based on a review of data through the end of 2007 [69]. There is potential to reduce non-CO_2 forcings below the alternative scenario [69].

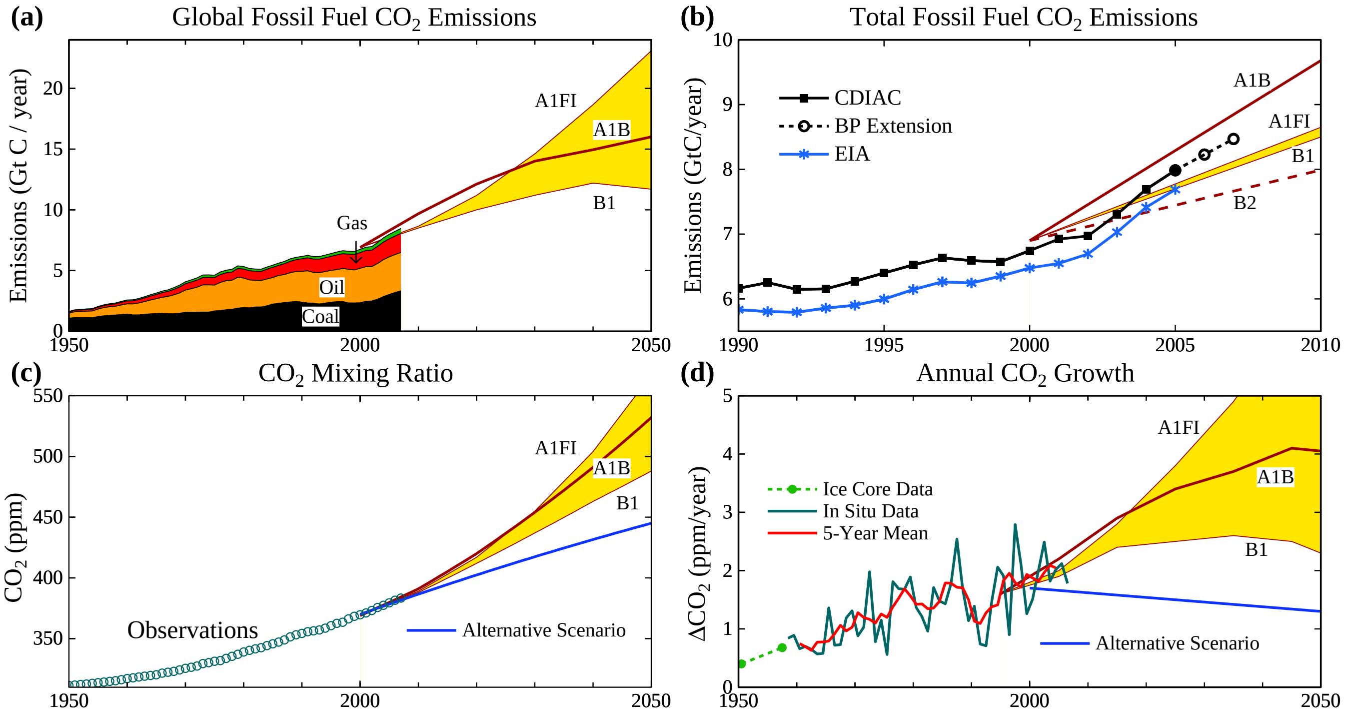


Fig. (S12). (**a**) Fossil fuel CO_2 emissions by fuel type [S32, S33], the thin green sliver being gas flaring plus cement production, and IPCC fossil fuel emissions scenarios, (**b**) expansion global emissions to show recent changes more precisely, the EIA values excluding CO_2 emissions from cement manufacture, (**c**) observed atmospheric CO_2 amount and IPCC and "alternative" scenarios for the future, (**d**) annual atmospheric CO_2 growth rates. Data here is an update of data sources defined in [6]. The yellow area is bounded by scenarios that are most extreme in the second half of the 21st century; other scenarios fall outside this range in the early part of the century.

13. FOSSIL FUEL AND LAND-USE CO_2 EMISSIONS

Fig. (**S13**) shows estimates of anthropogenic CO_2 emissions to the atmosphere. Although fossil emissions through 2006 are known with good accuracy, probably better than 10%, reserves and potential reserve growth are highly uncertain. IPCC [S34] estimates for oil and gas proven reserves are probably a lower limit for future oil and gas emissions, but they are perhaps a feasible goal that could be achieved *via* a substantial growing carbon price that discourages fossil fuel exploration in extreme environments together with national and international policies that accelerate transition to carbon-free energy sources and limit fossil fuel extraction in extreme environments and on government controlled property.

Coal reserves are highly uncertain, but the reserves are surely enough to take atmospheric CO_2 amount far into the region that we assess as being "dangerous". Thus we only consider scenarios in which coal use is phased out as rapidly as possible, except for uses in which the CO_2 is captured and stored so that it cannot escape to the atmosphere. Thus the magnitude of coal reserves does not appreciably affect our simulations of future atmospheric CO_2 amount.

Integrated 1850-2008 net land-use emissions based on the full Houghton [83] historical emissions (Fig. **S14**), extended with constant emissions for the past several years, are 79 ppm CO_2. Although this could be an overestimate by up to a factor of two (see below), substantial pre-1850 deforestation must be added in. Our subjective estimate of uncertainty in the total land-use CO_2 emission is a factor of two.

14. THE MODERN CARBON CYCLE

Atmospheric CO_2 amount is affected significantly not only by fossil fuel emissions, but also by agricultural and forestry practices. Quantification of the role of land-use in the uptake and release of CO_2 is needed to assess strategies to minimize human-made climate effects.

Fig. (**S15**) shows the CO_2 airborne fraction, AF, the annual increase of atmospheric CO_2 divided by annual fossil fuel CO_2 emissions. AF is a critical metric of the modern carbon cycle, because it is based on the two numbers characterizing the global carbon cycle that are well known. AF averages 56% over the period of accurate data, which began with the CO_2 measurements of Keeling in 1957, with no discernable trend. The fact that 44% of fossil fuel emissions seemingly "disappears" immediately provides a hint of optimism with regard to the possibility of stabilizing, or reducing, atmospheric CO_2 amount.

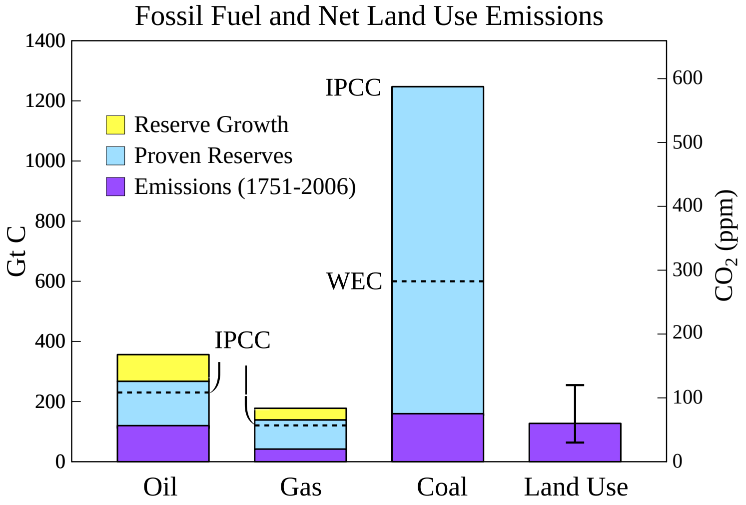


Fig. (S13). Fossil fuel and land-use CO_2 emissions, and potential fossil fuel emissions. Historical fossil fuel emissions are from the Carbon Dioxide Information Analysis Center [CDIAC, S32] and British Petroleum [BP, S33]. Lower limits on oil and gas reserves are from IPCC [S34] and higher limits are from the United States Energy Information Administration [EIA, 80]. Lower limit for coal reserves is from the World Energy Council [WEC, S35] and upper limit from IPCC [S34]. Land use estimate is from integrated emissions of Houghton/2 (Fig. **S14**) supplemented to include pre-1850 and post-2000 emissions; uncertainty bar is subjective.

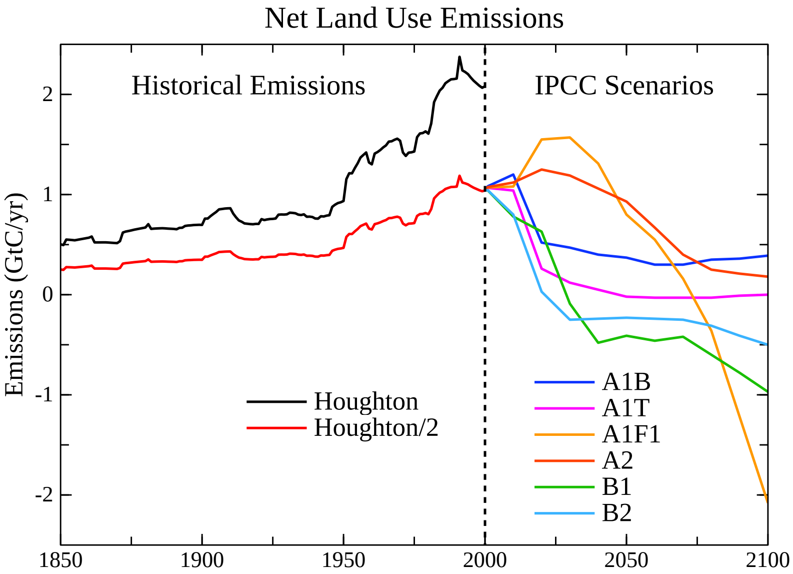


Fig. (S14). Left side: estimate by Houghton [83] of historical net land-use CO_2 emissions, and a 50 percent reduction of that estimate. Right side: IPCC [2] scenarios for land-use CO_2 emissions.

That optimism needs to be tempered, as we will see, by realization of the magnitude of the actions required to halt and reverse CO_2 growth. However, it is equally important to realize that assertions that fossil fuel emissions must be reduced close to 100% on an implausibly fast schedule are not necessarily valid.

A second definition of the airborne fraction, AF2, is also useful. AF2 includes the net anthropogenic land-use emission of CO_2 in the denominator. This AF2 definition of airborne fraction has become common in recent carbon cycle literature. However, AF2 is not an observed or accurately known quantity; it involves estimates of net land-use CO_2 emissions, which vary among investigators by a factor of two or more [2].

Fig. (**S15**) shows an estimate of net land-use CO_2 emissions commonly used in carbon cycle studies, labeled “Houghton” [83], as well as “Houghton/2”, a 50% reduction of these land-use emissions. An over-estimate of land-use emissions is one possible solution of the long-standing “missing sink” problem that emerges when the full “Houghton” land-use emissions are employed in carbon cycle models [2, S34, 79].

Principal competing solutions of the “missing sink” paradox are (1) land-use CO_2 emissions are over-estimated by about a factor of two, or (2) the biosphere is being “fertilized” by anthropogenic emissions, *via* some combination of increasing atmospheric CO_2, nitrogen deposition, and global warming, to a greater degree than included in typical carbon cycle models.

Reality may include contributions from both candidate explanations. There is also a possibility that imprecision in the ocean uptake of CO_2, or existence of other sinks such as clay formation, could contribute increased CO_2 uptake, but these uncertainties are believed to be small.

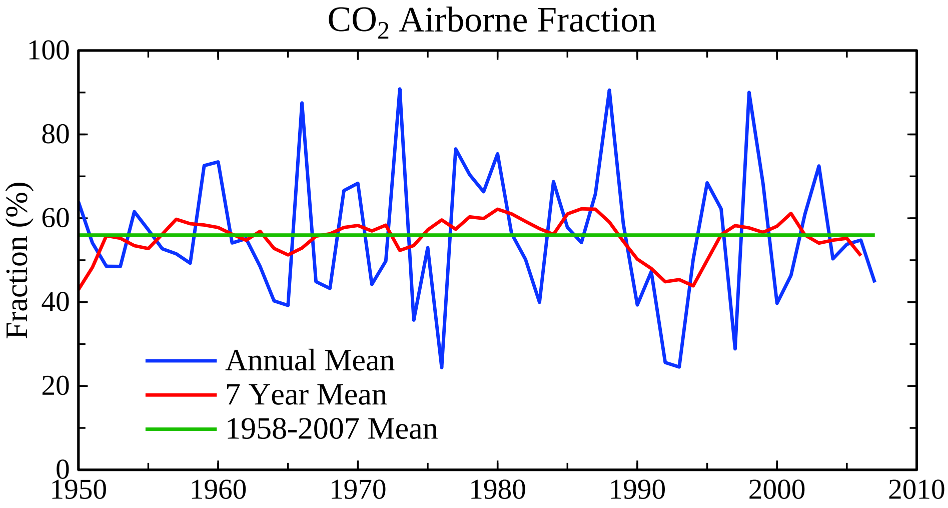


Fig. (S15). CO_2 airborne fraction, AF, the ratio of annual observed atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

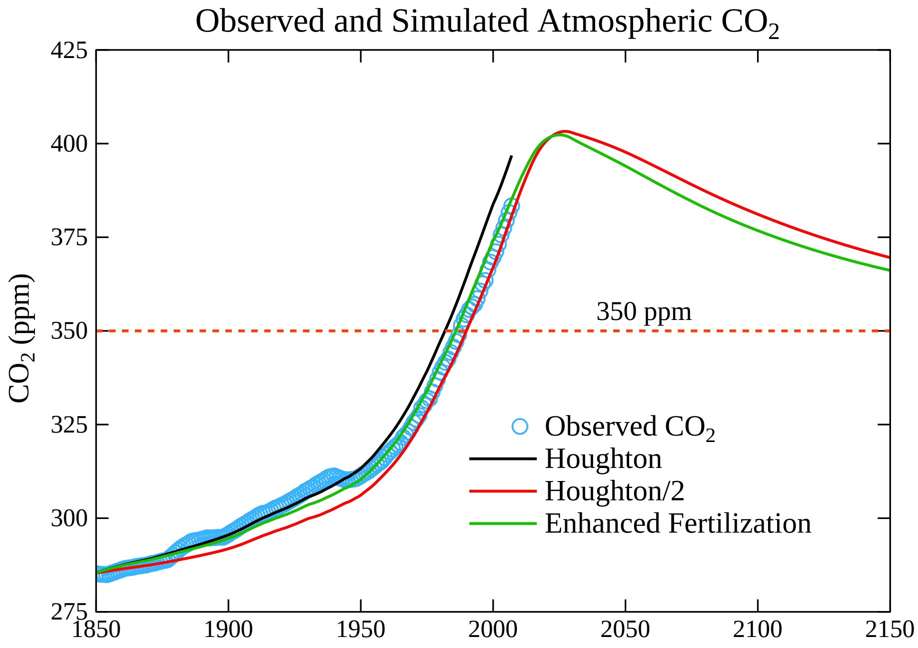


Fig. (S16). Computed and observed time evolution of atmospheric CO_2. "Enhanced Fertilization" uses the full "Houghton" land use emissions for 1850–2000. "Houghton/2" and "Enhanced Fertilization" simulations are extended to 2100 assuming coal phase-out by 2030 and the IPCC [2] A1T land-use scenario. Observations are from Law Dome ice core data and flask and in-situ measurements [6, S36, http://www.esrl.noaa.gov/gmd/ccgg/trends/].

Fig. (**S16**) shows resulting atmospheric CO_2, and Fig. (**S17**) shows AF and AF2, for two extreme assumptions: "Houghton/2" and " Enhanced Fertilization", as computed with a dynamic-sink pulse response function (PRF) representation of the Bern carbon cycle model [78, 79]. Fertilization is implemented *via* a parameterization [78] that can be adjusted to achieve an improved match between observed and simulated CO_2 amount. In the "Houghton/2" simulation the original value [78] of the fertilization parameter is employed while in the "Enhanced Fertilization" simulation the full Houghton emissions are used with a larger fertilization parameter. Both "Houghton/2" and "Enhanced Fertilization" yield good agreement with the observed CO_2 history, but Houghton/2 does a better job of matching the time dependence of observed AF.

It would be possible to match observed CO_2 to an arbitrary precision if we allowed the adjustment to "Houghton" land-use to vary with time, but there is little point or need for that. Fig. (**S16**) shows that projections of future CO_2 do not differ much even for the extremes of Houghton/2 and Enhanced Fertilization. Thus in Fig. (**6**) we show results for only the case Houghton/2, which is in better agreement with the airborne fraction and also is continuous with IPCC scenarios for land use.

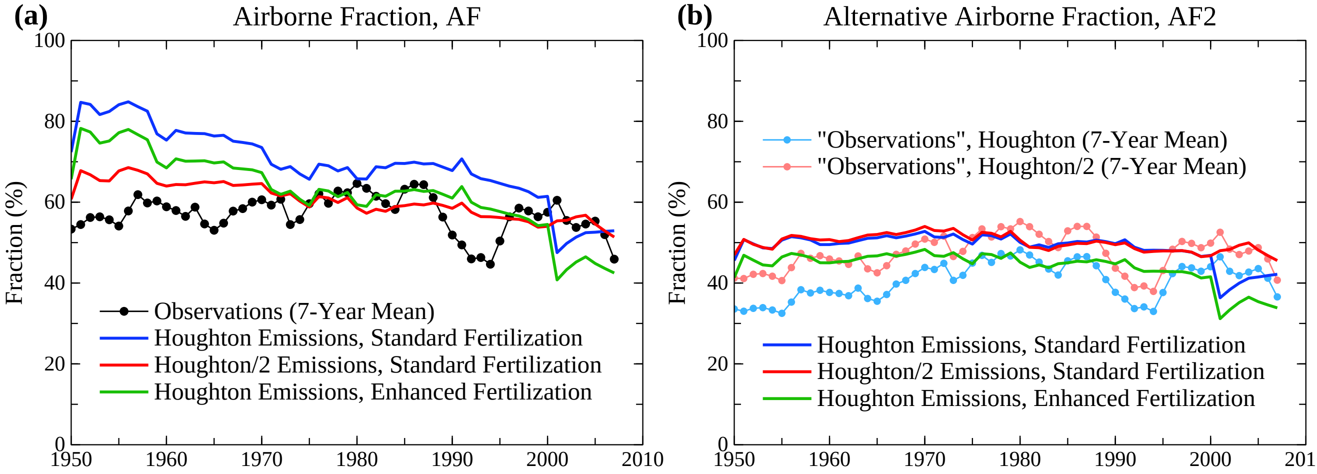


Fig. (S17). (**a**) Observed and simulated airborne fraction (AF), the ratio of annual CO_2 increase in the air over annual fossil fuel CO_2 emissions, (**b**) AF2 includes the sum of land use and fossil fuel emissions in the denominator in defining airborne fraction; thus AF2 is not accurately known because of the large uncertainty in land use emissions.

15. IMPLICATIONS OF FIG. (6): CO_2 EMISSIONS AND ATMOSPHERIC CONCENTRATION WITH COAL PHASE-OUT BY 2030

Fig. (**6**) provides an indication of the magnitude of actions that are needed to return atmospheric CO_2 to a level of 350 ppm or lower. Fig. (**6**) allows for the fact that there is disagreement about the magnitude of fossil fuel reserves, and that the magnitude of useable reserves depends upon policies.

A basic assumption underlying Fig. (**6**) is that, within the next several years, there will be a moratorium on construction of coal-fired power plants that do not capture and store CO_2, and that CO_2 emissions from existing power plants will be phased out by 2030. This coal emissions phase out is the sine qua non for stabilizing and reducing atmospheric CO_2. If the sine qua non of coal emissions phase-out is achieved, atmospheric CO_2 can be kept to a peak amount ~400-425 ppm, depending upon the magnitude of oil and gas reserves.

Fig. (**6**) illustrates two widely different assumptions about the magnitude of oil and gas reserves (illustrated in Fig. **S13**). The smaller oil and gas reserves, those labeled “IPCC”, are realistic if “peak oil” advocates are more-or-less right, i.e., if the world has already exploited about half of readily accessible oil and gas deposits, so that production of oil and gas will begin to decline within the next several years.

There are also “resource optimists” who dispute the “peakists’, arguing that there is much more oil (and gas) to be found. It is possible that both the “peakists” and “resource optimists” are right, it being a matter of how hard we work to extract maximum fossil fuel resources. From the standpoint of controlling human-made climate change, it does not matter much which of these parties is closer to the truth.

Fig. (**6**) shows that, if peak CO_2 is to be kept close to 400 ppm, the oil and gas reserves actually exploited need to be close to the “IPCC” reserve values. In other words, if we phase out coal emissions we can use remaining oil and gas amounts equal to those which have already been used, and still keep peak CO_2 at about 400 ppm. Such a limit is probably necessary if we are to retain the possibility of a drawdown of CO_2 beneath the 350 ppm level by methods that are more-or-less “natural”. If, on the other hand, reserve growth of the magnitude that EIA estimates (Figs. **6** and **S13**) occurs, and if these reserves are burned with the CO_2 emitted to the atmosphere, then the forest and soil sequestration that we discuss would be inadequate to achieve drawdown below the 350 ppm level in less than several centuries.

Even if the greater resources estimated by EIA are potentially available, it does not mean that the world necessarily must follow the course implied by EIA estimates for reserve growth. If a sufficient price is applied to carbon emissions it will discourage extraction of fossil fuels in the most extreme environments. Other actions that would help keep effective reserves close to the IPCC estimates would include prohibition of drilling in environmentally sensitive areas, including the Arctic and Antarctic.

National policies, in most countries, have generally pushed to expand fossil fuel reserves as much as possible. This might partially account for the fact that energy information agencies, such as the EIA in the United States, which are government agencies, tend to forecast strong growth of fossil fuel reserves. On the other hand, state, local, and citizen organizations can influence imposition of limits on fossil fuel extraction, so there is no guarantee that fossil resources will be fully exploited. Once the successors to fossil energy begin to take hold, there may be a shifting away from fossil fuels that leaves some of the resources in the ground. Thus a scenario with oil and gas emissions similar to that for IPCC reserves may be plausible.

Assumptions yielding the Forestry & Soil wedge in Fig. (**6b**) are as follows. It is assumed that current net deforestation will decline linearly to zero between 2010 and 2015. It is assumed that uptake of carbon *via* reforestation will increase linearly until 2030, by which time reforestation will achieve a maximum potential sequestration rate of 1.6 GtC per year [S37]. Waste-derived biochar application will be phased in linearly over the period 2010-2020, by which time it will reach a maximum uptake rate of 0.16 GtC/yr [85]. Thus after 2030 there will be an annual uptake of 1.6 + 0.16 = 1.76 GtC per year, based on the two processes described.

Thus Fig. (**6**) shows that the combination of (1) moratorium and phase-out of coal emissions by 2030, (2) policies that effectively keep fossil fuel reserves from significantly exceeding the IPCC reserve estimates, and (3) major programs to achieve carbon sequestration in forests and soil, can together return atmospheric CO_2 below the 350 ppm level before the end of the century.

The final wedge in Fig. (**6**) is designed to provide an indication of the degree of actions that would be required to bring atmospheric CO_2 back to the level of 350 ppm by a time close to the middle of this century, rather than the end of the century. This case also provides an indication of how difficult it would be to compensate for excessive coal emissions, if the world should fail to achieve a moratorium and phase-out of coal as assumed as our “sine qua non”.

Assumptions yielding the Oil-Gas-Biofuels wedge in Fig. (**6b**) are as follows: energy efficiency, conservation, carbon pricing, renewable energies, nuclear power and other carbon-free energy sources, and government standards and regulations will lead to decline of oil and gas emissions at 4% per year beginning when 50% of the estimated resource (oil or gas) has been exploited, rather than the 2% per year baseline decline rate [79]. Also capture of CO_2 at gas- power plants (with CO_2 capture) will use 50% of remaining gas supplies. Also a linear phase-in of liquid biofuels is assumed between 2015 and 2025 leading to a maximum global bioenergy from “low-input/high-diversity” biofuels of ~23 EJ/yr, inferred from Tilman *et al*. [87], that is used as a substitute for oil; this is equivalent to ~0.5 GtC/yr, based on energy conversion of 50 EJ/GtC for oil. Finally, from 2025 onward, twice this number (i.e., 1 GtC/yr) is subtracted from annual oil emissions, assuming root/soil carbon sequestration *via* this biofuel-for-oil substitution is at least as substantial as in Tilman *et al.* [87]. An additional option that could contribute to this wedge is using biofuels in powerplants with CO_2 capture and sequestration [86].

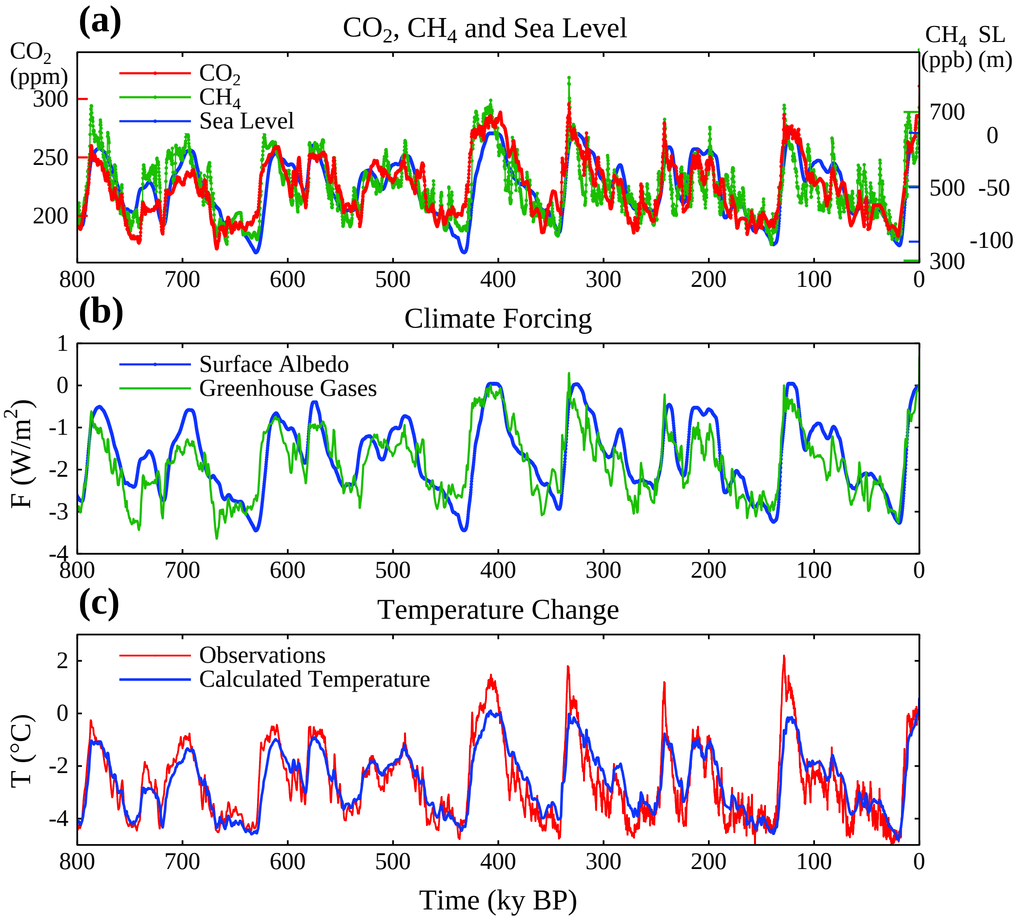


Fig. (S18). (**a**) CO_2 [S38], CH_4 [S39] and sea level [S16] for past 800 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from the sea level history of Bintanja *et al.* [S16]. (**c**) Calculated global temperature change based on the above forcings and climate sensitivity ¾°C per W/m^2. Observations are Antarctic temperature change from the Dome C ice core [S8] divided by two.

16. EPICA 800 KY DATA

Antarctic Dme C ice core data acquired by EPICA (European Project for Ice Coring in Antarctica) provide a record of atmospheric composition and temperature spanning 800 ky [S8], almost double the time covered by the Vostok data [17, 18] of Figs. (**1**) and (**2**). This extended record allows us to examine the relationship of climate forcing mechanisms and temperature change over a period that includes a substantial change in the nature of glacial-interglacial climate swings. During the first half of the EPICA record, the period 800-400 ky BP, the climate swings were smaller, sea level did not rise as high as the present level, and the GHGs did not increase to amounts as high as those of recent interglacial periods.

Fig. (**S18**) shows that the temperature change calculated exactly as described for the Vostok data of Fig. (**1**), i.e., multiplying the fast-feedback climate sensitivity ¾°C per W/m^2 by the sum of the GHG and surface albedo forcings (Fig. **S18b**), yields a remarkably close fit in the first half of the Dome C record to one-half of the temperature inferred from the isotopic composition of the ice. In the more recent half of the record slightly larger than ¾°C per W/m^2 would yield a noticeably better fit to the observed Dome C temperature divided by two (Fig. **S19**). However, there is no good reason to change our approximate estimate of ¾°C per W/m^2, because the assumed polar amplification by a factor of two is only approximate.

The sharper spikes in recent observed interglacial temperature, relative to the calculated temperature, must be in part an artifact of differing temporal resolutions. Temperature is inferred from the isotopic composition of the ice, being a function of the temperature at which the snowflakes formed, and thus inherently has a very high temporal resolution. GHG amounts, in contrast, are smoothed over a few ky by mixing of air in the snow that occurs up until the snow is deep enough for the snow to be compressed into ice. In the central Antarctic, where both Vostok and Dome C are located, bubble closure requires a few thousand years [17].

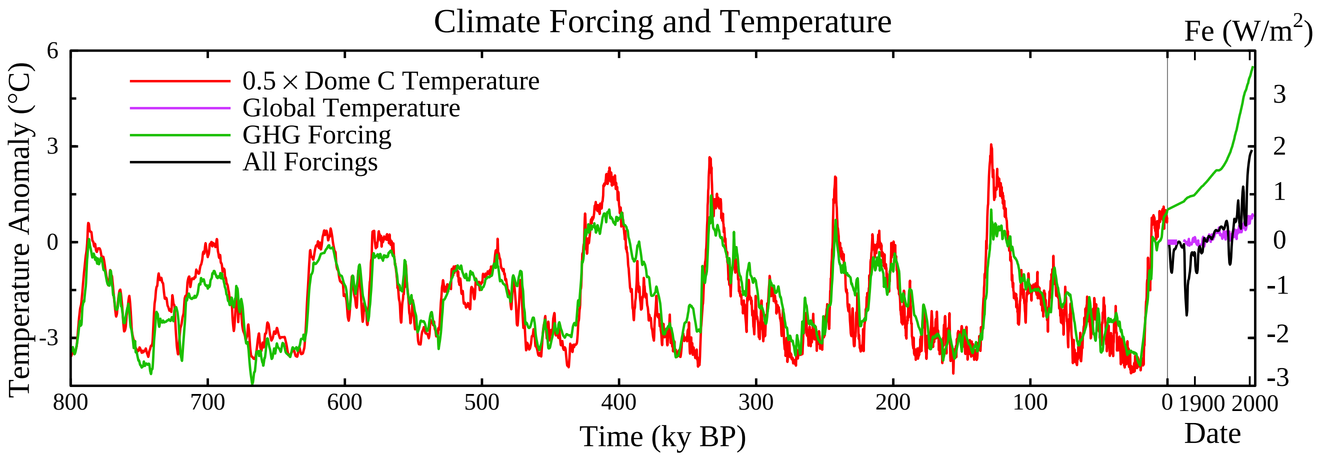


Fig. (S19). Global temperature change (left scale) estimated as half of temperature change from Dome C ice core [S8] and GHG forcing (right scale) due to CO$_2$, CH$_4$ and N$_2$O [S38, S39]. Ratio of temperature and forcing scales is 1.5°C per W/m^2. Time scale is expanded in the extension to recent years. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky before present. Net climate forcing and modern temperature zero points are at 1850. The implicit presumption that the positive GHG forcing at 1850 is largely offset by negative human-made forcings [7] is supported by the lack of rapid global temperature change in the Holocene (Fig. **S6**).

17. COMPARISON OF ANTARCTIC DATA SETS

Fig. (**S20**) compares Antarctic data sets used in this supplementary section and in our parent paper. This comparison is also relevant to interpretations of the ice core data in prior papers using the original Vostok data.

The temperature records of Petit *et al.* [17] and Vimeux *et al.* [18] are from the same Vostok ice core, but Vimeux *et al.* [18] have adjusted the temperatures with a procedure designed to correct for climate variations in the water vapor source regions. The isotopic composition of the ice is affected by the climate conditions in the water vapor source region as well as by the temperature in the air above Vostok where the snowflakes formed; thus the adjustment is intended to yield a record that more accurately reflects the air temperature at Vostok. The green temperature curve in Fig. (**S20c**), which includes the adjustment, reduces the amplitude of glacial-interglacial temperature swings from those in the original (red curve) Petit *et al.* [17] data. Thus it seems likely that there will be some reduction of the amplitude and spikiness of the Dome C temperature record when a similar adjustment is made to the Dome C data set.

The temporal shift of the Dome C temperature data [S8], relative to the Vostok records, is a result of the improved EDC3 [S40, S41] time scale. With this new time scale, which has a 1σ uncertainty of ~3 ky for times earlier than ~130 ky BP, the rapid temperature increases of Termination IV (~335 ky BP) and Termination III (~245 ky BP) are in close agreement with the contention [7] that rapid ice sheet disintegration and global temperature rise should be nearly simultaneous with late spring

(April-May-June) insolation maxima at 60N latitude, as was already the case for Terminations II and I, whose timings are not significantly affected by the improved time scale.

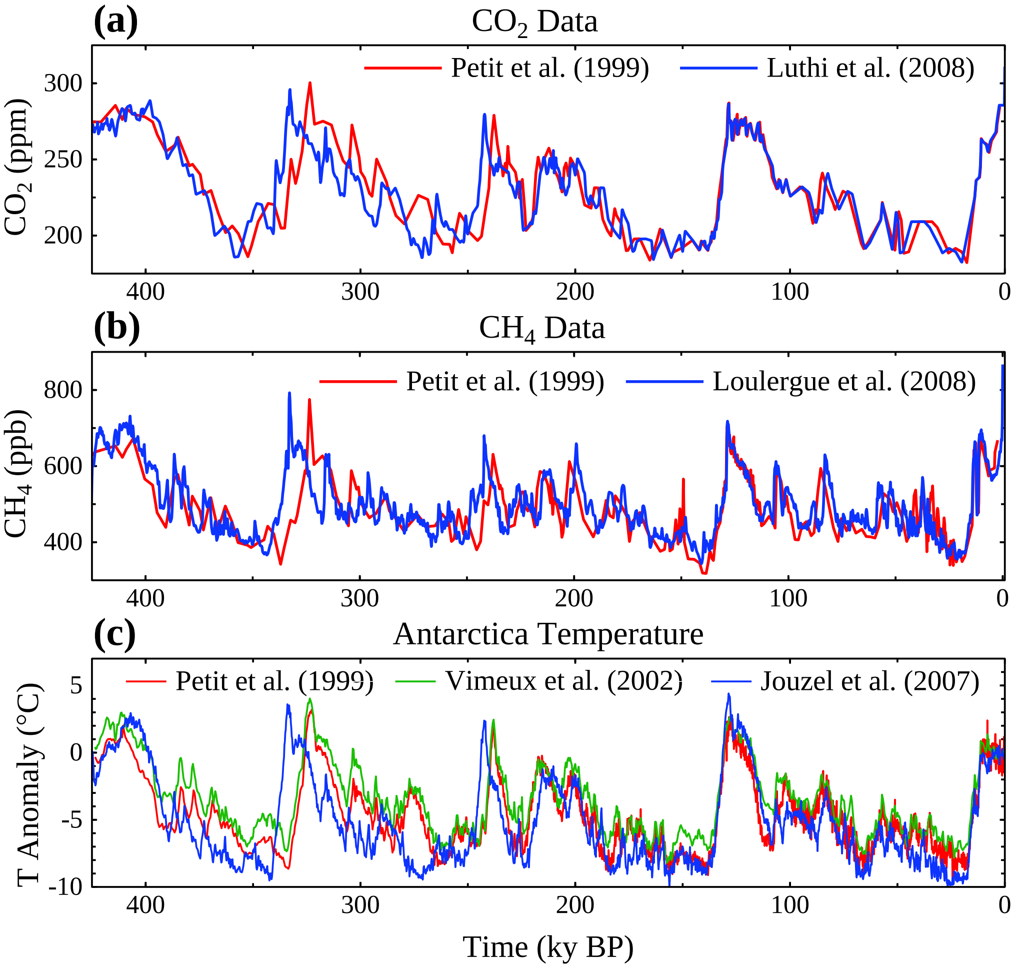


Fig. (S20). Comparison of Antarctic CO_2, CH_4, and temperature records in several analyses of Antarctic ice core data.

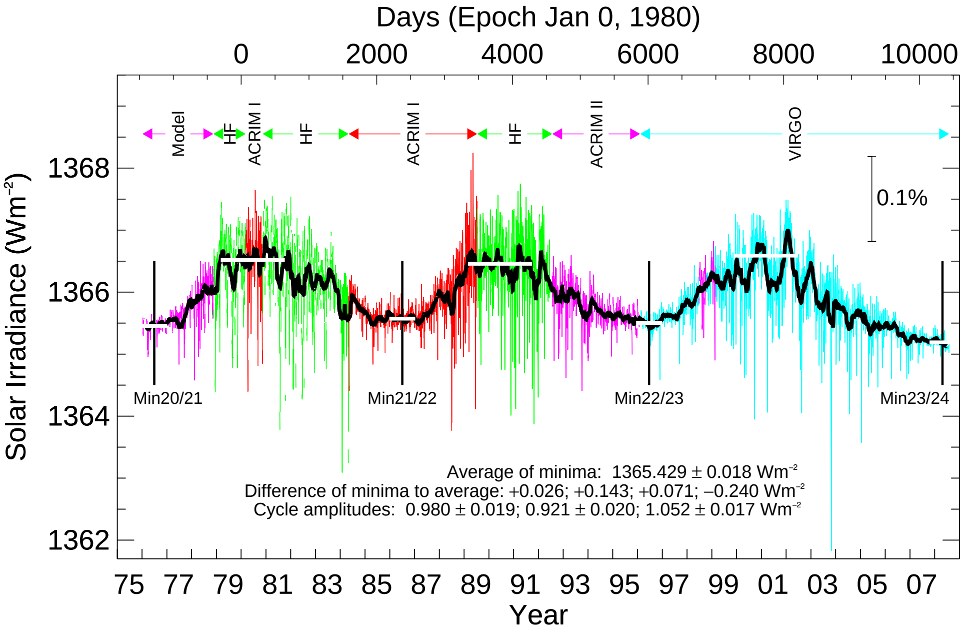


Fig. (S21). Solar irradiance from composite of several satellite-measured time series based on Frohlich and Lean [S44].

18. CLIMATE VARIABILITY, CLIMATE MODELS, AND UNCERTAINTIES

Climate exhibits great variability, forced and unforced, which increases with increasing time scale [2, 90, 91]. Increasing abilities to understand the nature of this natural variability and improving modeling abilities [S42] do not diminish the complications posed by chaotic variability for interpretation of ongoing global change.

Expectation that global temperature will continue to rise on decadal time scales is based on a combination of climate models and observations that support the inference that the planet has a positive energy imbalance [5, 8, 96]. If the planet is out of energy balance by +0.5-1 W/m^2, climate models show that global cooling on decadal time scales is unlikely [96], although one model forecast [95] suggests that the Atlantic overturning circulation could weaken in the next decade, causing a regional cooling that offsets global warming for about a decade.

The critical datum for determining the certainty of continued global warming on decadal time scales is the planet's energy imbalance. Improved evaluations of ocean heat storage in the upper 700 m of the ocean [97] yield ~0.5 x 10^{22} J/yr averaged over the past three decades, which is ~0.3 W/m^2 over the full globe. Our model has comparable heat storage in the ocean beneath 700 m, but limited observational analyses for the deep ocean [S43] report negligible heat storage.

If our modeled current planetary energy imbalance of 0.5-1 W/m^2 is larger than actual heat storage, the likely explanations are either: (1) the climate model sensitivity of 3°C for doubled CO_2 is too high, or (2) the assumed net climate forcing is too large. Our paleoclimate analyses strongly support the modeled climate sensitivity, although a sensitivity as small as 2.5 W/m^2 for doubled CO_2 could probably be reconciled with the paleoclimate data. The net climate forcing is more uncertain. Our model [8] assumes that recent increase of aerosol direct and indirect (cloud) forcings from developing country emissions are offset by decreases in developed countries.

These uncertainties emphasize the need for more complete and accurate measurements of ocean heat storage, as well as precise global observations of aerosols including their effects on clouds. The first satellite observations of aerosols and clouds with the needed accuracy are planned to begin in 2009 [98]. Until accurate observations of the planetary energy imbalance and global climate forcing are available, and found to be consistent with modeled climate sensitivity, uncertainties in decadal climate projections will remain substantial.

The sun is another source of uncertainty about climate forcings. At present the sun is inactive, at a minimum of the normal ~11 year solar cycle, with a measureable effect on the amount of solar energy received by Earth (Fig. **S21**). The amplitude of solar cycle variations is about 1 W/m^2 at the Earth's distance from the sun, a bit less than 0.1% of the ~1365 W/m^2 of energy passing through an area oriented perpendicular to the Earth-sun direction.

Climate forcing due to change from solar minimum to solar maximum is about ¼ W/m^2, because the Earth absorbs ~235 W/m^2 of solar energy, averaged over the Earth's surface. If equilibrium climate sensitivity is 3°C for doubled CO_2 (¾°C per W/m^2), the expected equilibrium response to this solar forcing is ~0.2°C. However, because of the ocean's thermal inertia less than half of the equilibrium response would be expected for a cyclic forcing with ~11 year period. Thus the expected global-mean transient response to the solar cycle is less than or approximately 0.1°C.

It is conceivable that the solar variability is somehow amplified, e.g., the large solar variability at ultraviolet wavelengths can affect ozone. Indeed, empirical data on ozone change with the solar cycle and climate model studies indicate that induced ozone changes amplify the direct solar forcing, but amplification of the solar effect is by one-third or less [S45, S46].

Other mechanisms amplifying the solar forcing have been hypothesized, such as induced changes of atmospheric condensation nuclei and thus changes of cloud cover. However, if such mechanisms were effective, then an 11-year signal should appear in temperature observations (Fig. **7**). In fact a very weak solar signal in global temperature has been found by many investigators, but only of the magnitude (~0.1°C or less) expected due to the direct solar forcing.

The possibility remains of solar variability on longer time scales. If the sun were to remain 'stuck' at the present solar minimum (Fig. **S21**) it would be a decrease from the mean irradiance of recent decades by ~0.1%, thus a climate forcing of about -0.2 W/m^2.

The current rate of atmospheric CO_2 increase is ~2 ppm/year, thus an annual increase of climate forcing of about +0.03 W/m^2 per year. Therefore, if solar irradiance stays at its recent minimum value, the climate forcing would be offset by just seven years of CO_2 increase. Human-made GHG climate forcing is now increasing at a rate that overwhelms variability of natural climate forcings.

Climate models are another source of uncertainty in climate projections. Our present paper and our estimated target CO_2 level do not rely on climate models, but rather are based on empirical evidence from past and ongoing climate change. However, the limited capability of models to simulate climate dynamics and interactions among climate system components makes it difficult to estimate the speed at which climate effects will occur and the degree to which human-induced effects will be masked by natural climate variability.

The recent rapid decline of Arctic ice [S47-S49] is a case in point, as it has been shown that model improvements of multiple physical processes will be needed for reliable simulation. The modeling task is made all the more difficult by likely connections of Arctic change with the stratosphere [S50] and with the global atmosphere and ocean [S51].

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Stabilizing climate requires near-zero emissions

H. Damon Matthews[1] and Ken Caldeira[2]

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[1] Current international climate mitigation efforts aim to stabilize levels of greenhouse gases in the atmosphere. However, human-induced climate warming will continue for many centuries, even after atmospheric CO_2 levels are stabilized. In this paper, we assess the CO_2 emissions requirements for global temperature stabilization within the next several centuries, using an Earth system model of intermediate complexity. We show first that a single pulse of carbon released into the atmosphere increases globally averaged surface temperature by an amount that remains approximately constant for several centuries, even in the absence of additional emissions. We then show that to hold climate constant at a given global temperature requires near-zero future carbon emissions. Our results suggest that future anthropogenic emissions would need to be eliminated in order to stabilize global-mean temperatures. As a consequence, any future anthropogenic emissions will commit the climate system to warming that is essentially irreversible on centennial timescales. **Citation:** Matthews, H. D., and K. Caldeira (2008), Stabilizing climate requires near-zero emissions, *Geophys. Res. Lett.*, *35*, L04705, doi:10.1029/2007GL032388.

1. Introduction

[2] Avoiding dangerous anthropogenic interference in the climate system has been a key international policy goal since the publication of the United Nations Framework Convention on Climate Change in 1992 [*United Nations*, 1992]. Since that time, scientific and policy literature concerning climate change mitigation has been centered around stabilizing concentrations of greenhouse gases in the atmosphere [*Wigley*, 2005; *Stern*, 2006; *Meehl et al.*, 2005]. However, stable greenhouse gas concentrations do not equate to a stable global climate. Model simulations have demonstrated that global temperatures continue to increase for many centuries beyond the point of CO_2 stabilization [e.g., *Matthews*, 2006]. As such, we are committed to future warming, even with stable greenhouse gas concentrations [*Hansen et al.*, 1985; *Wigley*, 2005; *Meehl et al.*, 2005]. This implies that stabilizing global climate within the next several centuries would require decreasing, rather than stabilized, greenhouse gas levels. In this paper, we demonstrate that to achieve atmospheric carbon dioxide levels that lead to climate stabilization, the net addition of CO_2 to the atmosphere from human activities must be decreased to nearly zero.

[3] Recent research has highlighted the very long lifetime of anthropogenic carbon in the atmosphere; while approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia [*Archer*, 2005]. A recent analysis by *Montenegro et al.* [2007] found that 25% of emitted CO_2 will have an atmospheric lifetime of more than 5000 years. Studies of the climate response to declining CO_2 concentrations have generally assumed that global temperatures will decrease in response to decreases in atmospheric CO_2 [*Friedlingstein and Solomon*, 2005]. However, as we demonstrate here, because of the high heat capacity of the ocean, global temperatures may not parallel decreases in atmospheric concentrations of greenhouse gases, but rather will increase and remain elevated for at least several centuries. Thus, fossil fuel CO_2 emissions may produce climate change that is effectively irreversible on human timescales.

[4] In this paper, we present a series of idealized climate simulations to assess the centennial-scale climate response to anthropogenic CO_2 emissions, and conversely, to quantify the emissions requirements for climate stabilization. We have used the University of Victoria Earth System Climate Model (UVic ESCM), an intermediate complexity global climate model which includes an interactive global carbon cycle. We present first a series of 500-year simulations forced by CO_2 emissions, in which a specified amount of carbon was added to the atmosphere either instantaneously, or following a business-as-usual emissions scenario. The model was then run for up to 500 years without additional carbon emissions to determine the persistence of climate warming resulting from past emissions. Second, we specified hypothetical future temperature trajectories for the UVic ESCM, and controlled emissions such that the specified future temperature changes were achieved. We used this method to estimate the CO_2 emissions requirements for climate stabilization at levels between 1 and 4 degrees above pre-industrial temperatures.

2. Methods

[5] We used version 2.8 of the UVic ESCM, an intermediate complexity coupled climate-carbon model with spatial resolution of 1.8 degrees latitude by 3.6 degrees longitude. The ocean is a 19-layer general circulation model, driven by specified wind stress at the surface and coupled to a dynamic-thermodynamic sea-ice model. The atmosphere is a vertically-integrated single layer model; both temperature and moisture are transported horizontally by a combination of diffusion and advection by specified wind fields [*Weaver et al.*, 2001]. Terrestrial vegetation distributions are calculated dynamically as a function of simulated regional climatic conditions, with the result that vegetation is able to both respond to and affect simulated climate changes

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[1] Department of Geography, Planning and Environment, Concordia University, Montreal, Quebec, Canada.

[2] Department of Global Ecology, Carnegie Institution of Washington, Stanford, California, USA.

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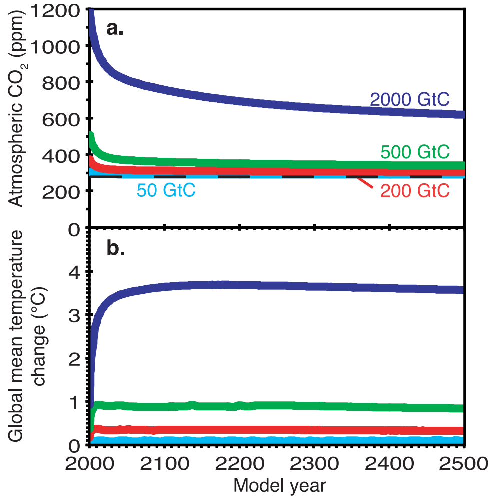

Figure 1. Climate response to an instantaneous carbon emission pulse at year zero. (a) Simulated atmospheric CO_2. (b) Simulated change in global mean surface air temperature, relative to pre-industrial.

[*Meissner et al.*, 2003]. Additionally, the UVic ESCM includes an interactive global carbon cycle [*Schmittner et al.*, 2008] which allows for the direct simulation of coupled carbon cycle and climate responses to anthropogenic carbon emissions. The version of the UVic ESCM used here does not include a sedimentary carbon model; as such we have restricted our simulations to a 500-year timescale over which time the effect of carbonate compensation on ocean carbon uptake is negligible.

[6] In forward mode, specified carbon emissions elicit climate and carbon cycle model responses. We ran the model in this mode for a series of idealized pulse-response simulations, in which emissions of 50, 200, 500 and 2000 billion tonnes (giga-tonnes of carbon: GtC) were added instantaneously to the atmosphere under pre-industrial conditions; we then ran the model with prognostic CO_2 and carbon sinks for 500 years with no additional carbon emission. In a second series of zero-emissions commitment scenarios, the model was spun-up transiently using historical CO_2 concentrations from 1800 to 2000. We then specified future business-as-usual emissions and calculated cumulative emissions relative to the year 2005. We set emissions to zero at cumulative emission levels of 0, 50, 200, 500 and 2000 GtC after 2005, and ran the model until the year 2500 with no further CO_2 emissions. In addition, we performed four simulations in which emissions were reduced linearly to zero from 2005 levels, such that total carbon emissions after 2005 were equal to 50, 200, 500 and 2000 GtC, respectively.

[7] In inverse mode, we are able to specify a desired global temperature trajectory and calculate anthropogenic carbon emissions which are consistent with this specified temperature profile. Emissions (E) were calculated at each model timestep as $E = K\,(T' - T_m)$, where T' is the desired target temperature and T_m is a running one-year global average of modelled surface air temperature. K is a constant which represents the approximate temperature response per unit of CO_2 emission, divided by the timescale of temperature response to CO_2 forcing. Emissions diagnosed in this way represent the total anthropogenic addition of carbon to the atmosphere, including both fossil fuel and net land-use change emissions.

[8] Historical temperatures were specified as an exponential curvefit to observed temperature data from 1880 to 2005. From 2005 to 2500, we constructed nine temperature profiles whereby global temperatures increased at constant rates of 0.1, 0.2 and 0.4°C/decade to stabilization levels of 1, 2 and 4 degrees above pre-industrial temperature. The transition from a fixed rate of temperature increase to temperature stabilization was smoothed using a 30-year running average.

3. Results and Discussion

[9] Figure 1 shows the climate response to an instantaneous pulse emission of carbon dioxide of between 50 and 2000 GtC. After 500 years, between 20 and 35% of the initial emission pulse remained in the atmosphere (with higher airborne fractions associated with larger emission pulses); the remaining carbon was split approximately 60/40 between ocean and land carbon sinks. The emissions pulse was followed immediately by climate warming, which then persisted for the remainder of the simulation. Averaged over the last 450 years of the simulation, temperatures increased by 0.09, 0.34, 0.88 and 3.6°C for emissions pulses of 50, 200, 500 and 2000 GtC, respectively. Historical emissions from fossil fuels and land-use change total approximately 450 GtC, which would represent about 0.8 degrees warming in the context of these pulse-response simulations. These numbers correspond roughly to a 0.175°C temperature increase for every 100 GtC emitted. This version of the UVic ESCM has an equilibrium climate sensitivity of 3.5°C for a doubling of atmospheric CO_2; as such, every 100 GtC emitted resulted in a step-wise warming of about 5% of the model's climate sensitivity.

[10] The amount of climate warming per unit of carbon emitted did not depend strongly on the timing nor duration of emissions. Figure 2 (thick lines) shows the result of a series of transient zero-emissions commitment simulations in which CO_2 emissions were set to zero when cumulative carbon emissions after 2005 reached 0, 50, 200, 500 and 2000 GtC (Figure 2a). After emissions were set to zero, simulated atmospheric CO_2 decreased as a function of time as natural carbon sinks continued to take up carbon (Figure 2b). Ocean temperatures increased throughout the simulation showing continued heat uptake, though the rate of heat uptake slowed as a function of time (Figure 2c). This slowing of ocean heat uptake balanced the decreasing radiative forcing from atmospheric CO_2; as a result, surface temperatures remained approximately constant (Figure 2d).

[11] Figure 2 also shows four additional simulations (thin lines) in which emissions were reduced to zero gradually such that total cumulative emissions after 2005 were equivalent to the thick-line zero-emissions commitment simulations. In these thin-line simulations, atmospheric CO_2 and global temperatures increased more gradually in response to gradually declining emissions; however, the final stabilization temperature was unchanged. Furthermore, the amount of additional warming that resulted per unit of carbon emitted in both sets of simulations was equivalent to the pulse-response cases shown above (approximately 5% of climate sensitivity per 100 GtC emitted), despite both higher

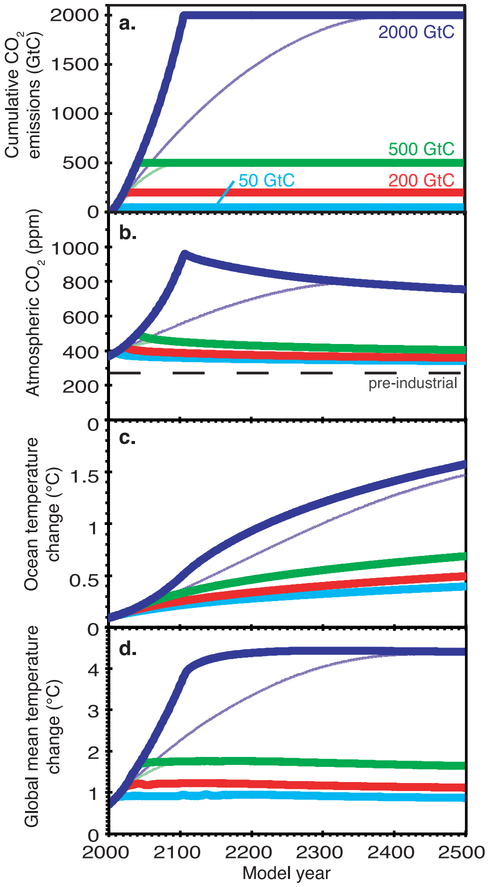

Figure 2. Climate response to transient followed by zero CO_2 emissions. (a) Specified cumulative CO_2 emissions relative to the year 2005. (b) Simulated atmospheric CO_2. (c) Simulated change in global mean ocean temperature relative to pre-industrial. (d) Simulated change in global mean surface air temperature relative to pre-industrial. Thick lines show business-as-usual followed by an abrupt elimination of emissions. Thin lines show the same post-2005 cumulative emissions but with a gradual reduction from 2005 emission levels to zero.

initial CO_2 levels in the atmosphere and the distribution of emissions over the next 10 to 100 years. This result is consistent with previous research which has shown that the declining radiative forcing per unit CO_2 increase at higher CO_2 levels is approximately counter-balanced by increased airborne fraction of emissions due to weakened carbon sinks [*Caldeira and Kasting*, 1993].

[12] The results shown here differ importantly from previous zero-emissions commitment analyses [e.g., *Friedlingstein and Solomon*, 2005], which have neglected the heat capacity of the deep ocean, and have therefore concluded that after emissions are stopped, global temperatures would decrease in response to declining atmospheric CO_2 concentrations. Our results also differ from previous studies of warming commitment which have analyzed the future warming commitment resulting from constant radiative forcing associated with stable atmospheric greenhouse gas levels [*Wigley*, 2005; *Meehl et al.*, 2005]. In contrast with these studies, our results suggest that if emissions were eliminated entirely, radiative forcing from atmospheric CO_2 would decrease at a rate closely matched by declining ocean heat uptake, with the result that while future warming commitment may be negligible, atmospheric temperatures may not decrease appreciably for at least 500 years.

[13] In the simulations described above, eliminating CO_2 emissions resulted in stable global temperatures for the following five centuries of model simulation. This result implies that stabilizing climate at a given temperature would require that anthropogenic CO_2 emissions be decreased to near-zero. We demonstrate this in a series of transient model simulations in which global temperatures in the UVic ESCM were constrained to follow a desired future climate trajectory. Results from these simulations are shown in Figure 3 for temperature stabilization levels of 1, 2 and 4°C above pre-industrial temperatures, with temperatures approaching stabilization at rates of 0.1, 0.2 and 0.4°C per decade after the year 2005. Also shown is a simulation in which climate was stabilized at year-2005 temperatures.

[14] Simulated global mean surface air temperatures for the ten temperature stabilization simulations followed closely the prescribed temperature trajectories (Figure 3a). Atmospheric CO_2 concentrations consistent with simulated temperature changes are shown in Figure 3b; in all cases, CO_2 concentrations reached a maximum value at the time of temperature stabilization, followed by a gradual decrease consistent with that shown in Figures 1 and 2. Also consistent with Figure 2, ocean temperatures increased throughout the simulation, though the rate of ocean heat uptake slowed with time after atmospheric temperatures were stabilized (Figure 3c). Cumulative CO_2 emissions from each simulation are shown in Figure 3d. At the year 2500, cumulative emissions depended only on the level of temperature stabilization, and not on the path taken to stabilization. Stabilizing climate change at 1°C above pre-industrial (approximately 0.2°C above present) required cumulative carbon emissions (from any source) after 2005 to be confined to less than 150 GtC. Stabilizing at 2 or 4°C above pre-industrial required cumulative emissions after 2005 of less than 725 and 1825 GtC, respectively. In all cases, annual emissions consistent with temperature-stabilization were reduced to nearly zero. Notably, stabilizing global temperature at present-day (year-2005) levels required emissions to be reduced to near-zero within a decade.

[15] The result shown here that each unit of CO_2 emissions results in a quantifiable step-wise increase of global temperatures, and its corollary that temperature stabilization requires near-zero CO_2 emissions, is not model specific; this same qualitative result can be demonstrated using a simple analytic model of the global climate-carbon system (see auxiliary material).[1] However, the specific amount by which global temperatures increased per unit of CO_2 emission—and correspondingly, the cumulative CO_2 emissions required to meet a given temperature target—does depend on several important model characteristics and assumptions. For example, future changes in non-CO_2 climate forcings (both natural and anthropogenic) could have an important effect on the magnitude of temperature changes associated with future carbon emissions. Furthermore, different models vary considerably with respect to both the strength of

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032388.

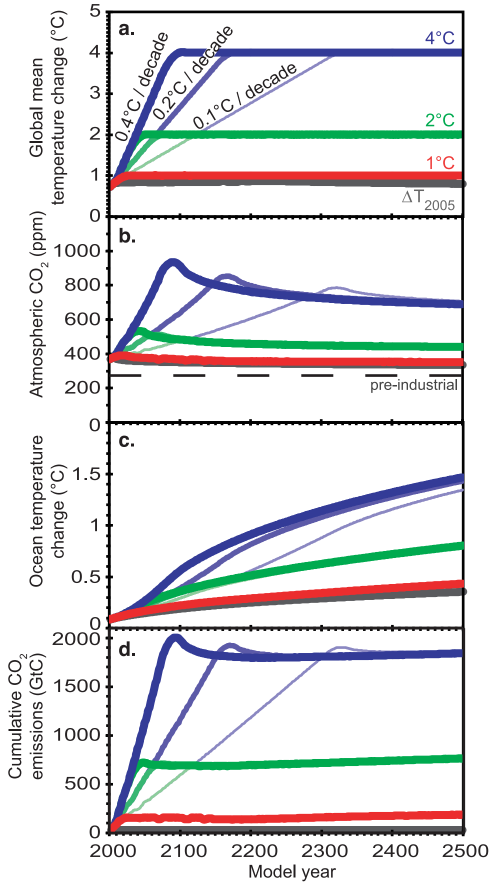

Figure 3. CO_2 emissions required for climate stabilization. (a) Simulated global mean surface air temperature relative to pre-industrial. (b) Simulated atmospheric CO_2. (c) Simulated change in global mean ocean temperature relative to pre-industrial. (d) Cumulative carbon emissions relative to the year 2005 (where near-constant cumulative emissions reflect near-zero yearly emissions). Colors indicate climate stabilization at 1 (red lines), 2 (green lines), and 4 (blue lines) °C above pre-industrial temperatures. Line styles indicate rates of warming (between 2005 and the time of temperature-stabilization) of 0.1 (thick lines), 0.2 (medium lines), and 0.4 (thin lines) °C per decade. The solid grey line shows climate stabilization at year-2005 temperatures.

carbon sinks (the carbon cycle sensitivity to CO_2 and climate changes) as well as the climate system's sensitivity to CO_2 increases (climate sensitivity).

[16] To examine the dependence of our results on the model's climate sensitivity, we repeated the temperature-stabilization simulations shown in Figure 3 with two additional versions of the model in which climate sensitivity after 2005 was approximately doubled and halved respectively by means of an adjustable temperature-longwave radiation feedback [*Matthews and Caldeira*, 2007]. Cumulative emissions from 2005 to 2500 for each of these simulations are given in Table 1. It is clear that the range of climate sensitivities explored here had a very large effect on the cumulative carbon emissions for a given temperature target. However, across all combinations of climate sensitivity and stabilization level, the rate of warming approaching a stabilization temperature had very little influence on the allowable cumulative emissions. This is consistent with the pulse-response and zero-emissions commitment experiments in which each unit of CO_2 emission produced a persistent increment of warming that was largely independent of the warming produced by other CO_2 emissions.

[17] In this study, we have made no attempt to construct economically optimal emissions scenarios for climate stabilization, but rather to quantify the climatic requirements for allowable emissions consistent with global temperature targets. It is evident that some of the temperature trajectories (and their associated emissions scenarios) illustrated here may not be economically feasible, as they require either abrupt transitions from very high to near-zero emissions, or even prolonged periods of negative emissions for combinations of high climate sensitivity and low temperature targets. It is also clear from these simulations that delays in emissions reductions now will lead to a requirement for much more rapid emissions reductions in the future in order to meet the same global temperature target. In addition, an important conclusion of our study is that if total future emissions can be constrained to within a given amount, the same long-term temperature target can be achieved by a wide range of specific emissions scenarios.

4. Conclusions

[18] International climate policies aimed at climate stabilization must reflect an understanding of the lasting effect of greenhouse gas emissions; as illustrated by a recent study, year-2050 emissions targets currently being proposed are likely insufficient to avoid substantial future climate warming [*Weaver et al.*, 2007]. We have shown here that the climate warming resulting from CO_2 emissions is not a transient phenomenon, but rather persists well beyond the timescale of human experience. In the absence of human intervention to actively remove CO_2 from the atmosphere [e.g., *Keith et al.*, 2006], each unit of CO_2 emissions must be viewed as leading to quantifiable and essentially permanent climate change on centennial timescales. We emphasize that a stable global climate is not synonymous with stable radiative forcing, but rather requires decreasing greenhouse gas levels in the atmosphere. We have shown here that stable global temperatures within the next several centuries can be achieved if CO_2 emissions are reduced to

Table 1. Effect of Climate Sensitivity on Cumulative Emissions Targets for Climate Stabilization[a]

Global temperature target (°C)	1			2			4		
Target rate of change (°C/yr)	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04
$\Delta T_{2X} \sim 1.8$ °C	787	789	788	1970	1977	1979	4806	4801	4794
$\Delta T_{2X} \sim 3.5$ °C	149	148	150	720	723	723	1823	1808	1804
$\Delta T_{2X} \sim 7$ °C	−166	−167	−167	115	115	116	633	607	599

[a] Effect of climate sensitivity measured by ΔT_{2X}. Cumulative emissions represent total GtC emitted from 2005 to 2500.

nearly zero. This means that avoiding future human-induced climate warming may require policies that seek not only to decrease CO_2 emissions, but to eliminate them entirely.

[19] **Acknowledgments.** We would like to acknowledge and thank M. Eby at the University of Victoria for his contribution to this research in the form of development of model code which enables simulation of specified global temperature input profiles. We would also like to thank A. Weaver, C. Jones and one anonymous reviewer for their helpful comments and suggestions.

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K. Caldeira, Department of Global Ecology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA.

H. D. Matthews, Department of Geography, Planning and Environment, Concordia University, 1455 de Maisonneuve Boulevard W., Montreal, QC, Canada H3G 1M8. (dmatthew@alcor.concordia.ca)

Attachment D

THE IMPACTS OF SEA-LEVEL RISE ON THE CALIFORNIA COAST

A Paper From:
California Climate Change Center

Prepared By:
Matthew Heberger, Heather Cooley, Pablo Herrera, Peter H. Gleick, and Eli Moore of the Pacific Institute

DRAFT PAPER

DISCLAIMER

This paper was prepared as the result of work funded by the California Energy Commission, the California Environmental Protection Agency, Metropolitan Transportation Commission, California Department of Transportation, and the California Ocean Protection Council (collectively "the funding agencies"). It does not necessarily represent the views of the funding agencies, their respective officers, agents and employees, or the State of California. The funding agencies, the State of California, and their respective officers, employees, agents, contractors, and subcontractors make no warrant, express or implied, and assume no responsibility or liability for the results of any actions taken or other information developed based on this paper; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This paper is being made available for informational purposes only and has not been approved or disapproved by the funding agencies, nor have the funding agencies passed upon the accuracy, currency, completeness, or adequacy of the information in this paper. Users of this paper agree by their use to hold blameless each of the funding agencies for any liability associated with its use in any form. This work shall not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood Insurance Studies and Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA).

Arnold Schwarzenegger, *Governor*

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Acknowledgments

In this report, the Pacific Institute evaluates the areas at risk from sea-level rise on the California coast and San Francisco Bay. We assess the population, infrastructure, and property at risk and provide an estimate of the cost of protecting those areas. We also offer a set of recommendations to inform policy- and decision-makers as they develop land-use plans for coastal regions. A series of maps that demonstrate the areas at risk are available on our website at www.pacinst.org/reports/sea_level_rise. It should be noted that these maps are not the result of detailed site studies and were created to quantify risk over a large geographic area. They are not meant to replace or supplement flood insurance maps from the Federal Emergency Management Agency or flood risk maps from the California Office of Emergency Services.

Major funds for this report were made through the California Energy Commission's Public Interest Energy Research (PIER) Program. Additional support was provided by the Metropolitan Transportation Commission and the Ocean Protection Council. We thank them for their generosity and foresight.

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Over the past century, sea level has risen nearly eight inches along the California coast, and general circulation model scenarios suggest very substantial increases in sea level as a significant impact of climate change over the coming century. This study includes a detailed analysis of the current population, infrastructure, and property at risk from projected sea-level rise if no actions are taken to protect the coast. The sea-level rise scenario was developed by the State of California from medium to high greenhouse gas emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) but does not reflect the worst-case sea-level rise that could occur. We also evaluate the cost of building structural measures to reduce that risk. If development continues in the areas at risk, all of these estimates will rise. No matter what policies are implemented in the future, sea-level rise will inevitably change the character of the California coast.

We estimate that a 1.4 meter sea-level rise will put 480,000 people at risk of a 100-year flood event, given today's population. Among those affected are large numbers of low-income people and communities of color, which are especially vulnerable. A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and more will also be at increased risk of inundation, as are vast areas of wetlands and other natural ecosystems. In addition, the cost of replacing property at risk of coastal flooding under this sea-level rise scenario is estimated to be nearly $100 billion (in year 2000 dollars). A number of structural and non-structural policies and actions could be implemented to reduce these risks. For example, we estimate that protecting some vulnerable areas from flooding by building seawalls and levees will cost at least $14 billion (in year 2000 dollars), with added maintenance costs of another $1.4 billion per year. Continued development in vulnerable areas will put additional areas at risk and raise protection costs.

Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 meter sea-level rise will accelerate erosion, resulting in a loss of 41 square miles (over 26,000 acres) of California's coast by 2100. A total of 14,000 people currently live in the area at risk of future erosion. Additionally, significant transportation-related infrastructure and property are vulnerable to erosion. Statewide flood risk exceeds erosion risk, but in some counties and localities, coastal erosion poses a greater risk. This report also provides a comprehensive set of recommendations and strategies for adapting to sea-level rise.

Keywords: sea-level rise, climate change, California, San Francisco Bay, flood, erosion, climate adaptation, climate impacts, levees, seawalls, greenhouse effect

1.0 Introduction

California's coastline, which includes more than 2,000 miles of open coast and enclosed bays, is vulnerable to a range of natural hazards, including storms, extreme high tides, and rising sea levels resulting from global climate change. Development along California's coast is extensive. In 2000, 26 million Californians lived in coastal counties, and by 2003, this number had grown to nearly 31 million (U.S. Census Bureau 2000; NOAA 2004). Indeed, six of the ten fastest growing coastal counties in the United States between 1980 and 2003 were in California (NOAA 2004). Major transportation corridors and other critical infrastructure are found along the California coast, including oil, natural gas, and nuclear energy facilities, as well as major ports, harbors, and water and wastewater plants. The California coast is also an extraordinary cultural and ecological resource and offers extensive tourism and recreational opportunities.

Flooding and erosion pose a threat to communities along the California coast and there is compelling evidence that these risks will increase in the future. Based on a set of climate scenarios prepared for the California Energy Commission's Public Interest Energy Research (PIER) Climate Change Research Program, Cayan et al. (2008) project that, under medium to medium-high emissions scenarios, mean sea level along the California coast will rise from 1.0 to 1.4 meters (m) by the year 2100.[1] Rising seas put new areas at risk of flooding and increase the likelihood and intensity of floods in areas that are already at risk. In areas where the coast erodes easily, sea-level rise will likely accelerate shoreline recession due to erosion. Erosion of some barrier dunes may expose previously protected areas to flooding.

National studies on the economic cost of sea-level rise suggest that while adapting to climate change will be expensive, so are the costs of doing nothing, as substantial investments are already at risk and vulnerable.[2] Because the economic costs of flooding are highly site-specific, regional analyses are critical for guiding land-use decisions and evaluating adaptive strategies.

The Pacific Institute published one of the earliest comprehensive regional assessments of sea-level rise (Gleick and Maurer 1990), concluding that a one-meter sea-level rise would threaten existing commercial, residential, and industrial structures around San Francisco Bay valued at $48 billion (in year 1990 dollars). Building or strengthening levees and seawalls simply to protect existing high-value development was estimated to require an immediate capital investment of approximately $1 billion (in year 1990 dollars) and would require an additional $100 million per year in ongoing maintenance.[3] The report also noted that substantial areas of the San Francisco Bay, especially wetlands and marshes, could not be protected and would likely be damaged or lost.

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[1] It is important to note that most climate models fail to include ice-melt contributions from the Greenland and Antarctic ice sheets, and as a result, the potential increase in mean sea level may be much higher.

[2] See, for example, Titus et al. (1992) and Yohe et al. (1996).

[3] This estimate does not include the cost of protecting and restoring wetlands, groundwater aquifers, etc.

This assessment updates and expands our 1990 analysis using more comprehensive data, new climate scenarios, and modern computerized analytical tools. We made extensive use of geographic information system (GIS) software and updated sea-level rise scenarios from the Scripps Institution of Oceanography to estimate the population, infrastructure, ecosystems, and property at risk. We also estimate the cost of armoring the coast, one potential adaptation strategy to reduce that risk. This work is part of a larger set of research projects by the California Climate Action Team to understand the impacts of climate change to Californians, funded by the California Energy Commission's Public Interest Energy Research (PIER) program. The Pacific Institute also received significant financial support from two other state agencies: the Ocean Protection Council and the Metropolitan Transportation Commission, part of the Department of Transportation.

1.1. Key Findings

Over the past century, sea level has risen nearly eight inches along the California coast, and general circulation model scenarios suggest very substantial increases in sea level as a significant impact of climate change over the coming century. This study includes a detailed analysis of the current population, infrastructure, and property at risk from projected sea-level rise if no actions are taken to protect the coast, and the cost of building structural measures to reduce that risk. We find the following:

- Under medium to medium-high greenhouse-gas emissions scenarios, mean sea level along the California coast is projected to rise from 1.0 to 1.4 meters (m) by the year 2100. A series of maps for the entire coast of California demonstrating the extent of the areas at risk are posted at www.pacinst.org/reports/sea_level_rise.[4]
- A 1.4 meter sea-level rise will put 480,000 people at risk of a 100-year flood event, given today's population. Populations in San Mateo and Orange Counties are especially vulnerable. In each, at least 110,000 people are at risk. Large numbers of residents (66,000) in Alameda County are also at risk.
- A demographic analysis identified large numbers of people at risk with heightened vulnerability, including low-income households and communities of color. Additionally, adapting to sea-level rise will require tremendous financial investment. Given the high cost and the likelihood that we will not protect everything, adaptation raises additional environmental justice concerns.
- A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and more will also be at increased risk of inundation in a 100-year flood event. This infrastructure at risk includes:

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[4] These maps are not the result of detailed site studies and were created to quantify risk over a large geographic area. They should not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood insurance Studies and Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA). Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.

  - nearly 140 schools;
  - 34 police and fire stations;
  - more than 330 U.S. Environmental Protection Agency (U.S. EPA)-regulated hazardous waste facilities or sites, with large numbers in Alameda, Santa Clara, San Mateo, and Los Angeles counties;
  - an estimated 3,500 miles of roads and highways and 280 miles of railways;
  - 30 coastal power plants, with a combined capacity of more than 10,000 megawatts;
  - 29 wastewater treatment plants, 22 on the San Francisco Bay and 7 on the Pacific coast, with a combined capacity of 530 million gallons per day; and
  - the San Francisco and Oakland airports.

- Vast areas of wetlands and other natural ecosystems are vulnerable to sea-level rise. An estimated 670 square miles, or 430,000 acres, of wetlands exist along the California coast, but additional work is needed to evaluate the extent to which these wetlands would be destroyed, degraded, or modified over time. A sea-level rise of 1.4 m would flood approximately 150 square miles of land immediately adjacent to current wetlands, potentially creating new wetland habitat if those lands are protected from further development.
- We estimate that nearly $100 billion (in year 2000 dollars) worth of property, measured as the current replacement value of buildings and contents, is at risk of flooding from a 100-year event with a 1.4 m sea level rise if no adaptation actions are taken. An overwhelming two-thirds of that property is concentrated on San Francisco Bay. The majority of this property is residential.
- Coastal armoring is one potential adaptation strategy. Approximately 1,100 miles of new or modified coastal protection structures are needed on the Pacific Coast and San Francisco Bay to protect against coastal flooding. The total cost of building new or upgrading existing structures is estimated at about $14 billion (in year 2000 dollars). We estimate that operating and maintaining the protection structures would cost approximately 10% of the initial capital investment, or around another $1.4 billion per year (in year 2000 dollars).
- Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 m sea-level rise will accelerate erosion, resulting in a loss of 41 square miles of California's coast by 2100. A total of 14,000 people live in areas at risk of erosion. In addition, significant transportation-related infrastructure and property are also at risk. Throughout most of the state, flood risk exceeds erosion risk, but in some counties, coastal erosion poses a greater risk.

- Continued development in vulnerable areas will put additional areas at risk and raise protection costs.

2.0 Methods

Numerous studies have attempted to quantify the cost of sea-level rise and have been based primarily on a framework developed in Yohe (1989) and refined in Yohe et al. (1996) and Yohe and Schlesinger (1998). That framework employs a cost-benefit model to evaluate the property at risk and the cost of protecting or abandoning that property. Property is protected if the value of the property exceeds the protection cost at the time of inundation, and the protection cost is equal to the construction cost of the protective structure. If the value of the property does not exceed the cost of protection, then the property is abandoned, with the cost equal to the value of the land and structure at the time of inundation. The total economic cost is then the sum of the protection cost plus the value of the lost property.

To determine the value of lost property, the Yohe approach considers land and structure values separately. In most locations, coastal land commands a premium price, with the price declining as one moves inland. With inundation, the Yohe method assumes that land values will simply migrate inland, and thus, the economic value of lost land is equal to the economic value of interior land. The value of structures is calculated under two conditions: with and without foresight. With perfect foresight, the economic value of structures is assumed to depreciate over time as the "impending inundation and abandonment become known" (Yohe and Schlesinger 1998), approaching $0 at the time of inundation. Without foresight, the structure value does not depreciate.

Despite its wide application, the Yohe method has a number of limitations, many of which are discussed in Hanemann (2008):

- First, it ignores any transfers among property owners and looks only at the net social cost. In reality, there will be winners (those who had inland property that is now closer to the coast and thus more valuable) and losers (those who have lost their property), and the gross social cost "could be enormous" (Yohe et al. 1996).
- Second, it assumes that coastal protection will be constructed just in time to avoid damage from flooding. This is unlikely. If coastal protection is constructed too late, then the property would incur some damage, thereby increasing the cost. If constructed too early, then the discounted net present value of the cost of building the structure would be higher (Hanemann 2008).
- Third, it only examines changes in mean sea level (eustatic change), thereby ignoring damage from storm surge and extreme events.
- Fourth, by focusing on property values, it ignores other potentially expensive costs. For example, the flooding of transportation infrastructure essential for moving people or goods, e.g., highways and ports, could cause major interruptions to the local economy. Flooding also causes impacts on the health and well-being of the affected individuals and environmental damage, including erosion, oils spills, and discharge of pollution

from coastal industry (Hanemann 2008). Over the long-term, flooding can lead to the loss of wetlands.

- Fifth, prioritization of protection based on property value may directly undermine an environmental justice framework for protection.

This study used a different approach to estimate the economic impact of sea-level rise. We adopted the scenarios developed for the PIER studies and mapped the extent of inundation from a 100-year flood event that is likely to occur with rising sea levels. We also identified areas at increased risk from erosion as a result of rising seas. The inundation and erosion geodata were overlaid with other geospatial data using GIS to produce quantitative estimates of the population, infrastructure, and replacement value of property at risk from sea-level rise, as well as the impacts on harder-to-quantify coastal ecosystems. We also produced an initial estimate of the cost of adaptation measures, specifically building seawalls and levees in high-valued coastal zones to protect against future flooding. Greater detail on the methods is provided below.

2.1. Study Area

The study area spans approximately 1,100 miles of California's Pacific coast and 1,000 miles of shoreline along the perimeter of the San Francisco Bay. The San Francisco Bay study area extends from the Golden Gate in the west to Pittsburg, California, in the east and San Jose in the south. The eastern boundary of the San Francisco Bay study was set according to where United States Geological Survey (USGS) researchers were able to extract reliable flood elevations from the Bay hydrodynamic model. We provide a more detailed analysis in the San Francisco Bay due to the extensive, high-valued development in the region and the availability of higher-resolution geographic data.

The study area of the erosion analysis extended from Santa Barbara to the Oregon border, covering about 930 miles (1,450 kilometers, km). Much of the Southern California coast was excluded from the erosion analysis due to the myriad of ongoing initiatives focused on climate change and hazards mapping.

2.2. Sea-Level Rise Projections

2.2.1. Mean Water Levels and Extreme Events

Sea levels are constantly in flux, subject to the influence of astronomical forces from the sun, moon, and earth, as well as meteorological effects like El Niño. A worldwide network of more than 1,750 tidal gages continuously collects data on water levels relative to a nearby geodetic reference, and new satellite-based sensors are extending measurements. Tide gage data indicate that the global mean sea level is rising. Water level measurements from the San Francisco gage (CA Station ID: 9414290), shown in Figure 1, indicate that mean sea level rose by an average of

2.1 millimeters (mm) per year from 1906 to 2001, equivalent to a change of eight inches in the last century.[5]

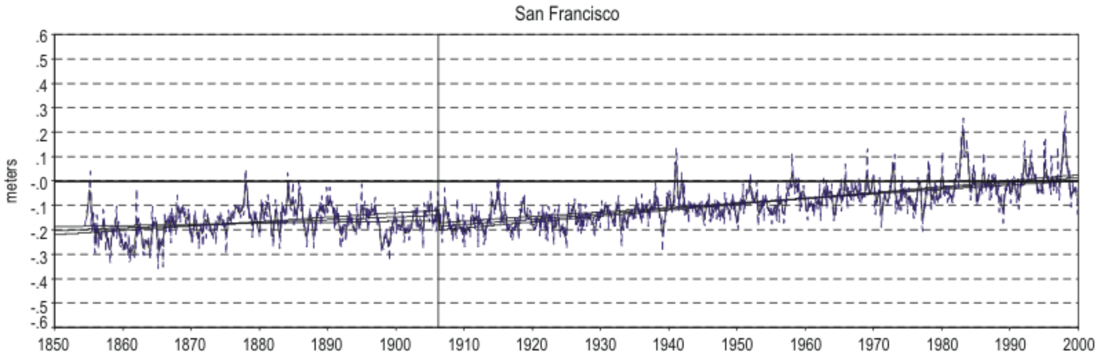

Figure 1. Trend in monthly mean sea level at the San Francisco tide station from 1854–2000

Source: NOAA Sea Levels Online, http://co-ops.nos.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

Sea levels are expected to continue to rise, and the rate of increase will likely accelerate. In order to evaluate climate change impacts, the Intergovernmental Panel on Climate Change (IPCC) developed future emission scenarios that differ based on assumptions about economic development, population, regulation, and technology (see Box 1 for a description of the scenarios). Based on these scenarios, mean sea level is projected to rise by 0.2 m to 0.6 m by 2100, relative to a baseline of 1980–1999, in response to changes in oceanic temperature and the exchange of water between oceans and land-based reservoirs, such as glaciers and ice sheets (Meehl et al. 2007).

Recent research by leading climate scientists, which includes more accurate sea-level measurements by satellites, indicates that sea-level rise from 1993–2006 has outpaced the IPCC projections (Rahmstorf et al. 2007). The authors suggest that the climate system, particularly sea levels, may be responding to climate changes more quickly than the models predict. Additionally, most climate models fail to include ice-melt contributions from the Greenland and Antarctic ice sheets and may underestimate the change in volume of the world's oceans.

To address these new factors, the PIER projects used sea-level rise forecasts developed by a team at the Scripps Institution of Oceanography led by Dr. Dan Cayan. Using a methodology developed by Rahmstorf (2007), Cayan et al. (2008) produced global sea-level estimates based on projected surface air temperatures from global climate simulations for both the IPCC A2 and B1 scenarios using the output from six global climate models: the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); the National Oceanic and

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[5] The solid vertical line shows the earthquake of 1906. NOAA researchers fit separate trendlines before and after major seismic events because of the possibility of vertical movement of the land surface where gages are located, disrupting consistent measurements.

Atmospheric Administration (NOAA) Geophysical Fluids Dynamics Laboratory (GFDL) version 2.1; the NCAR Community Climate System Model (CCSM); the Max Planck Institute ECHAM3; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Meteorologiques (CNRM) models.

Box 1: IPCC Climate Change Scenarios

The impacts of climate change will ultimately depend on future greenhouse gas concentrations. Future greenhouse gas emissions remain uncertain and are influenced by a variety of demographic, socio-economic, and technological factors. Scenarios can be a useful tool for examining how changes in these driving factors affect greenhouse gas concentrations. These scenarios can be useful for evaluating impacts associated with climate change as well as assessing adaptation and mitigation activities. The Special Report on Emissions Scenarios (SRES) outlines four storylines that differ according to demographics, social, economic, environmental, and technological factors and lead to different levels of greenhouse gas emissions. Each storyline has a number of different scenarios, referred to as a family. A total of 40 scenarios have been developed.

The four storylines are described below:

The **A1** storyline is characterized by "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income" (IPCC 2000). The A1 family is further divided into three subgroups that are differentiated according to energy source: fossil intensive (**A1FI**), non-fossil sources (**A1T**), and a mix of fossil and non-fossil sources (**A1B**).

The **A2** storyline is characterized by "self-reliance and preservation of local identities" (IPCC 2000). Population is expected to continuously increase, but economic growth and technological development are expected to be slow.

The **B1** storyline has the same population projections as the A1 storyline but "rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies" (IPCC 2000).

The **B2** storyline is characterized by "a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines" (IPCC 2000).

Additionally, Cayan et al. (2008) modified the sea-level rise estimates to account for water trapped in dams and reservoirs that artificially reduced runoff into the oceans (Chao et al. 2008). Absolute sea-level rise along the California coast was assumed to be the same as the global estimate. Based on these methods, Cayan et al. (2008) estimate an overall projected rise in mean sea level along the California coast for the B1 and A2 scenarios of 1.0 m and 1.4 m, respectively, by 2100 (Figure 2). The more severe A1FI scenario, which assumes a continued high level use of fossil fuels, was not used in this analysis, but is shown for comparative purposes.

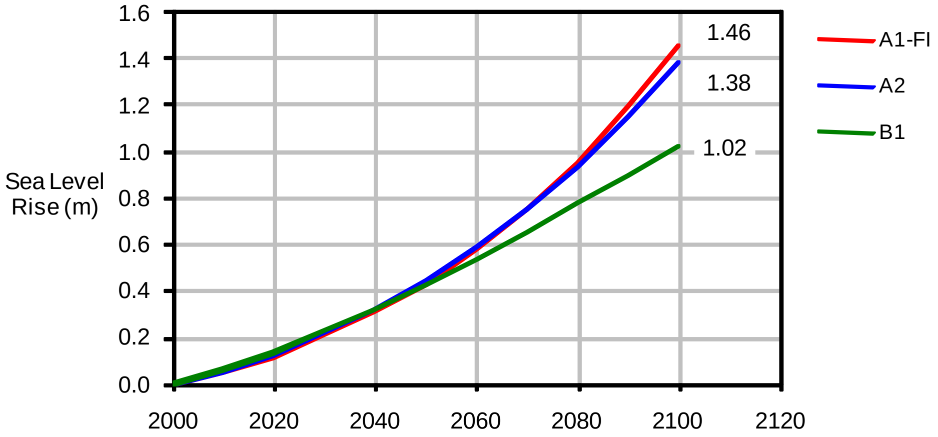

Figure 2. Scenarios of sea-level rise to 2100

Source: Dan Cayan, Scripps Institution of Oceanography, NCAR CCSM3 simulations, Rahmstorf method.

The majority of studies on climate change have emphasized changes in average conditions, yet the greatest socio-economic impacts tend to occur as a result of extreme events. Coastal flooding is often caused by storm surges, which are caused by high winds and pressure differentials associated with storms. Along the California coast, wave-induced storm surge can exceed 1.5 m (Cayan et al. 2006), flooding low-lying areas and eroding coastal bluffs. Increases in mean sea level are expected to increase the frequency and intensity of these extreme events. Although this study does not explicitly account for changes in storm surge, we do account for higher flood elevations associated with extreme events, as described below in Section 2.3.

2.3. Expected Risk to the Coast

2.3.1. Coastal Inundation Risk

Sea-level rise increases the risk of flooding in low-lying areas. For the California coast, we used GIS to produce maps of the areas at risk of inundation from a 1.4 m sea-level rise. For the San Francisco Bay, we produced maps of the areas at risk of inundation under three different sea-level rise scenarios: 0.5 m, 1.0 m, and 1.4 m. Below, we describe the methods used to determine the areas at risk of flooding along the Pacific coast and in the San Francisco Bay. Erosion is discussed in Section 2.3.2.

Pacific Coast

A flood is often described by its recurrence interval, which is the period of time between floods of a particular intensity that is based on historic conditions for a given area. The terminology used to describe the recurrence interval, however, can be misleading and is often misinterpreted. A "100-year flood" does not refer to a flood level that occurs every 100 years. Rather, it refers to a flood that has a 1/100, or 1%, chance of occurring in any year. Thus, over a typical 30-year mortgage period, a 100-year flood has a 1-in-4 chance of occurring (see Box 2).

For the Pacific coast, we approximate the potential future flood impact by adding projected sea-level rise estimates to water levels associated with a 100-year flood event; that is, current flood elevations for the 100-year flood are increased by 1.4 meters, the projected increase in sea level by 2100 under the A2 scenario (Figure 3).

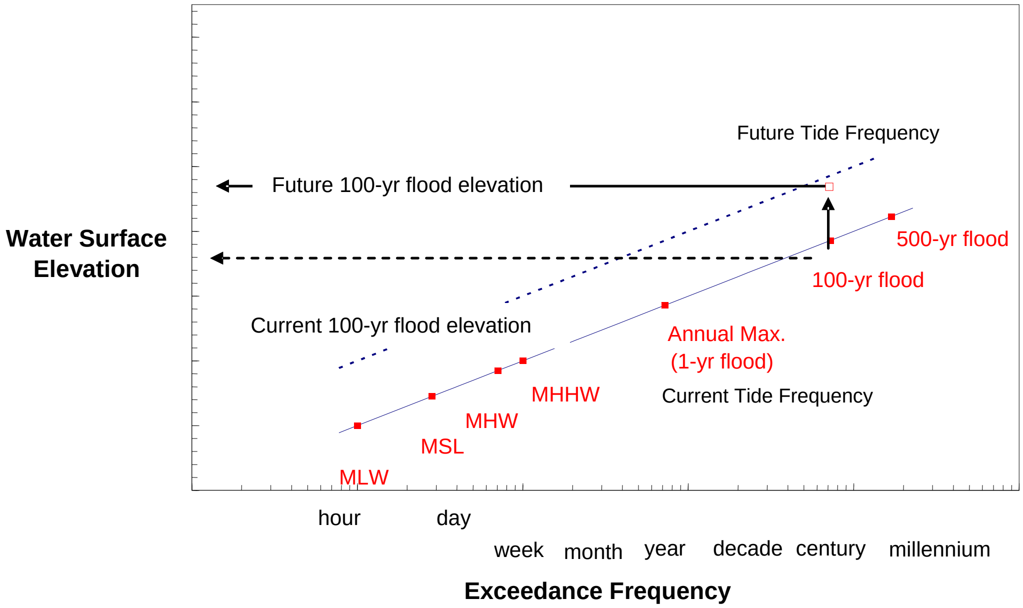

Figure 3. Determining future flood elevations

Note: The solid line represents the current tide frequency. The dotted line represents the future flood frequency. As can be seen, an increase in water surface elevation increases the frequency and intensity of flood events. For example, a 100-year flood event could become an annual flood event. The flood frequency estimates shown are for demonstration purposes only and are not based on actual data. See the Glossary for definitions of the abbreviations MLW, MSL, MHW, and MHHW.

This approach assumes that all tide datums, e.g., mean high tide and flood elevations, will increase by the same amount as mean sea level. There is some evidence that this assumption may not always hold true. Flick et al. (1999) found that, in San Francisco, mean higher high water (MHHW) was increasing at a rate of 258 mm per century, while the mean sea level increased at a lower rate of 217 mm per century (Figure 4). Thus, while the overall trend is one of rising seas, the intertidal range, i.e., the difference between MHHW and mean lower low water (MLLW), also seems to be widening. In addition, an increase in storminess due to climate change might cause more frequent storm surges and an increase in the frequency of high water events, although there is not yet consensus among climate scientists on changes in storm intensity or frequency, and such changes are not included here explicitly.

Box 2: Estimating Flood Risk

What are the chances that a 100-year flood will occur during a 30-year period?

To make this determination, we must apply basic probability theory. Flooding is a random event, i.e., the odds of it occurring in any year are independent of past conditions. Thus the odds of a storm not occurring over a 30-year period can be calculated using the following methodology.

If an event has an X percent chance of occurring in a given year, then the odds that the event will **not** occur in a given year are

$$1-X$$

The odds that an event will not occur in two successive years is

$$(1-X)(1-X) = (1-X)^2$$

And the odds of an event not occurring over y number of years is

$$(1-X)^y$$

Let's now calculate the odds that a 100-year flood event will not occur over 30 years.

In this case,

$$X = 1/100 = 0.01 \text{ and } y = 30$$

$$(1-X)^y = (1-0.01)^{30} = 0.74$$

Thus there is a 74% change that a 100-year storm will not occur over a 30-year period; and a 26%, or approximately a 1 in 4 chance that it will occur.

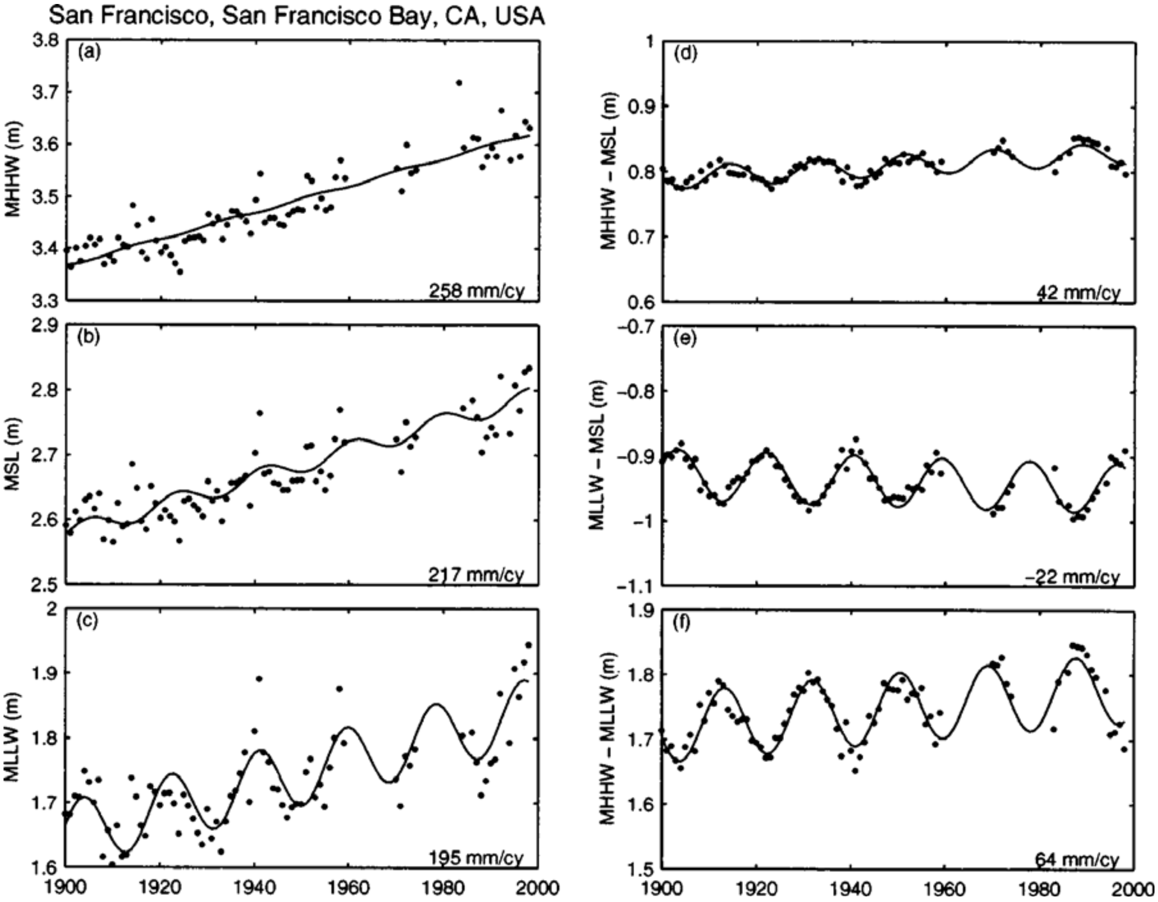

Figure 4. Rates of change of tidal datums, San Francisco from 1900–2000

Source: Flick et al. 1999

Existing flood levels were based on estimates of the 100-year flood elevation (also called the *base flood elevation* or BFE) from Flood Insurance Studies published by the Federal Emergency Management Agency (FEMA). The Federal Emergency Management Agency BFEs, however, only cover a part of the coast. We contracted with Philip Williams and Associates (PWA) to provide estimates of BFEs where none exist. Their work consisted of the following:

1. Compiled available coastal flood BFEs published by FEMA for the California coast.
2. Estimated BFEs where FEMA estimates are not available using professional judgment.
3. Converted elevations to the North American Vertical Datum (NAVD).
4. Adjusted elevations to nearest half foot based on observed sea-level rise to present day.

Further information on the methods used by PWA is available in a separate technical memorandum (Battalio et al. 2008).

We used automated mapping methods in GIS to delineate areas inundated by the current and future flood elevations. The key inputs to this analysis are digital elevation models (DEMs), gridded datasets that contain values representing elevations of the earth's surface. We used the most accurate, high-resolution, up-to-date terrain data available. For portions of the Central and Northern California coast, Interferometric Synthetic Aperture Radar (IfSAR) data were available from NOAA. NOAA's coastal service center assisted us in processing and obtaining each of these data sets.

For much of the Southern California coast, high-accuracy Light Detection and Ranging (LIDAR) data were available from Airborne LIDAR Assessment of Coastal Erosion (ALACE) project, a partnership between NOAA, the National Aeronautics and Space Administration (NASA), and USGS. The ALACE project emphasized shoreline change, and so the data were available for a relatively narrow swath of the coast. The coverage did not always extend inland far enough to fully map the coastal floodplain. In addition, there were several gaps in coverage along the entire coast. We supplemented these datasets, and filled in coverage gaps with topographic information from the USGS National Elevation dataset. Although these data are at a much lower resolution and accuracy, they allowed us to map the entire coast. The elevation datasets used for this project are summarized in Table 1.

Table 1. Elevation datasets used for mapping coastal flood risks

Dataset	National Elevation Dataset	ALACE 1998	ALACE 2002	So. Cal. IFSAR
Source/Mission	USGS	NASA, NOAA, USGS	NASA, NOAA, USGS	NOAA
Geographic Coverage	National	Stinson Beach to Santa Barbara	Northern border of California to Stinson Beach	Santa Barbara to Mexican border
Data Collection Method	Various	LIDAR	LIDAR	IFSAR
Resolution	10 m	3 m	2 m	3 m
Year Collected	Various	1998	2002	2003
Stated Vertical Accuracy	± 7.5 m	± 0.07 m	± 0.07 m	± 2.2 m

GIS raster math tools were used to compare the elevation of land surfaces with the adjacent flood elevation to determine the extent of flooding. Because of the large file sizes, and the large area being studied, we worked with the terrain datasets in over 600 tiles. Pacific Institute researchers wrote scripts to automate the processing steps on each of these tiles. The resulting inundation grids were boundary-smoothed and small isolated ponds and islands were removed. The raster datasets were then converted to vector polygons and merged so they could be used in the social and economic analyses. A separate technical memorandum is available at www.pacinst.org/reports/sea_level_rise that describes the GIS flood delineation methodology in greater detail.

San Francisco Bay

While our study looks at the entire California coastline, we also produced more detailed estimates of coastal flood risk in San Francisco Bay. While the distance from Oregon to Mexico is approximately 1,000 miles, the interior of San Francisco Bay has another 1,000 miles of coastline at risk. Inundation maps generated from the climate scenarios were provided to the Pacific Institute by Dr. Noah Knowles of the United States Geological Survey (Knowles 2008). Dr. Knowles developed a suite of computer models under the CASCADE project that simulate the hydrodynamics of San Francisco Bay under future climate scenarios. The Bay model simulates the water surface elevation for each hour from 2000–2099 and is driven by both upstream and downstream boundary conditions (Figure 5). The upstream boundary condition, inflow from the Sacramento/San Joaquin River Delta, is simulated by a hydrologic model of the upstream watershed and the CALSIM model to simulate the outflow from numerous upstream reservoirs. The downstream boundary condition is the water surface elevation of the ocean at the Golden Gate Bridge, which were provided by Dr. Cayan's group at Scripps.

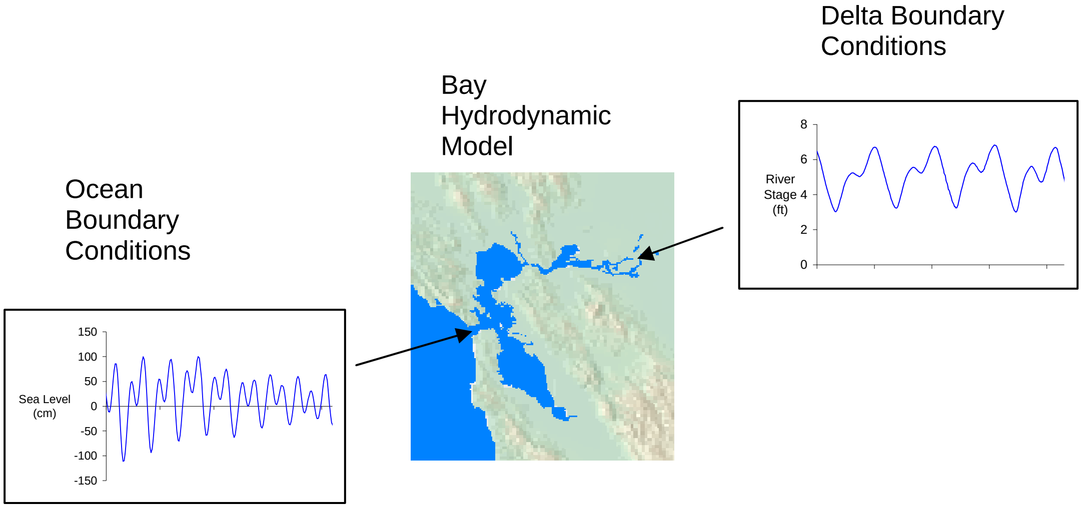

Figure 5. Simple schematic of USGS San Francisco Bay hydrodynamic model

Dr. Knowles performed statistical analyses on the Bay model output to determine flood quantiles at various times and provided outputs in the form of GIS raster files to the Pacific Institute. These files were provided for five flood recurrence intervals (Table 2) for each of four years between 2000 and 2099, for a total of 20 files. Based on this information, we produced GIS layers of the areas at risk of inundation with a 0.5 m, 1.0 m, and 1.4 m sea-level rise, which, for the A2 scenario, correspond to 2050, 2081, and 2099, respectively.

It is important to note that we report results based on the vertical rise in sea level rather than a particular year in which the rise is projected to occur. As shown in Table 3, the year in which a 0.5 m sea-level rise is projected to occur under the A2 and B1 scenarios differs by only three years. Additionally, sea-level rise estimates are continuously updated as climate science advances and greenhouse gas emissions change over time. Indeed, carbon dioxide emissions in 2005 and 2006 were well above even the highest future emissions scenario, as shown in Figure 6 (Raupach et al. 2007). Because the results of this analysis are driven by sea levels and are not directly tied to any set of scenarios, the results of this study will be relevant even when climate projections change.

Table 2. Recurrence intervals of inundation estimates

Flood Interval	Annual probability
1-year	1
10-year	0.1
50-year	0.02
100-year	0.01
500-year	0.002

Table 3. Year and estimated mean sea-level for inundation estimates under the A2 and B1 scenarios

Mean Sea-Level Rise (m)	Year Reached	
	A2	B1
0	2000	2000
0.5	2054	2057
1.0	2083	2098
1.4	2100	2125

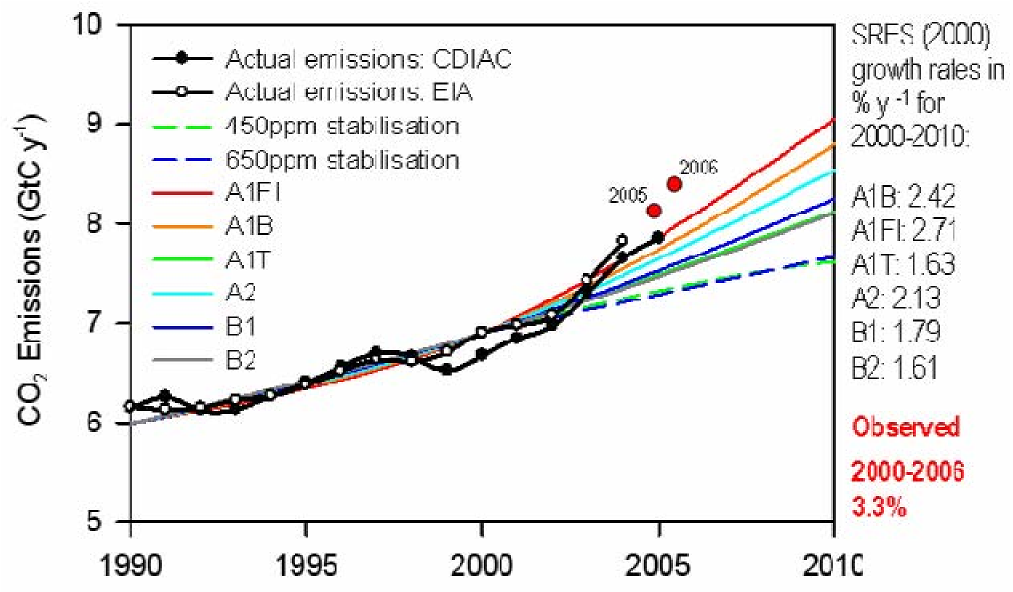

Figure 6. Historical and projected carbon dioxide emissions scenarios, 1990–2010

Note that actual emissions already appear to be exceeding the highest IPCC scenarios.

Source: Raupach et al. 2007

2.3.2. Erosion Risk

Large sections of the Pacific coast, especially those with rocky headlands or sea cliffs, are not vulnerable to flooding, but are highly susceptible to erosion. In areas where the coast erodes easily, higher sea levels are likely to accelerate shoreline erosion due to increased wave attack. In addition, erosion of some sand spits and dunes may expose previously protected areas to flooding.

The amount of erosion can be estimated by several methods. The most widely applied method of predicting shoreline recession based on a sea-level rise was developed by Bruun in 1962. This is based on the concept that the depth of water near the coast remains constant with sea-level rise, that the basic beach profile will remain the same, and that there is a well-defined offshore limit of sediment transport. The sediment required to maintain the beach profile through water-level changes is derived from erosion of the shore material. Based on this, an approximate estimate of the shoreline recession due to readjustment of the beach profile to an equilibrium state is 1.0-to-1.5 meters of shore recession per centimeter of sea-level rise.

Although once widely used, the Bruun rule has been largely abandoned because it makes several assumptions that may not be accurate (Pilkey and Cooper 2004). The formulation is based on a two-dimensional concept, while the sediment transport along a shoreline is a three-dimensional process. The Bruun rule assumes a shoreline profile in equilibrium, which is difficult to confirm at any site. Another problem is that this approach always predicts shoreline recession with offshore sediment transport as sea-level rises, yet there are several cases where shorelines have accreted as a result of sea-level rise due to the movement of sand onshore from offshore deposits. Depending on local sources and sinks of sediment, wave climate, topography, and other conditions governing sediment transport mechanisms, the predictions of shoreline recession obtained using the Bruun rule can significantly over- or underestimate the future recession. More specific methods are needed for particular sites, and should be conducted to better evaluate the impact of sea-level rise on a given region.

A team of scientists and engineers at Philip Williams Associates (PWA) developed an alternative approach to evaluate erosion risk. They evaluated potential future erosion by examining changes to a time series of total-water level (TWL) elevations. TWL is a water elevation determined by the sum of mean sea level, tides, waves and wave run-up, other storm components (including surge), and El Niños (Ruggiero et al. 1996; Ruggiero et al. 2001). Studies suggest that erosion will accelerate as sea levels rise and the coast is exposed to higher waves. Higher water levels result in greater wave energy being dissipated higher up on the shoreline and directly onto the face of cliffs and dunes. The exceedance of TWL above the elevation of the toe junction has been related to erosion (Sallenger et al. 2002; Ruggiero et al. 2001; Hampton and Griggs 2004; FEMA 2005).

To generate the TWL predictions, PWA used a 100-year time series of "measured tides" and deepwater waves from Dr. Dan Cayan and colleagues at Scripps (Cayan et al. 2008). The deepwater wave heights were transformed to 140 nearshore locations by the Coastal Data Information Program to account for differences in wave exposure and shoreline orientation. Finally wave run-up was calculated using the relationship between wave height, wave period, and beach slope (Stockdon et al. 2006). The combination of sea levels and wave run-up were evaluated over time to estimate future elevations of TWL, which were then intersected with the land elevations along 4,100 segments of the coast.

California's coastline is geologically and morphologically complex and each major geologic unit will exhibit differential response to rising sea levels. Philip Williams Associates classified the shoreline based on geologic formations and type, such as sea cliffs and dunes. For each type of coast, slightly different methods were used to project the response to rising seas. For sea cliffs, which accounted for 720 miles of the study area, erosion was estimated based on an acceleration of the historic erosion rate and a percent increase in TWL exceeding the elevation of the toe of the sea cliffs. The historic sea cliff erosion data were obtained from the USGS National Shoreline Change Assessment (Hapke and Reid 2007). The data were averaged by geologic unit with an additional factor of safety (two standard deviations) included to account for subtle changes in geology along the coast.

For the dune classified shorelines, which covered about 170 miles of the study area, erosion rates were based on the following information:

- Recession based on changes in TWL from sea level-rise.
- Historic shoreline change trends from the USGS National Shoreline Change Assessment (Hapke et al. 2006).
- The impact of a "100-year storm event" extracted from the TWL time series and estimated using a storm-response geometric model of dune erosion (Komar et al. 1999).

Based on this approach, PWA developed digital GIS shapefiles representing future coastal erosion hazard zones for cliff-backed and dune-backed coastal areas for 2025, 2050, and 2100 under a low (1.0 m) and a high (1.4 m) sea-level rise scenario. For this analysis, we evaluate the socio-economic impacts of erosion under the 1.4 m sea-level rise scenario for 2100. Note that for erosion, the year is important because it includes a background erosion rate plus accelerated erosion rates resulting from sea-level rise.

The study area of the erosion analysis extended from Santa Barbara to the Oregon border, covering about 930 miles (1,450 km). Much of the Southern California coast was excluded due to the myriad of ongoing initiatives focused on climate change and hazards mapping. Due to insufficient data, however, PWA was only able to include 80% of the 930 mile study area (see Section 2.4 for additional discussion of the limitations).

The erosion analysis represents a first-order evaluation of coastal hazards based on currently available projections of water levels and wave conditions and interpretations of sea-level rise, shoreline change rates, and geomorphic conditions. Available methods and data are not sufficient to model coastal erosion with high confidence. While the methodology used to develop the hazard zones was kept relatively simple and modular to facilitate understanding and future application with minimal effort, it represents one of the most comprehensive erosion hazard assessments under conditions of climate change ever completed for the California coast. For additional information, see PWA (2008).

2.3.3. Limitations of the Analysis

Researchers at Scripps Institution of Oceanography and USGS performed hydrographic modeling of the San Francisco Bay Estuary to determine the flood elevations under climate change scenarios. All models are subject to errors and inaccuracies. It was not possible to directly calibrate or verify a model that predicts flood frequencies. We performed an independent evaluation of USGS-predicted San Francisco Bay flood elevations and found that the model estimates of the 100-year water surface elevation for the year 2000 were generally similar to flood elevations predicted by the U.S. Army Corps of Engineers (1984a). We compared all 52 points on the San Francisco Bay shoreline shown on the 1984 Corps maps and found that 75% of the flood elevations were within 0.25 feet of those predicted by USGS. Most of the new estimates were slightly lower than the heights estimated by the Corps, as shown in Figure 7.

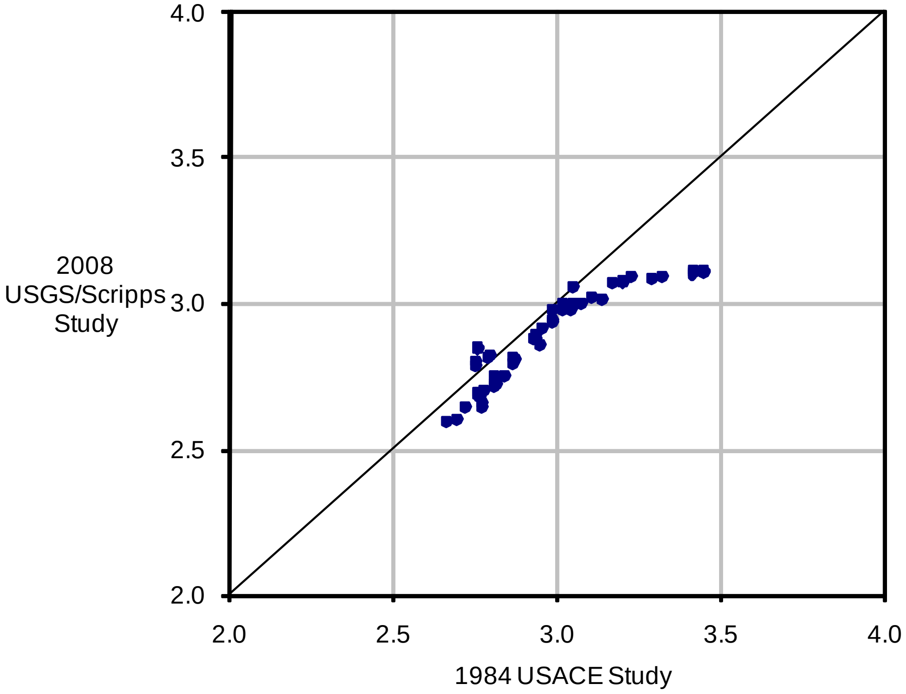

Figure 7. Comparison of 100-year flood elevations (in meters NAVD88)

Furthermore, the location of the shoreline is inexact and probably subjective. Knowles used a “mask” of open water as a filter, so as to report only land areas that are flooded. However, the shoreline is constantly in flux and difficult to map precisely. Further, there are errors and inaccuracies in the terrain data. The digital terrain model creates a smoothed or average surface from the raw elevation data, and it does not accurately depict breaks in elevation that occur at a vertical wall such as a cliff or a curb.

Another limitation is that the automatic, computerized method classifies flooding by depth only. The algorithm using depth alone to determine flooding does not factor in the presence of a flow pathway. In some cases, the high ground may be a levee specifically designed to protect adjacent low-lying areas. In other locations, there are simply depressions, but they are not really at risk because there is no path for seawater to flow into them. This means low-lying objects or features such as ditches, stormwater detention basins, subway tunnels, and empty swimming pools are filled in inappropriately at times, as shown in Figure 8.

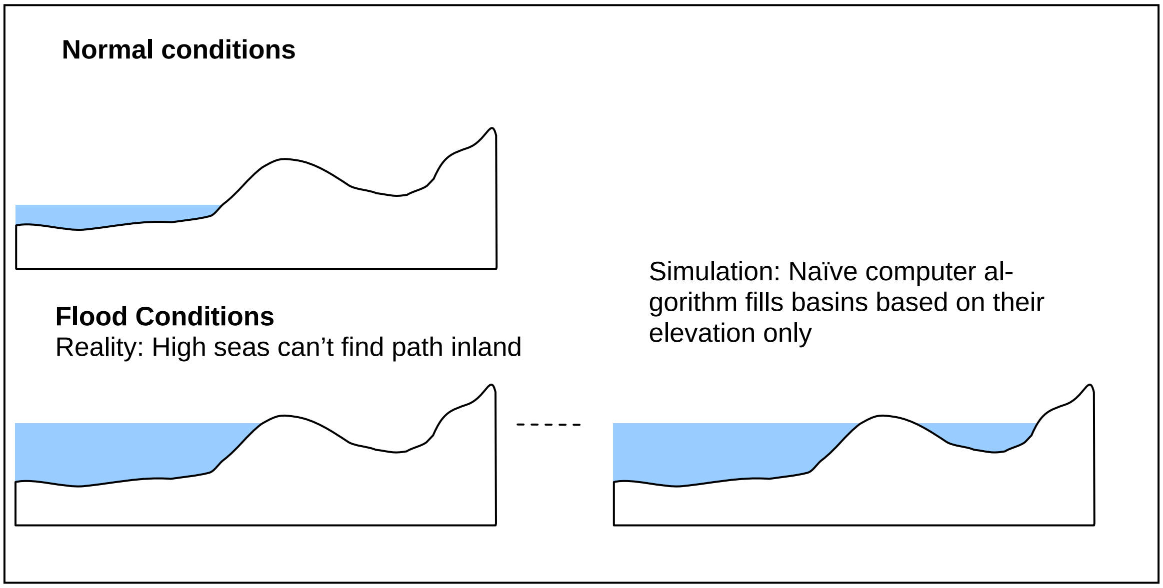

Figure 8. Limitations of the computer's ability to accurately map coastal flooding in areas protected by seawalls or levees or natural barriers

The study area for the erosion analysis was constrained by data availability. The erosion analysis covered only the 11 counties north of Santa Barbara County. Furthermore, data limitations limited the analysis to only 81% of the coast in the 11 counties (Table 4). The three counties with the least coverage include Humboldt County, Monterey, and Santa Barbara. Humboldt County included the Kings Range and the Lost Coast, public lands with no development. The Monterey County analysis was limited along the Big Sur coast where high levels of erosion currently affect the major transportation corridor of Highway 1 and are expected to continue. In Santa Barbara, missing data along the region between Pt. Conception and Goleta and the ending of the erosion analysis south of Santa Barbara harbor explain the missing erosion analysis. As a result, the vulnerability assessments underestimate the actual economic impact from erosion. Note that the flood analysis covered the entire Pacific coast of California and results for the erosion analysis were not adjusted to account for missing segments of the coast.

Table 4. Miles and fraction of coastline studied for the erosion hazard study, by county

County	Studied	Total	% Studied
Del Norte	42.7	49.7	86
Humboldt	72.9	123.3	59
Marin	69.5	75.2	93
Mendocino	145.5	151.4	96
Monterey	94.4	132.0	71
San Francisco	7.5	8.8	85
San Luis Obispo	77.0	102.6	75
San Mateo	57.8	59.6	97
Santa Barbara	84.4	116.5	72
Santa Cruz	46.0	46.0	100
Sonoma	63.0	68.9	91
Total	**760.7**	**934.1**	**81**

2.4. Resources Threatened by Sea-Level Rise

In any given area, rising seas pose a threat to many different types of resources. Among the vulnerable coastal systems are transportation facilities such as roadways, airports, bridges, and mass transit systems; electric utility systems and power plants; stormwater systems and wastewater treatment plants and outfalls; groundwater aquifers; wetlands and fisheries; and many other human and natural systems from homes to schools, hospitals, and industry. Any impacts on resources within the affected area may lead to secondary impacts elsewhere. Determining the types of resources threatened by sea-level rise is a crucial step toward choosing an appropriate level of response and method of protection.

2.4.1. Population

Sea-level rise and increased coastal flooding will lead to disruption due to evacuations, displacement from destruction of homes and property, and possibly the loss of lives. To determine populations at risk if no adaptation actions are taken, we overlay the inundation and erosion hazard maps with year 2000 census block data. We use current population data aggregated by census block, the highest resolution available for California. We make an assumption common in regional GIS analyses that the population is distributed evenly within a block's boundaries. So if our mapping shows that 50% of a 500-person census block is inundated by a flood, we estimate that 250 people are at risk. This method may underestimate (where the houses are clustered on the coast) or overestimate (when the houses are set back from the coast) the actual risk.

> *While disasters do not discriminate, the existing societal and environmental conditions before, during, and after a disaster produce differences in vulnerability among groups within the population affected.*

It is critical to understand that our estimates of populations at risk are based on current population data, not a projection of populations that might be at risk in the future. If no policies are put in place to limit new exposure in areas at risk of rising seas, our estimates will be low—perhaps substantially low. If, however, policymakers are proactive about reducing coastal risks in coming decades, the levels of risk could be substantially reduced.

We also evaluate potential environmental justice impacts of sea-level rise.[6] As seen during Hurricane Katrina, flooding and other natural disasters often do the greatest harm to low-income communities and communities of color. Hurricane Audrey, for example, struck the coast of Louisiana in 1957 and had a death rate of 38 per thousand among whites and 322 per thousand among blacks (Bates et al. 1963, cited in Pastor et al. 2006). A study of all U.S. disasters between 1970 and 1980 found that white households had $2,370 less of a financial burden following a disaster than other racial groups (Rossi et al. 1983). One year after Hurricane Katrina, the black population of New Orleans had decreased 57% while the white population had fallen 36% (Frey 2007). Racial disparities are mirrored in economic disparities where low-income communities have shouldered a disproportionate burden of harm resulting from disasters: reports following Hurricanes Hugo and Katrina pointed to a range of problems related to the "invisibility" of low-income communities before the disasters (Pastor et al. 2006).

The uneven distribution of natural disasters' harms mirrors racial and economic inequities in the distribution of other environmental risks and benefits, which in the 1980s catalyzed affected communities to develop the framework of "environmental justice." This framework was ultimately affirmed by the Environmental Protection Agency in its 1992 creation of what is now called the Office of Environmental Justice, which holds that

> "no group of people, including racial, ethnic, or socioeconomic groups, should bear a disproportionate share of the negative environmental consequences resulting from industrial, municipal, and commercial operations or the execution of federal, state, local, and tribal environmental programs" (U.S. EPA).

Presidential Order 12898 of 1994 expanded the application of environmental justice principles in its decree that "each Federal agency shall make achieving environmental justice part of its mission" (Presidential Executive Order 12898).

We use the environmental justice framework in two analyses that are relevant to understanding the full costs of sea-level rise in California. The first is a simple analysis looking for potential inequities in who is likely to be directly exposed to sea-level rise, within the geographic units at which relevant political decisions are made. In this case these geographic units include the state of California as a whole and each county affected by sea-level rise. We urge further studies looking at possible inequities at different spatial scales, e.g., within cities, neighborhoods, and metropolitan regions. Our second environmental justice analysis focuses on the factors of

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[6] Here, we evaluate the environmental justice impacts of flooding but not erosion. Additional analysis should examine erosion as well.

vulnerability and the differential vulnerability to the impacts of sea-level rise of people from different demographic groups.

A third analysis, which is beyond the scope of this study, should focus on potential inequities in the distribution of benefits of the resources that are invested in protecting from and adapting to sea-level rise. Here we focus on completing a part of the first and second analyses, and leave the third analysis for future studies.

Any analysis of populations affected by sea-level rise should include a broader discussion of vulnerability to these events. According to the Intergovernmental Panel on Climate Change, "Vulnerability to climate change is the degree to which these systems are susceptible to, and unable to cope with, adverse impacts" (Schneider et al. 2007). Vulnerability is a function of the magnitude of the impact, the sensitivity of the system to that impact, and the system's ability to adapt. Vulnerabilities, like lack of access to a vehicle or other means of transportation, are shaped by "intervening conditions" that are not tied to a specific hazard but will greatly determine the human impact of the disaster and the specific needs for preparedness, response, and recovery (Hewitt 1997).

Here, we report key population characteristics that increase vulnerability to the adverse impacts of flood events and disasters for low-income people and communities of color. We sort the types of vulnerabilities and key demographics correlated with increased vulnerability, according to the three phases of a disaster event: preconditions, disaster, and recovery and reconstruction (Hewitt 1997). Figure 9 offers a conceptual model of the relationship between demographics, vulnerabilities, and human impact. Our analysis is limited to two factors: the distribution of race and income. A more comprehensive analysis of the human impact of sea-level rise is needed for all vulnerable subgroups, including children, elderly, homeless, and incarcerated residents.

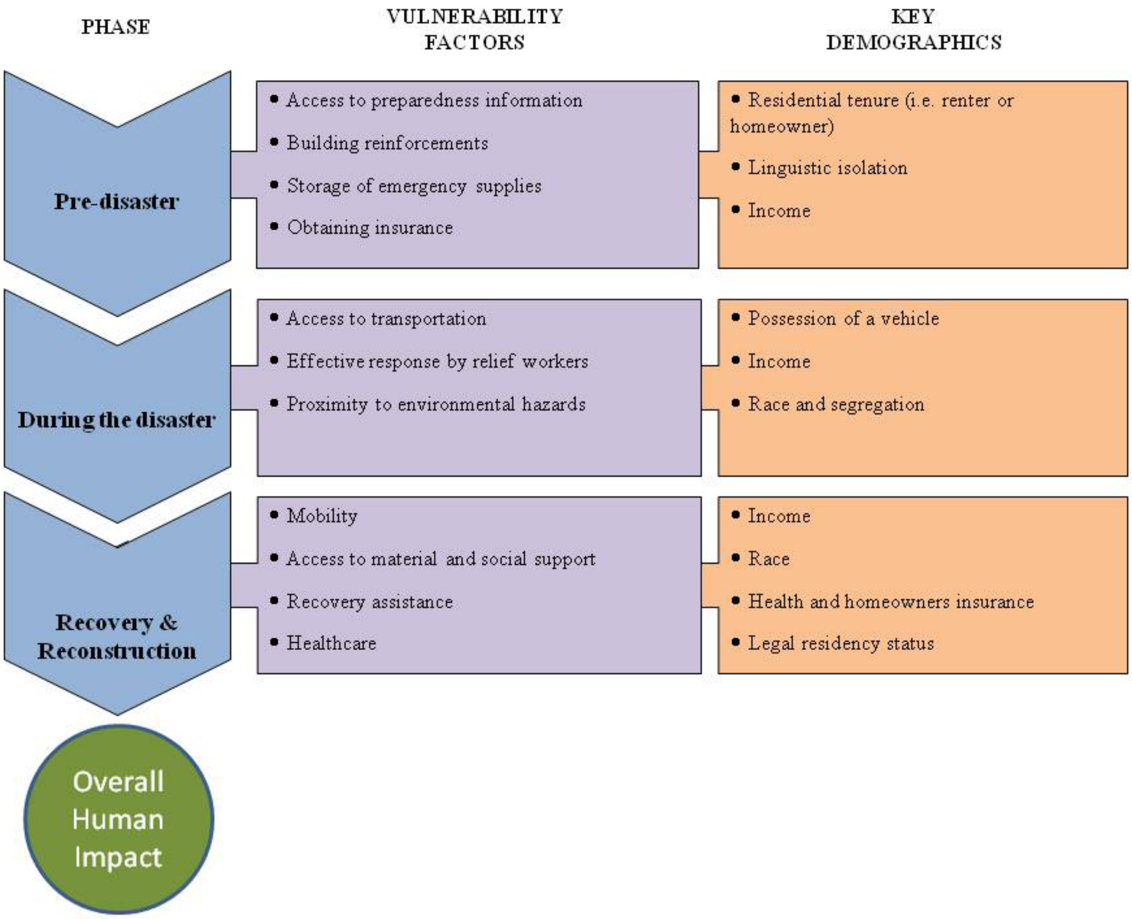

Figure 9. Relationship between demographics and vulnerabilities

2.4.2. Impacts on the Built Environment

Extensive development has occurred in areas already threatened by erosion and floods along the California coast. Residential homes along the California coast often draw a premium price as a result of their location. Some homes in coastal zones are protected by levees and revetments; many are not protected at all. Additionally, high-value commercial, industrial, and transportation facilities are also located along the coast. Such facilities make use of the waterfront for waste disposal, movement of goods or people, or commercial activities. Among the most common coastal facilities are airports, railroad tracks and terminals, highways, power plants, waste-disposal sites, waste-treatment plants, ports and docks, warehouses, salt ponds, and marinas. Existing forms of protection for these facilities vary greatly, from bulkheads and engineered seawalls to riprap and non-engineered levees. An increase in sea level will increase the severity of possible damages in threatened areas and will expand the size of flood and erosion zones.

Data on the replacement value of buildings and contents was taken from datasets supplied with the HAZUS model, which was developed for FEMA's Mitigation Division by the National Institute of Building Sciences. HAZUS was designed to help planners estimate the potential losses from natural disasters such as earthquakes, floods, and hurricane winds. HAZUS uses a database called the "General Building Stock Inventory" that contains the value of buildings and contents based on data from a number of sources including the U.S. Census Bureau, Dun & Bradstreet (a business listing service), and the U.S. Department of Energy. HAZUS estimates direct economic losses based on the repair and replacement of damaged or destroyed buildings and their contents, and includes the following:

- Cost of repair and replacement of damaged and destroyed buildings.
- Cost of damage to building contents.
- Losses of building inventory (contents related to business activities).

Replacement values are provided for residential, commercial, industrial, agricultural, religious, governmental, and educational developments and are compiled at the census block level. See Section 14.2 of the HAZUS technical manual for additional detail (FEMA 2006). To determine the replacement value for the areas at risk, we overlay the inundation maps with year 2000 census block data. We assume that if 50% of an area is affected, then 50% of its assets are at risk. For inundation risks, we use replacement value, as described in more detail below, because 1-100 year inundation does not completely destroy property and land value. In contrast, erosion often completely destroys the property. As a result, replacement value is not appropriate for evaluating the economic cost of erosion and was not used for that part of the study.

We compared replacement costs and the market value of homes at a few locations along the California coast and found that the replacement costs in HAZUS can substantially underestimate actual market values for residential properties. According to the HAZUS database, the median home replacement values range from $63,000 in Del Norte County to $135,000 in San Mateo County (Figure 10). In comparison, the median home price in California was $286,000 in November 2008. In Northern California, the median price was $307,000, and in the San Francisco Bay Area, the median price was $474,000. Of course, homes on the coast are usually much more expensive. For the erosion analysis, we assume that the value of the average coastal property is about $1.4 million (Heinz Center 2000).

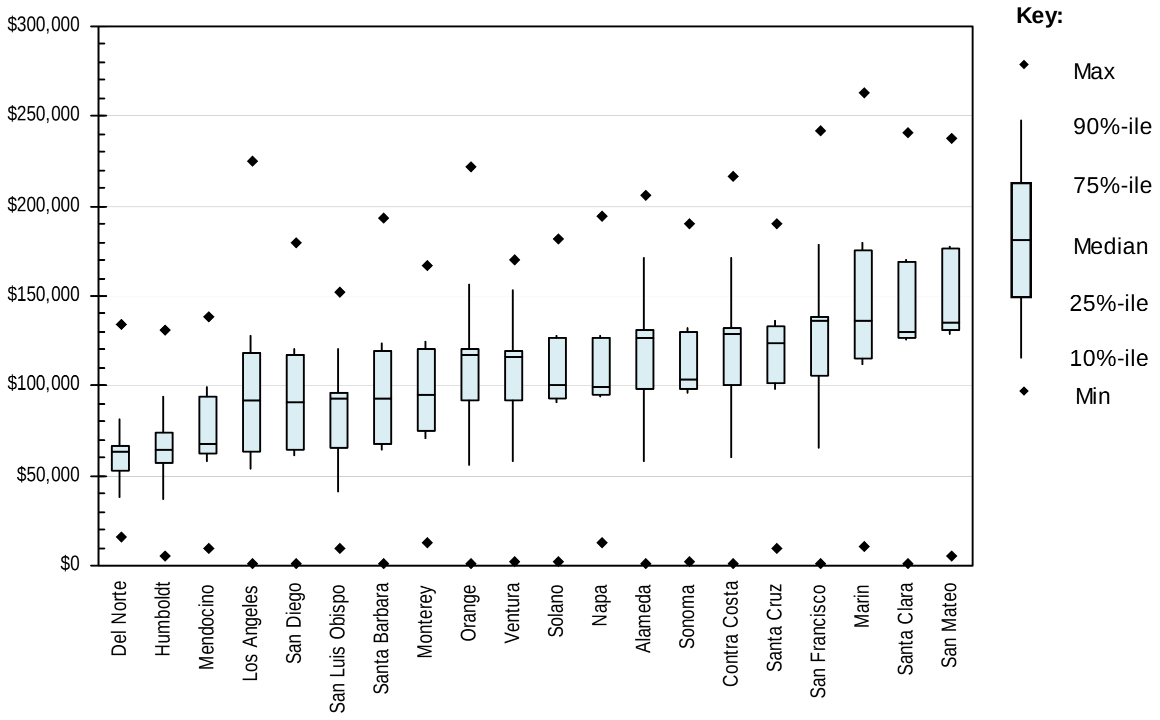

Figure 10. Distribution of census-block average replacement costs for single-family homes from HAZUS

The difference between the replacement value and the market value of a home is likely due to several factors. Home values are determined by more than the cost to build the house, including land value, neighborhood, school district, and dozens of other tangible and intangible factors. In addition, the HAZUS documentation warns that replacement value is based on national-average construction costs, which are much lower than construction costs in California. Future studies should include more detailed estimates of California construction costs.

Parcel data from each county's assessor's office provides higher spatial resolution, but there are some significant limitations to using these data. First, we were unable to obtain a complete coverage for all coastal counties. In some counties, parcel data have not been converted to a digital format, while others claimed that sharing these data was a threat to Homeland Security. Second, even where parcel boundary files are available, these must be linked to the value of the property. While obtaining a list of affected parcels is straightforward, most counties do not readily share their tax rolls or tables with assessed value. This information is part of the public record, and can legally be requested in person or by phone from a county assessor's office, but this approach is not feasible for a regional analysis where hundreds or thousands of parcels are affected. Third, even if assessed value were readily available to us, it often bears little relationship with the actual market value of a property. Finally, assessed value will not include any publicly owned buildings, so it would exclude many police and fire stations, government buildings, park buildings, schools, water treatment plants, and others.

Important transportation infrastructure is also at risk of flooding and erosion from projected increases in sea-level rise (Figure 11). We estimate the miles of roadways and railroads at risk by overlaying the GIS inundation and erosion hazard layers with transportation data from Tele Atlas. We note that because there are not elevations associated with the roadways, it is difficult to infer the extent to which the roadway is at risk from flooding. Additionally, the railroad data does not provide information on the number of tracks, e.g., single, double. We also do not provide estimates of the value of this infrastructure because adequate data are not available. Thus, the information on roads and railways is presented as miles of structures at risk rather than value, but it provides an indication of the areas at risk and those warranting additional analysis.

Figure 11. Flooding of a coastal road in Santa Cruz, California

Photo courtesy of David L. Revell

A number of other facilities along the coast are also at risk of flooding and erosion. We evaluate the sites and facilities at risk by overlaying the GIS inundation layer with the relevant spatial data. Data on the locations of schools and emergency facilities come from the HAZUS geographic database (FEMA 2006). Data on licensed healthcare facilities come from the California Office of Statewide Health Planning and Development (2006). Data on coastal power plants were provided by the California Energy Commission.

Data on U.S. EPA-monitored hazardous materials sites were from the U.S. EPA Geospatial Data Access Project 2008 and included Superfund sites, hazardous waste generators, facilities required to report emissions for the Toxics Release Inventory, facilities regulated under the National Pollutant Discharge Elimination System (NPDES), major dischargers of air pollutants with Title V permits, and brownfield properties.[7] The Pacific Institute developed a geographic database of wastewater treatment plants based on data in the U.S. EPA's Permit Compliance System (PCS) database, by interpreting aerial photos and by telephone and Internet research.

2.4.3. Natural Resources

Wetlands are among the Earth's most productive ecosystems. Once abundant across the United States, wetlands have been extensively drained and filled to make way for agricultural, industrial, commercial, and residential development. Pollution and invasive species threaten the health of the remaining areas. The U.S. EPA estimates that more than 220 million acres of wetlands existed in the lower 48 states in the 1600s. By 2000, only 100 million acres of wetlands remained (U.S. EPA 2001). In some parts of the United States, wetland loss was even more severe. In California, for example, more than 90% of the historic wetlands have been lost to development. Growing recognition of their importance and concern about their rapid decline has prompted wetland restoration efforts across the United States, including the San Francisco Bay. A recent U.S. Fish and Wildlife Service report suggests that the net wetland acreage actually increased between 1998 and 2004 for the first time as a result of restoration efforts and the construction of engineered wetlands (Dahl 2006).

While legislation has partly protected wetlands from further destruction, rising seas threaten to substantially modify or destroy remaining wetland habitat. Most coastal wetlands in the United States are within one tidal range of mean sea level (Titus 1988), i.e., between mean high tide and mean low tide. Thus, as noted by Titus (1988), if sea levels rose by one tidal range overnight, "then all of the existing wetlands in an area would drown." Rising seas, however, may also inundate land that is now dry, thereby creating new wetlands. Wetlands may also be able to adapt to rising water levels over time by trapping sediment or building on the peat the sediment creates, a process referred to as vertical accretion. These compensatory mechanisms may be hindered by coastal development that limits wetland migration or rates of sea-level rise that exceed natural accretion rates.

Spatial Extent of Wetlands

In this analysis, we use GIS data from the National Wetlands Inventory (NWI) to determine the current spatial extent of wetlands along the California coast and the San Francisco Bay. While there is currently no single source that contains the boundaries of all existing wetlands, the NWI is the best dataset available. It is important to note that all datasets likely underestimate the actual wetland area. Wetland delineation is a time- and labor-intensive task requiring extensive field work by experts; vast areas have never been subject to detailed study.

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[7] A *brownfield* is an abandoned industrial site available for redevelopment, often with environmental contamination.

The NWI does not make a clear distinction between coastal and upland wetlands. The datasets are distributed in tiles, with each tile containing a mix of marine, estuarine, and freshwater wetlands. We used a simple rule-based approach to decide which wetlands are coastal, or "coast-dependent"" we assume that coastal wetlands are generally limited to within 100 feet (horizontally) of the mean higher-high water line (Figure 12).

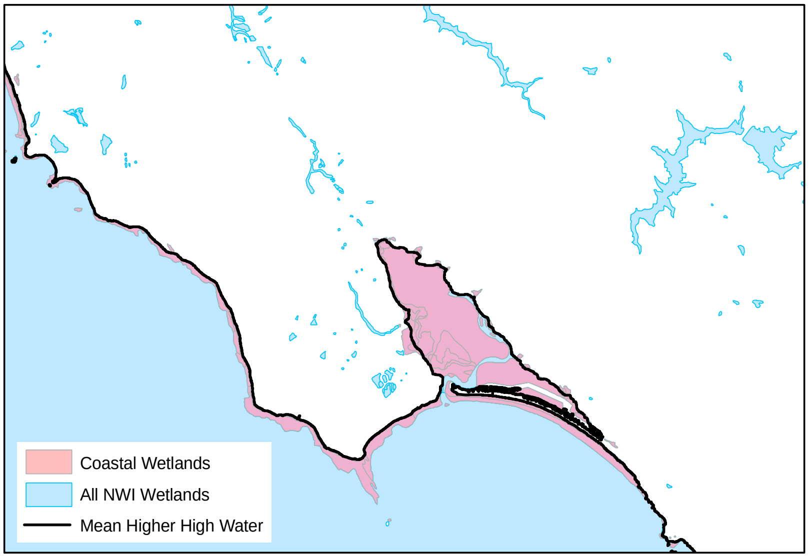

Figure 12. National Wetlands Inventory wetlands classified as "coastal" are below or adjacent to the MHHW line

Economic Value of Wetlands

Wetlands are highly diverse ecosystems that provide a variety of goods and services, including flood protection, water purification, wildlife habitat, recreational opportunities, and carbon sequestration. While there are rarely any direct market values for services provided by wetlands, such as biodiversity and flood control, there is a growing recognition that these services have real economic values and should be included in decision-making processes.

Methods for estimating the economic value of an ecosystem, including wetlands, can be done in one of three ways: direct, indirect, and proxy (Table 5). Each of these methods has strengths and weaknesses; each fails to fully capture the value of ecosystems. The unacceptable alternative, however, is to assign an economic value of $0—clearly acknowledged to be wrong. To put it simply, "we don't protect what we don't value" (Myers and Reichert 1997).

In recent years, a number of studies have attempted to estimate the economic value of wetlands. Based on a literature review and some original calculations, Costanza et al. (1997) estimate that the value of tidal marshes is around $5,700 per acre per year (in year 2007 dollars). In a meta-analysis of 39 wetland valuation studies, Woodward and Wui (2001) found that wetland values varied considerably according to the methods used, the type and location of wetlands evaluated, and the study characteristics. While the valuation method affected the value obtained, the method was not the primary determinant of value. However, study quality was not a strong determinant either; weak studies yielded wetland values similar to strong studies, but with more error, suggesting that the quality of the study affects precision. The authors conclude: "From our analysis it is clear that the prediction of a wetland's value based on previous studies is, at best, an imprecise science. The need for site-specific studies remains" (Woodward and Wui 2001).

For this analysis, we estimate the economic value of wetlands in California using recent cost estimates for restoring wetlands. Numerous wetland restoration projects have been initiated in the San Francisco Bay, with the cost of restoring these tidal marshes ranging from $5,000 to $200,000 per acre (Hutzel 2008). The South Bay wetland restoration project, for example, is estimated to cost about $67,000 per acre (Hutzel 2008). We note that these estimates represent the public's willingness to pay for these ecosystems rather than their actual value, but without a more detailed site-specific analysis, the restoration costs are the best estimates available. We do not evaluate the ability of wetlands to adapt to these changes through vertical accretion or landward migration, but note that these processes could reduce damage to wetlands. We urge more detailed wetland valuation studies be conducted to improve these estimates.

Table 5. Approaches for estimating ecosystem values

Approaches	Description	Example	Weaknesses	Strengths
Direct	Surveys can be used to ascertain people's willingness to pay for benefits provided by the wetland or the level of compensation they would expect for the loss of those benefits. Such surveys measure the value of specific benefits.	A survey that asks users what they would be willing to pay to retain a recreational area.	This approach requires sophisticated survey design, analysis and interpretation.	This approach can measure relatively subtle changes in value and can also be used to calculate the value of non-use benefits.
Indirect	Economists use mathematical models to estimate wetland values based on the market demand for related goods and services.	Expenditures and the distance traveled by people visiting a wetland are used as indicators of the value of the wetland for recreational purposes. Similarly, real-estate price differences could be used to estimate the value of the wetland's aesthetic benefits.	This approach cannot measure non-use benefits (e.g., option or bequest benefits) or benefits that do not currently exist (e.g., the benefits of an enlarged wetland).	This approach is usually faster and less expensive, as it can be based on easily accessible data.
Proxy	The values of other goods and services are used to approximate the values of wetland benefits.	The replacement cost for a wetland benefit (e.g., water filtration), such as the cost of installing a buffer strip or building a water treatment plant, is used as a measure of the value of the benefit.	This approach may confuse costs and benefits. For example, using the cost of a water treatment plant estimates the cost rather than the value of water filtration, (i.e., people's willingness to pay for clean water).	This approach can be more quickly calculated, but the result is only a very rough estimate of value.

Source: Environment Canada 2001

Impact of Sea-Level Rise on Wetlands

Evaluating the impacts of sea-level rise on a particular coastal wetland area requires site-specific data on various physical and biological factors, as described above. While this information is clearly important for developing adaptation strategies, it is beyond the scope of this analysis. A simple method to estimate wetland loss is to compare wetland elevations to future tide elevations. If the areas are permanently inundated in the future, they will be converted to open water and lose their value as wetland habitat. Data limitations, however, prevent us from performing even this simple analysis: the existing digital elevation models (DEMs) do not include data below the shoreline and the modeled mean lower low water mark, even with 1.4 m of sea-level rise, falls below this elevation. This means there are no data in the critical area where the boundary must be drawn. We recommend additional work in this area to create a DEM for the California coast that combines land surface elevations with accurate bathymetry to allow for more detailed study of potential wetland responses to sea-level rise. Given these data limitations, we evaluate the land cover *adjacent* to existing wetlands and the potential for these areas to support suitable wetland habitat. We note that this simplified analysis does not take into account erosion or accretion due to sediment movement, which is difficult to predict with any accuracy.

Wetlands exist in areas that are frequently but not permanently inundated. In *The Effects of Sea Level Rise on US Coastal Wetlands*, Park et al. (1989) assumed that all areas between mean lower water (MLW) and mean higher water springs (MHWS) are tidal wetlands (Figure 13). The MHWS is only a few centimeters from the mean higher high water (MHHW) datum, which is more readily calculated and tabulated in tide reports. We assume that wetlands will migrate to land areas that are below the future MHHW, which we estimate as current MHHW plus the projected 1.4 m sea-level rise.

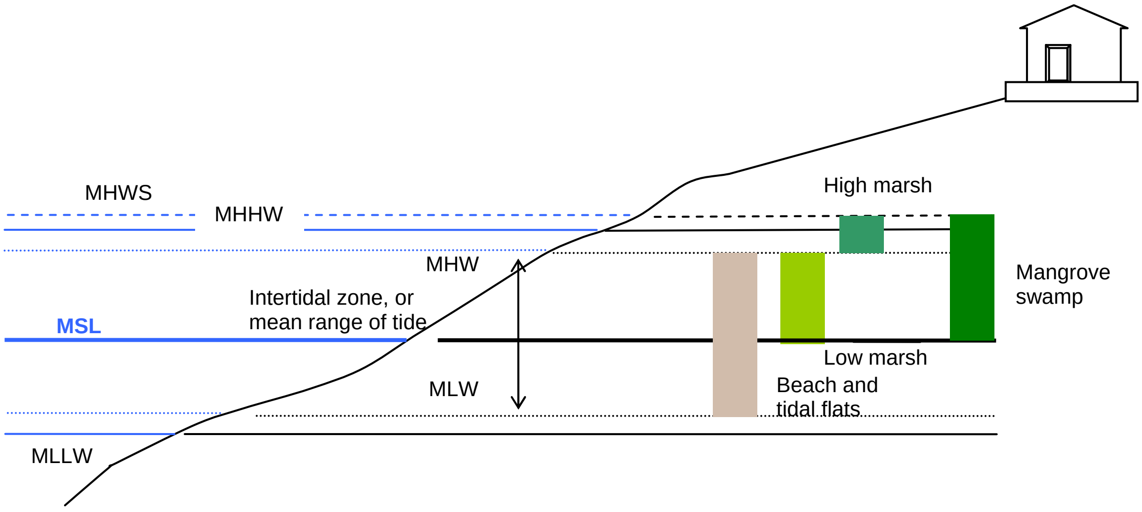

Figure 13. Assumed wetland area defined by the intertidal range

Adapted from Park et al. 1989.

The National Oceanic and Atmospheric Administration maintains tide stations along the California coast that provide measurements of MHHW. We interpolated the high-water elevation for the entire California Pacific coast using data from 12 long-term coastal tide gages. Each of these NOAA tide stations has been in continuous operation for over 25 years. The MHHW elevation for each of these stations is listed in Table 6. Using spatial interpolation tools available in ArcGIS software, we developed a continuous grid or "surface" of MHHW elevations in year 2000.[8] To estimate MHHW elevations with a 1.4 m sea-level rise for the Pacific coast of California, we created a second surface by adding 1.4 m to each pixel in the year 2000 MHHW surface. The difference between the high water lines is the "wetland migration zone": the land into which wetlands must migrate to survive.

Table 6. Mean higher high water (MHWH) for long-term tide stations on California's Pacific coast

NOAA Station ID	Station Name	MHHW
9410170	San Diego, CA	1.61
9410230	La Jolla, CA	1.57
9410660	Los Angeles, CA	1.61
9410840	Santa Monica, CA	1.60
9411340	Santa Barbara, CA	1.61
9412110	Port San Luis, CA	1.60
9413450	Monterey, CA	1.67
9414290	San Francisco, CA	1.80
9415020	Point Reyes, CA	1.75
9416841	Arena Cove, CA	1.76
9418767	North Spit, CA	1.99
9419750	Crescent City, CA	1.98

Note: Elevations in meters above NAVD88 vertical datum. Tide datums calculated by NOAA for the 1983–2001 epoch.

Source: http://tidesandcurrents.noaa.gov/

We analyzed the land cover in the potential wetland migration zone using 2001 land cover data from NOAA's Coastal Change Analysis Program (C-CAP).[9] We rated each land cover type according to its suitability to support wetland habitat in the future. We assume that natural lands such as woodland, grassland, or shrub could provide suitable habitat for wetland plants and animals in the future when they are in the new intertidal zone and are intermittently wetted. Other land cover types may be viable for conversion to wetlands, but at a loss of some direct value to humans, e.g., farmland or parks. The third and final category represents built-up

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[8] In some areas of Southern California, however, the available digital terrain data was not sufficiently detailed to complete the analysis. The terrain data did not include points below an elevation of 1.5 m NAVD88, and we could not map the current MHHW inundation extent for the entire coast. We mapped about 49% of Santa Barbara County, 23% of Los Angeles County, and 65% of Orange County. The coverage was 100% in the other 11 counties on the Pacific coast.

[9] The C-CAP data layer classifies land cover based on an adapted version of the Anderson et al. (1976) classification scheme and is estimated to have an accuracy of 85% (NOAA Land Cover Analysis website www.csc.noaa.gov/crs/lca/ccap.html).

areas that will likely provide unsuitable habitat for wetlands in the future due to the presence of buildings and other paved areas.

2.4.4. Limitations

Our analysis also has limitations related to the economic valuation methodology. For the flood analysis, we estimate the economic cost of sea-level rise based on estimates of the replacement value of buildings and their contents. We do not include estimates of the property or land value, which are much higher and should be included if inundation is permanent or leads the abandonment of property. Replacement values are also not appropriate for estimating the cost of erosion because it typically results in the total loss of property and land. We make a rough estimate of land values along the coast but note that additional study is needed.

Flooding and erosion can cause serious economic and social disruptions that are not captured in estimates of the buildings and infrastructure. For example, flooding events can cause deaths and injuries. Flooding or erosion of a major highway can prevent people from getting to work. Estimating the replacement value and even some wetland values thus substantially underestimates the total cost of flood impacts and as a result, our results should be considered conservative. A more detailed analysis would include transportation risks, lost work days, health issues, impacts on migratory bird habitat, and others.

We also do not factor in any expected changes in population density or the level of development in the regions at risk over the next century; these are largely unknown and will be determined by future policies. If policies are put in place to reduce development in regions of future flooding, society could over time reduce the risks. While limiting coastal development (an institutional adaptation) is likely the most effective way to reduce risk, this approach can also incur costs. Development permits designed to provide flexibility for future generations to address sea-level rise (e.g., development permits that allow development but stipulate that the area reverts to nature if seas rise a specified amount) may reduce today's cost. Conversely, if current development in coastal areas continues unchecked, a far larger population and a far larger infrastructure set will be vulnerable than at present. We make no estimates of these changes, but future research could look at different scenarios for growth and coastal development and integrate them into the assessment tools developed here.

2.5. Determine the Protective Responses Appropriate for the Region

Each of the resources and facilities described in Section 2.4 can be protected by some combination of structural and non-structural measures. Some of the possible structural measures include building or improving coastal defenses such as dikes and dunes, seawalls, bulkheads, and other structures. Non-structural measures include abandoning property and land and moving to less threatened areas and beach nourishment. Perhaps the most effective non-structural response is to prohibit development in regions likely to be threatened in the future. This choice, however, requires the most forethought and planning. Below, we describe some of the structural measures and their associated costs.

2.5.1. Structural Coastal Protection Measures

Beach Nourishment

The addition of beach sand to a shoreline has been used to construct beaches where none had previously existed and to replenish eroded sand. As a response to the expected increase in erosion due to sea-level rise, the purpose of beach nourishment is to restore the width of an eroding beach on a temporary basis, although nourishment can also provide long-term restoration in certain types of areas. The rate at which the replenished beach erodes is a function of wave action, the uniformity of placement of the sand, and the grain size (U.S. Army Corps of Engineers 1984b). The sand used for a beach nourishment project usually comes from offshore dredging and pumping to the desired site; less frequently material is imported from an off-site location. The cost of the material can vary greatly depending on its origin and associated transportation costs.

Groins

One type of structure designed to lessen the impact of coastal processes on a shoreline is a groin—a structure oriented perpendicular to the shore that serves to reduce the flow of sediment along a shore (the local littoral drift rate). Sand collects on the updrift side of the groin until it is filled to capacity, when longshore drift is allowed to pass. Groins are often used in fields (sets of more than one groin) to protect a long section of coastline. The shoreline immediately downfield of the groin field, however, is often subjected to accelerated erosion, especially when the groins are not filled with sand during construction (National Research Council 1987).

Sea-level rise can affect a groin by reducing its effectiveness due to “flanking” or “submergence.” A groin typically extends landward to the dune line, and the dune line may retreat due to sea-level rise, leaving the groin susceptible to flanking during high or storm tides, allowing sand to bypass the groin. Submergence of the groin can lead to overtopping by the longshore current, further decreasing the structures’ efficiency at stabilizing the area (National Research Council 1987).

Seawalls, Bulkheads, and Revetments

There are three principal forms of vertical shoreline walls used to protect upland areas from storm surges and high tides: seawalls, bulkheads, and revetments. The differences between seawalls, bulkheads, and revetments are in their protective function. Seawalls are designed to resist the forces of storm waves; bulkheads are to retain the fill; and revetments are to protect the shoreline against the erosion associated with light waves (U.S. Army Corps of Engineers 1984b). These structures tend to fix the position of the coast. While this strategy may protect upland development, there are two kinds of adverse consequences of these types of structures. *Placement loss* refers to the loss of beach due to the footprint of the structure. For seawalls this is not as great as a revetment, which is usually built at a 2:1 (horizontal:vertical) slope. The other impact of these structures is called *passive erosion.* As sea level rises, and the structure fixes the position of the shoreline, the beach in front of the structures can be “drowned,” resulting in a loss of recreation opportunities and habitat (Griggs 2005).

Breakwaters

Offshore breakwaters are above-water structures parallel to the shore that reduce both wave heights at the shoreline and littoral drift. Sea-level rise will reduce the protective capacities of breakwaters in two ways: rising water levels will effectively move the shoreline farther from the breakwater, increasing the ability of the waves to diffract behind the structure and reducing the sheltering and efficacy of the device; and the increased frequency of overtopping will diminish the ability of the breakwater to reduce the wave energy in the sheltered region (National Research Council 1987).

Dikes and Levees

Dikes or levees are embankments to protect low-lying land. A sea-level rise can result in reduced stability and increased overtopping of existing levees. New levees may be constructed to protect developed areas (National Research Council 1987). Whether existing levees can be modified for a rise in sea level depends on the availability of material for raising the levee, the suitability of the foundation material to support the additional weight of the material, the stability of the levee with the increased water level, and the accessibility of additional area for widening the base of the levee. Considerations for new levees also include issues such as land condemnation and interference of the levee with navigation (National Research Council 1987).

Raise Existing Structures (Roadways, Railroads, and Other Structures)

In some regions, building levees or seawalls to protect a small number of structures may not be cost effective. In these instances, raising the structures may be a better alternative. Roadways, railroads, and other structures may be raised so as to avoid damage from flooding. Over time, for example, we think it likely that important economic assets such as airports, transmission lines, or roadways will be raised rather than protected with levees or seawalls.

2.5.2. Cost of Structural Protection Measures

The cost of flood defenses is site-specific and little reliable information is available to generalize these costs. Gleick and Maurer (1990) developed cost estimates for building new coastal protection structures and raising existing ones, as well as raising roadways, railroads, and individual structures. We update these costs for this analysis based on a literature review (Table 7). Costs are converted to year 2000 dollars. Given the site specificity of construction costs, we relied on cost information from California where possible.

Data suggest that a new levee between 10 and 20 feet in height with a waterside slope of 3:1 would cost about $1,500 per linear foot (in year 2000 dollars). This represents a 320% increase over the 1990 estimate, much higher than the rate of inflation. The increase is likely due to large increases in construction and material costs in recent years. We estimate that raising existing levees would cost about $530 per linear foot (in year 2000 dollars). Seawalls, while providing significant protection, are among the most expensive option, estimated at about $5,300 per linear foot (in year 2000 dollars).

Table 7. Costs (in year 2000 dollars) for building new levees, raising existing levees, and building new seawalls

	Cost ($ per linear foot)	Location	Sources
New Levee	$725–$2,228	San Francisco, CA	Pang (2008)
Average New Levee	**$1,500**		
Raise Levee	$319	Central Valley, CA	Mount and Twiss (2005)
	$223–$1,085	San Francisco, CA	Moffatt and Nichol Engineers (2005)
	$278–$944	Central Valley, CA	Mount and Twiss (2005)
Average Levee Upgrade	**$530**		
New Seawall	$1,292	New England	Kanak (2008)
	$3,828	Southern California	Gustaitis (2002)
	$2,646–$6,173	Northern California	Stamski (2005)
	$5,654–$8,078	Philadelphia	PennPraxis (2008)
	$4,847	California	Crampton (2008)
Average New Seawall	**$5,300**		

Note: All costs are shown in year 2000 dollars. Costs shown for a new levee are based on a U.S. Army Corps of Engineers cost-estimation model, for a levee between 10 and 20 feet in height with a waterside slope of 3:1 and built using local materials.

In addition to the construction costs of the various structures described above, maintenance costs are often significant. In general, the greater the engineering employed in the construction of a shore protection scheme, the lower the proportion of maintenance costs. The maintenance cost of engineered riprap-revetment, for example, can amount to 2%–4% of the construction cost per year over the life of the project. This can be compared with the maintenance cost for a non-engineered revetment of 5%–15% of the construction cost per year (Fulton-Bennett and Griggs 1986). Average maintenance costs for levees are about 10% per year of the costs of construction. The estimated maintenance costs for seawalls run from 1%–4% per year, reflecting the higher level of engineering that goes into their construction. Because the majority of structures in our study are levees, we assume here an annual operation and maintenance cost equal to 10% of the capital cost of construction.

Levees, seawalls, and other structural methods have a number of environmental and social costs that are not reflected in the cost estimates shown in Table 7. Armoring the coast prevents natural movement and migration of the beach and associated ecosystems. In some areas, beaches may disappear completely, as shown in Figure 14. Structural measures can also increase vulnerability by encouraging development in flood-prone areas and giving those who live behind the structure a false sense of security. According to the United Nations,

> “protective works have a tendency to increase the level of development in floodprone areas, as the assumption is made that it is now safe to build and invest in areas that are protected. However, it must be recognized that at some point in the future the design event will likely be exceeded and catastrophic damages will result” (United Nations 2004).

In addition, structural measures require regular maintenance, a task that is often overlooked due to budgetary constraints. Failure to maintain protective structures can lead to structural failures and catastrophic damage.

Figure 14. An example of coastal armoring leading to the disappearance of beach

Source: David L. Revell

2.5.3. Estimating Needed Coastal Defenses

Details about what level of protection to choose are a function of the perception of the value of the threatened property, the cost of alternative measures, and political and societal factors. In this analysis, we evaluate one scenario: the cost associated with raising the height of existing structures to maintain current flood protection levels and building new structures to protect development that will be at risk of flooding with a 1.4 m sea-level rise. We do not evaluate coastal protection costs for erosion and urge additional studies on this topic.

In order to determine the cost of protecting development along the San Francisco Bay and California coast, we first needed to determine the location and type of existing coastal protection structures. Unfortunately, neither the U.S. Army Corps of Engineers nor any other agency maintains a comprehensive database with this information. The California Coastal Commission, however, recently compiled spatial data on the location and type of protective structure along the Pacific coast, e.g., groins, revetments, levees, and seawalls. Similar data were not available for the San Francisco Bay. Digital Flood Insurance Maps (DFIRMs) that showed the presence of protective structures in the San Francisco Bay, however, were available in some areas. We supplemented the DFIRMS with a visual assessment of aerial imagery of the region. Because the DFIRMs do not distinguish between the types of structure, we assumed that seawalls were located around high-density, highly valued areas and levees were located around all other areas.

Geospatial data on the existing coastal protection structures were overlaid with the inundation maps to determine where existing structures needed to be raised and new structures built. To make this determination, we made the following assumptions:

- Existing coastal protection structures are strengthened and raised by 1.4 m with no change in the type of protection, e.g., levees are raised but are not replaced by a seawall.
- New coastal protection structures are needed wherever built structures are at risk of flooding. Agricultural land was not protected, unless a levee already existed.
- Seawalls are used in areas along the Pacific coast that are currently not protected but will need protection in the future and in areas where space limitations due to development prohibit the construction of new levees.
- Levees are used within enclosed areas, like the San Francisco Bay, that are currently not protected but will need protection in the future. These bays are protected from wave action, and we assume that levees will provide sufficient protection.

3.0 Results

Here we report on the results of our analyses for San Francisco Bay and the Pacific coast. In particular, we report on the population, infrastructure, and property at risk from sea-level rise, as well as the impacts on harder-to-quantify coastal ecosystems. We also provide an estimate of the economic costs of building coastal protections of different types to protect lives and property from flooding. All economic values are reported in year 2000 dollars. Results are reported separately for the flood and erosion risks.

3.1. Flood-Related Risks

In this analysis, we use the 100-year flood levels to evaluate the vulnerability to inundation. The 100-year flood is used as a standard for planning, insurance, and environmental regulations. It is important to note that people, infrastructure, and property are already located in areas vulnerable to flooding from a 100-year event. Many Californians are already at risk from coastal flooding. Sea-level rise will cause more frequent and more damaging floods to those already at risk and will increase the size of the coastal floodplain, placing new areas at risk where there were none before. In Figure 15, for example, those areas shown in light blue are currently vulnerable to a 100-year flood event in the Santa Cruz area. With a 1.4 m sea-level rise, additional areas (shown in dark blue) will be at risk. Thus, the damage attributed to a 1.4 m sea-level rise is equal to the area currently vulnerable to a 100-year flood event (but now protected by levees, seawalls, etc.) plus new inundated areas, i.e., the areas shown in light blue and dark blue in Figure 15.

A series of maps for the entire coast of California demonstrating the extent of the areas at risk are posted at www.pacinst.org/reports/sea_level_rise. It should be noted again that these maps are not the result of detailed site studies, and were created to quantify risk over a large geographic area. **They should not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood insurance Studies and Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA). Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.**

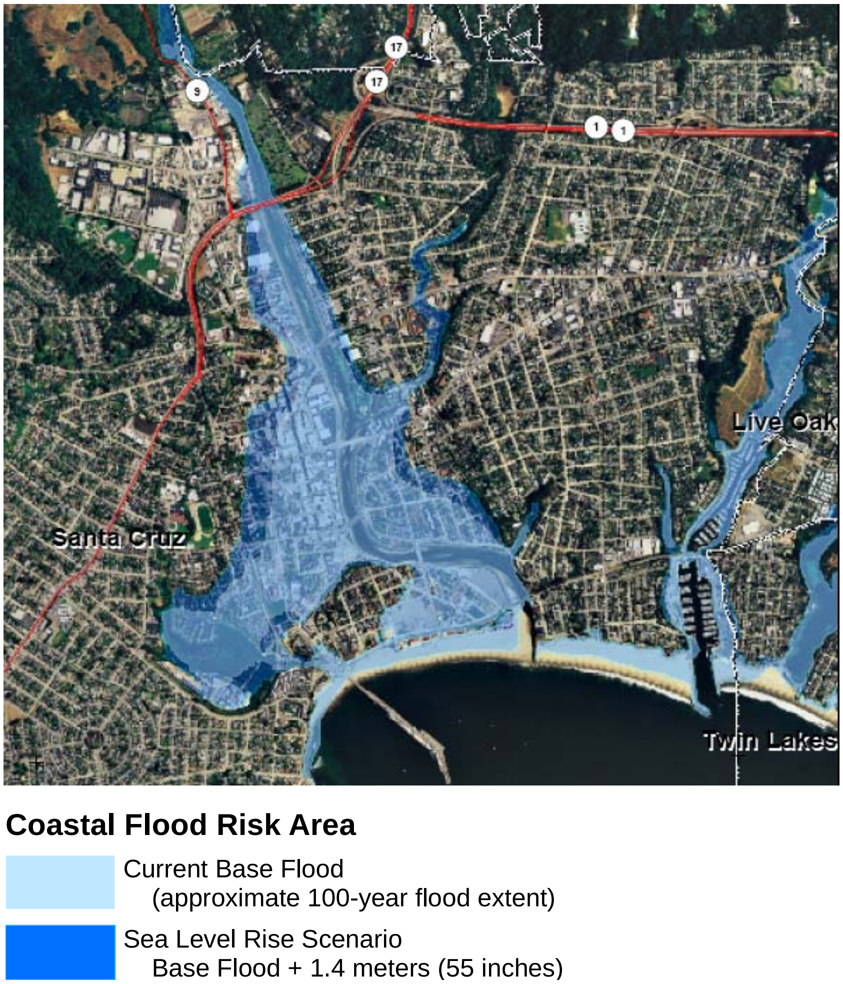
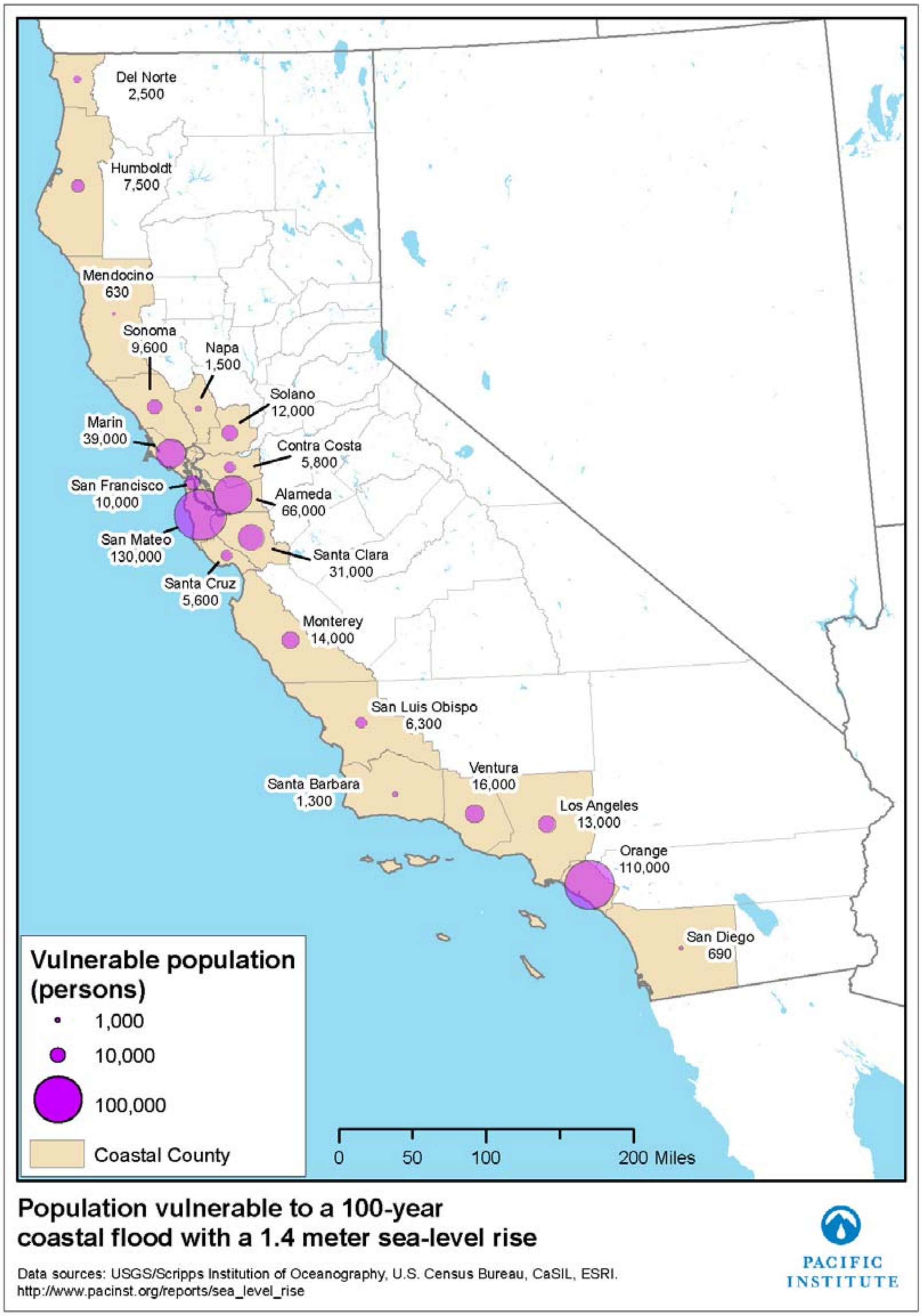


Figure 15. Estimated current and future 100-year coastal flood risk areas around Santa Cruz

3.1.1. *Population at Risk*

Major population centers are located all along California's coast. Nearly 26 million people lived in coastal counties in 2000. Of these, 74% lived along the Pacific coast and the remaining 26% lived along the San Francisco Bay. An estimated 260,000 people, or 1% of California's coastal population, live in areas that are currently vulnerable to a 100-year flood event. As discussed in Section 2.3.3, the inundated area does not adequately take into account existing flood barriers. It is likely that most existing coastal protection structures are sufficient to protect people living in these areas against the present-day flood risk. Most existing defenses, however, will not be adequate to protect inhabitants following significant sea level rise.

As sea levels rise, the area and the number of people vulnerable to flooding will also rise. Rising sea levels will overwhelm the existing protection structures, putting the 260,000 people currently living in vulnerable areas at increased risk. In total, we estimate that a 1.4 m sea-level rise will put around 480,000 people (nearly half a million) at risk from a 100-year flood event (Figure 16). Continued development in these regions could put additional people at risk.



Population vulnerable to a 100-year coastal flood with a 1.4 meter sea-level rise

Data sources: USGS/Scripps Institution of Oceanography, U.S. Census Bureau, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 16. Population vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise, by county

Table 8 shows the population vulnerable to a 100-year flood event along the Pacific coast by county. In 2000, an estimated 120,000 people lived in areas vulnerable to a 100-year flood event. A 1.4 m sea-level rise will increase the number of people vulnerable to a 100-year flood event to 210,000. More than half of these residents live in Orange County, although significant numbers of people are also at risk in Los Angeles, Monterey, San Mateo, Sonoma, and Ventura Counties.

Table 8. Population vulnerable to a 100-year flood along the Pacific coast, by county

County	Current Risk	Risk with 1.4 m sea-level rise	Percent increase
Del Norte	1,700	2,500	47
Humboldt	3,600	7,500	110
Los Angeles	3,600	13,000	270
Marin	520	620	20
Mendocino	520	630	22
Monterey	10,000	14,000	36
Orange	70,000	110,000	55
Sonoma	2,900	9,100	210
San Luis Obispo	4,600	6,300	35
Santa Barbara	660	1,300	98
Santa Cruz	4,500	5,600	24
San Francisco	3,400	6,500	94
San Mateo	11,000	16,000	49
San Diego	570	690	21
Ventura	7,000	16,000	120
Total	**120,000**	**210,000**	68

Note: Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

In San Francisco Bay, the population vulnerable to flooding is even greater. Table 9 shows the population vulnerable to a 100-year flood event in 2000 and with a 0.5 m, 1.0 m, and 1.4 m sea-level rise. In 2000, an estimated 140,000 people lived in areas at risk from a 100-year flood event. An increase in sea levels of 0.5 m has only a modest effect on the number of people at risk. With a 1.4 m increase in sea levels, however, the number of people at risk of a 100-year flood event doubles to 270,000. Populations in San Mateo County are especially vulnerable, accounting for about 40% of those at risk with a 1.4 m sea-level rise. Large numbers of residents in Alameda, Marin, and Santa Clara counties are also at risk.

Table 9. Population vulnerable to a 100-year flood along the San Francisco Bay, by county

County	Current risk	Risk with sea-level rise 0.5 m	1.0 m	1.4 m	Percent increase (with 1.4 m rise)
Alameda	12,000	22,000	43,000	66,000	470
Contra Costa	840	1,600	3,400	5,800	590
Marin	25,000	29,000	34,000	39,000	55
Napa	760	830	970	1,500	99
San Francisco	190	600	1,600	3,800	1900
San Mateo	80,000	88,000	99,000	110,000	34
Santa Clara	13,000	17,000	24,000	31,000	140
Solano	3,700	5,500	8,800	12,000	230
Sonoma	250	300	420	540	110
Total	**140,000**	**160,000**	**220,000**	**270,000**	**98**

Note: Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Environmental Justice Concerns

The analysis of the potential environmental justice impacts of sea-level rise considers who currently lives within the areas at risk and the vulnerabilities of this population to the potential adverse impacts. There is little difference between the overall racial and income demographics of Californians affected by a 1.4 m sea-level rise and those of the state as a whole. However, we do find some important differences between the racial and income demographics of those affected and those of the total population of each county.

Table 10 and Figure 17 show a simplified racial breakdown of the flood-affected population and the population of the counties as a whole. Sea-level rise induced flooding may disproportionately affect whites in the majority of counties along the California coast. In Los Angeles County, for example, 73% of those affected are white, while only 31% of the population in the county is white. Conversely, along the San Francisco Bay, however, communities of color are disproportionately impacted by sea-level rise. In total, communities of color are disproportionately impacted in 10 of the 20 counties studied. The greater proportion of people of color in areas affected by a 1.4-meter sea-level rise highlights the need for these counties to take concerted efforts to understand and mitigate potential environmental injustice.

The results presented above highlight the importance of conducting socio-economic analyses and comparisons at various geographic scales. It is significant to note that these numbers only reflect exposure to the hazard. In the next section, we also evaluate other vulnerability factors, such as access to transportation and ability to speak English.

Table 10. Total county population and population vulnerable to a 100-year flood with a 1.4-meter sea-level rise along the Pacific coast, by race

County	White		Asian, Black, Latino, Native American, or Other Race	
	Affected population (%)	County population (%)	Affected population (%)	County population (%)
Alameda	35	41	60	55
Contra Costa	28	58	69	39
Del Norte	75	70	21	26
Humboldt	82	82	15	15
Los Angeles	72	31	26	67
Marin	59	79	38	19
Mendocino	74	75	23	22
Monterey	29	40	69	57
Napa	63	69	35	29
Orange	80	51	18	46
San Diego	73	55	25	42
San Francisco	51	44	46	53
San Luis Obispo	85	76	13	22
San Mateo	46	50	51	47
Santa Barbara	68	57	30	41
Santa Clara	49	44	47	53
Santa Cruz	43	66	54	32
Solano	38	49	58	46
Sonoma	70	75	28	23
Ventura	56	57	41	41
All coastal counties	56	44	41	53

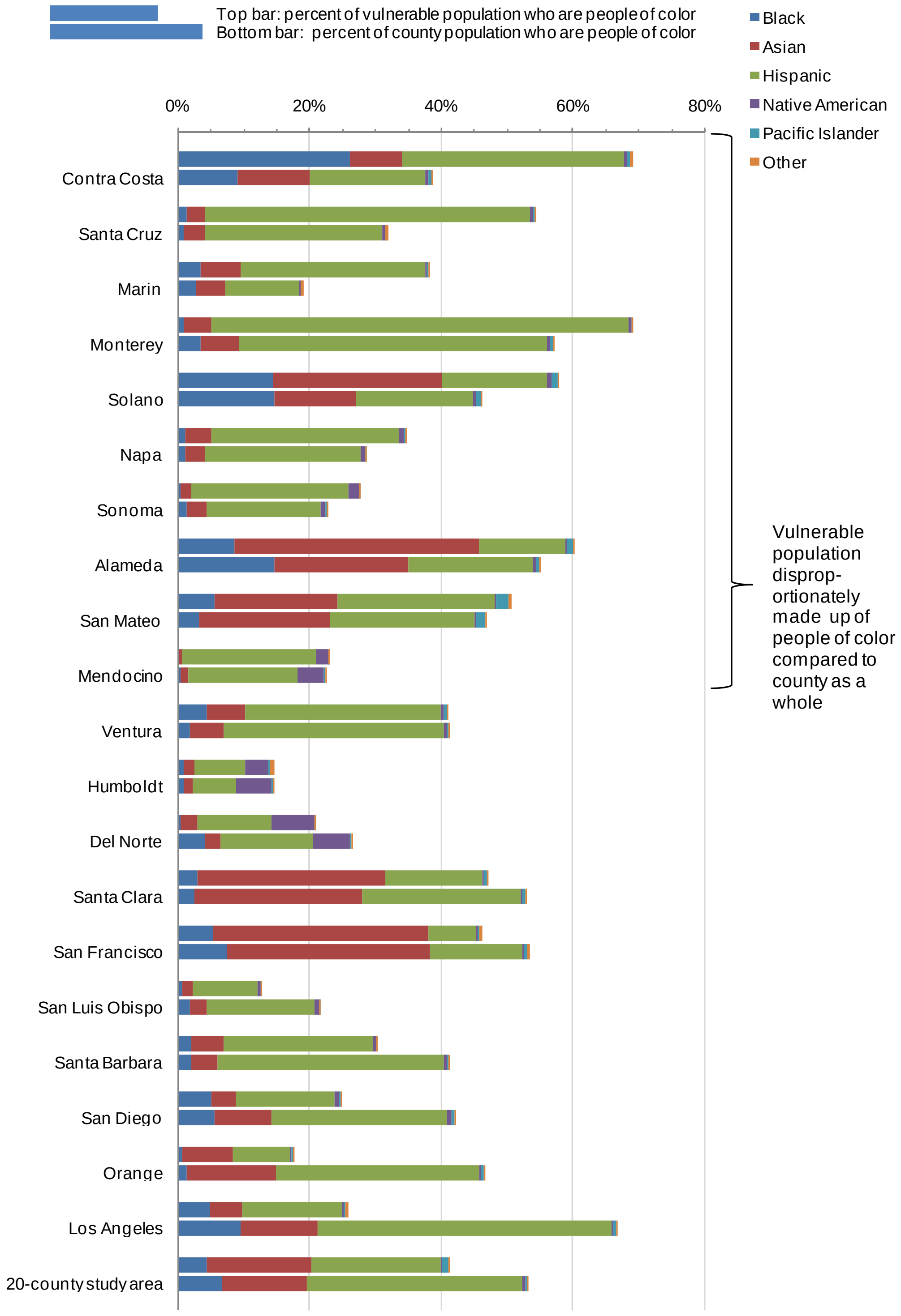


Figure 17. Total county population and population vulnerable to a 100-year flood with a 1.4 meter sea-level rise along the Pacific coast, by race

Note: The lower bar shows the percentage of the county's population that is classified as a person of color, and the top bar shows the percentage of the population at risk of a 100-year flood with a 1.4 m sea-level rise that is classified as a person of color. A county for which the top bar is longer indicates that there is a disproportionate impact on communities of color.

Preconditions

The period preceding a disaster is the key phase for taking action to reduce vulnerabilities and proactively prevent harm. For example, reinforcing residential buildings, obtaining insurance, and storing emergency supplies can reduce injury and loss. Studies show that those who are the most vulnerable are the least likely to adopt these preventive measures. Below, we evaluate key demographic factors affecting vulnerability during the pre-disaster phase, including residential tenure (renter or homeowner), income, and linguistic isolation.

Preventive measures such as reinforcing buildings and buying insurance are adopted at lower rates by people with low income levels (Bolin and Bolton 1986; Blanchard-Boehm 1997). In California, 31% of households earn less than 150% of the federal poverty threshold ($30,000). Low-income households make up 29% of the 20-county study area, slightly less than the statewide total.

An estimated 56,000 households along the Pacific coast, or about 27% of those vulnerable to a 100-year flood with a 1.4 m sea-level rise, earn less than $30,000. Likewise, an estimated 51,000 people along the San Francisco Bay, or about 19% of the affected population, earn less than $30,000 (Table 11). Income demographics vary markedly among the vulnerable populations and counties in this study (Figure 18). Our analysis indicates that there is a disproportionate impact on low-income households in 13 of the 20 coastal counties. These households are less likely than their counterparts to be able to afford emergency preparedness materials, buy insurance policies, and obtain needed building reinforcements.

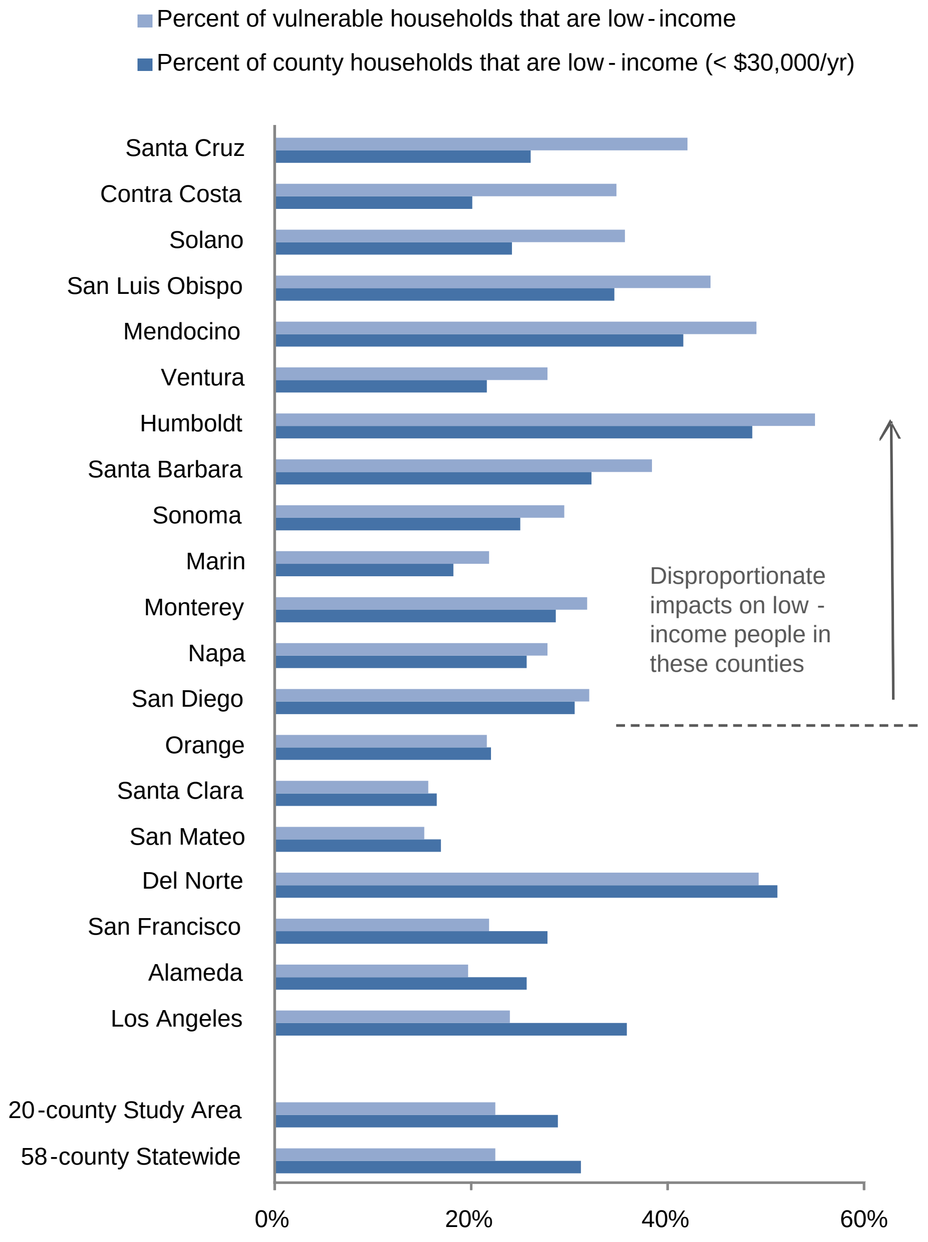


Figure 18. Percentages of low-income households among the population vulnerable to a 100-year flood with a 1.4 m sea-level rise compared with the county total

Note: The lower bar shows the percentage of low-income households in the county, and the top bar shows the percentage of low-income households within the population at risk of a 100-year flood with a 1.4 m sea-level rise. A county for which the top bar is longer indicates that there is a disproportionate impact on low-income households.

Table 11. Key demographics of populations vulnerable to a 100-year flood event with a 1.4 m sea-level rise

	Pacific Coast		**San Francisco Bay**	
	Number in 100-year flood zone	**Percent of total in flood zone**	**Number in 100-year flood zone**	**Percent of total in flood zone**
Households				
Linguistically isolated	4,700	4	9,700	9
With no vehicle	7,600	7	8,200	7
People				
Earn less than 150% the federal poverty threshold ($30,000)	56,000	27	51,000	19
People of color	60,000	29	148,000	55
Who rent (not own) their home	45,000	43	47,000	41

Data source: Census 2000

Renters are also less likely to reinforce buildings and buy insurance because the decision to make major improvements and financial gains typically lies with the property owner. Of those vulnerable to a 100-year flood event with a 1.4 m sea-level rise, about 45,000 people along the Pacific coast and 47,000 people along the San Francisco Bay rent their homes. These households comprise 43% and 41%, respectively, of the homes within the areas at risk.

Language ability is also an important factor in assessing vulnerability (Wang and Yasui 2008). Earthquake preparedness materials following the 1987 Whittier-Narrows earthquake in California, for example, were available only in English, despite other language needs of the victims (Tierney 1993, cited in Pastor et al. 2006). Additionally, emergency response crews may be unable to communicate with non-English speakers. A recent study of 148 emergency preparedness and public health entities found that only 72% provided links on their website to translated materials, and only 14% offered courses for service providers that addressed potential language issues and cultural competence (Andrulis et al. 2008). Among the population at risk from a 100-year flood event with a 1.4 m sea-level rise, 9,700 households along the San Francisco Bay and 4,700 households along the Pacific coast are "linguistically isolated," meaning no one over age 14 speaks English well (Table 11). These 14,000 households are the most likely to need preparedness materials and outreach strategies suitable for non-English speakers of various backgrounds.

Even among those for whom language is not a barrier, cultural factors can influence the effectiveness of preparedness outreach. Numerous studies show that black and Latino communities prefer neighborhood meetings as a way of receiving information about hazards (Blanchard-Boehm 1997; Perry and Mushkatel 1986; Phillips and Ephraim 1992, cited in Pastor et al. 2006). The historic role of African-American churches in providing disaster planning and response provides a unique asset and partner to public efforts in these communities (Trader-Leigh 2008).

The representation of low-income and people of color in the groups with heightened vulnerabilities during the pre-disaster phase are higher than these communities' representation in the overall population. In 2000, 65% of white Californian heads of households were homeowners, while 55% of Asian, 46% of Native American, 44% of Latino, and 39% of black heads of household owned their home (U.S. Census Bureau 2000). Eighty-one percent (81%) of Californians who cannot speak English "well" or "well at all" are people of color, while people of color are 31% of the California population (U.S. Census Bureau 2000). Additionally, people of color tend to earn less than white wage earners. The median household income of black, Latino, and Native households in California was $15,000 less than white and Asian households (Census 2000). These factors raise vulnerability to a disaster and increase the likelihood that communities of color and low-income Californians will share a disproportionate burden of harm.

During a disaster

The ability to remain safe and/or evacuate high-risk areas during a flood event is shaped by factors such as quality of residential structures, access to transportation, availability of emergency supplies, effective service by emergency responders, and exposure to environmental hazards. Key demographics associated with these vulnerabilities are income, possession of a vehicle, race, and proximity to environmental hazards that compound health risk, such as toxic waste facilities.

Low-income communities have been unable to evacuate during disasters like Hurricane Andrew due to lack of financial means to buy supplies or transportation (Morrow and Enarson 1996). In a survey after Hurricane Katrina, 55% of respondents who did not evacuate said one of the main reasons was that they did not have a car or other means of transportation (Brodie et al. 2006). Our study shows that nearly 16,000 households in areas vulnerable to a 100-year flood event with a 1.4 m sea-level rise do not have a vehicle (Table 11). Half of these households are located along the San Francisco Bay and the remaining half along the Pacific coast. These households will be more vulnerable to the adverse effects of sea-level rise due to their increased chance of lacking the transportation means necessary to evacuate.

Race has been an important factor influencing the effectiveness of past emergency response efforts. Perceptions of emergency response workers toward neighborhoods that are predominantly people of color can increase the vulnerability of these communities. In a recent report, the International Federation of Red Cross and Red Crescent Societies (IFRCC) found that "stereotypical views of a specific group can overwhelm the scientific methods employed to prioritize the order of relief works, even if some of those involved are professionally trained, such as disaster managers and relief workers" (Klynman 2007). Along the Pacific coast, we estimate that nearly 59,000 Asian, black, and Latino residents live in areas vulnerable to a 100-year flood event with a 1.4 m sea-level rise. The numbers are even higher along the San Francisco Bay, where an estimated 133,000 Asian, black, and Latino residents live in vulnerable areas. The areas with the highest concentrations of people of color are more likely to be subject to problems with stereotypes that may result in less effective emergency services.

Section 3.1.3, below, describes the number of U.S. EPA-regulated facilities that are at risk of flooding. These facilities contain a range of toxic chemicals that result in increased risk during a flood event due to the possibility that environmental hazards could be released and nearby residents exposed. In California as a whole, the population living within 3 kilometers (1.8 miles) of a commercial hazardous waste facility is disproportionately (81%) people of color compared to communities without such facilities (51% people of color) (Bullard et al. 2007). The same national study concluded that "race continues to be an independent predictor of where hazardous wastes are located, and it is a stronger predictor than income, education, and other socioeconomic indicators" (Bullard et al. 2007). The combination of higher concentrations of environmental hazards and higher rates of demographic characteristics that increase vulnerability has been termed "double jeopardy" by the Institute of Medicine (1999).

This disproportionate representation of people of color living near hazardous waste facilities is coupled with an overrepresentation among households with no vehicle. While black and Latino households comprised 7% and 22% of California's households in 2000, respectively, they comprised 13% and 32% of the households with no vehicle (U.S. Census Bureau 2000), and, as noted above, people of color are also over-represented among low-income Californians. Their higher rates of characteristics associated with vulnerabilities during the time of a disaster raise the possibility that communities of color and low-income people will be disproportionately affected.

Recovery and reconstruction

Following a flood event or other disaster, a range of conditions determines the victims' ability to recover and reconstruct their homes and lives. Important vulnerability factors include the ability to move where opportunities arise, obtain insurance compensation for losses, and receive medical care and public services. The demographic characteristics of income, insurance coverage, legal residency status, and race affect the vulnerability of individuals living in potential flood areas.

White and upper middle-class groups have been found to receive more disaster recovery assistance than black and low-income groups (Bolin and Bolton 1986; Fothergill 2004). For example, following the 1995 flooding of New Orleans, low-income elderly women were one-third as likely than other elderly victims to receive FEMA low-interest loans (Childers 1999). Disaster recovery services have often targeted homeowners to the disadvantage of renters and residents of public housing (Pastor et al. 2006). Reconstruction efforts of the past have inadequately rebuilt housing suitable for low-income families. Four years after the Loma Prieta earthquake, half of the affected multifamily units remained uninhabitable (Comerio et al. 1994). Government agencies explicitly denied housing assistance to those who were homeless before the earthquake (Tierney 2007).

The loss of wealth to homeowners resulting from a disaster is greater for those whose home equity comprises a greater proportion of their wealth. This effect is particularly problematic for black homeowners, whose home equity accounts for 20% more of their wealth than white homeowners (Oliver and Shapiro 1995; Gittleman and Wolff 2000).

Legal residency status influences recovery efforts as well. Undocumented residents fear that participating in recovery assistance programs will put them at risk of deportation (Subervi-Velez et al. 1992; Yelvington 1997). Data on the number of undocumented immigrants are elusive, but the Public Policy Institute of California (2008) estimates that 8% of Californians are undocumented. The number and distribution of undocumented immigrants in areas vulnerable to current and future flood events deserves further study.

Recovery for disaster victims suffering adverse health effects is dependent upon their access to health insurance. The uninsured get about half as much medical care as the insured, are less likely to receive preventive screening and care, and overall have worse health outcomes (Bovbjerg and Hadley 2007). Race is a predictor of rates of health insurance coverage in California: 34% of California Latinos did not have health insurance in 2005, while 22% of Native Californians, 18% of Asians, 15% of black Californians, and 13% of whites were not insured, according to the California Health Interview Survey (Brown et al. 2007).

The correlation of lower income and race, and the over-representation of communities of color among those without legal residency and without health insurance, increases these communities' vulnerability to the harms of sea-level rise even in the period following a disaster. The history of disparate treatment of people of color in recovery assistance services suggests another level of increased vulnerability.

Summary of Environmental Justice Concerns

The adverse impacts of sea-level rise on Californians will depend upon the population's vulnerabilities, which are heightened for certain demographic groups. Race and income cut across many of the key vulnerabilities, with low-income and communities of color overly represented in the most vulnerable segments of the population. Additionally, adapting to sea-level rise will require tremendous financial investment. Given the high cost and the likelihood that we will not protect everything, adaptation raises additional environmental justice concerns. Specifically, what we choose to protect and how we pay for it may have a disproportionate impact on low-income neighborhoods and communities of color. Decisions about how to use public funds can lead to inequitable distribution of costs and benefits, whether they are based on economics (protect the most valuable assets) or utility (protect the largest number of people). We urge, therefore, that policy makers planning responses to sea-level rise understand and address environmental justice concerns carefully and proactively.

3.1.2. Emergency and Healthcare Facilities at Risk

Table 12 shows the schools and emergency and healthcare facilities along the Pacific coast that are currently at risk from a 100-year flood event and that will be at risk with a 1.4 m sea-level rise. Numerous schools are vulnerable to flooding along the Pacific coast. In 2000, 30 schools were vulnerable to a 100-year flood event. With a 1.4 m sea-level rise, however, the number of schools at risk nearly doubles, rising to 56 schools. Emergency and healthcare facilities are also at risk.

Table 12. Schools and emergency and healthcare facilities along the Pacific coast that are at risk from a 100-year flood event in 2000 and with a 1.4 m sea-level rise

Facility	Current risk	Risk with 1.4 m sea-level rise
Schools	30	56
Healthcare facilities	5	13
Fire stations and training facilities	2	6
Police stations	4	8

Note: Healthcare facilities include clinics, long-term care facilities, hospitals, and home health agencies/hospices. Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

Table 13 shows the schools and emergency and healthcare facilities along San Francisco Bay that are currently at risk of a 100-year flood event and that will be at risk with a 0.5, 1.0, and 1.4 m sea-level rise. The risk for each of these facilities is greater than along the remainder of the Pacific coast. Schools in particular are at significant risk. In 2000, 35 schools were at risk of a 100-year flood event. With a 1.4 m sea-level rise, the number of schools at risk more than doubles, to 81. Significant numbers of healthcare facilities are also at risk. In 2000, there were 15 healthcare facilities at risk of a 100-year flood. With a 1.4 m sea-level rise, however, the number of healthcare facilities at risk rises to 42.

Table 13. Schools and emergency and healthcare facilities along San Francisco Bay that are at risk of a 100-year flood event in 2000 and with a 0.5 m, 1.0 m, and 1.4 m sea-level rise.

Facility	Current risk	Risk with sea-level rise		
		0.5 m	1.0 m	1.4 m
Schools	35	41	60	81
Healthcare facilities	15	19	29	42
Fire stations and training facilities	6	7	10	11
Police stations	5	6	8	9

Note: Healthcare facilities include clinics, long-term care facilities, hospitals, and home health agencies/hospices. Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

3.1.3. Hazardous Materials Sites

The presence of land or facilities containing hazardous materials in areas at risk of inundation increases the risk of exposure to toxic chemicals for nearby residents and ecosystems. For example, sediment samples in New Orleans taken one month after Hurricane Katrina found excess levels of arsenic, lead, and the gasoline constituent benzene, all considered toxic pollutants by the U.S. EPA (Adams et al. 2007). Those living or working near these facilities may be affected by the potential release and spreading of contamination through floodwaters or through flood-related facility malfunctions.

We evaluated sites containing hazardous materials at risk of flooding along the Pacific coast and the San Francisco Bay. Here, we report on a range of sites monitored by the U.S. EPA, including Superfund sites; hazardous waste generators; facilities required to report emissions for the Toxics Release Inventory; facilities regulated under the National Pollutant Discharge Elimination System (NPDES); major dischargers of air pollutants with Title V permits; and brownfield properties. An estimated 130 U.S. EPA-regulated sites are currently vulnerable to a 100-year flood event (Table 14). Nearly 60% of these facilities are located in San Mateo and Santa Clara counties. Sea-level rise will put additional facilities, people, and the environment at risk. The number of facilities at risk increases by 250% with a 1.4 sea-level rise, with more than 330 facilities at risk of a 100-year flood event. San Mateo, Alameda, and Santa Clara counties have the highest numbers of U.S. EPA-regulated sites within future flood areas.

Table 14. U.S. EPA-regulated sites within areas vulnerable to 100-year flood event in 2000 and with a 1.4 m sea-level rise

County	Sites currently at risk	Risk with 1.4 m sea-level rise
Alameda	6	63
Contra Costa	4	22
Del Norte	1	3
Humboldt	10	13
Los Angeles	13	26
Marin	1	6
Monterey	1	1
Napa	1	2
Orange	4	16
San Diego	-	13
San Francisco	-	4
San Luis Obispo	-	1
San Mateo	39	78
Santa Barbara	1	5
Santa Clara	41	53
Santa Cruz	5	6
Solano	2	5
Sonoma	-	2
Ventura	5	13
Total	**134**	**332**

Data Source: EPA Geospatial Data Access Project 2008
Note: Table combines risk for those counties along the San Francisco Bay and Pacific coast.

3.1.4. *Infrastructure at Risk*

Roads and Railways

Roads and railways are vulnerable to flooding due to a 100-year flood today and with sea-level rise (Tables 15, 16, and 17). In 2000, 300 miles of roads and highways and 70 miles of railways along the Pacific coast were at risk of flooding. With a 1.4 m sea-level rise, an estimated 530 miles of roads and highways and 110 miles of railways are at risk from a 100-year flood event (Figures 19 and 20).

Table 15. Miles of roads and railways vulnerable to a 100-year flood in 2000 and with a 1.4 m sea-level rise along the Pacific coast, by county and type

	Highways (miles)		Roads (miles)		Railways (miles)	
County	**Current risk**	**Risk with 1.4 m sea-level rise**	**Current risk**	**Risk with 1.4 m sea-level rise**	**Current Risk**	**Risk with 1.4 m sea-level rise**
Del Norte	6.6	8.2	59	80	-	-
Humboldt	37	58	120	190	21	28
Los Angeles	14	31	42	140	5.6	14
Marin	1.2	4.1	22	27	-	-
Mendocino	5.6	7.9	28	41	2.7	4.0
Monterey	27	31	85	110	19	23
Orange	32	48	340	490	5.3	6.6
San Diego	0.62	8.0	12	57	3.0	9.8
San Francisco	0.20	0.37	17	22	-	-
San Luis Obispo	5.3	7.4	10	21	0.019	0.31
San Mateo	3.4	5.0	23	30	-	-
Santa Barbara	1.5	8.0	9.1	25	3.4	7.0
Santa Cruz	9.4	11	52	67	4.2	5.5
Sonoma	4.5	5.9	14	20	-	-
Ventura	2.4	11	69	150	3.7	10
Total	150	250	910	1,500	68	110

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Risks to transportation-related infrastructure are substantially higher along San Francisco Bay (Tables 16 and 17). In 2000, nearly 800 miles of roads and highways and 78 miles of railways were at risk of flooding from a 100-year event. Much of this infrastructure is protected by levees, seawalls, and other structures. Projected sea-level rise estimates increase this risk markedly. Even a relatively modest increase in sea levels of 0.5 m puts 1,130 miles of roads and highways and 94 miles of railways at risk. The projected 1.4 m rise in sea level more than doubles the roads and railways at risk of flooding, placing 1,800 miles of roads and highways and 173 miles of railways at risk of flooding from a 100-year event.

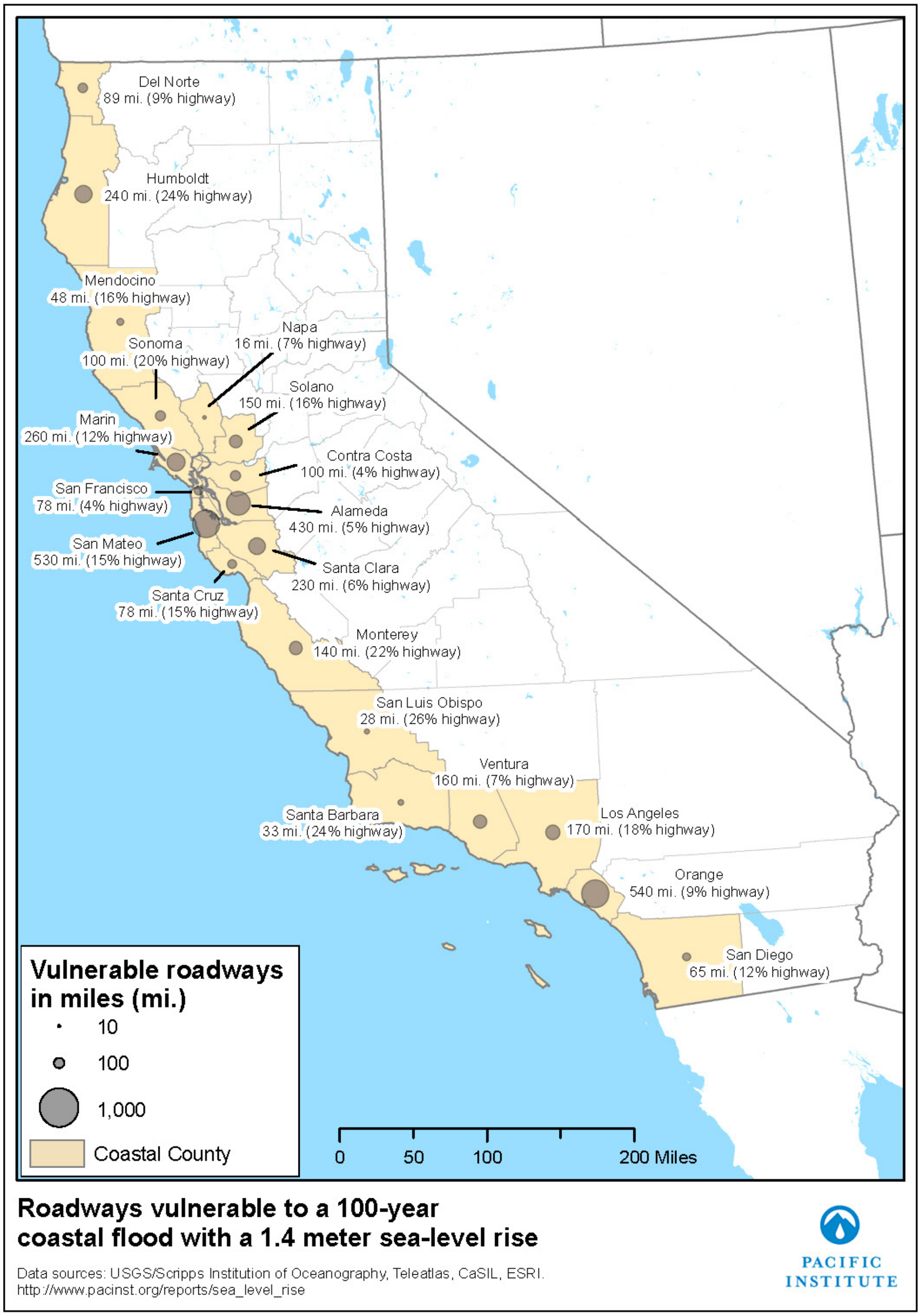


Figure 19. Roadways vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

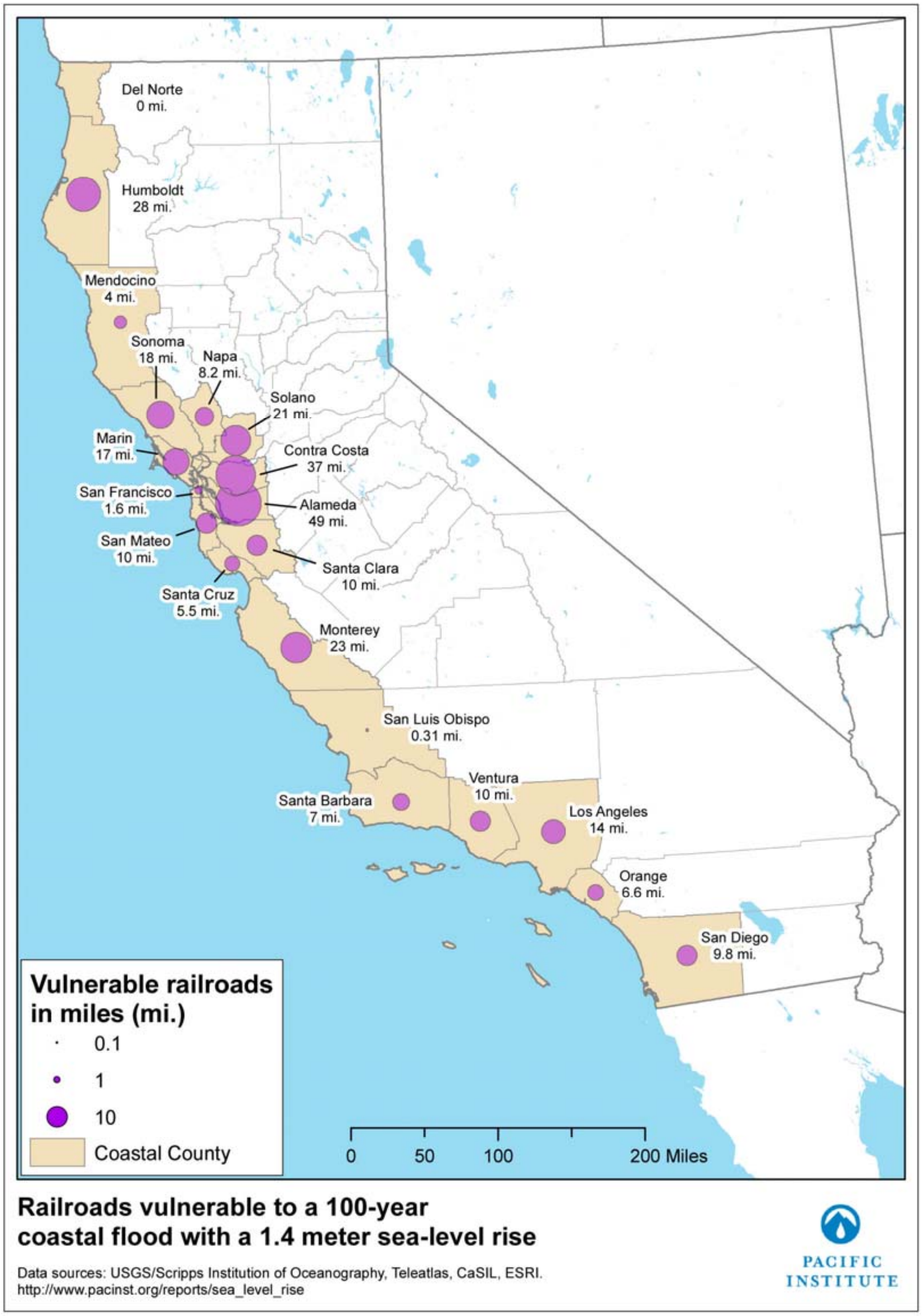


Figure 20. Railroads vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

Table 16. Miles of roads vulnerable to a 100-year flood along San Francisco Bay, by county and type

County	Current Risk		Risk with sea-level rise					
			0.5 m		1.0 m		1.4 m	
	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)
Alameda	1.1	76	4.8	160	14	280	23	410
Contra Costa	2.4	20	2.7	42	3.4	67	4.5	96
Marin	16	110	20	150	24	180	28	200
Napa	0.70	7.0	0.70	9.0	0.80	11	1.2	15
San Francisco	0.30	3.4	0.60	11	1.5	29	3.1	53
San Mateo	27	300	49	360	66	390	72	420
Santa Clara	9.4	110	12	150	14	180	15	220
Solano	5.7	53	14	78	19	100	23	120
Sonoma	11	53	12	57	13	59	14	61
Total	**72**	**730**	**120**	**1,000**	**160**	**1,300**	**180**	**1,600**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Table 17. Miles of railways vulnerable to a 100-year flood along San Francisco Bay, by county

County	Current risk	Risk with sea-level rise			Percent increase (with 1.4 m rise)
		0.5 m	1.0 m	1.4 m	
Alameda	9.1	17	35	49	81
Contra Costa	10	17	25	37	73
Marin	12	15	16	17	29
Napa	6.0	7.0	7.9	8.2	27
San Francisco	0.26	0.56	0.91	1.6	84
San Mateo	3.7	5.2	7.8	10	65
Santa Clara	5.9	7.2	8.9	10	43
Solano	9.3	12	17	21	56
Sonoma	11	14	17	18	39
Total	**68**	**94**	**140**	**170**	**61**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

We do not attempt to quantify the cost of flooding on roads and railways. In some cases, damages may be minor, resulting in temporary closures and modest repairs. As the frequency and intensity of flooding increases, however, closures may become longer and the cost of repair may rise. Eventually, roads and railways may need to be raised or rerouted. The cost of repairing, moving, or raising roads and railways is highly site-specific and dependent on the level of damage that is sustained.

Furthermore, flooding and closure of roads and railways can have significant impacts on the local, state, and national economy. Railways are particularly important for the conveyance of goods shipped to and from California ports. In addition, road closures can prevent people from getting to work, causing major economic disruptions. Additional research is needed to improve our understanding of specific transportation risks.

Power Plants

Figures 21, 22, and 23 show California's coastal power plants vulnerable to a 100-year flood event with a 1.4 m sea-level rise. In some cases, actual power generating infrastructure is at risk; in others, intake or other peripheral structures are vulnerable. Specific site assessments are needed for each coastal plant. In total, around 30 coastal power plants, with a combined capacity of more than 10,000 megawatts (MW), are at risk from a 100-year flood with a 1.4 m sea-level rise. The capacities of the vulnerable power plants range from a relatively small 0.2 MW plant to one that is more than 2,000 MW. The majority of vulnerable plants are located in Southern California and along the San Francisco Bay.

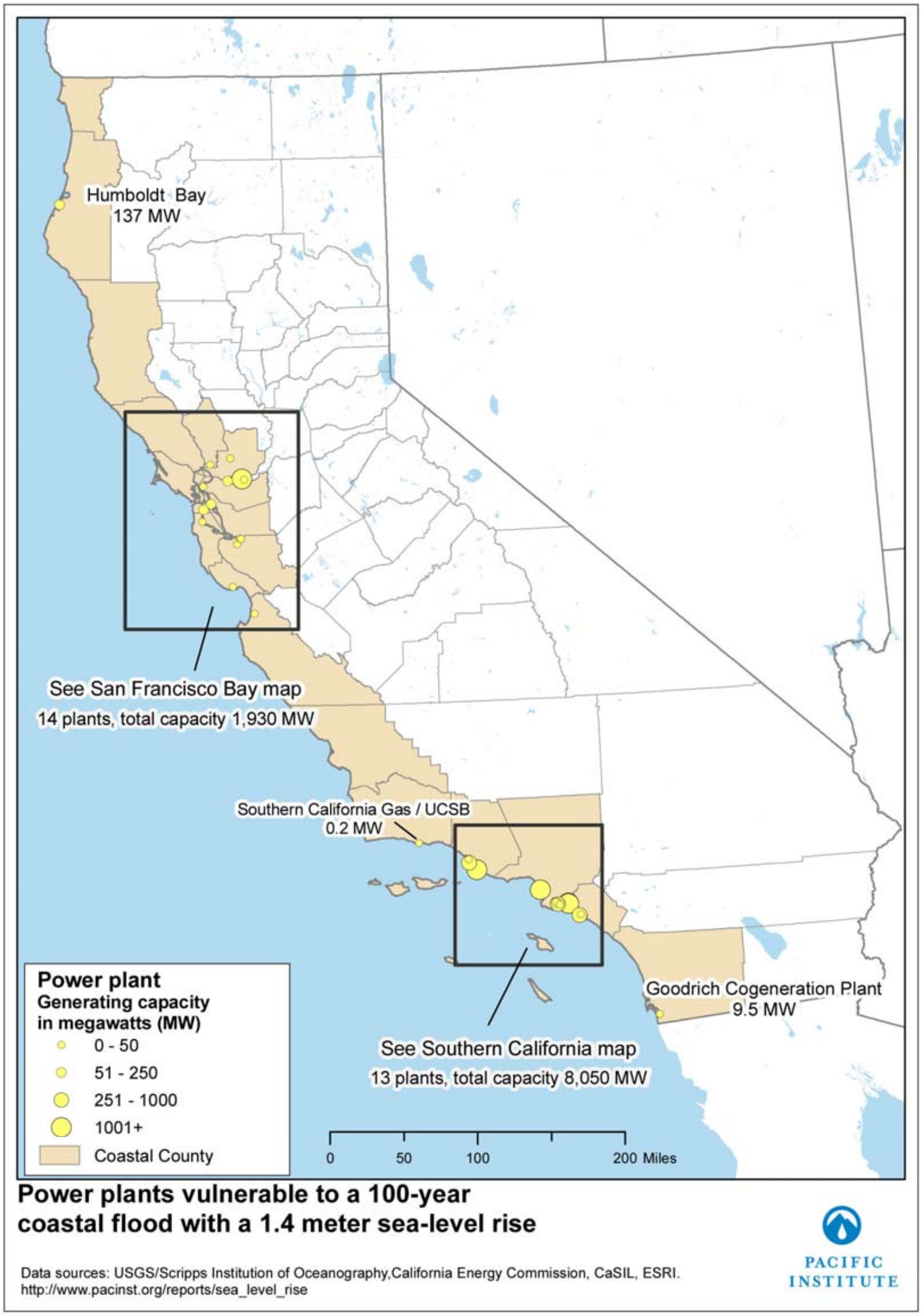


Figure 21. Power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

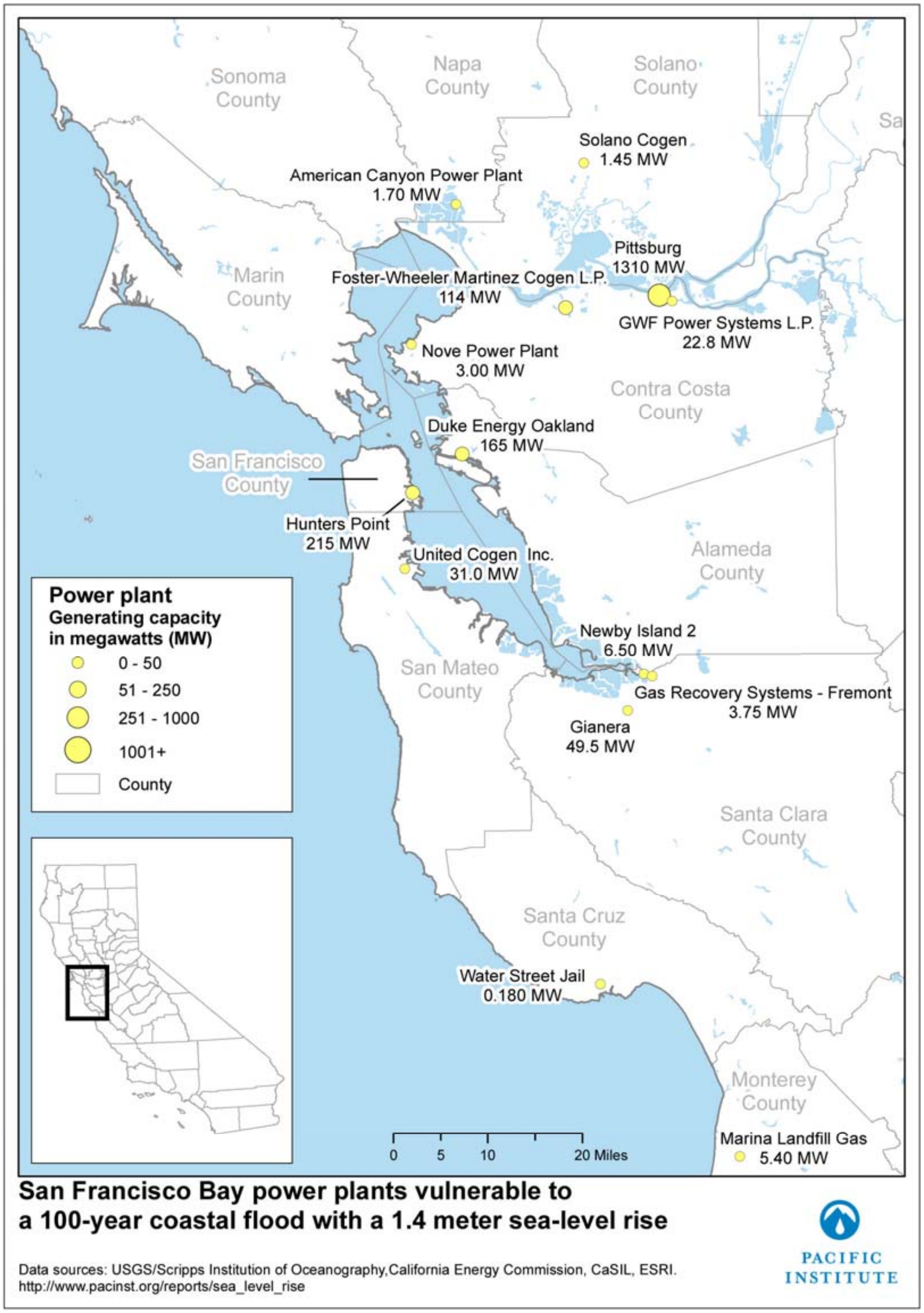
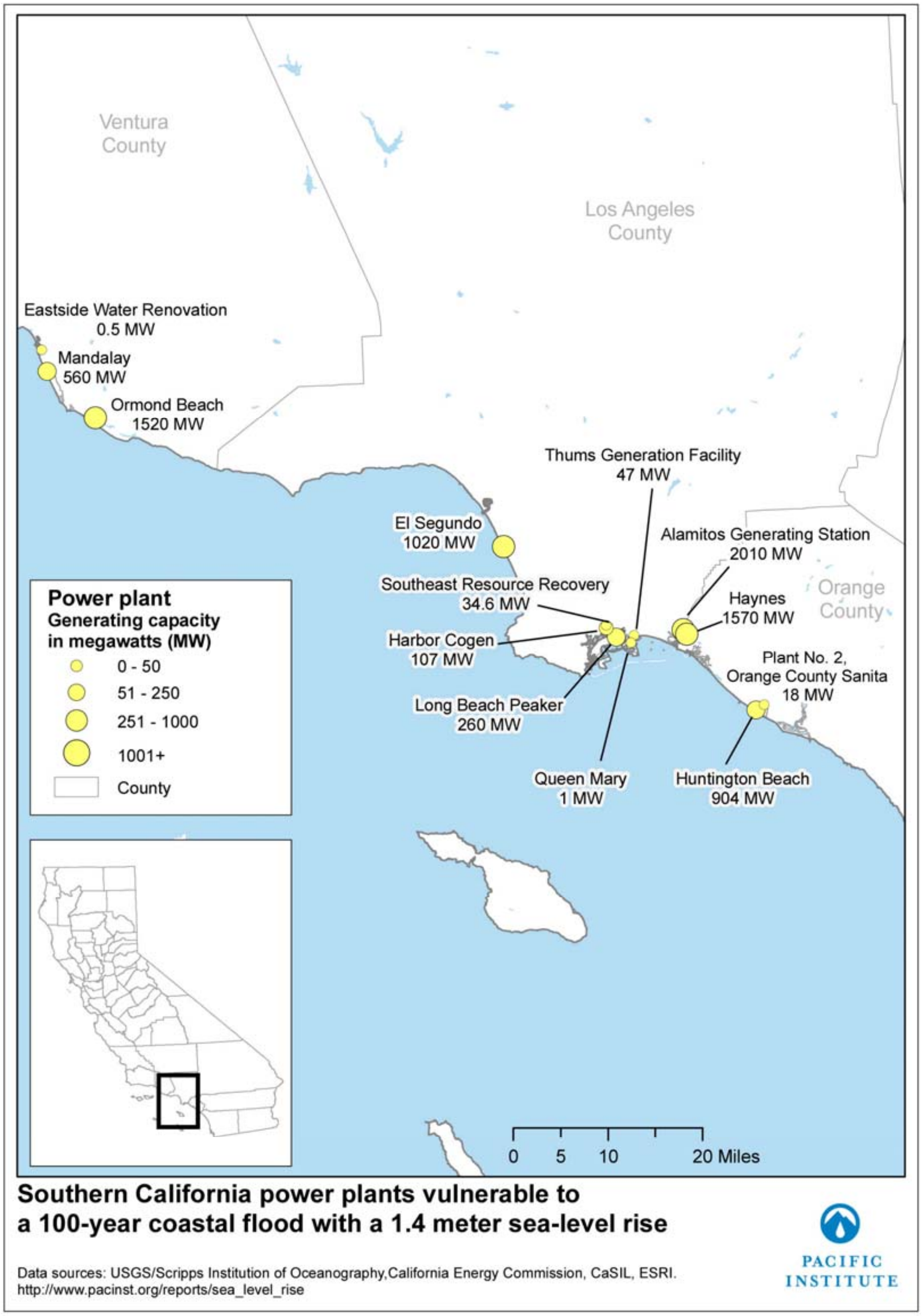


Figure 22. San Francisco Bay power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise



Southern California power plants vulnerable to a 100-year coastal flood with a 1.4 meter sea-level rise

Data sources: USGS/Scripps Institution of Oceanography,California Energy Commission, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 23. Southern California power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

Wastewater Treatment Plants

Figures 24 and 25 show the wastewater treatment plants vulnerable to a 100-year flood event with a 1.4 m sea-level rise. We identified a total of 29 vulnerable wastewater treatment plants: 22 on the San Francisco Bay and 7 on the Pacific coast. The combined capacity of these plants is 530 million gallons per day (MGD). Inundation from floods could damage pumps and other equipment, and lead to untreated sewage discharges. Besides the flood risk to plants, higher water levels could interfere with discharge from outfalls sited on the coast. Cities and sanitation districts should begin to assess how higher water levels will affect plant operations and plan for future conditions.

Ports

Goods movement in California, and especially the San Francisco Bay Area, is critically important to the state's economy. A recent report by the Metropolitan Transportation Commission stated that "over 37 percent of Bay Area economic output is in manufacturing, freight transportation, and warehouse and distribution businesses. Collectively, these goods-movement-dependent businesses spend approximately $6.6 billion on transportation services. The businesses providing these services also play a critical role as generators of jobs and economic activity in their own right" (MTC 2004).

Our assessment of future flood risk with sea-level rise show significant flooding is possible at California's major ports in Oakland, Los Angeles, and Long Beach. These ports are central to the economy of California, the nation, and the world. The Port of Los Angeles-Long Beach, for example, handles 45%–50% of the containers shipped into the United States. Of these containers, 77% leave the state; half by train and half by truck (Christensen 2008). Many port managers have already experienced how disasters can affect their operations. Following the Loma Prieta earthquake in 1989, for example, the Port of Oakland sustained damages that interrupted business for 18 months. These disruptions have economic implications for the nation and the world, as evident by a 2002 contract dispute that resulted in a work slowdown at west coast ports and cost the U.S. economy an estimated $1billion to $2 billion per day. Others speculated that Japan and China would lose several percentage points off their gross domestic product if the ports closed for longer than a week (Farris 2008).

In addition to directly affecting port operations, sea-level rise may cause other interruptions to goods movement at ports. Sea-level rise can reduce bridge clearance, thereby reducing the size of ships able to pass or restricting their movements to times of low tide. Higher seas may cause ships to sit higher in the water, possibly resulting in less efficient port operations (National Research Council 1987). These impacts are highly site specific, and somewhat speculative, requiring detailed local study. We also note the connection between possible direct impacts of sea-level rise on the ports themselves and possible flooding of transportation (rail and road) corridors to and from the ports.

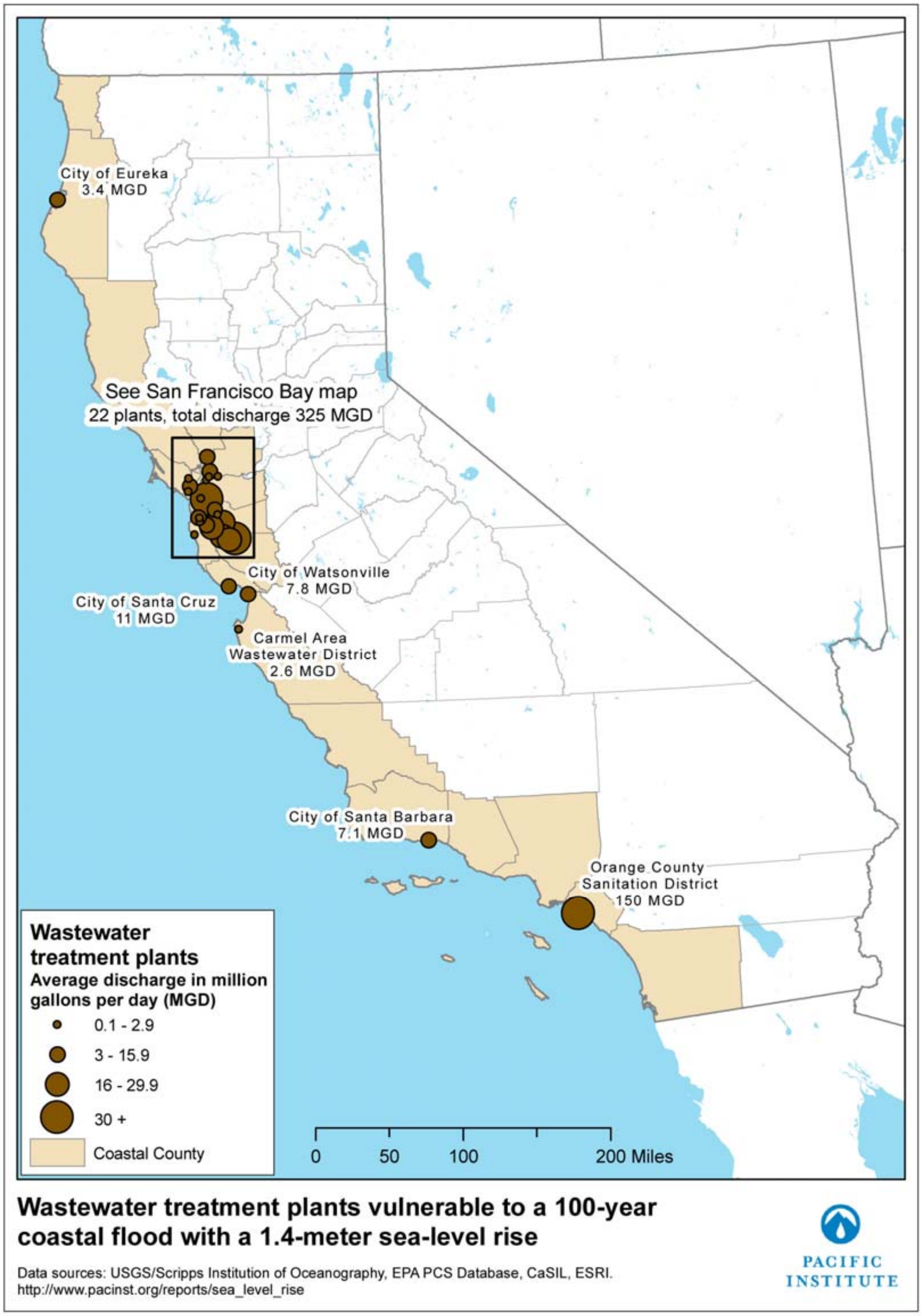
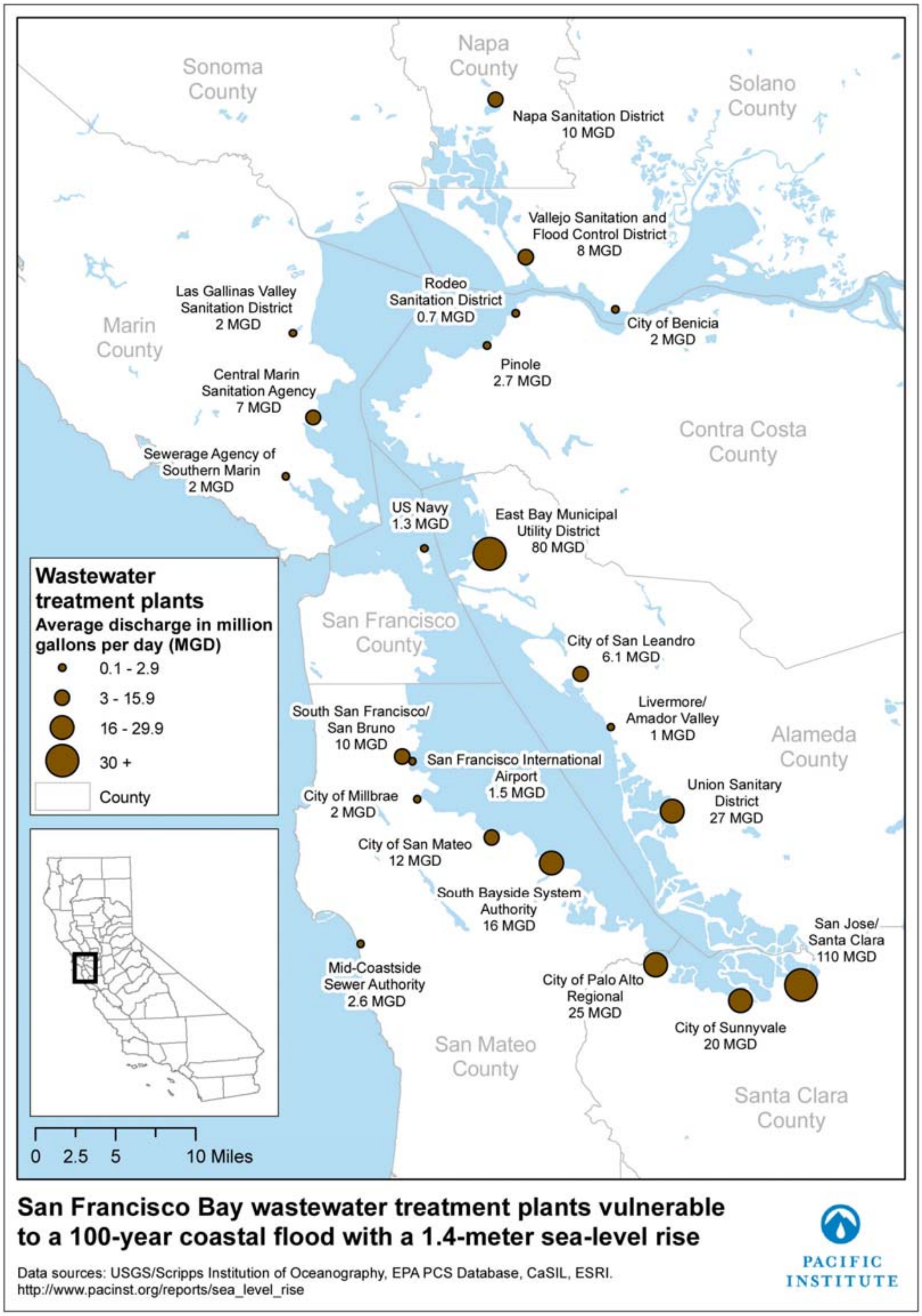


Figure 24. Wastewater treatment plants on the Pacific coast vulnerable to a 100-year flood with a 1.4 m sea-level rise



San Francisco Bay wastewater treatment plants vulnerable to a 100-year coastal flood with a 1.4-meter sea-level rise

Data sources: USGS/Scripps Institution of Oceanography, EPA PCS Database, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 25. Wastewater treatment plants on the San Francisco Bay vulnerable to a 100-year flood with a 1.4 m sea-level rise

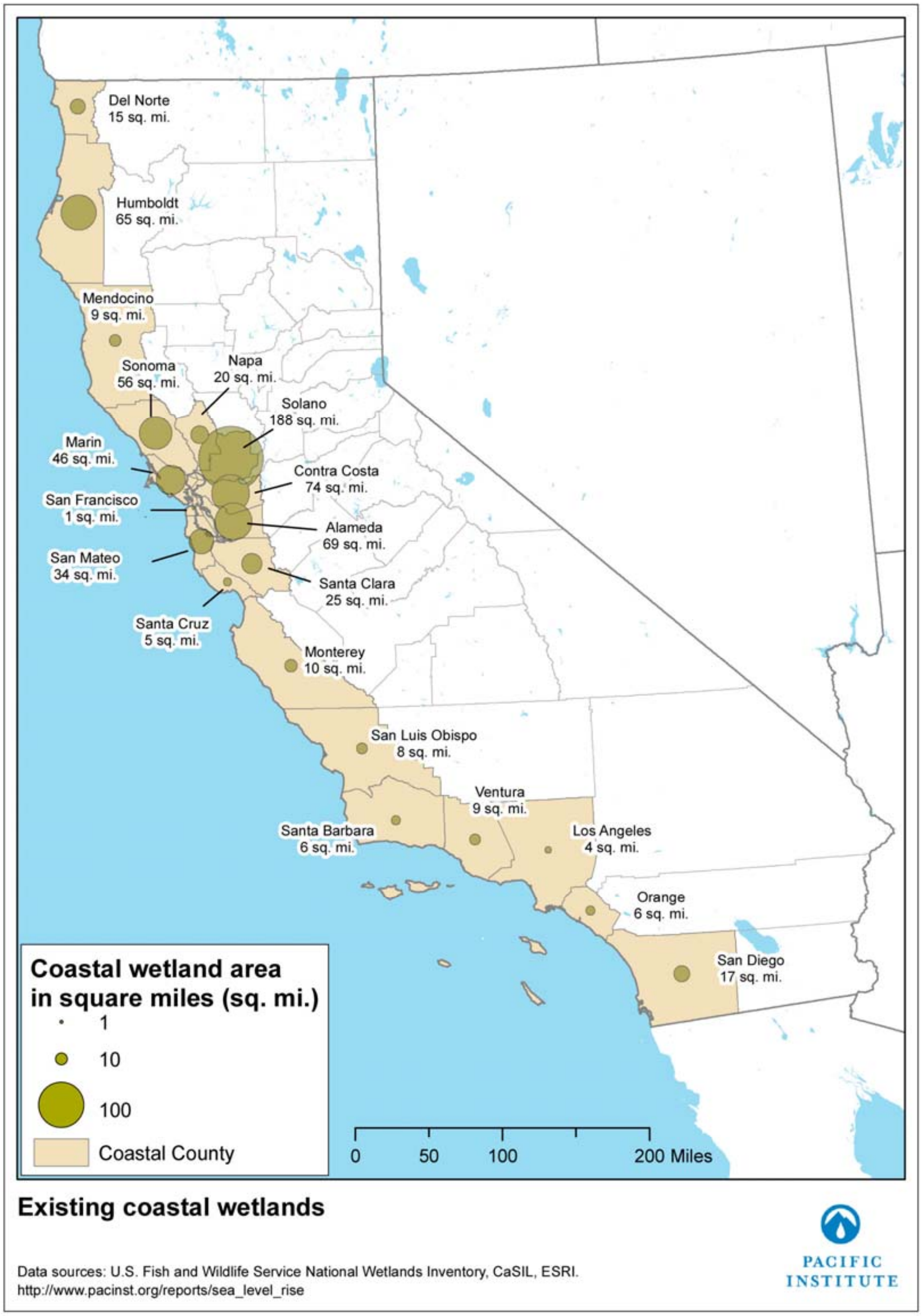
Airports

The San Francisco and Oakland airports are vulnerable to flooding with a 1.4-meter sea level rise. Other major airports near the coast, such as the San Diego, San Jose, and Los Angeles airports, were not identified as vulnerable in our analysis.

The economic impact of a disruption in airport traffic in San Francisco and Oakland is potentially large, and it would have significant effects on the state and regional economy. In 2007, the Oakland International airport transported 15 million passengers and 647,000 metric tons of freight. Activity at the San Francisco International airport is even greater than in Oakland. The San Francisco International Airport is the nation's thirteenth busiest airport, transporting 36 million people in 2007 (Airports Council International 2007). It also plays a significant role in the movement of goods regionally and internationally. In 2007, the San Francisco airport handled 560,000 metric tons of freight. San Francisco Airport ranked twelfth among foreign trade freight gateways by value of shipments in 2005, handling $25 billion in exports and $32 billion in imports (Bureau of Trade Statistics 2006), more than double that of the $23.7 billion handled by vessels at the Port of Oakland.

3.1.5. Wetlands

Today, there are approximately 430,000 acres, or 670 square miles, of coastal wetlands in California (Figure 26). Based on an approximated wetland value of $5,000 to $200,000 per acre, we estimate that California's coastal wetlands are worth from $2.2 billion to $86 billion. Large wetland areas are found in almost every county on the California coast (Table 18). The vast majority of coastal wetlands are in San Francisco Bay and the Sacramento-San Joaquin Delta.



Existing coastal wetlands

Data sources: U.S. Fish and Wildlife Service National Wetlands Inventory, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 26. Existing coastal wetlands

There are also significant and important coastal wetlands in Northern California, especially in and around Humboldt and Eureka. Much of the Central California coast, from the Lost Coast in Mendocino County to Big Sur in Monterey, San Luis Obispo, and Santa Barbara counties, is dominated by rugged hills and cliffs plunging into the sea. In these areas, there are very few coastal wetlands. There are critically important wetlands that may be of small size, but that serve vital ecological functions—we understand that size is not the only measure of wetland value. We note that adequate wetland delineation has not been performed on vast areas of California and the actual wetland area may be larger.

Table 18. Existing California coastal wetland area by county

County	Area (acres)	Area (square miles)	Percent of state total
Alameda	44,000	69	10
Contra Costa	47,000	73	11
Del Norte	9,300	15	2.2
Humboldt	42,000	66	10
Los Angeles	2,400	3.8	0.6
Marin	29,000	45	6.8
Mendocino	6,000	9.4	1.4
Monterey	6,600	10	1.6
Napa	13,000	20	3.0
Orange	3,800	5.9	0.9
San Diego	11,000	17	2.6
San Francisco	770	1.2	0.2
San Luis Obispo	5,300	8.3	1.2
San Mateo	22,000	34	5.1
Santa Barbara	4,000	6.3	0.9
Santa Clara	16,000	25	3.7
Santa Cruz	3,400	5.3	0.8
Solano	120,000	190	28
Sonoma	36,000	56	8.4
Ventura	5,700	8.9	1.3
Total	**430,000**	**670**	**100**

Note: Numbers may not add up due to rounding.

Evaluating the impacts of sea-level rise on a particular coastal wetland area requires site-specific data on various physical and biological factors. A simple method to estimate wetland loss is to compare wetland elevations to future tide elevations. Data limitations, however, prevent us from performing even this simple analysis, i.e., there are no data in the critical area where the boundary must be drawn. Given these data limitations, we evaluated the land cover *adjacent* to existing wetlands and the potential for these areas to support suitable wetland habitat. We note that this simplified analysis does not take into account erosion or accretion due to sediment movement, which is difficult to predict with any accuracy.

We estimate that a sea-level rise of 1.4 m provides approximately 150 square miles of potential wetland migration area. Of this amount, 83 square miles, or 55%, would make viable wetland habitat (Table 19). These areas should be protected to ensure their viability as wetland habitat is maintained. Twenty-three square miles, or 15%, is land that is viable for wetland migration but at some loss of value, including parks, orchards, and agricultural land. The remaining 30% of the available accommodation space is unsuitable for wetland migration.

Table 19. Wetland migration frontier area classified by land cover type and conversion potential

Land cover type	Total frontier area (square miles)
Not viable for wetland migration	
High Intensity Developed	12
Medium Intensity Developed	12
Low Intensity Developed	21
Subtotal	**45**
Viable for wetland migration, but will cause property loss	
Developed Open Space	4.7
Pasture/Hay	11
Cultivated	7.0
Subtotal	**23**
Viable for wetland migration	
Evergreen Forest	0.28
Deciduous Forest	0.040
Mixed Forest	0.27
Scrub/Shrub	1.3
Grassland	16
Bare Land	0.89
Palustrine Scrub/Shrub Wetland	0.85
Palustrine Forested Wetland	0.47
Palustrine Emergent Wetland	4.7
Estuarine Scrub/Shrub Wetland	42
Estuarine Forested Wetland	2.4
Estuarine Emergent Wetland	0.11
Estuarine Aquatic Bed	0.046
Unconsolidated Shore	4.0
Water	10
Subtotal	**83**
Total	**150**

Figures 27, 28, 29, and 30 and Table 20 summarize the potential wetland migration area by county. Solano County has the largest wetland migration area, totaling 22 miles, and 85% of that area is currently viable wetland habitat. Of the potential 20 miles of wetland migration area in Humboldt County, only 39% is viable wetland habitat, although an additional 54% is viable but with some economic loss. San Francisco and Los Angeles Counties have only small potential wetland migration areas, in part because there are few wetlands in these counties. Unfortunately, those that do exist are at high risk because 70% and 60% of the potential wetland migration area in San Francisco and Los Angeles Counties, respectively, is not viable wetland habitat.

Table 20. Land area available for wetland migration, by county, in square miles, with percent of county total in italics

County	Wetland migration viable		Migration viable with loss of value		Migration not viable		Total	Percent of State Total
Alameda	8.5	*49%*	0.94	*5%*	8.1	*46%*	17	10%
Contra Costa	8.1	*72%*	0.68	*6%*	2.5	*22%*	11	6.7%
Del Norte	2.1	*81%*	0.39	*15%*	0.13	*5%*	2.6	1.6%
Humboldt	7.7	*39%*	11	*54%*	1.2	*6%*	20	12%
Los Angeles*	0.10	*35%*	0.012	*4%*	0.17	*60%*	0.28	0.17%
Marin	5.7	*54%*	0.29	*3%*	4.7	*44%*	11	6.3%
Mendocino	1.3	*93%*	0.035	*2%*	0.059	*4%*	1.4	0.8%
Monterey	4.1	*56%*	2.6	*36%*	0.60	*8%*	7.3	4.3%
Napa	2.9	*80%*	0.24	*6%*	0.51	*14%*	3.7	2.2%
Orange*	0.72	*22%*	0.20	*6%*	2.4	*72%*	3.3	2.0%
San Diego	3.7	*64%*	0.33	*6%*	1.7	*30%*	5.8	3.4%
San Francisco	0.20	*18%*	0.15	*13%*	0.80	*70%*	1.1	0.7%
San Luis Obispo	0.78	*69%*	0.081	*7%*	0.27	*24%*	1.1	0.7%
San Mateo	2.9	*20%*	0.54	*4%*	11	*76%*	15	8.7%
Santa Barbara*	0.87	*86%*	0.023	*2%*	0.12	*12%*	1.0	0.6%
Santa Clara	2.2	*29%*	0.81	*11%*	4.6	*60%*	7.6	4.5%
Santa Cruz	0.98	*40%*	1.1	*43%*	0.42	*17%*	2.5	1.5%
Solano	19	*85%*	0.87	*4%*	2.5	*11%*	22	13%
Sonoma	7.6	*87%*	0.53	*6%*	0.59	*7%*	8.8	5.2%
Ventura	**3.4**	*45%*	2.2	*29%*	2.0	*26%*	7.6	4.5%
Total	**83**	***55%***	**23**	***15%***	**45**	***30%***	**150**	**100%**

*Given data limitations, we mapped about 49% of Santa Barbara County, 23% of Los Angeles County, and 65% of Orange County. The coverage was 100% in the other 11 counties on the Pacific coast.

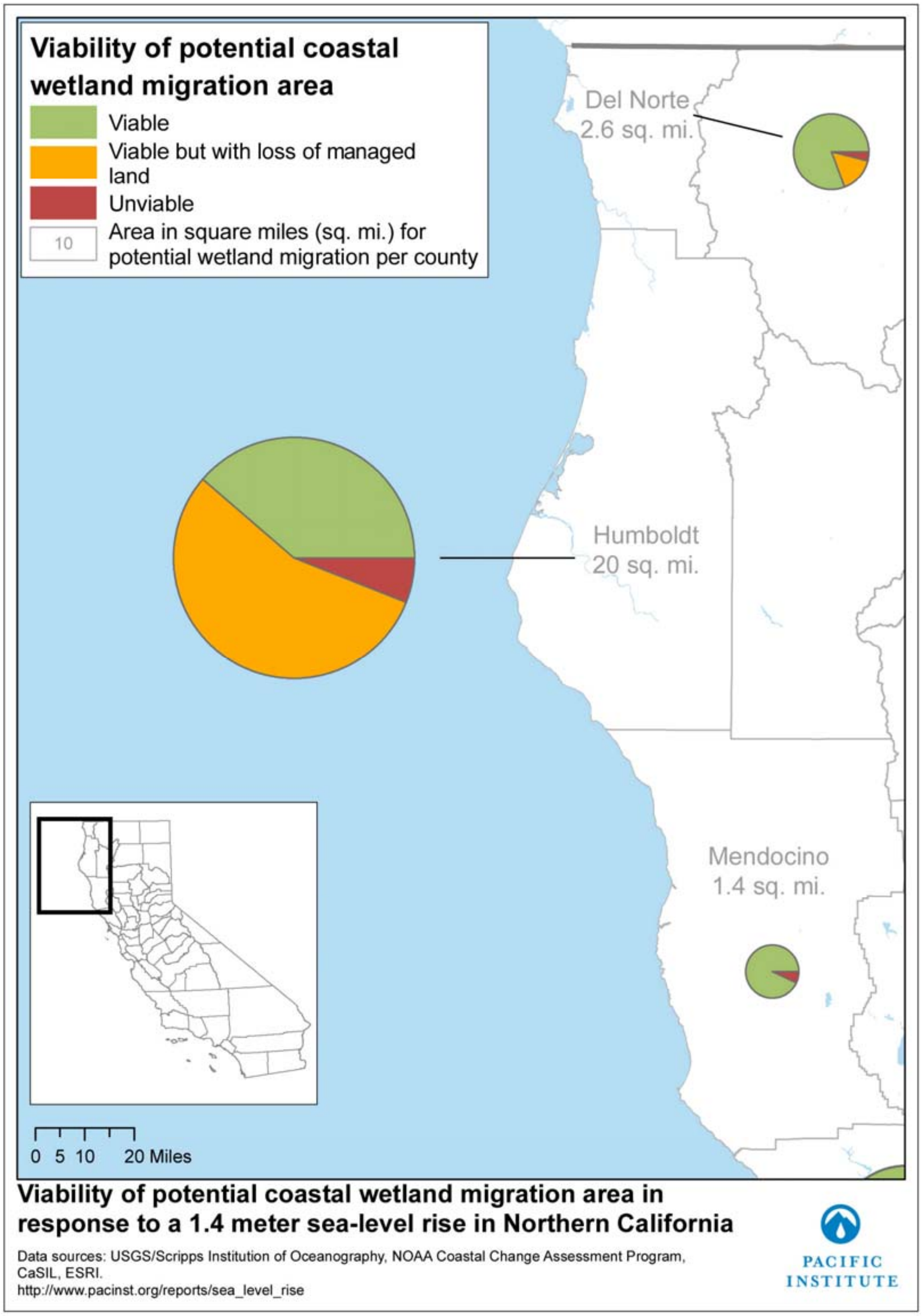
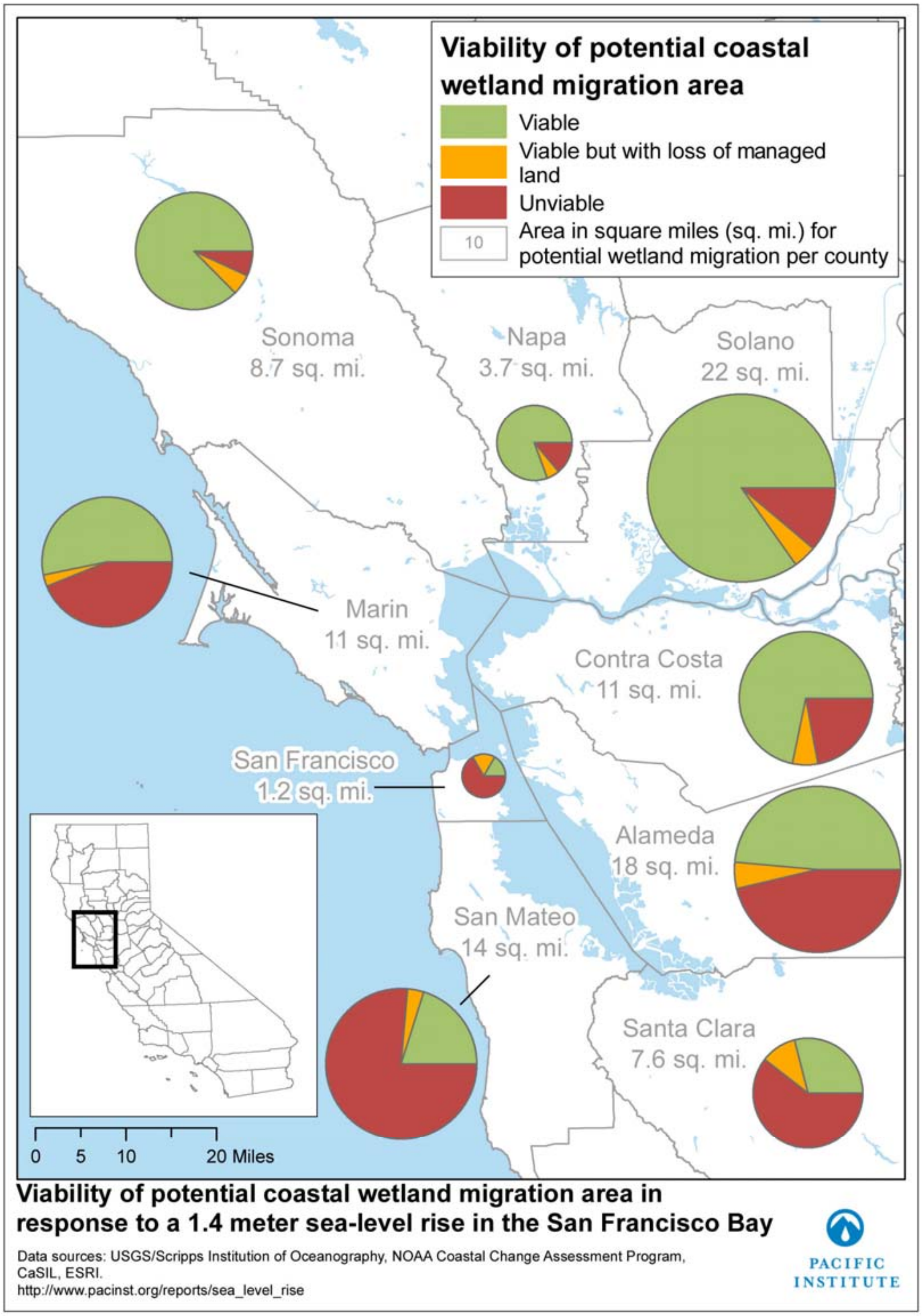


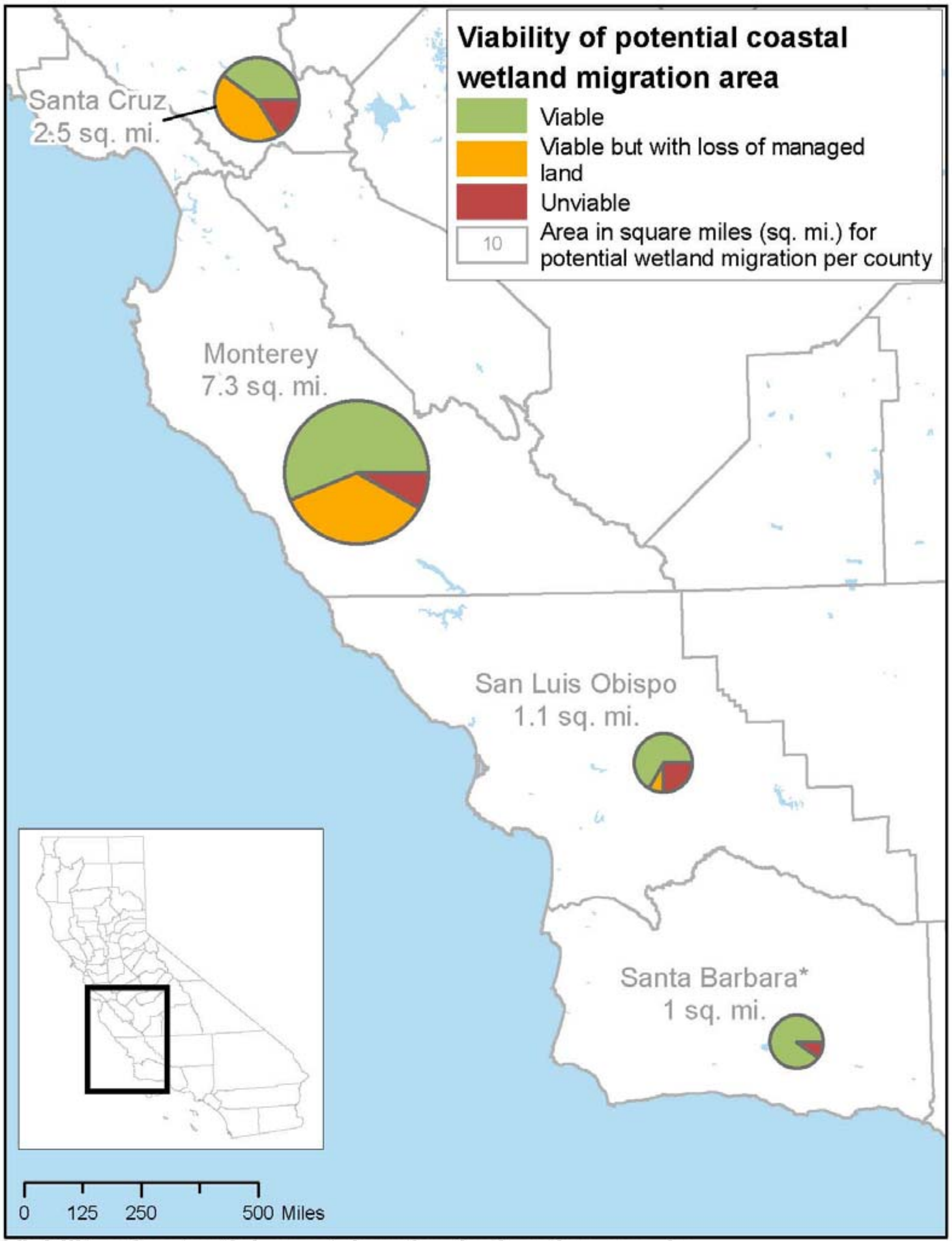
Figure 27. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Northern California



Viability of potential coastal wetland migration area in response to a 1.4 meter sea-level rise in the San Francisco Bay

Data sources: USGS/Scripps Institution of Oceanography, NOAA Coastal Change Assessment Program, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 28. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in the San Francisco Bay



Viability of potential coastal wetland migration area in response to a 1.4 meter sea-level rise in Central California

* 49% of Santa Barbara County coastline mapped.

Data sources: USGS/Scripps Institution of Oceanography, NOAA Coastal Change Assessment Program, CaSIL, ESRI.

http://www.pacinst.org/reports/sea_level_rise

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Figure 29. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Central California

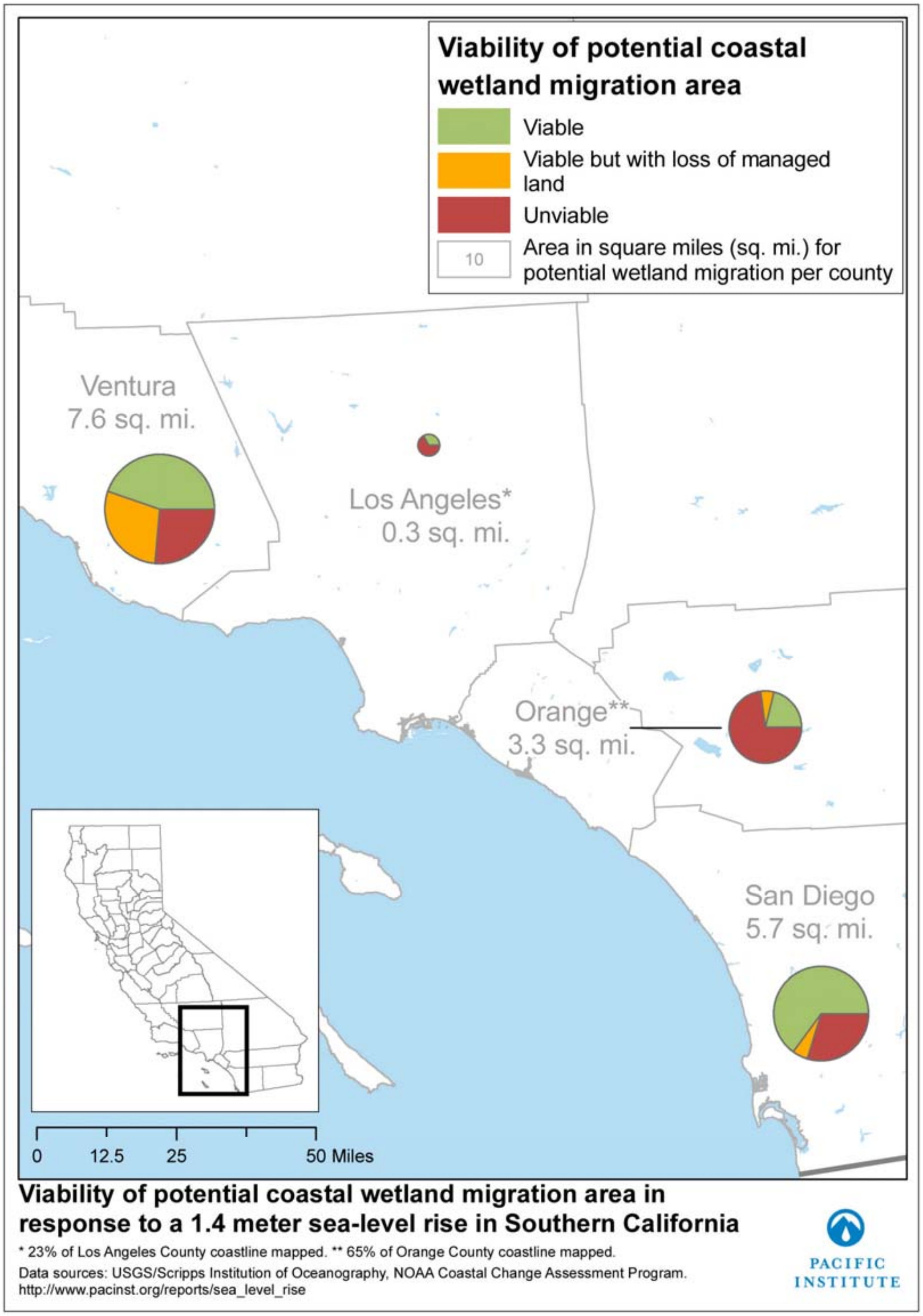
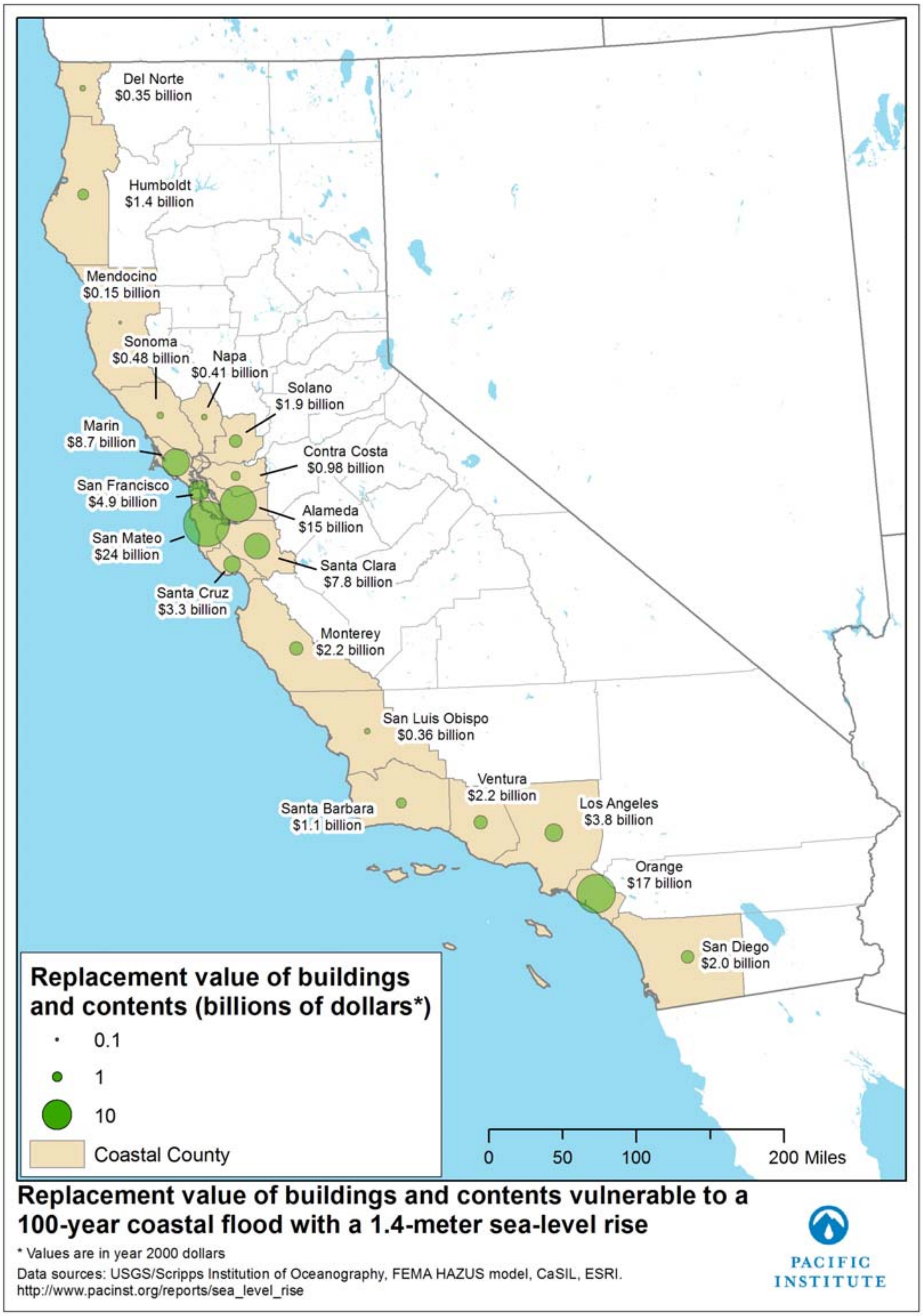


Figure 30. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Southern California

3.1.6. Property at Risk

Significant property is at risk of flooding from 100-year flood events as a result of a 1.4 m sea-level rise (Cayan et al. 2008). In total, we estimate that the replacement value of this property totals nearly $100 billion (Figure 31). An overwhelming two-thirds of that property is concentrated on San Francisco Bay, indicating that this region is particularly vulnerable to impacts associated with sea-level rise due to extensive development on the margins of the Bay (Figure 32).



Replacement value of buildings and contents vulnerable to a 100-year coastal flood with a 1.4-meter sea-level rise

* Values are in year 2000 dollars

Data sources: USGS/Scripps Institution of Oceanography, FEMA HAZUS model, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

Figure 31. Replacement value of buildings and contents vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

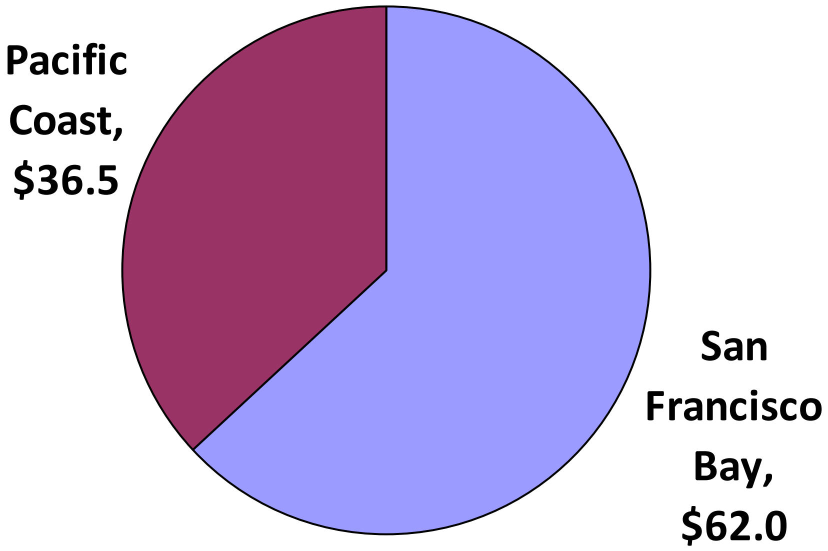


Figure 32. Replacement value (in billions of year 2000 dollars) of buildings and contents at risk of a 100-year flood event with a 1.4 m sea-level rise, by region

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

Pacific Coast

Within each region, vulnerability to sea-level rise is highly variable. Table 21 shows the replacement value of buildings and their contents at risk of a 100-year flood event with a 1.4 m sea-level rise for the Pacific coast by county. Property at risk during a 100-year flood increases from about $21 billion in 2000 to $37 billion (in year 2000 dollars) with a 1.4 m sea-level rise. About $17 billion of property, or about 50% of the total property at risk, is in Orange County. Los Angeles, Santa Cruz, Monterey, and Ventura Counties also have significant assets at risk, totaling in excess of $2 billion each.

Table 21. Replacement value of buildings and contents (millions of year 2000 dollars) at risk of a 100-year flood event along the Pacific coast, by county

County	Current risk	Risk with 1.4 m sea-level rise	Percent increase
Del Norte	240	350	43
Humboldt	680	1,400	110
Los Angeles	1,400	3,800	180
Marin	220	260	16
Mendocino	120	150	22
Monterey	1,700	2,200	36
Orange	11,000	17,000	63
San Diego	690	2,000	190
San Francisco	670	890	33
San Luis Obispo	220	360	67
San Mateo	730	910	26
Santa Barbara	460	1,100	140
Santa Cruz	2,400	3,300	34
Sonoma	170	200	20
Ventura	980	2,200	120
Total	**21,000**	**37,000**	**71**

Note: All values are shown in millions of year 2000 dollars. Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

All economic sectors are vulnerable to impacts associated with sea-level rise. Figure 33 shows the breakdown of the buildings and contents at risk of 100-year flood by major economic sector for the Pacific coast (specific sectors, such as transportation, are discussed in Section 3.2). More than 70% of the assets at risk are residential. The commercial sector, accounting for nearly 20% of the value at risk, will also likely encounter significant costs. Agriculture, education, religion, and government each account for about 1% of the assets at risk, thus, their exposure to risk is relatively small.

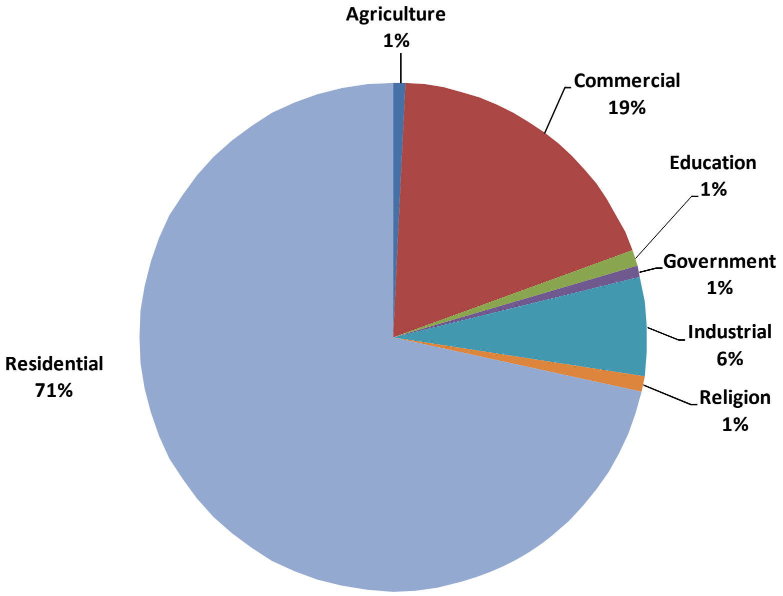


Figure 33. Value of buildings and contents at risk of 100-year flood event with a 1.4 m sea-level rise along the Pacific coast, by major economic sector

San Francisco Bay

The value of assets at risk on San Francisco Bay is substantially higher than along the Pacific coast. Table 22 shows the replacement value of buildings and their contents vulnerable to a 100-year flood event with a 0.5 m, 1.0 m, and 1.4 m sea-level rise. Note that the model used to develop inundation maps for San Francisco Bay allows us to determine the property at risk from any flood intensity. Assets at risk during a 100-year flood increase from about $29 billion in 2000 to $36 billion, $49 billion, and $62 billion (in year 2000 dollars) with a 0.5 m, 1.0 m, and 1.4 m sea-level rise, respectively.

The assets at risk are not evenly distributed among the counties on San Francisco Bay (Table 22). San Mateo and Alameda counties have the greatest assets at risk, accounting for about 60% of the total assets at risk with sea-level rise. Marin, Santa Clara, and San Francisco counties are also exposed to a high degree of risk; exposure to risk in these counties is higher than in all other counties along the Pacific coast, with the exception of Orange County. Exposure to risk in Sonoma and Napa counties is relatively modest.

Table 22. Value of buildings and contents at risk of a 100-year flood on San Francisco Bay, by county (in millions of year 2000 dollars)

County	Risk with sea-level rise			Percent Increase (1.4 m)
	0.5 m	1.0 m	1.4 m	
Alameda	5,300	10,000	15,000	370
Contra Costa	330	620	980	430
Marin	5,900	7,400	8,500	79
Napa	260	320	410	89
San Francisco	370	1,400	4,000	3400
San Mateo	18,000	21,000	23,000	41
Santa Clara	4,700	6,400	7,800	110
Solano	940	1,400	1,900	210
Sonoma	180	240	280	82
Total	**36,000**	**49,000**	**62,000**	**110**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

As it is along the Pacific coast, the residential sector on San Francisco Bay faces the greatest risk. Figure 34 shows the buildings and contents at risk of a 100-year flood by major economic sector on San Francisco Bay (specific sectors, such as transportation, are discussed in Section 3.1.4). Of the $62 billion of property at risk with a 1.4 m sea-level rise, about 50% of the assets at risk are residential, substantially smaller than along the Pacific coast. The commercial and industrial sectors face much greater risk on San Francisco Bay than on the Pacific coast. Agriculture, education, religion, and government each account for about 1% of the assets at risk, thus their exposure to risk is fairly small.

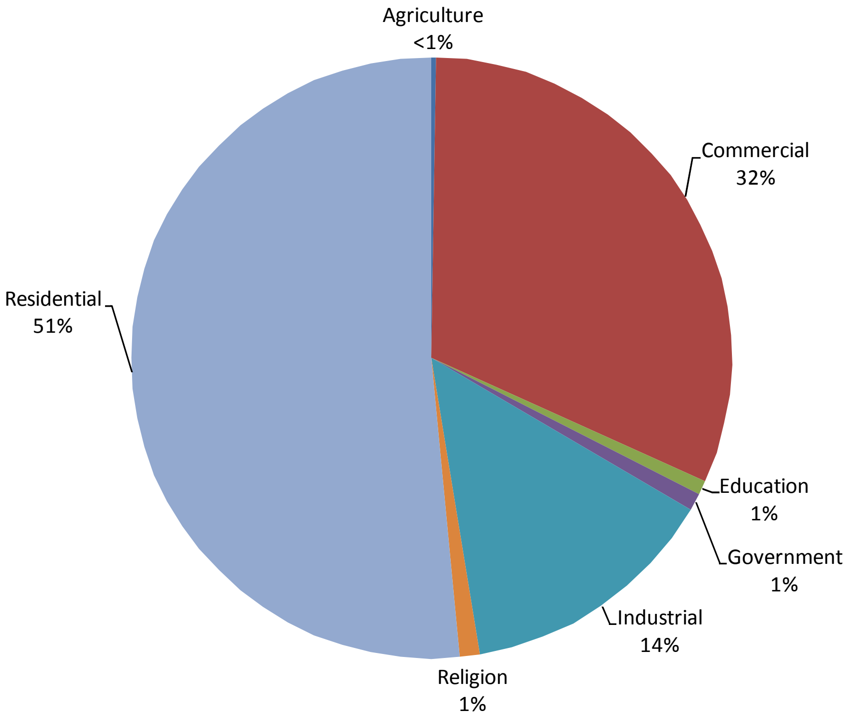


Figure 34. Value of buildings and contents at risk of a 100-year flood with a 1.4 m sea-level rise on San Francisco Bay, by major economic sector

3.1.7. Cost of Protection

Approximately 1,070 miles of new or modified coastal protection structures are needed on the Pacific Coast and San Francisco Bay (Table 23). The total cost of building new or upgrading existing structures is estimated at about $14 billion (in year 2000 dollars). The majority of the investment is needed in Southern California. Nearly 20% of that investment would be needed in Los Angeles County alone. Significant investments would also be needed in Orange and San Diego counties. Mendocino would need the least amount of coastal armoring, although this area is particularly vulnerable to erosion, which is not reflected in this analysis. We estimate that operating and maintaining the protection structures would cost approximately 10 percent of the initial capital investment, or around another $1.5 billion per year.

Table 23. Estimated length (in miles) and capital cost of required defenses needed to guard against flooding from a 1.4 m sea-level rise, by county.

County	Raise levee (miles)	New levee (miles)	New seawall (miles)	Total (miles)	Capital Cost (millions of year 2000 dollars)
Alameda	45	49	16	110	$950
Contra Costa	26	29	8.0	63	$520
Del Norte	-	38	1.0	39	$330
Humboldt	-	36	6.6	42	$460
Los Angeles	0.88	2.5	94	97	$2,600
Marin	43	77	7.7	130	$930
Mendocino	-	0.29	1.2	1.4	$34
Monterey	27	6.4	19	53	$650
Napa	2.8	62	-	64	$490
Orange	-	11	66	77	$1,900
San Diego	-	-	47	47	$1,300
San Francisco	-	10	21	31	$680
San Luis Obispo	-	7.4	5.4	13	$210
San Mateo	35	29	9.2	73	$580
Santa Barbara	2.4	5.6	4.5	13	$180
Santa Clara	47	4.0	-	51	$160
Santa Cruz	3.9	1.6	9.3	15	$280
Solano	2.7	63	8.0	73	$720
Sonoma	30	15	1.3	47	$240
Ventura	-	0.35	28	29	$790
Total	**270**	**450**	**350**	**1,100**	**$14,000**

3.2. Erosion-Related Risks

3.2.1. Population at Risk from Erosion

The erosion hazard zone totals 41 square miles within the 11 coastal counties evaluated in this analysis (Table 24). There is significant variation in the areas at risk of erosion. In Humboldt County, for example, 6.2 square miles of coast would be lost by 2100 under a sea-level rise scenario of 1.4 meters. In San Francisco, however, the erosion-related risk is small.

Table 24. Erosion with a 1.4 m sea-level rise, by county.

County	Dune erosion (sq. miles)	Cliff erosion (sq. miles)	Total erosion (sq. miles)
Del Norte	1.9	2.6	4.5
Humboldt	3.7	2.4	6.1
Marin	1.0	3.7	4.7
Mendocino	0.74	7.5	8.3
Monterey	1.9	2.5	4.4
San Francisco	0.23	0.30	0.53
San Luis Obispo	1.4	1.5	2.9
San Mateo	0.82	2.4	3.2
Santa Barbara	0.62	1.9	2.6
Santa Cruz	0.87	0.9	1.8
Sonoma	0.60	1.6	2.2
Total	**14**	**27**	**41**

As discussed in Section 2.3.2, dunes and cliffs will exhibit differential responses to rising sea levels. Our results indicated that cliffs will erode an average distance of about 66 m by the year 2100 (Table 25). In some areas, however, erosion is projected to be much higher. In Del Norte County, for example, cliffs erode a maximum distance of 520 m. Cliff erosion is much less severe in the other counties along the coast, although still significant. Dunes exhibit much less resistance to erosion. On average, dunes will erode about 170 m by 2100. In Humboldt County, for example, dunes are projected to erode nearly 600 m by 2100.

Table 25. Average and maximum erosion distance in 2000 for cliffs and dunes, by county.

County	Dune erosion		Cliff erosion	
	Average distance (m)	Maximum distance (m)	Average distance (m)	Maximum distance (m)
Del Norte	180	400	160	520
Humboldt	160	600	61	260
Marin	140	270	110	240
Mendocino	190	440	33	160
Monterey	180	400	37	220
San Francisco	150	230	90	220
San Luis Obispo	140	330	78	280
San Mateo	230	430	31	220
Santa Barbara	190	320	54	240
Santa Cruz	170	340	36	130
Sonoma	150	320	41	190
Average	**170**	**370**	**66**	**240**

Table 26 shows the population at risk from erosion with a 1.4 m sea-level rise in 2100. Flood-related risk is shown for comparative purposes. In the 11 coastal counties north of Santa Barbara, a total of 14,000 people live within areas at risk of erosion. In comparison, 69,000 people are vulnerable to a 100-year flood event within these counties. In most counties, the flood-related risk is substantially higher than the erosion-related risk. In Mendocino and Santa Barbara counties, however, erosion poses a greater threat than flooding. In Marin, the flood-related and erosion-related risks are comparable. In addition to those who live in areas vulnerable to erosion, approximately 6,600 people are employed in facilities located there, of which 95% are employed in the commercial sector and the remaining 5% are employed in the industrial sector.

Table 26. Population vulnerable to flood and erosion from a 1.4 m sea-level rise along the Pacific coast, by county

County	Flood-related Risk	Erosion-related Risk
Del Norte	2,500	620
Humboldt	7,400	580
Marin	620	570
Mendocino	630	930
Monterey	14,000	820
San Francisco	6,500	1,200
San Luis Obispo	6,200	1,100
San Mateo	16,000	2,900
Santa Barbara	1,300	2,100
Santa Cruz	5,600	2,600
Sonoma	9,100	300
Total	**69,000**	**14,000**

Note: Numbers may not add up due to rounding.

3.2.2. Emergency and Healthcare Facilities at Risk from Erosion

Emergency and healthcare facilities at risk from erosion along the California coast are limited. The analysis identified a single health care facility near Pacifica that is vulnerable to erosion. There are no schools or fire and police stations within the erosion hazard zone.

3.2.3. Infrastructure at Risk from Erosion

Roads and Railways

Significant transportation-related infrastructure is vulnerable to erosion. Nearly 240 miles of highways and roads and 10 miles of railways are at risk of erosion in the 11 coastal counties north of Santa Barbara (Table 27). This is far fewer than the transportation-related infrastructure at risk from flooding but as mentioned previously, erosion causes far greater and potentially more permanent damage than flooding. In addition, areas such as Big Sur already have significant routine highway maintenance costs due to existing erosion conditions and these costs are likely to increase as erosion rates increase (Figure 35).

Little critical infrastructure is located within the erosion hazard zone. We identified but no wastewater treatment plants within the area at risk of erosion.

Table 27. Miles of roads and railways vulnerable to erosion and flood from a 1.4 m sea-level rise along the Pacific coast, by county and type

	Highways (miles)		Roads (miles)		Railways (miles)	
County	**Erosion-risk**	**Flood-risk**	**Erosion-risk**	**Flood-risk**	**Erosion-risk**	**Flood-risk**
Del Norte	4.3	8.2	14	80	-	-
Humboldt	6.0	58	20	190	-	28
Marin	2.1	4.1	19	27	-	-
Mendocino	13	7.9	25	41	-	4.0
Monterey	11	31	15	110	2.1	23
San Francisco	0	8.0	17	25	-	-
San Luis Obispo	2.5	0.4	18	22	-	0.3
San Mateo	9.8	11	18	67	-	-
Santa Barbara	0.74	7.4	12	21	6.4	7.0
Santa Cruz	2.4	5.0	20	30	1.6	5.5
Sonoma	6.2	8.0	8.4	57	-	-
Total	**58**		**180**		**10**	

Note: Numbers may not add up due to rounding.

Figure 35. Road erosion along Highway 1 with deployment of erosion mitigation strategy

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3.2.4. Property at Risk from Erosion

Land on or near the coast is highly desirable and often commands a premium price. Homes lost to erosion cannot be replaced because the land will have disappeared. As a result, the replacement values reported in the HAZUS database cannot be used in evaluate erosion. A detailed estimate of the value of land and homes that would be completely lost was beyond the scope of this analysis. In order to bound the problem, however, we sought to determine the number of parcels at risk by overlaying the erosion hazard zone layer with the available parcel data. Note that the erosion hazard zone was identified for portions of 11 of California's coastal counties. Eight of these 11 counties had parcel data in digital format.

Parcels are used by counties to levy property taxes. Assessor's offices divide entire counties into parcels, which can represent publicly-owned land, roads, lakes, and other features. A single parcel may also contain an apartment building with many hundreds of residences. Thus, this is an imprecise way of estimating how much property may be lost to coastal erosion. This is an area of study that can and should be pursued in more detail by local governments and regional planning agencies.

We estimate that approximately 10,000 parcels lie within the erosion hazard zone, as summarized in Table 28. Of these parcels, 66%, or two-thirds, lie completely in the erosion hazard zone, meaning the property would be lost completely. The remaining third are partially eroded. If we assume that the value of the average coastal parcel is $1.4 million (Heinz Center 2000), then the economic cost to property of erosion from a 1.4 m sea-level rise would total $14 billion. More work on the economic consequences of erosion is needed.

Table 28. Number of properties within the erosion zone hazard zone with a 1.4 m sea-level rise, by county

County	Number of parcels
Del Norte	No data
Humboldt	570
Marin	1,300
Mendocino	No data
Monterey	1,600
San Francisco	850
San Luis Obispo	No data
San Mateo	1,900
Santa Barbara	580
Santa Cruz	3,000
Sonoma	500
Total	**10,000**

Note: Numbers may not add up due to rounding.

4.0 Conclusions and Recommendations

4.1. Conclusions

Rising sea levels will be among the most significant impacts of climate change to California. Sea level will rise as a result of thermal expansion of the oceans and an increase in ocean volume as land ice melts and runs off. Over the past century, sea level has risen nearly eight inches along the California coast and general circulation model scenarios suggest very substantial increases in sea level due to climate change over the coming century. This study evaluates the current population, infrastructure, and property at risk from projected sea-level rise if no actions are taken to protect the coast. The sea-level rise scenario was developed by the State of California from medium to medium-high greenhouse gas emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) but does not reflect the worst case sea-level rise that could occur.

We estimate that a 1.4 m sea-level rise will put 480,000 people at risk of a 100-year flood event. Among those affected are large numbers of low-income people and communities of color, which are especially vulnerable. A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and wetlands is also vulnerable. In addition, $100 billion (in year 2000 dollars) worth of property is at risk of coastal flooding. A number of structural and non-structural policies and actions could be implemented to reduce these risks. For example, we estimate that protecting vulnerable areas from flooding by building seawalls and levees will cost $14 billion (in year 2000 dollars), along with an additional $1.4 billion per year (in year 2000 dollars) in maintenance costs. Continued development in vulnerable areas will put additional assets at risk and raise protection costs. Determining what to protect, how to pay for it, and how those choices are made raises concerns over equity and environmental justice.

Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 m sea-level rise will accelerate erosion, resulting in a loss of 41 square miles of California’s coast by 2100. A total of 14,000 people live in areas at risk of erosion. In addition, significant transportation-related infrastructure and property are also at risk. Throughout most of the state, flood risk exceeds erosion risk, but in some counties, coastal erosion poses a greater risk. We also provide, below, a set of recommendations for actions and policies that can reduce future risks and vulnerabilities.

4.2. Recommendations

Climate changes are inevitable, and adaptation to unavoidable impacts must be evaluated, tested, and implemented. Sea levels have risen observably in the past century, and scientists forecast that sea-level rise will continue for centuries, even if we stop emitting greenhouse gases immediately. As a result, coastal areas will be subject to increasing risk of inundation and erosion. Below, we provide a series of recommendations and principles to guide the adaptation process.

4.2.1. Principles for Adaptation

The decisions about what to protect, how to protect it, and who will have to pay will be both challenging and controversial. Given the complexity of these issues, it is important to develop an open and transparent process involving all affected stakeholders. Below, we provide some general principles to guide this process:

- Human life must be protected.
- Critical ecological systems should be preserved.
- Development and protection of the coast should be governed by the principles of sustainability. Simply stated, this means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).
- Equal and full participation must be a central element of any decision-making process. No social or economic group should be excluded from decision-making that will affect its well-being.
- Communities must determine the resources and features they value, e.g., beaches, public access, fisheries, etc., and develop plans to protect those resources.
- Consideration should be given to equitable distribution and apportionment of costs and benefits of adaptation measures.
- Adaptation strategies should account for the distinct vulnerabilities of potentially affected subpopulations.
- Local and regional planning processes must begin early to incorporate estimates of sea-level rise and strategies for adaptation.

4.2.2. Recommended Practices and Policies

Climate change must be integrated into the design of all coastal structures.

Current efforts to build, maintain, or modify structures in coastal areas at risk of sea-level rise must now be based on estimates of that rise. The costs of modifying structures in the design phase are often far lower than the costs of later reconstruction or flood damage.

The federal government and the insurance industry should develop and implement a methodology for integrating climate change into insurance policies and strategies.

Properly designed insurance policies are vital for helping landowners choose whether to protect or abandon risky property. The design, availability, and cost of flood insurance will be a key instrument in implementing floodplain policy. For example, the government should not continue to subsidize flood insurance for properties that have suffered repetitive losses. Nor should insurance be available for properties highly likely to be inundated under future conditions.

Federal flood insurance maps should include information on future flood risks due to sea-level rise.

The Federal Emergency Management Agency's official flood insurance studies show hazard zones that reflect past or present flood risks. Because these are the *de facto* planning documents used by most local governments, they should be updated to show the *future* hazard areas and include the current science on climate change and sea-level rise.

Wetlands and the potential migratory paths should be protected.

Development should be prohibited on natural lands that are immediately adjacent to wetlands at risk. These buffer areas may be the only areas suitable for future wetland restorations projects.

Future development should be limited in areas that are at risk from rising seas.

In regions at risk that are not yet heavily developed, local communities and coastal planning agencies have the opportunity to limit development and reduce future threats to life and property. Policies that maintain such low-lying areas will help to accommodate rising seas. In addition to insurance policies, discussed above, such policies may include local ordinances, statewide coastal development policies, and explicit purchases of land for conservation purposes. This is often the least expensive option for currently undeveloped areas.

While limiting coastal development is the most effective way to reduce risk, this approach can incur costs today. Development permits designed to provide flexibility for future generations to address sea-level rise will reduce today's cost. For example, permits might allow development but stipulate that the area reverts to nature if seas rise by a specified amount.

Local planning processes need to involve communities most vulnerable to harm when developing appropriate preparation and adaptation strategies.

The particular needs of vulnerable communities, and appropriate adaptation policies, are best identified and developed through processes in which the affected communities are at the center of decision making. The vulnerabilities to sea-level rise created by access to transportation, legal residency, income, and language abilities can only be fully understood and protected when members of these communities are directly involved in the process.

Consider phased abandonment of low- and medium-density areas at high risk.

In some low- and medium- density areas, the monetary and environmental cost of holding back the sea may become unacceptably high. The lowest-cost option may be to allow natural processes take place. Policies that prevent flood-damaged homes or businesses from rebuilding may help ease this transition.

Protect vital societal resources, especially those that are "coastal-dependent."

In many cases, the value of an area's infrastructure far exceeds the cost to raise structures or build protective barriers. For example, the San Francisco airport and the Port of Long Beach are extremely important to the state and national economy. In choosing what to protect, we should favor infrastructure that necessarily belongs on the coast, such as ports, bridges, and marinas.

Cost-benefit analyses should explicitly evaluate the social and environmental costs of building coastal protection structures.

Armoring the coastline can save lives and property, but it also comes at a cost. The natural dynamics that occur between water and land are disrupted. Beaches and wetlands disappear and habitat is lost. Traditional cost-benefit analyses, such as those required for all US Army Corps of Engineers projects, do not adequately account for these inherent tradeoffs.

Coastal emergencies are inevitable. Coastal communities should improve disaster response and recovery.

In this analysis, we have focused on increased risk of coastal flooding and erosion as a result of sea-level rise. California is also subject to tsunamis, earthquakes, wildfires, terrorist attack, and other hazards. Improving community preparedness provides benefits for responding to any type of emergency. Before a disaster strikes, communities must plan for evacuation routes, emergency action plans, and shelters, and take into account the specific needs of vulnerable populations. In addition, roles and responsibilities must be clearly defined among local, state, and federal agencies.

Coastal managers should consider adopting the principles of "No Adverse Impact" when designing and permitting flood protection, beach nourishment, and other coastal protection projects.

Current coastal protection projects are often done with no regard for how they will affect adjacent portions of the coast. According to the Association of State Floodplain Managers: "Over the past 50 years a system has developed through which local and individual accountability has been supplanted by federal programs for flood control, disaster assistance, and tax incentives that encourage and subsidize floodplain occupation and development." We recommend that coastal managers consider adopting a policy similar to "No Adverse Impact" where the "actions of one property owner are not allowed to adversely affect the rights of other property owners" (ASFM 2008).

4.2.3. Additional Research and Analysis

Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.

The analysis presented here provides an initial estimate of the impacts of sea-level rise along the California coast. More detailed assessments of local impacts and potential response strategies are needed. While the effects of sea-level rise, responses, and threatened resources must all be evaluated at a local level, broader regional effects must also be incorporated into final protection strategies.

Our analysis was hindered by inadequate data on existing coastal structures. Existing levees and other flood defenses should be surveyed, assessed, and cataloged.

The U.S. Congress passed the Water Resources Development Act of 2007, creating a National Levee Safety. The act requires the establishment and maintenance of an inventory of the nation's levees and inspection of all federally owned, operated, or constructed levees. This program should be fully funded and quickly implemented, and the information it compiles should be made readily available to residents, local government, and others.

Conduct further research focused on all vulnerable subpopulations, including children, elderly, homeless, physically disabled, and people with limited mobility (e.g., incarcerated residents and healthcare facility patients), accurately measuring and analyzing the potential human costs of sea-level rise and adaptation measures.

This analysis does not include various demographic groups that can be expected to have unique vulnerabilities to potential disasters. For pre-disaster, disaster response, and recovery efforts to effectively safeguard all Californians, further study is needed to identify all vulnerable populations and assess the unique vulnerabilities of each group.

Assess the environmental justice implications of potential mitigation measures, and develop strategies to effectively safeguard all communities.

The measures taken to adapt to sea-level rise must not distribute costs and benefits of protection in ways that place a disproportionate burden on the low-income households and communities of color who are most vulnerable to a potential disaster. The means of prioritizing protection measures must be analyzed with and held to the principles of environmental justice.

Natural ecosystems are at serious risk from sea-level rise, but are undervalued or ignored in traditional economic analyses. Improved methods for incorporating them into future studies are needed.

Wetlands are highly diverse ecosystems that provide a variety of goods and services, including flood protection, water purification, wildlife habitat, recreational opportunities, and carbon sequestration. Large tracts of wetlands along the California coast are vulnerable to sea-level rise. No satisfactory method for incorporating their environmental values has been developed, and we thus risk ignoring them when we make policy decisions. This would be a serious mistake. Additional work is needed to evaluate the costs and values of natural ecosystems.

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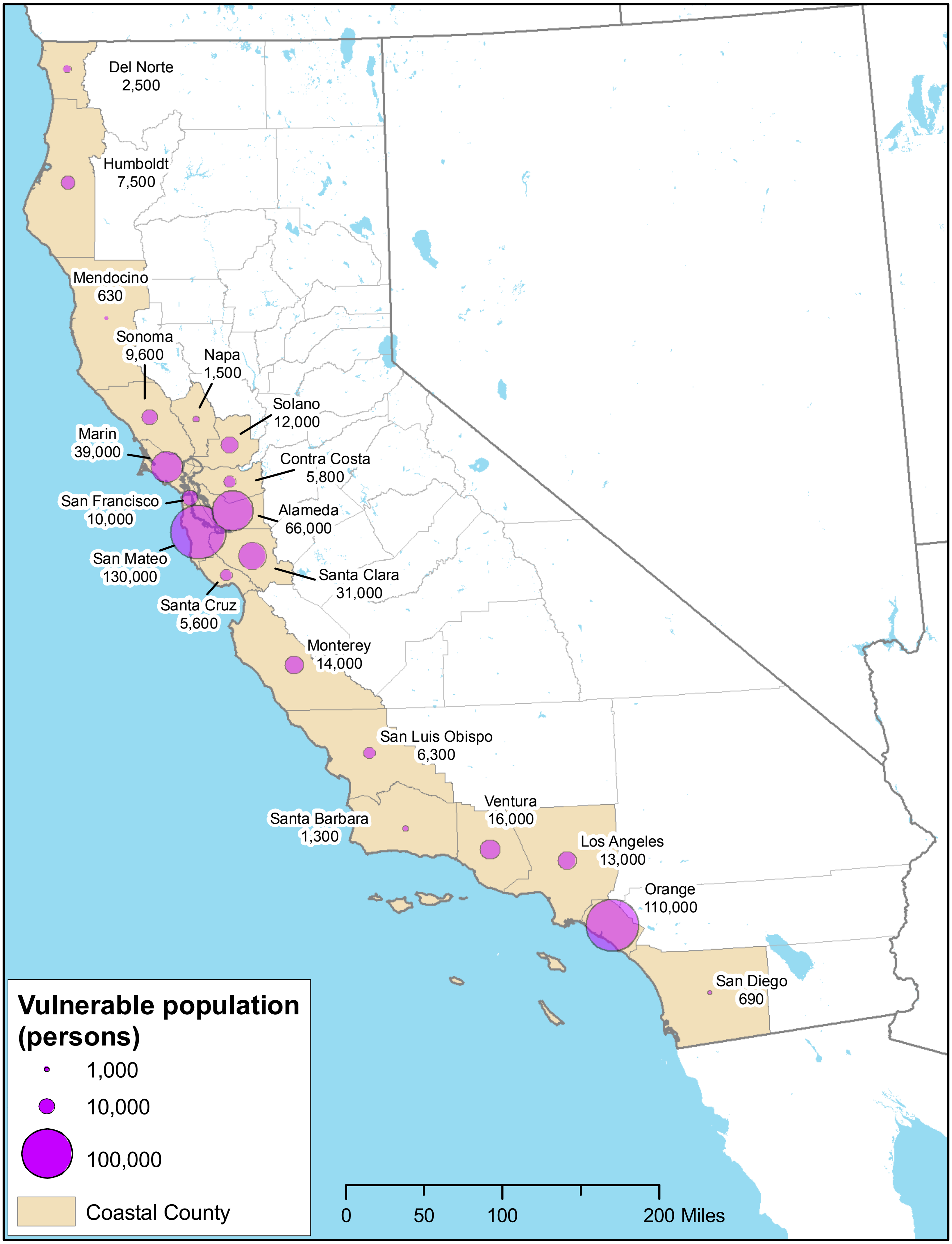
6.0 Acronyms and Abbreviations

ALACE	Airborne LIDAR Assessment of Coastal Erosion
ASFM	Association of State Floodplain Managers
BFE	Base flood elevation; elevation of floodwaters with an annual probability of 1%. Also referred to as the 100-year flood.
CALSIM	A computer simulation model of river basins developed by California's Department of Water Resources
CASCADE	Computational Assessments of Scenarios of Climate Change in the Delta Ecosystem; a suite of computer models of the hydrology and biology of California's Sacramento/San Joaquin river delta developed by the US Geological Survey
C-CAP	Coastal Change Analysis Program, a NOAA initiative
CCC	California Coastal Commission
CCSM	Community Climate System Model

CNRM	Centre National de Recherches Meteorologiques (France's National Center for Meteorological Research)
DEM	Digital Elevation Model, a digital database of land surface elevations
DFIRM	Digital Flood Insurance Map, electronic maps and databases published by FEMA
EPA	US Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GFDL	Geophysical Fluids Dynamics Laboratory
GIS	Geographic Information System
HAZUS	Hazards U.S. Multi-Hazard, a computer model for estimating damages from natural disasters
IFRCC	International Federation of Red Cross and Red Crescent Societies
IfSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging, a remote sensing technology used to collect terrain elevation data
MGD	million gallons per day
MHHW	Mean higher-high water
MHW	Mean high water
MHWS	Mean high water springs
MIROC	The Model for Interdisciplinary Research on Climate
MLLW	Mean lower-low water
MLW	Mean low water
MSL	Mean sea level
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988; modern reference system for measuring heights above the earth's surface
NCAR	National Center for Atmospheric Research
NPDES	National Pollutant Discharge Elimination System
NGVD29	National Geodetic Vertical Datum of 1929; a reference system for

	measuring heights above the earth's surface, superseded by NAVD88
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System; an EPA program to track and regulate pollutants discharged to surface waters of the United States
NRC	National Research Council
NWI	National Wetlands Inventory, a geographic database of US wetlands published by the US Fish and Wildlife Service
OPC	Ocean Protection Council
PCM	Parallel Climate Model
PCS	Permit Compliance System; an EPA database of licensed discharges to the surface waters of the United States
PIER	Public Interest Energy Research
PWA	Philip Williams and Associates
SLR	Sea level rise
TWL	Total water level
USACE	US Army Corps of Engineers
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey

Attachment E



Population vulnerable to a 100-year coastal flood with a 1.4 meter sea-level rise

Data sources: USGS/Scripps Institution of Oceanography, U.S. Census Bureau, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

PACIFIC INSTITUTE

Attachment F

Goleta Water District
4699 Hollister Ave
Goleta, CA 93117

March 30, 2009

University of California Santa Barbara
Office of Campus Planning and Design
c/o Vision 2025
Santa Barbara, CA 93106-1030

RE: Comment Letter to the University of California at Santa Barbara 2008 Long Range Development Plan, Recirculated Draft Environmental Impact Report Sections

The Board of Directors of the Goleta Water District has directed me to submit this letter and attachments which together constitute the Goleta Water District's formal comments on the University of California at Santa Barbara (the University) 2008 Long Range Development Plan (LRDP) Recirculated Draft Environmental Impact Report (RDEIR). These comments (Attachment A) focus on RDEIR Section 4.14, Water. In addition, the District provides comments on portions of RDEIR Section 4.10, Population and Housing, that discuss topics that affect water demand yet are not considered in the Water section. Attachment B consists of a copy of the 1991 Measure H91, Goleta Water District Ordinance No. 91-01, SAFE Water Supplies Ordinance (SAFE Ordinance) and the 1994 Measure J94, Goleta Water District Amendment to the SAFE Ordinance. Attachment C consists of written comments on LRDP RDEIR Section 4.14 made to Goleta Water District representatives by Mr. Bill Brennan, Executive Director of the Central Coast Water Authority (CCWA). Comments by Mr. Brennan are incorporated herein by reference.

GENERAL COMMENT

The Goleta Water District (the District) is a California Environmental Quality Act (CEQA) Responsible Agency which has discretionary approval power over the project. During the scoping and initial research period of the Draft Environmental Impact Report (DEIR), the District was not asked to participate in the development of the DEIR. Because of this, the District believes the RDEIR presents incomplete data regarding both current and future water supplies and demands. Below is a summary of the problematic issues within the RDEIR.

- The University misinterprets and incorrectly cites District documents as well as current regulations and ordinances. The RDEIR cites data from the District's 2005 Urban Water Management Plan (UWMP) and May 22, 2008 Water Supply Assessment (WSA) for the City of Goleta. Significant changes have rendered much of the material in those documents obsolete; updates are included in the attached comments. The RDEIR additionally misinterprets regulations and ordinances in place (e.g., the SAFE Ordinance). The comments provided by the District will assist in a better analysis of these issues. The District is in the process of developing a Groundwater Management Plan (GWMP) leading to an updated Water Supply Management Plan (WSMP) and preparation of a 2010 Urban Water Management Plan. The District suggests that the University refer to these plans as well as work with the District in revising the RDEIR and in future planning.

- The University states "rights" to specific water amounts, with these amounts used as a baseline for future development scenarios. This is inaccurate; certain water agreements between the University and the District are subject to modification and termination.

- The University's water supply figures are overestimates. The University's analysis within the RDEIR demonstrates an incomplete understanding of Santa Barbara County's dynamic water supply system. Water supply figures are not static numbers; water supplies from groundwater, Lake Cachuma and the State Water Project (SWP) are constantly in flux and subject to various legal, regulatory, seismic, and climatic constraints which can reduce availability. The RDEIR does not demnstrate a realistic understanding of how these constraints affect water supply.

- The University assumes that greater water storage and pumping capacity equates to greater potable water supply, and that the increased use of recycled water will offset portions of future potable water demand. It is the District's opinion that pumping capacity does not equal water supply, and that recycled water cannot offset 100% of future potable water demand. Although improvements are being made to augment both potable and recycled water capacity, current and future water supply conditions warrant more conservative estimates of water supply. In addition, there is no market or funding for the recycled water production and distribution described in the University's document.

- The University's water demand figures are underestimates. The University is not using the correct water duty factors (wdf). Usage estimates are based upon limited data periods; calculations should be derived from data that spans a longer period. The University should provide its calculations and support its conclusions with factual data. Absent such data, the District cannot accept the water duty factors as provided in the document.

- The University's baseline water use calculations are incorrect and the most current data is not being used to support future demand calculations. Baseline calculations should come from current water usage values or usage at the time of application.

It is the District's opinion that within the RDEIR, the University must address these critical issues and develop more comprehensive mitigation options. In the current document, the RDEIR overestimates water supply and underestimates water demand. The District believes the University's LRDP potable water demand exceeds the District's available potable water supply. In accordance with CEQA, the proposed project will have Significant and Unavoidable Class I Impacts to potable water supply that cannot be feasibly mitigated during the planning period.

The Board of the Goleta Water District encourages the University to work cooperatively with the District in the future to make the most efficient and productive use of the community's limited water supplies.

Please see Attachment A for a detailed list of comments.

Respectfully,

Eric E. Ford
Interim General Manager
Goleta Water District

Att: Attachment A – Specific Comments on the UCSB LRDP Draft Recirculated EIR
Attachment B – SAFE Water Supplies Ordinance (1991 and 1994, as amended)
Attachment C – Comments by Mr. Bill Brennan, Executive Director of the Central Coast Water Authority