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16 January 2003; accepted 13 February 2003

Climate Sensitivity Uncertainty and the Need for Energy Without CO_2 Emission

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The UN Framework Convention on Climate Change calls for "stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system." Even if we could determine a "safe" level of interference in the climate system, the sensitivity of global mean temperature to increasing atmospheric CO_2 is known perhaps only to a factor of three or less. Here we show how a factor of three uncertainty in climate sensitivity introduces even greater uncertainty in allowable increases in atmospheric CO_2 concentration and allowable CO_2 emissions. Nevertheless, unless climate sensitivity is low and acceptable amounts of climate change are high, climate stabilization will require a massive transition to CO_2 emission–free energy technologies.

Climate sensitivity (ΔT_{2X}) is the global mean climatological temperature change resulting from a doubling of atmospheric CO_2 content. Climate sensitivity is thought, based primarily on models, to lie in the range of 1.5° to 4.5°C (*1*, *2*). Cloud feedbacks remain the greatest source of uncertainty in model predictions of global mean warming (*3*). Aerosols, non-CO_2 greenhouse gases, internal variability in the climate system, and land use change also affect Earth's temperature (*2*). Uncertainty in aerosol radiative forcing precludes a more accurate, observationally based estimate of climate sensitivity to a CO_2 doubling (*4*, *5*).

Here, we focus on CO_2-induced climate change because CO_2 is the dominant source of change in Earth's radiative forcing in all Intergovernmental Panel on Climate Change (IPCC) scenarios of the future (*1*, *6*, *7*), and future aerosol emissions diminish in all of the IPCC SRES scenarios (*7*). On the basis of the roughly logarithmic relation between CO_2 concentration and global warming (*1*), we determined that the atmospheric CO_2 concentration (P_{stab}) needed to stabilize CO_2-induced climate change at a warming of ΔT_{stab} can be approximated as follows

$$\frac{P_{stab}}{P_{280}} = 2^{\left(\frac{\Delta T_{stab}}{\Delta T_{2X}}\right)} \quad (1)$$

where ΔT_{2X} is the climate sensitivity and P_{280} is the reference preindustrial atmospheric CO_2 concentration [here, 280 parts per million (ppm)]. The stabilization target for atmospheric CO_2 (P_{stab}) increases exponentially with the ratio of stabilization temperature change (ΔT_{stab}) to climate sensitivity (ΔT_{2X}). However, neither ΔT_{2X} nor ΔT_{stab} are necessarily "instantaneous" temperatures; rather, they are "climatological" global mean surface temperatures that could be attained if CO_2 concentrations were held constant long enough for the heat stored in the oceans during global warming to equilibrate with the atmosphere. If climate sensitivity is 1.5°C, stabilization at 2°C of CO_2-induced warming could be achieved at CO_2 concentrations of 700 ppm; however, if climate sensitivity is 4.5°C, then CO_2 would need to be leveled off at only 380 ppm, a level only marginally higher than today's value of 370 ppm. Top-down models of global energy systems suggest that we can stabilize climate with CO_2 concentrations well below 500 ppm and still grow the economy by an order of magnitude over this century (*8*–*10*). However, basic physics, chemistry, engineering, and environmental considerations indicate this may prove difficult to achieve (*11*).

How does uncertainty in climate sensitivity contribute to uncertainty in predictions of allowable emissions? Typically, carbon dioxide stabilization pathways (*12*) have been used to predict future allowable CO_2 emissions (*12*, *13*) and carbon emissions–free energy demand (*14*). Such an approach ignores the major uncertainty in climate sensitivity. Our goal is to show how uncertainty in climate sensitivity propagates to uncertainty in allowable carbon emissions for a specified climate change scenario. Similar uncertainties would propagate for other pathways, but with different quantitative results.

Many previous studies have focused arbitrarily on a doubling of the preindustrial atmospheric CO_2 content (of roughly 280 ppm). Here, we examine CO_2 emissions and energy requirements for a 2°C global and annual mean warming. This choice is also somewhat arbitrary, as nobody knows exactly how much we can interfere with the climate system without constituting the "dangerous interference" proscribed by the Framework Convention (*15*).

We constructed stabilization pathways (*16*) leading to a 2°C warming after year 2150, approximating the WRE550 scenario (*12*). For each of the stabilization pathways, we computed the allowable CO_2 emission levels over time (Fig. 1) using a globally aggregated (i.e., reduced form) Earth system model, the Integrated Science Assessment Model (ISAM) (*17*, *18*). The global carbon cycle component of ISAM is used to simulate the exchange of carbon dioxide between the atmosphere, reservoirs of carbon in the terrestrial biosphere, and the ocean column and mixed layer (*19*, *20*). ISAM considers interactions among radiative forcing, physical climate, and the carbon cycle to estimate changes in both climate and carbon cycle processes. ISAM has been used in recent and past assessments of the IPCC (*1*, *2*, *21*) and the World Meteorological Organization (WMO) (*22*, *23*).

If climate sensitivity is in the upper half of the accepted range, climate stabilization at a 2°C warming would require immediate reductions in fossil fuel carbon emissions (Fig. 1). Even in the case with low climate sensitivity, allowable end-of-century CO_2 emissions are roughly half of

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the emissions implied by the IPCC IS92a reference scenario assumptions (*1*, *6*, *14*).

On the basis of our current understanding, we have determined that climate sensitivity uncertainty exceeds carbon cycle uncertainty in its impact on allowable emissions. For CO_2 stabilization scenarios, the IPCC estimates (*13*) that carbon cycle uncertainties translate into uncertainty in year 2100 allowable emissions "approaching an upper bound" of –14 to +31%. For the climate stabilization scenario described here, climate sensitivity uncertainty in the 1.5° to 4.5°C range introduces –100 to +429% uncertainty in year 2100 allowable CO_2 emissions relative to results at a 3°C climate sensitivity (Fig. 1).

How does uncertainty in climate sensitivity introduce uncertainty in predicted demand for non–CO_2-emitting energy sources? In our energy analysis, we follow the approach of Hoffert *et al.* (*14*), who have shown that to stabilize atmospheric CO_2 content we need massive amounts of carbon-free energy and massive improvements in the efficiency of energy use. There is no doubt that long-term economic projections are unreliable, as they cannot anticipate unforeseen technological or socioeconomic revolutions. Nevertheless, emission scenarios frameworks have tried to limit these uncertainty problems by providing ranges of greenhouse gas emissions [e.g., the IPCC IS92 and SRES future emissions of greenhouse gases and aerosols precursors (*1*, *6*, *7*)]. These scenarios were not assigned probabilities by the IPCC authors, nor were they considered as predictions of the future; these scenarios illustrated various assumptions about economics, demography, and policy on future emissions. Nevertheless, others have attempted to evaluate their likelihood (*24*). Here, we adopt the economic assumptions of the IS92a scenario (*1*, *6*) and estimate, for a range of climate sensitivities, the amount of carbon emissions–free energy required to stabilize climate at a 2°C warming. We take the CO_2 emissions from the IS92a scenario and subtract from it the amount of carbon that can be released under the climate stabilization pathway described. The result is the amount of additional CO_2 emissions that must be avoided to achieve climate stabilization. We then estimate the amount of additional carbon-free power needed to replace the fossil fuel CO_2 emissions, assuming the use of the same fossil fuel mix as used in the IS92a report. Because the IS92a scenario already assumed the use of nuclear and some renewable energy sources, this must be included to obtain total carbon emissions–free primary power required for climate stabilization. The percentage of primary power that must come from non–CO_2-emitting sources, for the allowable CO_2 emissions shown in Fig. 1, is shown in Fig. 2.

For climate stabilization at a 2°C warming under IS92a economic assumptions, large amounts of carbon emissions–free energy will be required by mid-century, regardless of likely climate sensitivity (Figs. 2 and 3). By the end of the century, between ~75 and 100% of total power demand will need to be provided by non–CO_2-releasing energy sources. In the calculation here, a 2°C warming with a 1.5°C climate sensitivity has allowable carbon emissions equivalent to a 4°C warming with a 3°C climate sensitivity (Eq. 1). Hence, even for a 4°C warming and climate sensitivity in the middle of the IPCC accepted range, stabilization of climate would require 75% of our primary power to be generated by non–carbon emitting sources.

Here, we investigated uncertainties in allowable CO_2 emissions and carbon emissions–free power requirements introduced by uncertainties in climate sensitivity, for a specific set of temperature stabilization pathways. However, time-varying allowable emission rates are sensitive to the details of the stabilization pathway; mean or cumulative emissions are less sensitive (*12*). Figure 3 shows the rate at which carbon emissions–free energy sources must be added to the power generating capacity to achieve CO_2 stabilization. To achieve stabilization at a 2°C warming, we would need to install ~900 ± 500 MW of carbon emissions–free power generating capacity each day over the next 50 years. This is roughly the equivalent of a large carbon emissions–free power plant becoming functional somewhere in the world every day. In many scenarios, this pace accelerates after mid-century. If climate sensitivity is in the middle of the IPCC range, under IS92a assumptions, even stabilization at a 4°C warming would require installation of 410 MW of carbon emissions–free energy capacity each day.

Uncertainty in climate sensitivity could perhaps be reduced by a well-designed program of climate model evaluation and improvement and by observationally narrowing uncertainties in non-CO_2 sources of radiative forcing (e.g., aerosols, solar variation), changes in heat storage among various components of Earth's climate system, top-of-atmosphere radiative fluxes, and changes in Earth's surface temperature. But, uncertainty in climate sensitivity is only one factor affecting uncertainty in allowable CO_2 emissions. Uncertainty is introduced when determining (i) acceptable amounts and rates of climate change, (ii) greenhouse gas and aerosol concentrations consistent with those amounts and rates of climate change, and (iii) greenhouse gas and aerosol emissions consistent with those concentrations. Predicting future carbon

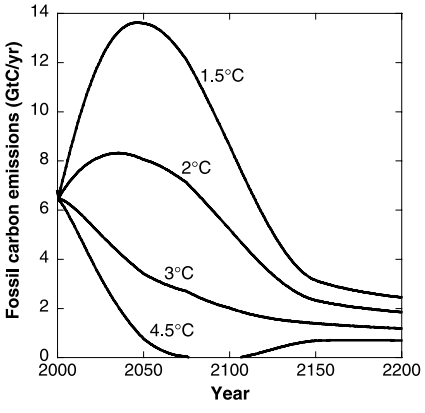

Fig. 1. Allowable emissions of CO_2 to the atmosphere to produce climate stabilization at a 2°C global mean warming relative to the preindustrial state, shown for different climate sensitivities. To achieve this climate stabilization, we could either allow today's emission rate to double by mid-century or need to bring emissions near zero, depending on whether climate sensitivity is 1.5° or 4.5°C per CO_2 doubling.

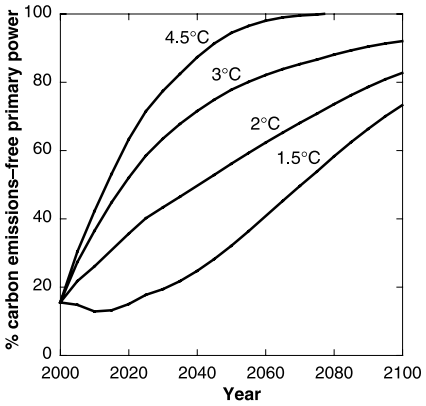

Fig. 2. Percentage of primary power from carbon emissions–free sources that would be required for stabilization of atmospheric CO_2 by year 2150 at a level that would produce a 2°C global mean warming, shown for several possible climate sensitivities to a doubling of atmospheric CO_2 (in °C/doubling). Economic assumptions are from the IS92a "business-as-usual" scenario (*1*, *6*).

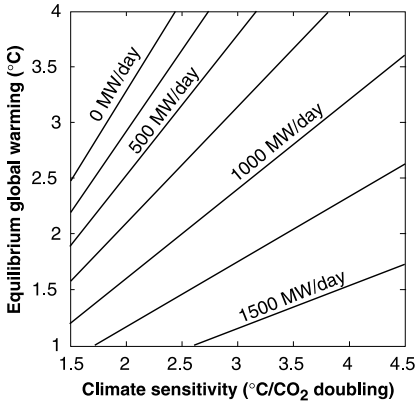

Fig. 3. Mean rate of increase in installed capacity in carbon emissions–free primary power required over the period from year 2000 to year 2050 to stabilize climate, shown as a function of climate sensitivity to a CO_2 doubling and equilibrium mean global warming under scenarios defined by Eq. 2. Economic assumptions are from the IS92a scenario (*1*, *6*). For comparison, nuclear and renewable primary power capacity was added at the rate of ~40 MW/day over the 1990s, representing ~10% of total capacity added during this period (*7*).

emissions–free energy requirements incorporates further uncertainties in projection of future economic conditions, energy-use efficiency, demographics, and other factors. Nevertheless, climate stabilization will require new energy technologies and structural changes in our economy (*14*, *24*).

In summary, the amount of global mean temperature change produced by a change in atmospheric CO_2 content is known perhaps only to a factor of three. This uncertainty propagates from climate stabilization pathways, to allowable carbon dioxide emissions, and ultimately to carbon emissions–free power requirements. Climate sensitivity uncertainty introduces much greater uncertainty in allowable CO_2 emissions than does carbon cycle uncertainty. For CO_2 stabilization by year 2150 leading to a CO_2-induced global mean warming of 2°C, estimated allowable carbon emissions later this century could be less than 0 GtC or greater than 13 GtC (1 GtC = 10^{12} kg C) per year, depending on whether climate sensitivity is 4.5° or 1.5°C per CO_2 doubling, respectively. With this climate stabilization scenario and IPCC IS92a "business-as-usual" economic assumptions, if climate sensitivity is at the high end of the IPCC range, then by the end of this century nearly all of our primary power will have to come from non–CO_2 emitting sources. Perhaps surprisingly, even if climate sensitivity is at the low end of the accepted range, by the end of this century over three-quarters of our primary power will need to come from sources that do not release CO_2 into the atmosphere. We do not yet have CO_2 emission–free energy technologies that can be applied cost-effectively today at the required scale (*11*). Given the long lead times needed to bring new energy technologies to implementation, we need to develop appropriate energy technologies now. With such technologies, the industrialized world can evolve to and the industrializing world can develop with an environmentally acceptable energy infrastructure—one "that would prevent dangerous anthropogenic interference with the climate system."

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16. In our stabilization scenarios, atmospheric CO_2 concentrations match the historical period and increase to the stabilization value at year 2150. For year 2000, we specify the CO_2 amount in the atmosphere (P_{2000} = 372 ppm) and its rate of increase (r_{2000} = 1.99 ppm/year). For year 2150 and thereafter, we specify the amount of CO_2 in the atmosphere (P^{∞}_{stab}) and set the first and second time derivatives of the atmospheric CO_2 concentration at zero. With these five constraints, we derive the fourth order polynomial representing CO_2 concentration for the years 2000 to 2150

$$P_{stab}[\Delta t] = P_{2000} + r_{2000}\Delta t + \left(\frac{-3r_{2000}\Delta t_{stab} + 6\Delta P^{\infty}_{stab}}{\Delta t^{2}_{stab}}\right)\Delta t^{2} + \left(\frac{3r_{2000}\Delta t_{stab} - 8\Delta P^{\infty}_{stab}}{\Delta t^{3}_{stab}}\right)\Delta t^{3} + \left(\frac{-r_{2000}\Delta t_{stab} + 3\Delta P^{\infty}_{stab}}{\Delta t^{4}_{stab}}\right)\Delta t^{4}$$

where $\Delta P^{\infty}_{stab} = P^{\infty}_{stab} - P_{2000}$, Δt is the number of years after 1 January 2000, and Δt_{stab} is the number of years until CO_2 stabilization occurs (here, 150 years).
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25. K.C. thanks M. Wickett, K. Taylor, and C. Green for their help. This work was performed under the auspices of the DOE by the Lawrence Livermore National Laboratory under contract no. W-7405-Eng-48. Some of the research of K.C. and A.K.J. was supported by the DOE Office of Biological and Environmental Research.

12 September 2002; accepted 25 February 2003

Identification of a Testicular Odorant Receptor Mediating Human Sperm Chemotaxis

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Although it has been known for some time that olfactory receptors (ORs) reside in spermatozoa, the function of these ORs is unknown. Here, we identified, cloned, and functionally expressed a previously undescribed human testicular OR, hOR17-4. With the use of ratiofluorometric imaging, Ca^{2+} signals were induced by a small subset of applied chemical stimuli, establishing the molecular receptive fields for the recombinantly expressed receptor in human embryonic kidney (HEK) 293 cells and the native receptor in human spermatozoa. Bourgeonal was a powerful agonist for both recombinant and native receptor types, as well as a strong chemoattractant in subsequent behavioral bioassays. In contrast, undecanal was a potent OR antagonist to bourgeonal and related compounds. Taken together, these results indicate that hOR17-4 functions in human sperm chemotaxis and may be a critical component of the fertilization process.

More than a decade ago, about a thousand vertebrate genes were found that code for olfactory receptor proteins. These receptors are coupled to complex signaling pathways, and despite their name, they also reside in tissues other than those involved in olfaction. Several distinct ORs are expressed predominantly or exclusively in human spermatogenic cells (*1, 2*). Immunocytochemistry indicates that receptor proteins are localized to the sperm flagellar midpiece (*2*). These observations have led to speculation that ORs function in chemosensory signaling pathways, and hence in direct sperm chemotaxis (*3–5*). Here, we determined the ligand specificity and functional importance of hOR17-4, a newly identified testicular OR. Sequential studies were con-