TECHNICAL RESPONSE

CLIMATE CHANGE

Response to Comment on "Long-term climate forcing by atmospheric oxygen concentrations"

Christopher J. Poulsen,[1*] Clay Tabor,[2] Joseph White[3]

Goldblatt argues that a decrease in pressure broadening of absorption lines in an atmosphere with low oxygen leads to an increase in outgoing longwave radiation and atmospheric cooling. We demonstrate that cloud and water vapor feedbacks in a global climate model compensate for these decreases and lead to atmospheric warming.

Poulsen *et al.* (*1*) report the results of a global climate model (GCM) used to investigate the climate response to changing atmospheric oxygen (O_2) levels and find that a reduction in O_2 leads to surface warming and enhanced precipitation as a result of radiative changes and cloud, lapse rate, and water vapor feedbacks. The results of Poulsen *et al.* (*1*) differ from previous estimates using a one-dimensional radiative-convective model (RCM) that only crudely represents climate feedbacks (*2*), raising questions from Goldblatt (*3*) about the representation of clear-sky radiation processes in the Global Environmental and Ecological Simulation of Interactive Systems (GENESIS) GCM and the mechanisms that lead to atmospheric warming in the model. We address these two points below.

The GENESIS 3 radiation code is based on the NCAR Community Climate Model (CCM3) radiation scheme (*4*). As noted in Goldblatt, a standard method for testing radiation codes in GCMs is to calculate radiation fluxes using a stand-alone offline version of the radiation code with fixed atmospheric profiles. We have completed this analysis for clear-sky conditions using the same atmospheric profiles of temperature and water vapor for 10 and 21% O_2 scenarios as Goldblatt to facilitate comparisons between GENESIS 3 and Spectral Mapping Atmospheric Radiative Transfer (SMART) models. Clear-sky top of the atmosphere (tropopause) longwave and shortwave responses are approximately –2.5 and 0.3 W m^{-2}, smaller but in line with the results from the SMART model (Fig. 1). Differences in the magnitude of responses obviously result from differences in the radiation code but also stem from choice in insolation, zenith angle, and interpolation of the atmospheric profiles to the radiation model. In sum, as expected, the GENESIS 3 radiation code captures reductions in longwave absorption through Mie scattering and shortwave absorption through Rayleigh scattering.

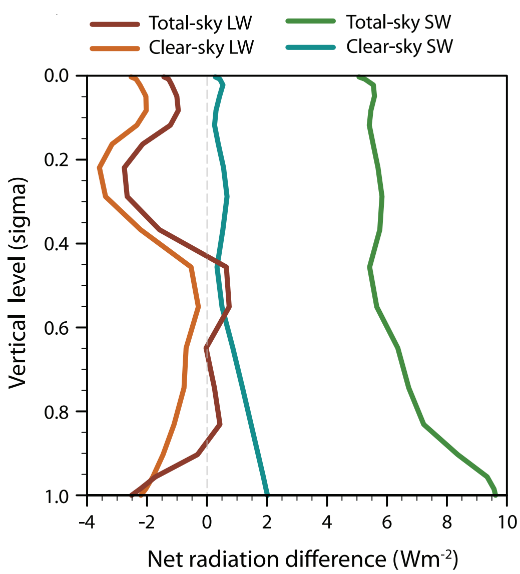

Fig. 1. Clear-sky and total-sky profiles of net shortwave (SW) and longwave (LW) radiation differences between cases with 10 and 21% O_2, estimated using the GENESIS 3 radiation model, which is based on the CCM3 radiation scheme. Clear-sky profiles are consistent with responses simulated by Goldblatt using the SMART model and indicate a decrease in the net TOA radiation as a result of increased LW loss associated with a reduction in pressure broadening of absorption lines of radiatively active gases. In contrast, total-sky profiles that include clouds show an increase in the net TOA radiation. The radiation profiles are estimated using the stand-alone GENESIS 3 radiation scheme using atmospheric profiles of water vapor and temperature provided to us by Goldblatt. For total-sky estimates, cloud profiles come from climatologies of the 21 and 10% O_2 GENESIS simulations. Both sets of profiles assume a TOA solar input of 338 W m^{-2} and a zenith angle of 60°.

It is well known that clouds have a large influence on Earth's radiation budget and that cloud feedbacks can determine the climate response to a forcing (*5*). As a crude illustration of the influence of clouds due to a reduction in O_2, we include results for total-sky conditions using global-average cloud profiles from climatologies of GENESIS 10 and 21% O_2 simulations. The total (cloudy and clear sky) top-of-atmosphere (TOA) response to a reduction in O_2, –1.4 and 5.1 W m^{-2} in longwave and shortwave, respectively, is much different and the net (longwave + shortwave) response is opposite in sign (positive) than the clear-sky response (Fig. 1), confirming the importance and warming effect of cloud feedbacks. We note that the response described here differs, mainly in the surface total-sky longwave response, from the GCM response because the temperature and water vapor profiles are from Goldblatt and do not account for GCM-simulated water vapor and lapse rate feedbacks.

As illustrated by our radiation scheme calculations, feedbacks are responsible for the warming response in GENESIS. The initial response to lower O_2 is an increase in surface shortwave forcing, a warming of the surface and boundary layer, and a reduction in atmospheric stability. Low-level warming has two direct effects: a decrease in low-level, mainly stratus, clouds and an increase in convective activity. Low-level stratus cloud fraction is determined in the model by a relative humidity threshold and the presence of either vertical ascent (for frontal clouds) or low-level stratification (for marine stratocumulus clouds) (*6*, *7*). With greater surface shortwave radiative heating under low O_2, the low-level relative humidity rises slightly (<2%), whereas both vertical velocities in regions of mean ascent and low-level inversions decrease [see, e.g., figs. S3 and S5 in (*1*)]. The net result is a decrease in low-cloud fraction, which acts as a positive feedback on surface shortwave forcing. Between equilibrium runs of 10 and 21% O_2, this positive cloud feedback leads to a net surface shortwave forcing difference of 4.8 W m^{-2}.

Enhanced surface shortwave forcing under low O_2 also drives both deeper and more frequent convection. (The overall increase in convection and reduction in mean vertical velocities are confirmed by corresponding increases and decreases in simulated global-average convective and large-scale precipitation.) Convective moistening of the lower and mid-troposphere is seen in higher relative humidity (by up to 10%) and increases the downward longwave flux at the surface by 9.2 W m^{-2}, acting as an additional positive feedback on surface radiative forcing.

In addition to positive feedbacks, there are two weaker negative feedbacks: (i) the moistening of the atmosphere scatters incoming shortwave radiation, reducing the surface net clear-sky

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shortwave forcing by –0.9 W m^{-2}, and (ii) the reduction in low-level clouds allows greater longwave escape from the surface by 5.6 W m^{-2}.

The explanations above address the two concerns raised by Goldblatt. The feedback mechanisms above were detailed in Poulsen *et al.* With that said, we agree that the description of scattering in Poulsen *et al.* was not as clear as it could have been and should have been referred to as total scattering (Rayleigh and Mie). We do not agree with a series of generalizations made by Goldblatt that are not relevant to Poulsen *et al.* Briefly, the reference to (*8*) is inappropriate. That study examines the differences in radiation code response to atmospheric CO_2, which is not at issue here. Likewise, characterizing the GENESIS GCM cloud forcing in a study of the ice-free mid-Cretaceous based on snowball earth simulations with globally prescribed surface ice is irrelevant. There is no way to assess that the GENESIS cloud response in the snowball Earth comparison study is less correct than the other GCMs considered in that study; the authors of the study do not make such a claim (*9*). Incidentally, Poulsen *et al.* is not the first to have found that clouds may be important in explaining past warm climates [e.g., (*10*–*13*)].

Poulsen *et al.* considers the climate system response to changes in atmospheric mass and, in this way, is a step forward. The study identifies a new forcing and provides mechanisms that potentially mitigate climate model mismatches with past climates. Nonetheless, we caution that the results, as in all modeling studies, have some element of model dependence and must be confirmed through additional climate modeling efforts that incorporate feedbacks. Our hope is that the study motivates a closer look at the effects of changes in atmospheric mass as a potential climate forcing throughout Earth history.

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