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Global warming due to increasing absorbed solar radiation

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[1] Global climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) are examined for the top-of-atmosphere radiation changes as carbon dioxide and other greenhouse gases build up from 1950 to 2100. There is an increase in net radiation absorbed, but not in ways commonly assumed. While there is a large increase in the greenhouse effect from increasing greenhouse gases and water vapor (as a feedback), this is offset to a large degree by a decreasing greenhouse effect from reducing cloud cover and increasing radiative emissions from higher temperatures. Instead the main warming from an energy budget standpoint comes from increases in absorbed solar radiation that stem directly from the decreasing cloud amounts. These findings underscore the need to ascertain the credibility of the model changes, especially insofar as changes in clouds are concerned. **Citation:** Trenberth, K. E., and J. T. Fasullo (2009), Global warming due to increasing absorbed solar radiation, *Geophys. Res. Lett.*, *36*, L07706, doi:10.1029/2009GL037527.

1. Introduction

[2] Climate model changes from 1950 to 2100 in energy-related quantities provide a new perspective on issues important for climate change, and highlight the role of changing clouds that lead to an opening of an aperture for solar radiation. In contrast the conventional wisdom is that longwave (LW) radiation anomalies dominate the planetary imbalance and warming is from a "blanketing" effect. The models are those used for the AR4 from the Third Coupled Model Intercomparison Project (CMIP3) [*Randall et al.*, 2007; *Meehl et al.*, 2007]. Here the focus is on the A1B moderate emissions scenario. The observational context is given by *Fasullo and Trenberth* [2008a, 2008b].

[3] The main control on incoming top-of-atmosphere (TOA) solar radiation aside from the sun-Earth geometry is the planetary albedo, which can change at high latitudes as snow and ice change, or more generally as clouds or aerosols change [*Stephens et al.*, 2008]. At the same time, clouds help control outgoing longwave radiation (OLR), and fewer clouds can open the "iris" of the Earth [*Lindzen et al.*, 2001] to allow more radiation to escape from lower and warmer parts of the atmosphere and surface. Decreasing cloud amount also increases absorbed solar radiation (ASR) [*Lin et al.*, 2002]. These changes represent a feedback and not a forcing, however. The net radiation at TOA R_T = ASR-OLR.

[4] Understanding and correctly simulating these feedbacks are important. As greenhouse gases, including carbon dioxide, increase in the atmosphere, the increase in radiative forcing results in higher surface temperatures, increased water-holding capacity of the atmosphere, increased evaporation, and larger water vapor amounts. As water vapor is the dominant greenhouse gas, it results in a positive feedback and roughly doubles the surface temperature change [*Randall et al.*, 2007]. Associated with this feedback is an increase in OLR due to differential surface and tropospheric warming, the so-called lapse rate feedback, which partially offsets the increased greenhouse effect from water vapor [*Randall et al.*, 2007]. Decreases in snow and ice reduce the albedo and further amplify climate change, most notably in high latitudes over a small part of the globe [*Soden and Held*, 2006; *Bony et al.*, 2006; *Randall et al.*, 2007].

[5] But how should clouds change? Linkages between clouds and the energy budget are well established, and changes in cloud as the climate changes are a key feedback and the largest source of uncertainty in climate modeling [*Soden et al.*, 2004; *Bony et al.*, 2006; *Wyant et al.*, 2006]. Clouds block the sun and thus cause a cooling, but clouds also have a greenhouse effect and produce warming. In many regions, such as where there is deep convection, these two effects strongly compensate [e.g., *Kiehl*, 1994]. However, due to their disproportionate impact on shortwave (SW) and LW fluxes, low clouds play a particularly important role in climate as they are able to reduce ASR while having relatively little impact on OLR. The question of how clouds change is complicated by changes in atmospheric particulates (aerosol) not directly connected to the climate change but which can serve as cloud condensation nuclei and alter clouds in several ways. Here we show how clouds and radiation change in current climate models. Because these changes are physically significant and they amplify warming in most models, the basis for the reality of these changes deserves close scrutiny.

[6] Traditionally, the role of clouds has been viewed through the lens of "cloud radiative forcing" (CRF) which can be broken down into SW CRF and LW CRF, isolating the effects on ASR and OLR. In models this is computed by differencing the total radiation and the computed amount that would occur in the absence of clouds (so-called clear sky). The convention has been that "clear sky" includes aerosols, but is really a misnomer. Given difficulties in detecting whether some clouds seen from satellite are purely aerosol, purely water, or some mixture (which is likely), and given that clear-sky observations are biased towards quiescent conditions, this separation is at best artificial, and more weight should be placed on the unambiguous total changes in radiative fluxes, as done here. Moreover, as a measure of feedback, CRF can also be misleading when clear sky variability is not negligible [*Soden et al.*, 2004].

2. CMIP3 Archive

[7] One member (run1) of each model's simulation ensemble is chosen from the CMIP3 archive http://www-

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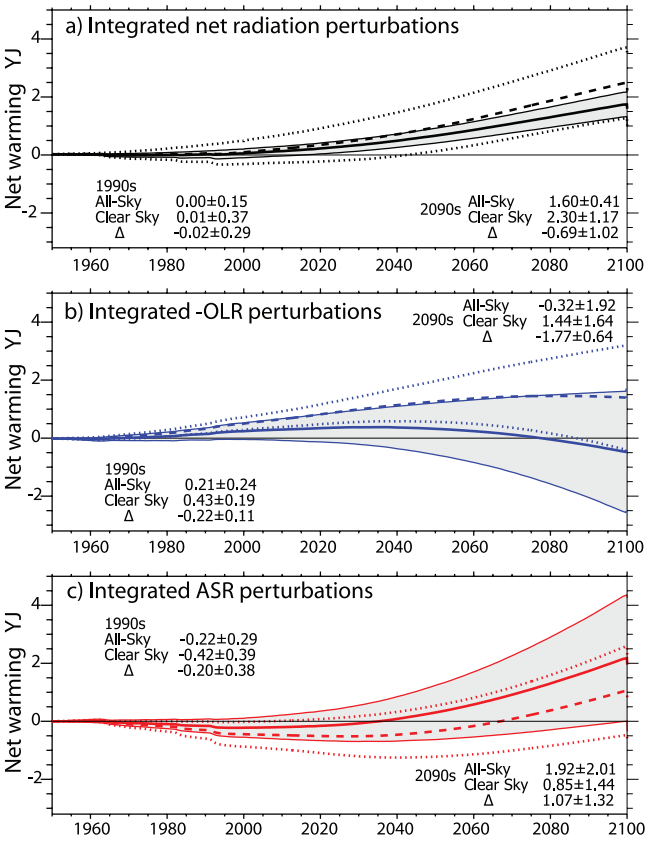

Figure 1. Integrated perturbations in (a) total net radiation R_T, (b) -OLR, and (c) ASR relative to 1900 to 1950 in 10^{24} Joules (YottaJoules, YJ) (R_T = ASR-OLR) for the clear sky (dashed) and all-sky (solid) for the A1B scenario. The range of plus and minus one standard deviation is shaded grey for all-sky. Values are given for the 1990s and 2090s for all-sky, clear sky and their difference, the CRF.

pcmdi.llnl.gov/ based on the Climate of the 20th Century (20c3m) simulations. We considered all 24 models but some have incomplete information, some apparently do not conserve energy, and some have artificial "flux adjustments" of energy, and these were excluded. Thirteen models were retained but computations were made for all. To examine changes over time, we remove the bias and examine differences relative to a base period of 1900 to 1950. The A1B and A2 IPCC scenarios, characterized as moderate and high emissions, were examined. Results are robust to choice of models and scenarios. Examination of runs by the same models forced only by increases in carbon dioxide at a rate of 1% per year, which remove complications from aerosols, confirm similar feedbacks.

3. Changing Energy Balance

[8] The integrated accumulated energy is examined (Figure 1) as this is what would be recorded in the changing heat content of the oceans [*Domingues et al.*, 2008]. It reduces the effects of natural variability which can be quite large in both individual models and their ensemble mean. The different behavior in TOA energy balance for the 1950 to 2000 period, versus that further into the future is noted, and observational constraints exist only on the past era [*Fasullo and Trenberth*, 2008a, 2008b].

[9] As greenhouse gases and associated radiative forcing increase, the models amplify the effect through increases in water vapor. Hence both clear sky and all-sky integrated OLR decrease initially (Figure 1) and there is a net heating of the planet. Snow and ice also begin to decrease and reduce albedo at high latitudes (Figure 2), thereby providing further amplification through ASR increases – the ice-albedo feedback. This feedback is strongly seasonal and greatest in spring, but occurs over only limited areas. A strong negative feedback develops as the planet warms and temperatures rise, thereby increasing OLR. From 1950 to 2000, the net result globally is a decrease in OLR and a net heating. Only after about 2050 does the increase in temperature become large enough to overwhelm the increasing greenhouse effect (Figure 1) and by 2100, the mean integrated planetary warming due the longwave feedback plus forcing is near zero in most models.

[10] This begs the question of why the temperature increase by 2085 to 2095 of 3.2 ± 0.6°C (relative to 1900 to 1950) is so large. In most models, the late 21st century planetary imbalance is not dominated by the ice-albedo effect, but rather stems from changes in clouds (Figure 3)

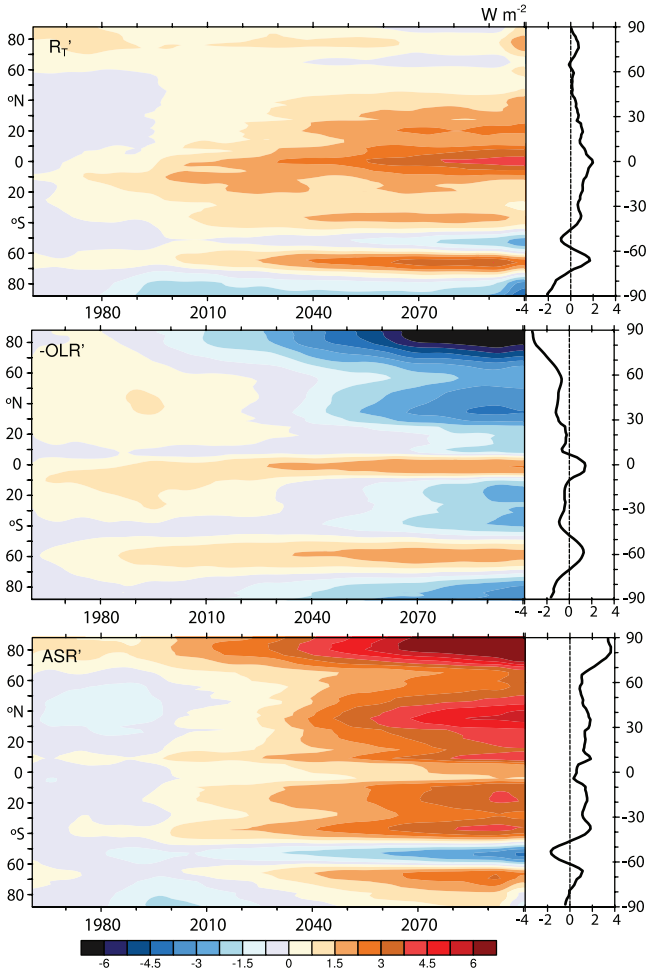

Figure 2. Latitude-time series from 1960 to 2100 of zonal average (top) net radiation R_T, (middle) -OLR, and (bottom) ASR in W m^{-2}, where R_T = ASR-OLR. (right) Average for 1950 to 2100.

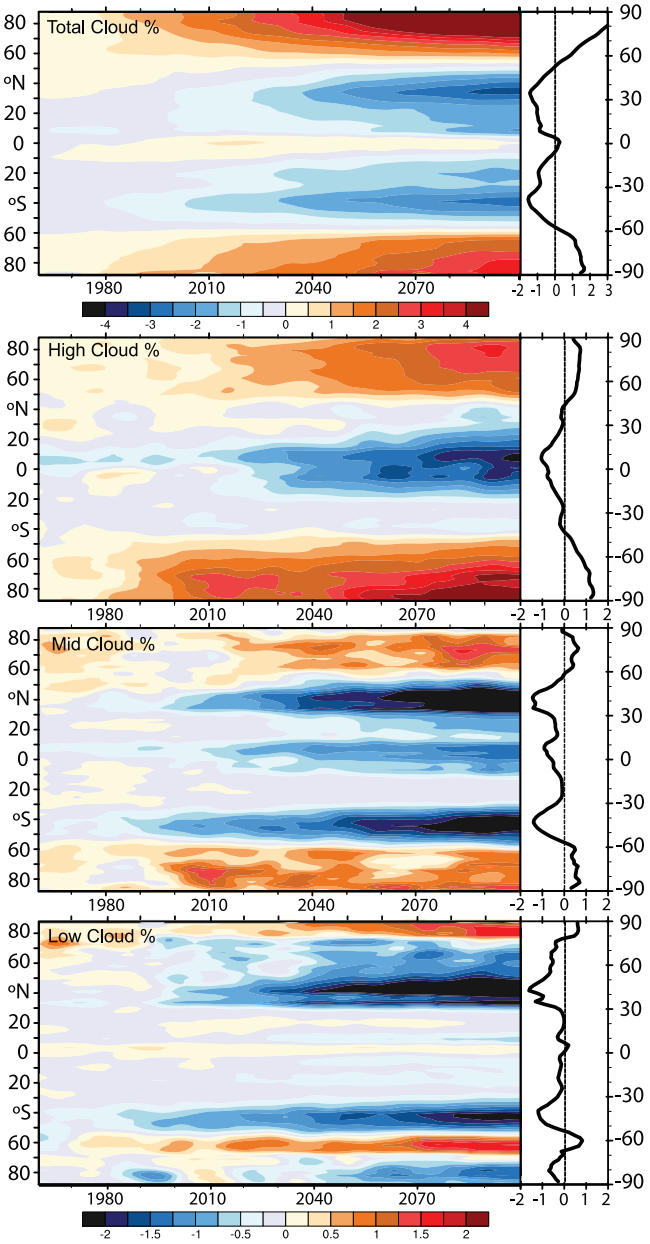

Figure 3. Latitude-time sections 1960 to 2100 of zonal mean percentage of area cloud amount change for the total, high, middle and low cloud. Note the different color key for total cloud. (right) Average for 1950 to 2100.

and aerosols. From 1950 to 2000, increases in sulfate aerosols decrease the ASR by increasing reflected solar radiation (RSR), and this is slightly offset by a modest decrease in clouds. In regions of decreasing sea ice, clouds tend to increase, partially offsetting the surface albedo change. By 2070 the integrated clear sky ASR anomaly (Figure 1) is positive as aerosols decrease (in the A1B scenario) and ice-albedo effects increase. But integrated all-sky ASR anomalies become positive by 2040 owing mainly to decreasing cloud amount and this continues throughout the 21st century (Figure 3). As clouds also have a greenhouse effect, their decrease offsets the impact of increases in greenhouse gases. The net effect is a huge change in LW CRF, but a modest change in OLR. Although varying substantially among models, the accumulated ensemble mean OLR perturbation is zero by 2080. There is substantial SW CRF although the increase in SW heating is bigger, and ASR dominates R_T (Figure 1).

[11] The spread among models (Figure 1) is large for both ASR and OLR, and the five coarsest resolution models have the weakest increase in ASR. Two of those models do not exhibit positive accumulated ASR but nevertheless have similar increases in R_T. The much smaller spread for R_T indicates large cancellation within each model owing to effects of clouds on both OLR and ASR.

[12] The total amount of clouds (Figure 3) is best defined, but changes in the low, middle and high cloud can also be estimated using definitions from the International Satellite Cloud Climatology Project (ISCCP) [*Schiffer and Rossow*, 1983]. The treatment of cloud overlap by radiation codes varies with model, however. At high latitudes, poleward of about 60°N and 50°S, large surface warming and decreasing sea ice are accompanied by more open ocean and local sources of moisture. Hence atmospheric moisture increases along with cloud cover, especially high cloud, which helps offset the reduced albedo from loss of snow and ice. In contrast, at low and especially mid latitudes, cloud amount decreases. Changes in low cloud are more important for SW CRF while changes in high cloud matter most for LW CRF in most models. In 2090 the total cloud decrease is 1.1 ± 0.5%.

[13] The spatial distribution of the linear trend in LW and SW radiation and cloud (Figure 4) for the 21st century reveals that the zonal average changes are fairly representative except for the tropical Pacific, where changes to more El Niño-like conditions occur [*Meehl et al.*, 2007]. The sea level pressure trends (not shown) reveal aspects of the change in atmospheric circulation, and suggest that conditions are more anticyclonic in the subtropics and especially mid-latitudes and with lower pressures at high latitudes. These changes are strongly reflected in ocean storm-track cloud, with a decrease in overall extratropical storm frequency, an increase in intensity, and a poleward shift of the storm tracks [*Yin*, 2005]. This appears to already be taking place as the tropics widen [*Seidel et al.*, 2008] perhaps more than models project.

4. Discussion and Conclusions

[14] Observations of changes in clouds and radiation [*Trenberth et al.*, 2007] are compromised by changes in instrumentation and calibration. At the surface, evidence of "dimming" until the 1990s, suggesting an increase in aerosols and/or clouds and reduced solar radiation at the surface, has reversed to become one of brightening. However, the sparse surface network is not global or representative of the oceans. Over the United States, an increase in cloudiness is associated with a change in atmospheric circulation [*Dai et al.*, 2006], but surface cloud observations are diminishing. Large disparities between surface and space-based observations from ISCCP show that trends from the latter are not reliable. Satellite estimates of cloud changes are compromised by the changing satellites but the corrected High Resolution Infrared Radiometer Sounder (HIRS) cloud observations from 1979 through 2001 show no trends in cloud cover [*Wylie et al.*, 2005]. Similarly for observations of the Earth's radiation, changes in instrumen-

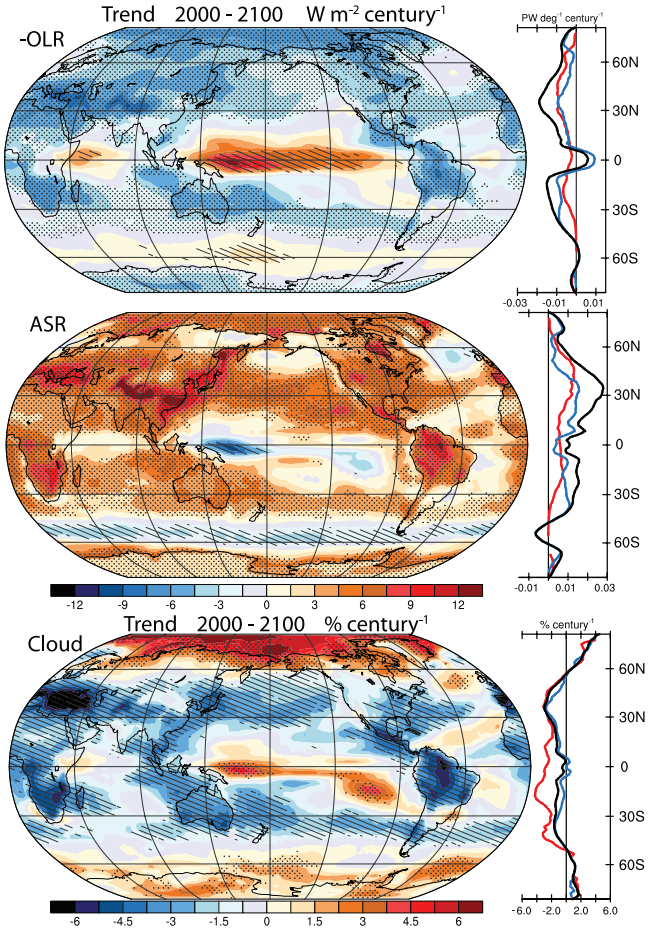

Figure 4. Linear trends from 2000 to 2100 in annual mean -OLR, ASR, (W m^{-2}) and cloud (%) per century from the mean of the CMIP3 climate models. At right is the zonal integrated amount in Petawatts per degree latitude per century for ASR and OLR, and % $century^{-1}$ for the zonal mean averages for cloud over ocean (blue), land (red) and total (black). Hatching (25th percentile) and stippling (75th percentile) is where ¾ of models share the trend sign.

tation do not allow changes to be detected between the Earth Radiation Budget Experiment (ERBE) and more recent Clouds and the Earth's Radiant Energy System (CERES) observations [*Fasullo and Trenberth*, 2008a]. A continuous record from Earth Radiation Budget Satellite (ERBS) is compromised by a discontinuity (late 1993) [*Trenberth et al.*, 2007].

[15] Boundary-layer clouds constitute the largest contributor to the range of cloud feedbacks among climate models [*Bony and Dufresne*, 2005; *Wyant et al.*, 2006]. The expansion of relatively dry regions of large-scale descent play a major role in tropical LW cooling by opening the Earth's iris to space, and changes in their area or humidity could affect water vapor feedback strength [*Lindzen et al.*, 2001]. Many papers refute the negative feedback and iris hypothesis of *Lindzen et al.* [2001] [e.g., *Hartmann and Michelsen*, 2002; *Randall et al.*, 2007]. Observational evidence questions decreases to convective clouds [*Del Genio et al.*, 2005] and properly accounting for SW CRF instead suggests a slight positive feedback [*Lin et al.*, 2002], seen here.

[16] Two climate models (NCAR and GFDL) show similar changes in large-scale lower tropospheric stability in regions of large-scale subsidence, which cover much of the tropics, but simulate the change in clouds differently thereby altering the model sensitivities [*Medeiros et al.*, 2008]. Generally, observations suggest that stronger lower tropospheric stability associated with widespread trade-wind inversions produces an increase in low cloud [*Klein and Hartmann*, 1993]. This relation is parameterized into the NCAR model but not the GFDL model. The changes in clouds in the CMIP3 models are more typical of those in the GFDL model. The NCAR model is the only model with increasing cloud, although the main increase is in the Arctic in the winter half year when it has little effect on ASR.

[17] Nevertheless, this raises the question of whether warming could be offset by increased low-level cloud cover as a negative cloud feedback [*Miller*, 1997]. Observations suggest that cloud undergoes a decrease in optical depth and positive SW CRF as temperatures rise [*Tselioudis and Rossow*, 1994], and the seasonal cycle, El Niño-related variations and other changes show that SW CRF decreases as SSTs rise in large-scale subsidence regimes [*Bony et al.*, 2004; *Bony and Dufresne*, 2005]. However, these studies do not provide information on how low clouds should respond when other aspects such as the large-scale dynamics, lapse-rate and temperature inversions also change [*Miller*, 1997].

[18] A key question is how large the role of changing cloud is in the overall climate change? The NCAR model is the only one with increasing cloud between 60°N and 60°S, but has a climate sensitivity of 2.7 K for doubling of carbon dioxide, only slightly lower than the overall mean of all models which average 3.2 ± 0.7 K. The transient climate response at time of doubling of carbon dioxide of 1.6 K is typical of many models which average 1.7 ± 0.4 K. Hence without the change in model clouds, warming would still occur and, while it may not be quite as large, it would be manifested somewhat differently owing to the change in solar radiation at the surface. Changes in CRF in climate models vary from positive to negative [*Meehl et al.*, 2007] yet all feature similar global temperature increases.

[19] The responses to global warming of both deep convective clouds and low-level clouds differ among models [*Randall et al.*, 2007] and suggest that differences in model cloud feedbacks in the 2090s mostly arise in the SW (see the spread in Figure 1). The changes in clouds in climate models are surprisingly large and play an important role in the climate change projections for the 21st century. They are, however, associated with changes in the atmospheric circulation that have some basis in observations. Understanding the physical processes that control the response of boundary-layer clouds and their radiative properties to a change in climate is exceedingly important but remains quite limited. New observations from CLOUDSAT and CALIPSO satellite missions [*Stephens et al.*, 2008] along with increased resolution of climate models may help resolve these issues.

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