Supplementary information for "Dependency of global precipitation on surface temperature"

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1 Cloud radiative forcing and cloud masking

"Cloud Radiative Forcing" (CRF), as described by *Cess et al.*, [1990], means estimating the radiative effects of clouds on climate by subtracting clear-sky fluxes from all-sky fluxes. However, because clouds intercept clear-sky radiation, there is a "cloud masking" effect that occurs independent of any changes in cloud [*Soden et al.*, 2004].

Consider the following thought experiment. Looking down from the Top Of Atmosphere (TOA), we imagine that all longwave clear-sky radiation can be thought of as coming from an emission layer, L, Figure 1.

Under some climate change outgoing TOA clear-sky longwave radiation from L increases by x Wm^{-2}. We now imagine that this particular region of sky is actually covered by an opaque cloud C that sits above the emission

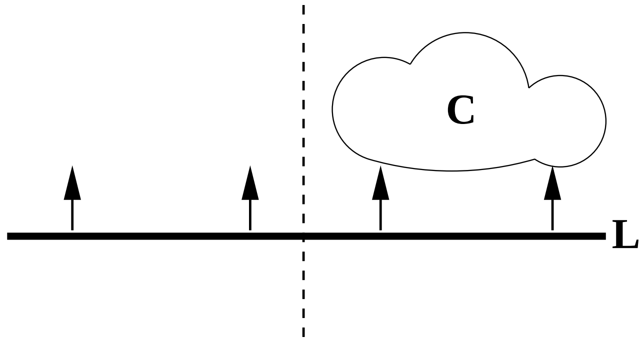

Figure 1: Outgoing clear-sky longwave radiation changes with climate change (left side). Where a cloud, C, lies between the clear-sky emission layer, L, and the TOA, it will intercept the clear-sky radiation and be erroneously attributed with applying an opposing longwave cloud feedback even if there are no changes in cloud cover or cloud radiation (right side).

layer L. We impose that C does not change under climate change, and hence provides no positive longwave cloud feedback. However, because C intercepts the radiation from L, when we calculate the CRF, we find it equal to $-x$ because all-sky outgoing longwave has not changed – this comes purely from the opaque cloud C in this region – but clear-sky longwave has increased by x. This is an example of the cloud masking effect.

At the TOA in GCMs, the cloud masking effect acts most strongly on the positive net downward clear-sky water vapor feedback [*Soden et al.*, 2004]. Hence, cloud masking tends to produce a negative net downward global mean effect at the TOA in the longwave. Similar effects may also occur at the surface. All are difficult to separate from true longwave cloud feedbacks without more sophisticated calculations requiring additional GCM simulations (e.g. *Colman*, [2003]).

2 SBDART experiments

In order to explore the effect of cloud masking on our GCM results, we conduct a number of idealised experiments using the Santa Barbara DISORT Atmospheric Radiative Transfer code (SBDART) (see acknowledgements in the paper). SBDART allows us to calculate radiative fluxes at the TOA and surface for prescribed atmospheric temperature and pressure profiles, water vapor content, greenhouse gas and ozone concentration, and cloud cover.

We use tropical mean data (20°N – 20°S) from each of the QUMP ensemble members (excluding QUMPlo-ent) to initialise SBDART. Cloud cover is specified very approximately, by noting that time-mean low clouds cover about 10% of the tropics, and time-mean high clouds about 20%. Hence, our study represents an exploration rather than a thorough investigation. Anomalies are calculated by subtracting SBDART equilibrium "control" runs from equilibrium 2xCO_2 runs. We also isolate the water vapor feedback by subtracting control runs from runs in which only the atmospheric water vapor concentration is changed to 2xCO_2 values. Cloudy fluxes are calculated by subtracting clear-sky anomalies from all-sky anomalies. All changes in SBDART cloud fluxes are attributable to cloud masking, because we impose control cloud throughout.

Results are shown in Figure 2. We compare our SBDART results to QUMP anomalies, also calculated as $2\times CO_2$ minus control. All radiative fluxes are plotted with respect to changes in tropical mean surface temperature, ΔT_{trop}. Surprisingly, SBDART fails to capture TOA behavior – even in the clear-sky, Figure 2a. A full investigation is needed, but it appears that this may be related to large spatial variability in tropical outgoing longwave radiation (OLR) in QUMP. QUMP mean OLR anomalies are negative. However, some regions show large positive changes in OLR. The TOA cloud OLR is fairly temperature independent in QUMP and SBDART, Figure 2b, which makes sense in the case of SBDART because clear-sky OLR is also almost temperature independent.

Behavior at the surface is more uniform, with increases in clear-sky downwelling longwave radiation (DLR) everywhere in QUMP. The SBDART runs produce similar behavior, capturing the temperature / radiation relationship for clear and cloudy skies. The water vapor feedback accounts for the bulk of the cloud masking effect in SBDART.

It is a plausible hypothesis, then, that cloud masking could account for the cloud DLR seen in the GCM runs, and that it is dominated by water vapor. Understanding total longwave cloud absorption will require expanding the survey beyond the tropics and understanding why our SBDART simulations do not capture the TOA response. It could be that GCM gridbox resolution integration of SBDART is necessary. At the very least, it will be important to recognise that the tropical atmosphere contains both deep convection and sinking zones and that these have very different radiative properties at the TOA.

3 References

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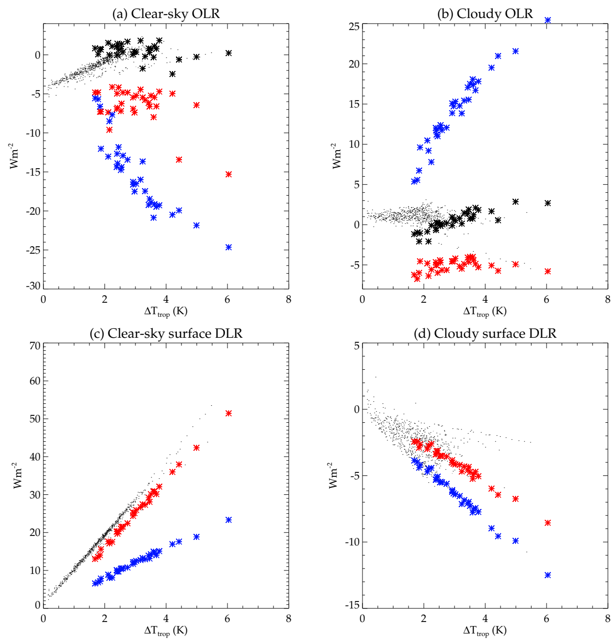

Figure 2: (a) Clear-sky outgoing TOA longwave radiation (OLR), (b) Cloudy OLR, (c) Clear-sky downward surface longwave radiation (DLR) and (d) Cloudy DLR, in QUMP slab transients (small black dots), QUMP equilibrium 2×CO_2 minus control (black stars), SBDART (red stars) and SBDART water vapor feedback only (blue stars). All fluxes are tropical mean (20°N – 20°S). QUMP equilibrium data are not available for (c) and (d).