A SIMULATION OF THE CLEAR-SKY SUPER-GREENHOUSE EFFECT

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SUMMARY

- **The Super-Greenhouse Effect (SGE) constitutes a potentially unstable *clear-sky longwave radiative feedback* to surface temperature (T_s) that involves *water vapour.***

- **The SGE is defined at the top of the atmosphere as:**
$dOLR/dT_s < 0\ Wm^{-2}K^{-1}$.
- **At the surface as the SGE is defined as:**
$dF_{net}/dT_s < 0\ Wm^{-2}K^{-1}$.

OLR is the clear-sky outgoing longwave radiation (Wm^{-2}) and F_{net} is the clear-sky surface net upward longwave cooling (Wm^{-2}).

- **The SGE is investigated using a simulation of the Earth's clear-sky longwave radiation budget that utilises 15 years of the ECMWF Re-Analysis data.**

- **Regions exhibiting the SGE are confined to the tropics for the top of the atmosphere radiation budget, but apply globally at the ocean surface over the seasonal cycle.**

- **Over interannual time scales the SGE acts mainly over the tropical Oceans.**

- **The SGE is generally manifest as a heating of the surface rather than in the atmosphere.**

- **OLR appears to be controlled by T_s at high latitudes and by Tropospheric Relative Humidity, TRH (%), at middle and low latitudes**

- **At the top of the atmosphere, the SGE occurs only in regions undergoing a significant change in the large scale circulation such as the shift in the Hadley circulation over the seasonal cycle.**

BACKGROUND AND OBJECTIVES

There exists a water vapour feedback to the climate system whereby the amount and distribution of atmospheric water vapour respond to a surface temperature, T_s (K), perturbation and alter the Earth's ability to cool through emission of outgoing longwave radiation, OLR (Wm^{-2}). A potentially unstable radiative feedback, which almost certainly involves water vapour, has been identified over regions of high sea surface temperature where where clear-sky OLR is observed to decrease with increasing surface temperature. This situation is termed the super-greenhouse effect (SGE) [**Halberg & Inamdar (1993)**].

The present study uses a 15 year simulation of the Earth's clear-sky radiation budget (CLERA, described in **Slingo *et al*. (1997)**) to investigate the spatial and temporal nature of this effect. The effects of clouds are not considered in the present study thereby providing information concerning clear-sky feedbacks only. There is no bias introduced by cloud-clearing algorithms as in similar satellite studies because radiative calculations are applied to clear-sky profiles. These are provided by the ECMWF re-analysis project which constitutes one of the most robust decadal scale analyses of the atmosphere available. Unique to this study is the global coverage (land and ocean), length of the data set (15 years) and the ability to simulate globally surface irradiance, which cannot be directly measured by satellite, as well as OLR. The following questions are addressed in this study:

- **What regions of the Earth exhibit a SGE?**
- **Is the spatial extent of the SGE regions dependent on the time-scale (e.g., seasonal and interannual)?**
- **How do the surface and the top of the atmosphere SGE differ geographically?**
- **Does the SGE constitute a potentially unstable feedback to the atmosphere or the surface or both?**
- **What controls the SGE at the surface and at the top of the atmosphere?**
- **What bearing does the SGE have on the water vapour feedback and climate-change?**

The SGE is defined at the surface as $dF_{net}/dT_s < 0\ Wm^{-2}K^{-1}$ and at the top of the atmosphere as $dOLR/dTs < 0\ Wm^{-2}K^{-1}$ where F_{net} is the clear-sky surface net upward longwave cooling (Wm^{-2}).

RESULTS

Spatially, the SGE is characterised by an increase in clear-sky longwave trapping by the atmosphere and a decrease in surface clear-sky longwave cooling with increasing surface temperature. To illustrate this, figure 1 shows atmospheric greenhouse trapping, G (which is the difference between surface emission, σT_s^4, and OLR, with units of Wm^{-2}) and surface longwave cooling, F_{net}, for 1 K sea surface temperature bins in July 1985. Above sea surface temperatures of about 295 K there are large increases in G and decreases in F_{net} with increasing T_s. Also plotted is the percentage global area for each temperature bin. This shows the regions of high T_s that display a SGE cover a relatively large portion of the globe

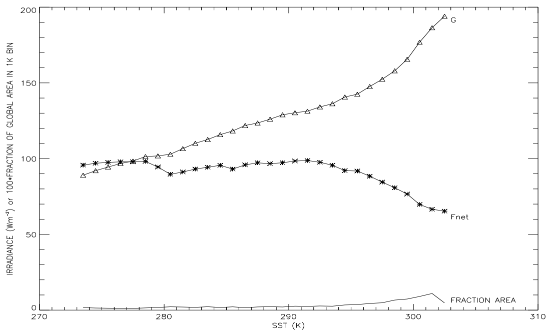

Figure 1: Clear-sky atmospheric greenhouse trapping, G (Wm^{-2}), and clear-sky surface net longwave cooling, F_{net} (Wm^{-2}), for 1K sea surface temperature bins. Also shown is the fraction global area of each temperature bin.

Using the 12 monthly means of the seasonal cycle, the sensitivity of OLR and F_{net} to T_s may be calculated using least squares fit linear regression. Figure 2 shows the regions of the globe exhibiting a SGE of the Earth-atmosphere system of negative $dOLR/dT_s$ (top), and a SGE at the surface of negative dF_{net}/dT_s (bottom). While the SGE observed from the top of the atmosphere applies mainly to the tropics, at the surface a SGE applies globally over the oceans. This implies that different mechanisms control the surface and top of atmosphere SGE. Interestingly, a thin band centred on the equator appears to show no SGE over the seasonal cycle. This may be explained by considering the top of atmosphere SGE to be determined by a north-south shift in the Hadley Circulation over the seasonal cycle; only regions only regions undergoing a significant change in the large scale imposed vertical motion produce the necessary changes in humididty to induce a SGE situation.. Undertaking the same calculations for the 15 years of the interannual time scale yields different results (not shown): The SGE regions both at the top of the atmosphere and at the surface are mainly confined to the tropical oceans. Here the largest top of atmosphere SGE signal is over the tropical central Pacific, a region that undergos a shift in the Walker circulation over the interannual time scale.

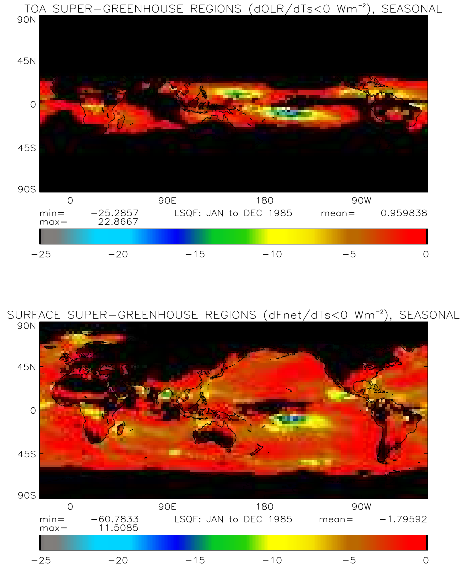

Figure 2: Least squares fit $dOLR/dT_s$ ($Wm^{-2}K^{-1}$) (top) and dF_{net}/dT_s ($Wm^{-2}K^{-1}$) (bottom) over the seasonal cycle in 1985. Only regions exhibiting a SGE are shown.

For both time scales, over all but a few regions of the tropical ocean, F_{net} decreases at a greater rate with increasing T_s than OLR does; thus although the atmosphere is less able to cool to space over regions of highest T_s, it is able to cool more effectively back, locally, to the surface. Therefore the SGE generally constitutes a potentially unstable longwave radiative feedback to the surface rather than to the atmosphere.

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To explain the dependence of the surface and top of the atmosphere SGE in terms of atmospheric absorption and emission, it is necessary to examine a clear-sky radiation budget, calculated by a narrow band radiative transfer scheme [described in **Forster & Shine (1997)**] for a tropical standard atmosphere (figure 3):

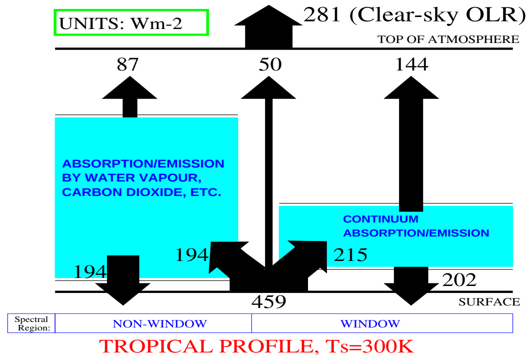

Figure 3: Narrow band calculated irradiance for a tropical standard profile split up into window and non-window regions of the longwave spectrum.

In the strongly absorbing non-window regions of the infrared spectrum (defined as 0-450 cm^{-1}, 610-710 cm^{-1}, 1310-2000 cm^{-1} and 2240-2400 cm^{-1}) almost all of the surface longwave emission is re-emitted locally back to the surface. Cooling of the surface occurs in the window region of the infrared spectrum (defined as 450-610 cm^{-1}, 710-1310 cm^{-1}, 2000-2240 cm^{-1} and 2400-3000cm^{-1}), which is controlled by the water vapour continuum absorption, itself dependent to a large extent on the column water vapour amounts. Cooling to space can be described by,

$$OLR = \int_0^{\infty}\left[B_v(0)Tr(0,\infty) + \int_0^{\infty} B_v(z)\frac{d}{dz}Tr_v(z,\infty)dz\right]dv \quad ,$$

where B_v denotes black body emission of wavelength v and $Tr_v(a,b)$ denotes the transmission at wavelength v between altitude a and b. Both B and Tr include an implicit integration over the zenith angle. This may be simplified for convenience to,

$OLR = Tr.\sigma T_s^4 + OLR_{atm}$,

where **Tr** is the effective clear-sky transmissivity of the atmosphere and $\mathbf{OLR_{atm}}$ is theclear-sky broad-band longwave emission to space from the atmosphere. Figure 3 shows that for the tropical profile much of the OLR is due to the OLR_{atm} term which depends on temperature and water-vapour amount throughout the atmosphere. In the strongly absorbing regions of the spectrum, OLR_{atm} mostly originates from the upper troposphere, while the emission is from lower in the atmosphere for the less absorbing regions of the spectrum. Because atmospheric temperature and water vapour have opposing effects on OLR_{atm}, a more informative parameter to explain variations in OLR is the relative humidity [e.g., **Soden & Fu (1995)**].

Figure 4 shows July mean Tropospheric Relative Humidity, TRH (%), calculated by applying a Gaussian weighting function centred on about 450 mb to the ECMWF Re-analysis RH fields for the 15 July's between 1979 and 1993. The moist upwelling regions of the Hadley Cell show up as shades of brown and red with TRH greater than 50 %, while the relatively dry subtropical subsidence zones show up as shades of blue with mean TRH of below 30%.

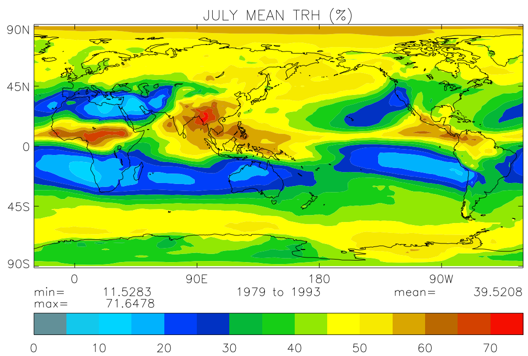

Figure 4: Mean Tropospheric Relative Humidity, TRH (%), for July, 1979 to 1993, calculated by applying a weighting function to the ECMWF Re-analysis RH that is maximum at approximately 450 mb.

The importance of Tropospheric Relative Humidity, TRH (%), and T_s in controlling OLR is highlighted by plotting the least squares fit correlation coefficient for $OLR=aT_s+b$ (figure 5, top) and OLR=aTRH+b (figure 5, bottom) over the interannual time scale (15 July's from 1979 to 1993). Strong positive correlation between clear-sky OLR and T_s over high latitude land regions is due to large atmospheric transmissivity causing the $Tr.\sigma T_s^4$ term to dominate in controlling the clear-sky OLR. At low latitudes areas of negative correlation between clear-sky OLR and T_s show the SGE regions over the interannual time scale. The strong negative correlation between OLR and T_s in the tropical central Pacific is likely a facet of the shiftin the Walker circulation over the El Nino Southern Oscillation cycle.

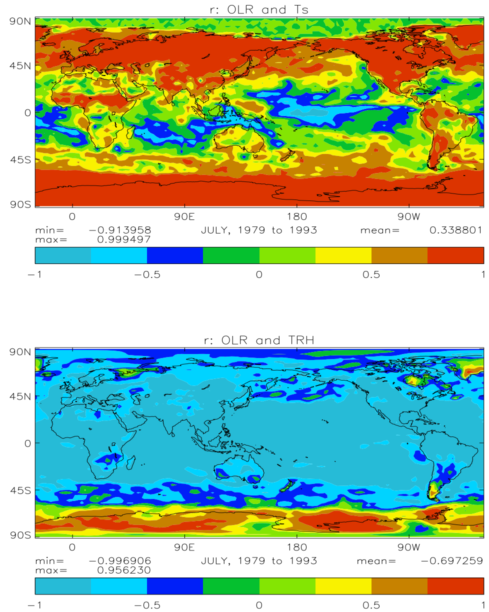

Figure 5: Least squares fit correlation coefficient, r, for OLR=aTs+b (top) and OLR=aTRH+b (bottom) over the 15 year interannual cycle for July

There is strong negative correlation between OLR and TRH in all but the highest latitudes with a global mean correlation of minus 0.7. This shows TRH to be an important parameter in explaining the variation in clear-sky OLR. Plotting the OLR sensitivity to TRH (figure 6) with mean TRH shows the low relative humidity regions to have the largest sensitivity. These regions are the relatively dry downwelling zones of the Hadley Circulation which show up in figure 4 as blue. The simulated sensitivity agrees with narrow band calculated sensitivities when relative humidity is perturbed between 100 and 1000 mb for a tropical standard profile (solid line in figure 6)

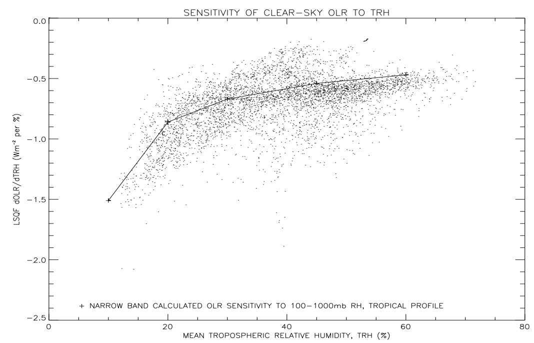

Figure 6: Least squares fit dOLR/dTRH (Wm^{-2} per %) over the 15 year interannual time scale for July plotted with mean TRH (%) and for r<-0.75. The solid line shows the narrow band calculated dOLR/dTRH for a tropical standard profile when relative humidity is varied between 100 and 1000 mb.

CONCLUSIONS

- **The geographical nature of regions exhibiting a SGE depends on the time scale considered. Therefore the mechanisms involved in giving rise to a SGE are dependent on the time scale of the variability.**
- **The simulated SGE at the surface and the top of the atmosphere act over different regions of the globe. This implies that different mechanisms control the SGE at the surface and at the top of the atmosphere.**
- **The surface SGE is likely to be driven to a large extent by the strong coupling between surface temperature and column moisture.**
- **The SGE at the top of the atmosphere is highly sensitive to relative humidity variations throughout the troposphere and is therefore likely to be influenced strongly by changes in the large scale circulation.**
- **This is highlighted by considering that the top of atmosphere SGE regions coincide with areas undergoing the largest shift in the large scale imposed regime such as the shift in the Hadley circulation over the seasonal cycle and the Walker circulation over interannual time scales.**
- **Because clear-sky OLR is strongly dependent on TRH which itself is dependent on the large scale circulation, a dynamical as well as thermodynamical water vapour feedback is likely to operate over the time scales relevant for climate change.**

Future work will address the questions**:**

- **At what level in the troposphere are relative humidity variations most important in influencing OLR variability?**
- **How do cloud radiative feedbacks interact with the super-greenhouse effect?**

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