

## CLAUSIUS CLAPEYRON AND THE REGULATION OF GLOBAL WARMING

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Satellite-based observations suggest that the response of global evaporation to Earth's warming is near the Clausius-Clapeyron relationship. However computer models that are the basis for predictions of dangerous anthropogenic global warming have an evaporation response that is only about one-third the Clausius-Clapeyron relationship. The computer model predictions of anthropogenic global warming are likely exaggerated.

### 1 Introduction

In large part it is precipitation that regulates life on Earth. Soil moisture is essential to sustain plant growth and biodiversity flourishes where water is abundant. Precipitation also has a bearing on local climate. It has long been recognised that the availability of surface water regulates evaporation and local temperature. Where there is abundant surface water and plant growth the local evaporation constrains temperature and in hot climates temperatures are very much higher in the absence of surface evaporation [1].

The hydrological cycle, including the evaporation of surface water and condensation of atmospheric water vapour to form clouds and precipitation, is an essential component of energy flow through the climate system. The Clausius-Clapeyron relationship is the rate of increase of saturated vapour pressure with temperature and is important in regulating many of the processes of the hydrological cycle. For example, as the temperature of the atmosphere increases its water holding capacity also increases according to the Clausius-Clapeyron relationship.

If we are to understand anthropogenic global warming and the potential threat of dangerous climate change, then it is essential to have a detailed knowledge of the processes of energy flow through the climate system. Much attention has been given to the exchange of energy by radiation processes, including absorption of solar energy at the Earth's surface and

the transfer of infrared radiation from the surface through the atmosphere to space. While a necessary consideration, these radiation processes are not sufficient to fully explain the greenhouse effect and its enhancement by changing concentrations of atmospheric carbon dioxide ( $\text{CO}_2$ ). Indeed, non-radiative exchange of energy between the surface and atmosphere associated with the hydrological cycle are also a crucial consideration.

The greenhouse gases (mainly water vapour and  $\text{CO}_2$ ) and clouds of the atmosphere emit more infrared-radiation energy, both back to the surface and to space, than that absorbed from the surface emission [2]. The ongoing loss of infrared radiation tends to cool the atmosphere. Very little solar radiation is absorbed as it passes through the atmosphere and, because of the Earth's geometry, most solar energy is absorbed at the tropical surface. Overall, radiation processes tend to warm the tropical surface and cool the global atmosphere.

The global energy balance is achieved by exchange of heat and latent energy from the surface to the atmospheric boundary layer and the vertical distribution of this non-radiative energy through the troposphere by buoyant convective overturning [3]. Energy is also transported from the tropics to polar regions by the atmospheric circulation [4]. Evaporation and convection are components of the global energy balance. The latent energy taken from the surface

during evaporation is released to the atmosphere by condensation and precipitation during convection. This released energy is available to offset the infrared radiation losses, or radiative cooling, of the atmosphere. Globally, the non-radiative energy exchange between the surface and the atmosphere is in steady state with the net radiative cooling of the troposphere.

The greenhouse effect arises because of thermodynamic requirements for buoyant convection. Most deep convection takes place in the tropics. Here the reduction in temperature with altitude (or temperature lapse rate) must exceed the saturated adiabatic lapse rate (approximately  $-6.5\text{ }^{\circ}\text{C}/\text{km}$  near the surface and increasing to near  $-10\text{ }^{\circ}\text{C}/\text{km}$  in the high troposphere). That is, for vertical distribution of energy by buoyant convection the surface temperature must be warmer than that of the middle and upper troposphere. The surface temperature is a function of both the effective blackbody temperature of the Earth (globally averaged, approximately  $-19\text{ }^{\circ}\text{C}$ ) and the average altitude in the atmosphere from which infrared radiation to space emanates (a little more than 5 km). The altitude of emission and the critical temperature lapse rate ensure that, on average, the surface temperature is about  $33\text{ }^{\circ}\text{C}$  warmer than the effective blackbody emission temperature, or about  $14\text{ }^{\circ}\text{C}$ . This is the greenhouse effect.

Anthropogenic global warming is an enhancement of the greenhouse effect as the concentration of  $\text{CO}_2$  in the atmosphere is increased by burning fossil fuels.

An increase in concentration of  $\text{CO}_2$  in the atmosphere affects the flow of infrared radiation in two ways. Firstly, as is commonly understood, the radiation to space is reduced; secondly, the downward infrared radiation at the surface

is increased. The magnitude of the increased downward radiation at the surface is only marginally different from the reduction in upward radiation at the tropopause and hence the overall radiation cooling of the troposphere is little changed. Although the concentration of  $\text{CO}_2$  changes this does not directly warm the troposphere.

The principal effect of the increased  $\text{CO}_2$  concentration is through the increased downward infrared radiation and its influence on the surface energy budget (see box 1). The enhanced downward infrared radiation increases the input energy to the surface and the surface temperature rises. As the temperature rises the surface loses additional energy in three ways: i) through increased infrared emission, ii) through direct heat exchange, and iii) through evaporation of latent energy. Each of these energy loss processes is enhanced, directly or indirectly, as the surface temperature increases.

The surface energy processes are critical for regulating the enhanced greenhouse effect and are well understood. The critical factor defining the eventual steady-state surface temperature is how surface energy loss is partitioned between the three loss processes. For example, it is well understood that the surface temperature of freely evaporating water bodies and transpiring vegetation over land surfaces is considerably lower than that of dry arid land surfaces. A detailed formulation and evaluation of surface temperature sensitivity to increasing concentrations of  $\text{CO}_2$ , under differing conditions of evaporation response, is given elsewhere by the author [5]. Table 1, taken from that study, gives indicative results that underscore the importance of evaporation in determining the new steady-state temperature.

	Rate of increase of evaporation	Surface temperature response
Rate of increase of evaporation (and latent heat exchange) with surface temperature	$6\% \text{ }^{\circ}\text{C}^{-1}$ (satellites)	$0.9\text{ }^{\circ}\text{C}$
	$2\% \text{ }^{\circ}\text{C}^{-1}$ (Average GCM)	$2.2\text{ }^{\circ}\text{C}$
	$1\% \text{ }^{\circ}\text{C}^{-1}$ (Low-end GCM)	$3.4\text{ }^{\circ}\text{C}$

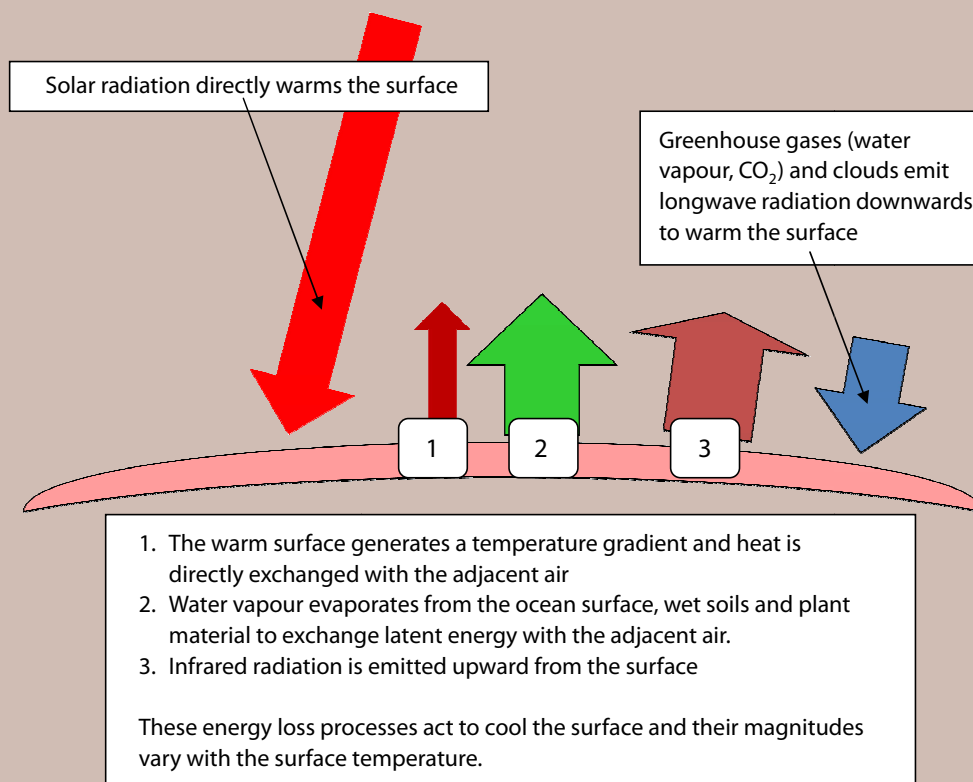
Tab. I Indicative values of expected steady-state surface temperature response to double carbon dioxide forcing depending on the rate-of-surface evaporation change with temperature. The higher value of rate-of-evaporation increase is a little less than the Clausius-Clapeyron relationship and is based on satellite estimates of global precipitation; the lower values represent those found in computer models of the climate system (GCMs) used in the IPCC Fourth Assessment (taken from Kininmonth [5]).

**BOX 1****The surface energy budget: The uncertainty of evaporation**

Some of the solar energy entering the Earth's atmosphere is reflected back to space from the clouds and surface and a little is absorbed within the atmospheric layer. A large fraction of the solar energy reaches the surface and is absorbed to warm the surface. The greenhouse gases (water vapour and  $\text{CO}_2$ ) and clouds of the atmosphere emit longwave radiation back to Earth and this energy also acts to warm the surface.

The Earth's surface achieves energy balance and temperature equilibrium because it loses energy by way of direct heat exchange and evaporation of latent energy to the adjacent atmosphere, and by emission of longwave radiation from the surface.

As  $\text{CO}_2$  concentration in the atmosphere increases so also the longwave radiation to the surface increases; there is an energy imbalance at the surface and the temperature begins to rise. As the temperature is raised the surface energy loss processes increase to find a new steady-state temperature. The magnitude of the temperature rise is confounded by uncertainty as to the rate of increase of evaporation with temperature. Theory and satellite assessments suggest a rise near the Clausius-Clapeyron relationship of  $6\% \text{ } ^\circ\text{C}^{-1}$  but model studies simulate a value closer to  $2\% \text{ } ^\circ\text{C}^{-1}$ . If the rate is near the Clausius-Clapeyron relationship then the global temperature rise from a doubling of  $\text{CO}_2$  concentration is likely less than  $1 \text{ } ^\circ\text{C}$  and not dangerous; if the rate is  $2\% \text{ } ^\circ\text{C}^{-1}$  or less as models suggest, then the global temperature rise might be more than  $2 \text{ } ^\circ\text{C}$  leading to dangerous climate change.



If evaporation and latent energy exchange increase near the Clausius-Clapeyron relationship (globally near 6 percent per degree Celsius,  $6\% \text{ }^{\circ}\text{C}^{-1}$  as given by satellite estimates) then the surface temperature response to a doubling of  $\text{CO}_2$  concentration is muted. However, if the increase is lower, as is simulated in the computer models of the climate system (GCMs), then most of the radiation forcing from increased  $\text{CO}_2$  concentration must be taken up as infrared-radiation emission and the surface temperature increase becomes much larger.

## 2 The hydrological cycle

There is uncertainty about quantification of the global average evaporation response to surface temperature variation and this uncertainty cascades through to predictions of global temperature response to  $\text{CO}_2$  forcing.

In GCMs the surface evaporation is calculated using a standard formula taking account of wind speed, near-surface stability and the specific humidity gradient. If the wind speed, stability and surface relative humidity remain constant, then the evaporation will increase with temperature according to the Clausius-Clapeyron relationship, or near  $7\% \text{ }^{\circ}\text{C}^{-1}$ .

Evaporation is a very difficult quantity to measure with accuracy. However water vapour only spends about two weeks in the atmosphere between evaporation and precipitation. Over periods of a month or longer the global precipitation approximates to the global evaporation, and precipitation is amenable to measurement. A number of satellite-based methods have been developed to estimate precipitation and regional estimates have been validated using surface observations. Wentz *et al.* [6] have used satellite-based methods to estimate the change in precipitation (and therefore evaporation) as global surface temperature varied during the 1980s and 1990s. Their estimate of about  $6\% \text{ }^{\circ}\text{C}^{-1}$  is only slightly less than the Clausius-Clapeyron relationship. The difference was rationalised as being reasonable because of the existence of arid land areas with reduced evapotranspiration compared to that of transpiring forests and the oceans.

Analyses of the GCM used in support of anthropogenic-global-warming predictions of the 2007 IPCC Fourth Assessment Report (AR4) have identified that, on average, the rate of increase of global evaporation with temperature in these models is only about  $2\% \text{ }^{\circ}\text{C}^{-1}$  [7]. For individual models the rate of increase of evaporation with temperature ranges between  $1\% \text{ }^{\circ}\text{C}^{-1}$  and  $3\% \text{ }^{\circ}\text{C}^{-1}$  [6]. The reasons for the apparently low rate of increase of evaporation with temperature in the GCM has been studied by Richter and Xie [8] who found a consistent decrease in surface wind speed, increase in boundary layer stability and increase in boundary layer relative humidity; each of these contributes

to suppressing the rate of increase of evaporation below the Clausius-Clapeyron relationship.

The relationships set out in table 1 highlight the importance of identifying what is a realistic rate of increase of evaporation with temperature. The range of sensitivity of global temperature to double  $\text{CO}_2$  suggests that the response could be less than  $1 \text{ }^{\circ}\text{C}$  and not dangerous if the evaporation response is near the Clausius-Clapeyron relationship, as might be expected with a water planet. Alternatively, if the evaporation response is as the GCM simulations suggest, then a dangerous temperature rise significantly greater than  $2 \text{ }^{\circ}\text{C}$  is plausible. It is important to identify the real rate of increase of evaporation with temperature for Earth and resolve the uncertainty.

## 3 The global energy budget

A steady-state climate system requires that the non-radiation energy exchanges (heat and latent energy) between the surface and the atmosphere should equate with the radiative cooling of the atmosphere. Clearly, if radiation cooling of the atmosphere is constrained, then the ability of the atmosphere to receive heat and latent energy from the surface is also constrained and the surface will warm. Such constraints do not occur if the atmospheric temperature and moisture structures and the cloud distribution can readily respond to changing surface energy exchanges and modify the radiation cooling of the atmosphere.

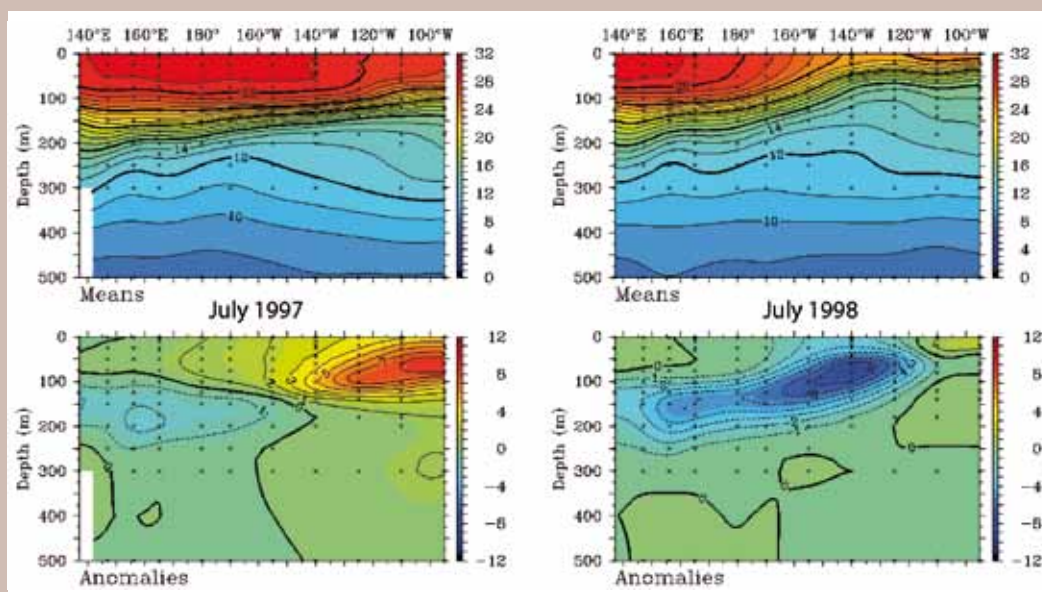
Set out in table 2 are indicative values for the radiation cooling of the troposphere (units  $\text{W}/\text{m}^2$ ) for changes in atmospheric  $\text{CO}_2$  concentration and global temperature. The  $\text{CO}_2$  concentrations are 400 ppm (near present values) and 800 ppm (a doubling of concentration expected near the end of the century). The radiation cooling has been computed using the MODTRAN program of the University

CO <sub>2</sub> concentration		
	400 ppm	800 ppm
US Standard Atmosphere	-138.8	-137.3
US Standard Atmosphere +1 °C	-141.6	-139.6

Tab. 2 Indicative values of radiation cooling of the troposphere ( $\text{W}/\text{m}^2$ ) with different  $\text{CO}_2$  concentrations and global temperatures.

**BOX 2****Ocean dynamics changes surface temperature patterns**

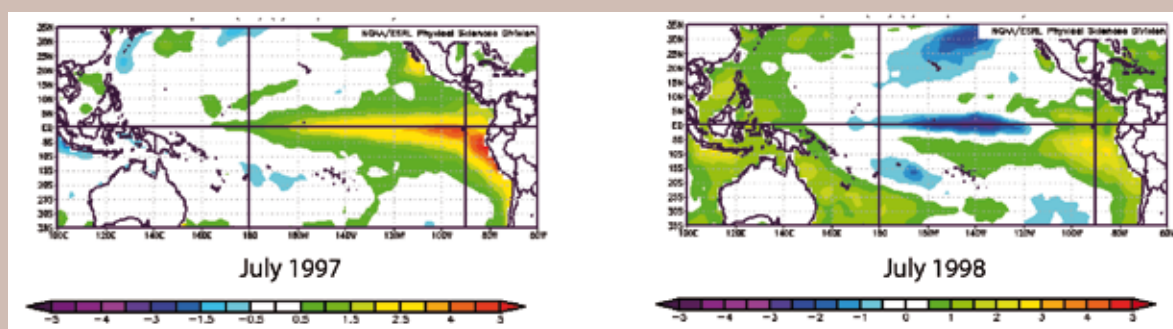
El Niño is a climate event that has a life cycle of about a year and recurs with varying intensity every few years. Not only is there significant change to the tropical temperature patterns of the Pacific Ocean but also there are dramatic global impacts on climate. In July 1997 an El Niño event was nearing peak intensity but by July 1998 the event had collapsed.



(Depth sections from the TAO Program Office of the US NOAA/Pacific marine Environmental laboratories from their web site <http://www.pmel.noaa.gov/tao/disdel/disdel.html>)

The warm tropical oceans are no more than a thin lens overlying the cold interior. The top panels (LHS – July 1997; RHS – July 1998) are depth sections of the upper 500 metres of the equatorial Pacific Ocean stretching approximately 12000 km from New Guinea to Ecuador. There is a strong vertical temperature gradient at about 200 metres separating the warm mixed surface layer from the cold subsurface water that extends to the ocean floor. The cold ocean interior is maintained by the thermohaline circulation as cold saline water sinks during formation of polar sea ice in autumn and winter. Across the tropical oceans ascending cold subsurface water that is displaced by sinking polar water mixes into the surface layer to regulate temperature.

The lower panels are of the temperature anomalies for July 1997 (LHS) and July 1998 (RHS). These highlight the variability of tropical surface mixed layer temperature due to changes in upwelling and mixing of cold subsurface water over the equatorial Pacific Ocean.



(Anomaly of Sea surface temperature)

The ocean surface temperature anomaly charts (July 1997 – LHS; July 1998 – RHS) show that changing upwelling regulates surface temperature over an extensive area of the tropical Pacific Ocean.



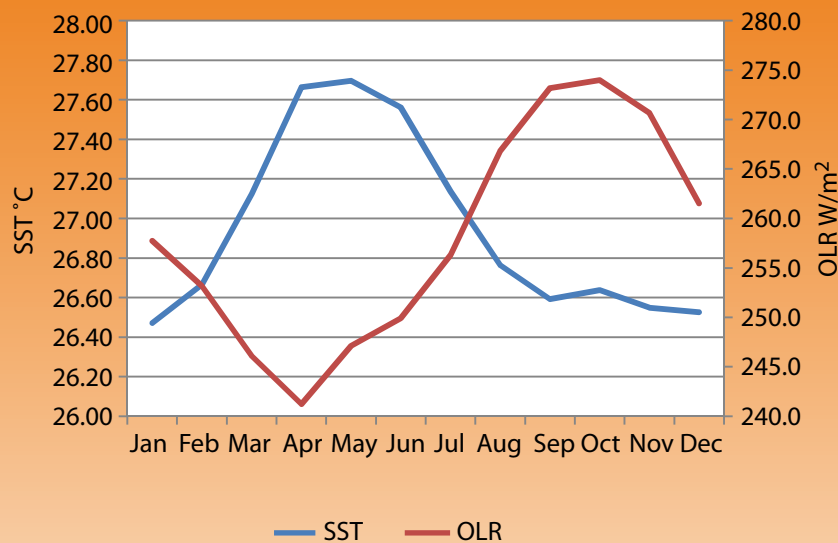


Fig. 1 A comparison of monthly average sea surface temperature (SST) and outgoing longwave radiation to space (OLR) over the Niño 3.4 region of the equatorial Pacific Ocean (Lat 5° N to Lat 5° S; Long 170° W to Long 120° W). Note that there is a negative correlation between the sea surface temperature because as sea surface temperature increases there is an increase in the intensity of deep convection in order to disperse the additional heat exchanged from the surface; more deep convection clouds with cirrus outflow means that the infrared radiation to space decreases because it originates from a higher colder altitude.

of Chicago [9] and is for the troposphere based on the US Standard Atmosphere (tropopause at 10.5 km) under clear-sky conditions. In these calculations the relative humidity of the atmosphere has been held constant so that atmospheric water vapour increases with temperature according to the Clausius-Clapeyron relationship (the water vapour feedback condition). Table 2 indicates that the radiation cooling of the troposphere decreases slightly as the CO<sub>2</sub> concentration increases but increases as the surface and tropospheric temperature increase. Overall, for a doubling of CO<sub>2</sub> concentration and a 1 °C temperature increase, there is a small increase in radiation cooling of about 0.8 W/m<sup>2</sup>.

The global average latent energy exchange from the surface can be estimated from the global precipitation and is about 78 W/m<sup>2</sup>. If the rate of evaporation increases according to the Clausius-Clapeyron relationship of 7 % °C<sup>-1</sup>, then a 1°C surface temperature rise would increase the rate of latent energy exchange by about 5.6 W/m<sup>2</sup>. This is significantly greater than the indicative 0.8 W/m<sup>2</sup> increase in radiation cooling attributed to the doubling of CO<sub>2</sub> concentration and a 1°C temperature increase set out in table 2.

On this evidence it is possible that there is a relatively slow rate of change of radiation cooling of the troposphere and evaporation response could be constrained to a value well below the Clausius-Clapeyron relationship. That is, the low rate of evaporation increase of the GCMs that is significantly less than the Clausius-Clapeyron relationship might be a

realistic response to changing CO<sub>2</sub> concentration. Under these conditions, for a new steady-state surface temperature the additional energy accumulation at the surface from the enhanced CO<sub>2</sub> back radiation forcing is required to be offset by significantly greater infrared-radiation emission. The steady-state temperature increase under these conditions would be higher for a doubling of CO<sub>2</sub> concentration than if the evaporation rate is closer to the Clausius-Clapeyron relationship.

However there is still the contrary satellite-derived estimate of surface evaporation change to consider. This latter indicates that evaporation does indeed increase near the Clausius-Clapeyron relationship. We are left with the dilemma: does radiation cooling of the atmosphere constrain surface evaporation (as suggested by the GCM response), or does the atmosphere respond, as the satellite analyses suggest, and generate appropriate structures for additional radiation cooling needed to accommodate a higher rate of evaporation?

#### 4 Surface temperature forcing

Most of the non-radiative energy exchange between the Earth's surface and the atmosphere takes place over the tropics and the distribution through the atmosphere by way of deep convection is largely over the equatorial region. Across the equatorial Pacific Ocean there are both

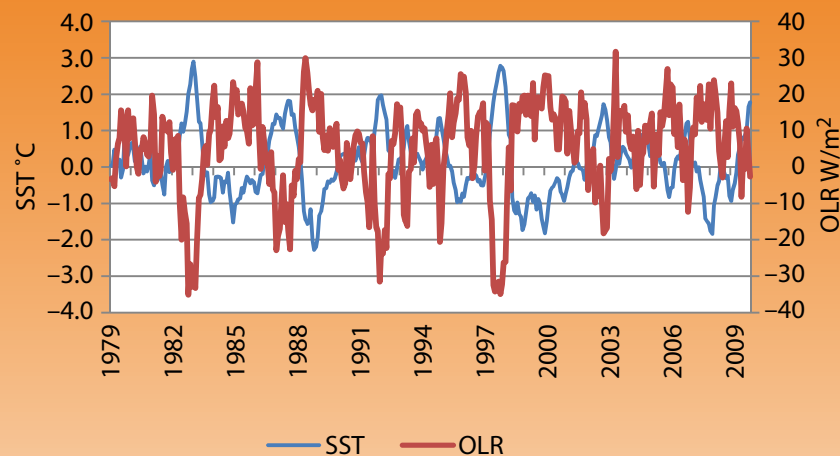


Fig. 2 Monthly anomalies of sea surface temperature (SST) and outgoing longwave radiation (OLR) to space over the Niño 3.4 region of the equatorial Pacific ocean (Lat 5° N-Lat 5° S; Long 170° W-Long 120° W) covering the satellite period 1979–2009. Note that as sea surface temperature increases during major El Niño events (reduced mixing of cold subsurface water into the surface layer) then the accompanying increase in deep convection clouds causes a decrease in longwave radiation to space. Outgoing longwave radiation to space increases during La Niña events because enhanced mixing of cooler subsurface water into the surface layer reduces surface temperatures and convection is suppressed.

seasonal and interannual variations in surface temperature and cloudiness to test for consistent relationships between surface temperature variation and atmospheric response.

**Box 2** illustrates how ocean dynamics can vary temperature patterns across the tropical Pacific Ocean. The apparently warm tropical ocean is only a thin lens overlying the deep cold interior. The interior of the ocean is kept cold by the thermohaline circulation where highly saline and near freezing polar waters under winter sea ice sinks to the ocean floor. The slow return ascent of this cold water in the tropics means that as it mixes into the surface layer it regulates the temperature.

The easterly Trade Winds blowing across the equatorial Pacific Ocean cause the maximum upwelling and mixing of cold subsurface water to occur off the coasts of South and Central America and out into the equatorial Pacific Ocean. Thus changes in the strength of the Trade Winds will vary the rate of upwelling and hence the surface temperature. The Trade Winds across the Pacific Ocean vary seasonally and also on an interannual period with the well-known El Niño phenomenon.

**Figure 1** shows that the annual range of sea surface temperature variation over the so-called Niño 3.4 region of the equatorial Pacific Ocean (Lat 5° N to Lat 5° S; Long 120° W to Long 70° W) is a little more than 1 °C. When sea surface temperature is a maximum during the months April through June there is a build-up of deep convection clouds that cause

the outgoing longwave radiation to space to emanate from the high cold cirrus outflow cloud tops and thus reduce in intensity. The reduction in intensity of OLR as the clouds evolve is more than 30 W/m<sup>2</sup> and near an order of magnitude greater than the radiation forcing (about 4 W/m<sup>2</sup>) from a doubling of CO<sub>2</sub> concentration.

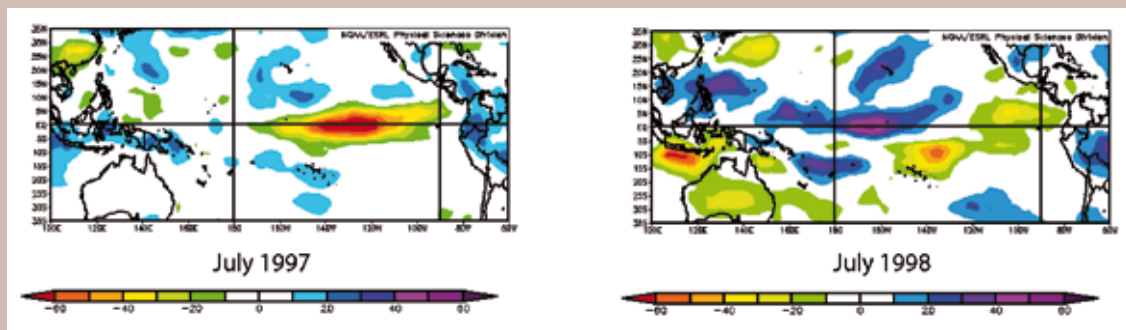
**Figure 2** is a time history of surface temperature anomaly and outgoing longwave radiation anomaly over the Niño 3.4 region since 1979. The variation of surface temperature anomaly covers a range that some expect of global warming from a doubling of CO<sub>2</sub> concentration. The response of equatorial convection suggests that as surface temperature rises then additional energy is shed from the surface as heat and latent energy. Convection increases to transfer the additional energy vertically. These observations give no indication that radiation cooling of the troposphere is constraining deep convection in any way. The local build-up of convection and reduction in outgoing longwave radiation to space are a direct response to increase in surface temperature and the corresponding increase in non-radiative energy exchange from the surface. The local build-up of convection enhances the vertical transfer of energy away from the boundary layer.

**Box 3** describes how the atmospheric circulation, cloud distribution, and patterns of outgoing longwave radiation respond to changing ocean temperature patterns. A surface temperature increase across the equatorial Pacific Ocean

## BOX 3

**Changing ocean surface temperature regulates local convection and radiation to space**

The changing surface temperature over the equatorial oceans affects both the stability of the local troposphere and the exchange of heat and latent energy between the surface and atmosphere. As the local ocean temperature rises the added atmospheric instability and surface energy exchange allows more and deeper convection clouds to develop. With more and deeper convection clouds the radiation to space is largely from the cold cloud tops and the magnitude is reduced.



(Anomaly of outgoing radiation - ORL)

During the 1997 El Niño event the surface temperatures over the central and eastern equatorial Pacific Ocean became warmer than usual giving rise to a shift in the normal patterns of convection from the western to the central and eastern equatorial Pacific Ocean. The El Niño event was well developed by July 1997 and the pattern of anomalies of outgoing longwave radiation to space (LHS) was significantly reduced over the convection clouds of the central and eastern Pacific Ocean. The El Niño event had collapsed by July 1998 and the now colder waters of the central Pacific Ocean were inhibiting convection. The pattern of outgoing longwave radiation to space (RHS) was significantly increased because the reduction in convection clouds meant that more outgoing longwave radiation to space was coming from the lower warmer layers of the troposphere.

The atmospheric circulation, cloud distribution and radiation to space are all very responsive to changing patterns of tropical ocean surface temperature.

Sea surface temperature and outgoing longwave radiation Images in Boxes 2 and 3 are provided by the US NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at <http://www.esrl.noaa.gov/psd/data/correlation/> [10].

(from whatever cause) will move the favoured location of deep convection, increase the rate of overturning and enhance the movement of heat and moisture away from the atmospheric boundary layer. This is in contrast to the reported performance of GCMs that suppress convective overturning as surface temperature increases, thus suppressing the ability of GCMs to shed additional energy from the surface by non-radiative processes. As a consequence, in the GCMs there is an unrealistic increase in the surface temperature in order that the additional energy from CO<sub>2</sub> forcing is lost by surface radiation emission to the atmosphere.

The observations of Pacific Ocean surface temperature and convection suggest that the low evaporation response to CO<sub>2</sub> forcing that is reproduced in GCMs is unrealistic.

### 5 The role of convection

The analysis of Richter and Xie [8] clearly points to changing boundary layer conditions that tend to inhibit free evaporation as surface temperature rises. The data from the equatorial Pacific Ocean suggest that these inhibiting factors in the models do not exist in the climate system; non-radiative heat exchange proceeds as surface temperature



risers and the energy is rapidly distributed through the troposphere by convective overturning. Key questions relate to why the GCMs do not respond to a surface temperature rise and increase the rate of convective overturning, thus more effectively removing energy from the boundary layer to maintain conditions suitable for ongoing evaporation.

A clue to the puzzle lies in the seminal paper of Riehl and Malkus [3] that explained how the heat and latent energy accumulating in the tropical boundary layer is distributed through the troposphere by way of deep equatorial convection. The authors found that they could not derive an energy budget for the equatorial trough zone when the rate of convective overturning is linked only to the large-scale wind field. They postulated buoyant ascent of boundary layer air within undiluted cloud towers where the mass ascent was offset, in part, by saturated downdraughts. The downdraughts originate in the middle troposphere where energy is a minimum and they are sustained by evaporation of cloud droplets and falling rain. To achieve energy balance Riehl and Malkus found it necessary to enhance the mass transport in the undulate updraughts by 60% above that dictated by the large-scale circulation; the corresponding magnitude of mass transport within the downdraughts was 38% of the updraught value.

There are many studies that identify how the mesoscale structures of deep cumulus clouds evolve. The heat and latent energy of the boundary layer is transformed to potential energy in the protected updraughts that penetrate to tropopause height. The potential energy is subsequently realised as heat during compensating clear air mass subsidence and the realised heat is available to offset ongoing radiation cooling. The downdraughts gain negative buoyancy as unsaturated middle tropospheric air is cooled and brought to saturation through mixing with and evaporation of cloud material and falling raindrops. The cooler air in the downdraughts sinks to the surface and spreads out; it displaces the higher energy boundary layer air that is being entrained into the updraughts. The downdraught air acts to ventilate the boundary layer with cooler and dryer air from the middle troposphere.

There are two lessons from the Riehl and Malkus analysis. Firstly, the physics of cloud formation, including the generation of buoyancy forces, overwhelm the stable stratification of the large-scale circulation to generate convective overturning that involves both updraughts and downdraughts. Secondly, the magnitude of the downdraughts is a large fraction of the vertical mass transport and both enhances the overall vertical energy transport and strongly ventilates the boundary layer to enhance the conditions for non-radiative surface energy exchange.

Characteristics of the GCMs used in the IPCC Fourth Assessment suggest that there are significant deficiencies in the model specification of deep convective clouds. Held and Soden [7] have identified that as temperature and specific humidity of the model atmospheres increase then the rate of convective overturning decreases; although this behaviour is internally consistent with the model construct it is not what is observed over the Niño 3.4 region of the Pacific Ocean. Nor is it consistent with studies that identify strengthening of the tropical Hadley Cell circulation during the warming of the 1980s and 1990s. The lack of ventilation of the model boundary layer suggests that the strength of the convective downdraughts is under-specified in the GCMs.

## 6 Discussion

The rate of increase of evaporation with temperature is a critical determinant of the potential for dangerous anthropogenic global warming. If the rate is near the Clausius-Clapeyron relationship, a proposition supported by limited observational evidence, then the warming of the Earth from a doubling of CO<sub>2</sub> concentration is constrained and not likely to be dangerous for the planet. If, however, the rate is significantly less than the Clausius-Clapeyron relationship, as indicated by the performance of GCMs, then continued unconstrained use of fossil fuels and emission of CO<sub>2</sub> into the atmosphere may cause global temperature rise to exceed 2 °C leading to dangerous disruption to the climate system.

The GCMs used to model the climate system are energy conserving and expected to represent the energy flow through the climate system. The absorption of solar radiation, its transformation to longwave radiation, and the interaction of longwave radiation with the so-called greenhouse gases before emission to space are well understood and specified. However the non-radiative processes, especially those sub-grid scale processes associated with the clouds and the hydrological cycle, are also critically important in regulating the energy flow and establishing the steady state of the climate system. The physics of sub-grid scale clouds and the interactions between clouds and the larger-scale circulation are not well understood nor well quantified.

The GCMs used in support of the IPCC Fourth Assessment have been shown to be capable of representing many of the aspects of the steady-state climate system. However when CO<sub>2</sub> concentration is increased, and the system moves from its prior steady state, there are reported anomalous responses that impact on the magnitude of warming. A decrease in convective overturning allows the stability and relative humidity of the boundary layer to increase. As a consequence, the rate of increase of evaporation (and

exchange of latent energy to the atmosphere) is constrained. For a new steady state consequent on increased CO<sub>2</sub> concentration and water vapour feedback the additional radiation energy accumulating at the surface must be lost to the atmosphere as radiation emission. This latter requires a higher surface temperature than if evaporation increased with surface temperature according to the Clausius-Clapeyron relationship.

The proposition made here is that it is inadequacies in the formulation of sub-grid scale convection in the GCMs that contribute to the anomalous model behaviour under CO<sub>2</sub> forcing. Empirical studies suggest that the vertical energy transport within deep convection is inadequately specified; the updraught mass flow must be significantly augmented by saturated downdraughts if the required vertical mass and energy exchanges are to be achieved. The downdraughts, that bring cooler and relatively dry air to the surface, are expected to regulate the boundary layer stability and relative humidity such that evaporation can readily respond to the additional heating.

There is need for global equivalence between the exchanges of non-radiative energy from the surface and radiative cooling of the troposphere. The observed responsiveness of equatorial convection to relatively small changes in ocean surface temperature suggests that local and regional convection are not constrained by prevailing radiation cooling of the troposphere. Convection is only limited by the ability of convective buoyancy forces to overcome the local stability of the troposphere. It is the troposphere thermal structure and radiative cooling that respond to the needs for convection.

The uncertainty surrounding the specification of sub-grid scale convection in GCMs has important ramifications

for predictions of anthropogenic global warming from burning fossil fuels and increasing CO<sub>2</sub> concentration. If, as empirical observations of global precipitation suggest, the rate of increase of evaporation with temperature is near the Clausius Clapeyron relationship then model projections of anthropogenic global warming are exaggerated and a doubling of CO<sub>2</sub> concentration is unlikely to see global temperatures exceed 1 °C.

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