THE GREENHOUSE EFFECT

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Summary
The greenhouse effect on the Earth is identified by the difference between the effective radiating temperature of the planet and its surface temperature. The difference between the energy emitted by the surface and that emitted upward to space by the upper atmosphere quantified it; it can therefore be defined as the long wave energy trapped in the atmosphere. Climate forcing and the response of the climate system within which climate feedback mechanisms are contained, will be defined in this review. Quantitative examples will illustrate what could happen if the greenhouse effect is perturbed by human activities, in particular if CO_2 atmospheric concentration would double in the future. Recent measurements by satellites of the greenhouse effect will be given. The net cooling effect of clouds on the Earth and whether or not there will be less cooling by clouds as the planet warms, are discussed following a series of papers recently published by Ramanathan and his collaborators.

1. THE EARTH'S ENERGY BALANCE

Greenhouse gases such as water vapour and CO_2 bring about the greenhouse effect through the property that they absorb strongly in the infrared region of the electromagnetic spectrum. In order to understand clearly this greenhouse effect, we must first look upon the global Earth's energy balance.

Recent satellite measurements show that the so-called solar constant S_0 is about 1365-1372 Wm^{-2} (Willson et al., 1986; Ramanathan et al., 1989a); this solar irradiance is the solar energy per unit area intercepted perpendicularly at the mean Earth-Sun distance per unit time. Changes in this solar constant constitute the primary external forcing of the climate system. The most apparent phenomenon that could cause the solar output to vary at the 10 to 100 years time scale is sunspots. Detailed investigations show that during sunspot maximum, spots may cover 1 to 2 % of the disk and bright areas surrounding the spots known as faculae cover an even larger area than do the spots. From three years of ERBE (Earth Radiation Budget Experiment) solar observations, it was possible to show that solar irradiance varies with sunspot activity, being lowest at the sunspot minimum. Before the sunspot minimum in 1986, it has indeed decreased at a rate of 0.02 %/yr and has increased at the same rate after (Figure 1).

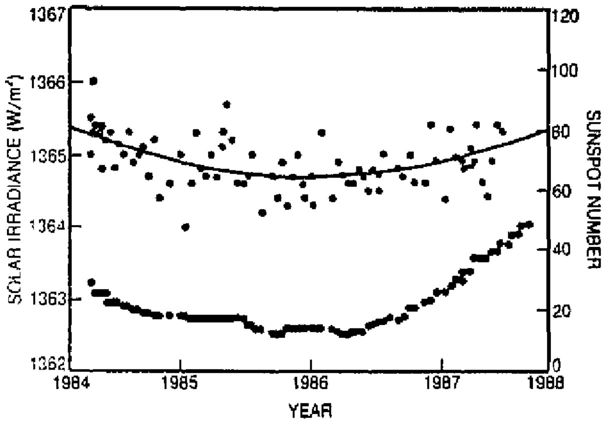

Figure 1. The solar constant from 1984 to 1988 derived from the solar monitor on the Earth Radiation Budget Satellite. The upper curve and dots refer to the solar irradiance and the lower dotted curve to the smoothed sunspot members (from Willson and Hudson, 1988 and Ramanathan et al., 1989a).

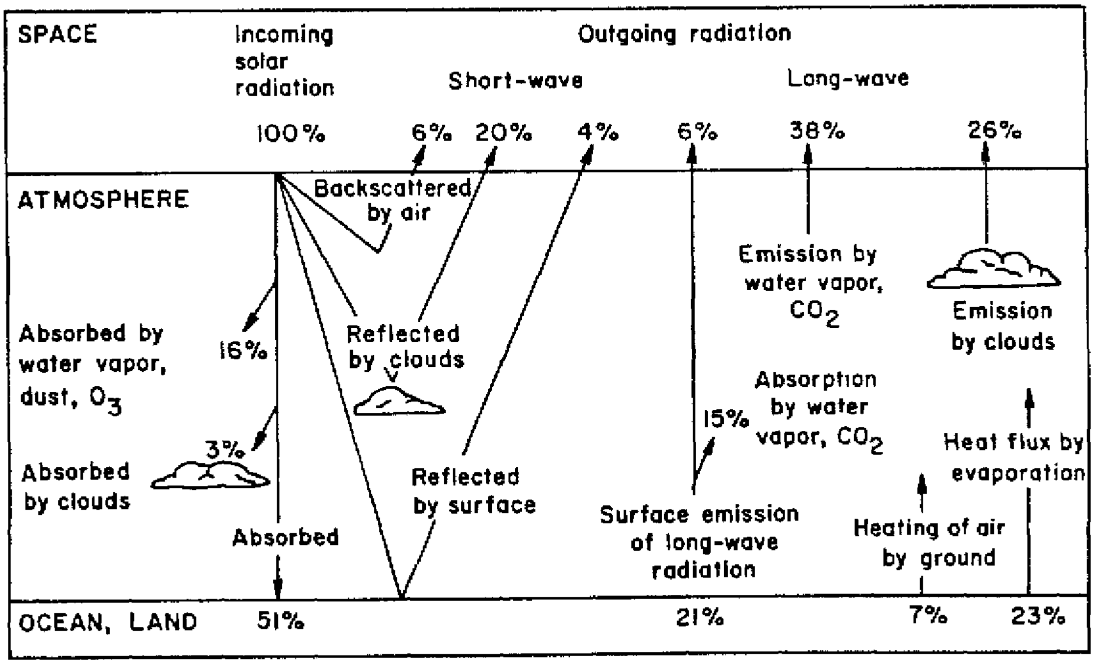

Figure 2. Energy balance of the Earth. 100 % incoming solar radiation represent 342 Wm^{-2}. The net surface emission of long-wave radiation (21 %) is the result of the 6% emission in the atmospheric window and of the balance (15 %) between the surface emission absorbed by the overlying atmosphere (110 %) and the downward long-wave emission by the atmopshere (95 %). All the numbers may differ slightly from one climatology to another due to the uncertainty of the data. The atmospheric window is a term which applies to the region of the absorption spectrum of water vapour existing from about 8.5 to 11 μm. Surface emission in this range of wavelengths is, in contrast to surface emission of other wavelengths, little absorbed by water vapour and, in the absence of cloud, escape to space.

This sunlight, the source of energy for the Earth-atmosphere system, is principally in the visible region, where the Earth's atmosphere is almost transparent. According to the Wien displacement law, the wavelength of maximum emission for a Sun which radiates as a 6,000 K black body in the spectral range from 1.2 to at least 10 μ, is 0.5 μm. Almost 99 % of this sun's radiation is contained in the short wavelengths from 0.15 to 4.0 μm. Of this, 9 % is in the ultraviolet ($\lambda \leq 0.4 \mu m$), 45 % is in the visible ($0.4 \leq \lambda \leq 0.74 \mu m$) and 46 % is in the nea-infrared $\lambda \geq 0.74 \mu m$.

Of the total amount of incoming radiation around 30 % is reflected by clouds (20 %), by particles in the atmosphere (6 %) and by the Earth's surface (4 %), while the other 70 % is absorbed by ozone in the stratosphere (3 %), by water vapour, clouds and aerosols in the troposphere (16 %) and by the Earth's surface (51 %) (Figure 2). These numbers are approximative and may vary slightly from one climatology to another due to the unaccuracy of the observations. Satellite measurements show, for example, that the planetary albedo α (the fraction of the solar irradiance reflected by the planet's surface and atmosphere) is equal to 0.30 $\pm$ 0.03.

To maintain total energy balance, long-wave radiation equivalent to the 70 % incoming solar radiation which was absorbed, needs to be re-emitted to space. This outgoing long-wave radiation is provided by satellite data for the top of the atmosphere (237 Wm^{-2}) along with the estimates of solar radiation (342 Wm^{-2}) and of reflected solar radiation (105 Wm^{-2}). The other quantities of the energy balance are obtained from various published model and empirical estimates. These quantities include the already mentionned atmosphere and surface absorption of solar radiation (68 and 169 Wm^{-2}, respectively), but also the upward long-wave emission by the surface (390 Wm^{-2}, which provides the bulk of the energy emitted to space and among which about 20 Wm^{-2} are directly escaping to space through the so-called atmospheric window), the downward long-wave emission by the atmosphere (327 Wm^{-2}) and the latent and sensible heat fluxes from the surface (90 and 16 Wm^{-2} respectively) (Figure 2). In fact, the atmosphere constantly loses 106 Wm^{-2} of radiating energy because it emits 327 Wm^{-2} to the surface and 217 Wm^{-2} to space and absorbs only 370 Wm^{-2} in the infrared and 68 in the visible. In other words, there is radiative cooling of the atmosphere and a corresponding radiative heating of the Earth's surface, the equilibrium being restored by sensible (16 Wm^{-2}) and latent (90 Wm^{-2}) heat transfer which "convectively" couple the surface to the atmosphere.

2. THE EFFECTIVE RADIATING TEMPERATURE OF THE PLANET EARTH

To illustrate the strong links between the radiation budget, the climate and the circulation of the atmosphere and the oceans, it is useful to examine simple models. The simplest zero-dimensional model of climate considers the long-term average (on a time scale greater than one year) of the global and annual mean temperature. A balance between the absorbed solar energy and the emitted energy governs the temperature T_e defined by :

$$B = \frac{S_0}{4}(1 - \alpha) - \sigma T_e^4 \tag{1}$$

T_e is the effective radiating temperature of the surface-atmosphere system assumed to emit like a blackbody at equilibrium and σ is the Stefan-Boltzman constant equal to 0.567 10^{-7} Wm^{-2} K^{-4}. If the balance B is zero, T_e is expected to be 255 K and represents the temperature at which satellites see the top of the atmosphere emitting long-wave radiation to space. Although, the atmopshere emits in specific wavelength bands and so, the emission departs significantly from that of a black body, T_e is still a useful parameter provided it is considered as the effective radiating temperature of the Earth.

3. THE GREENHOUSE EFFECT

If the atmosphere did not impede the radiative energy flow, the surface temperature T_s would be the same as T_e. However, T_s is observed to be 288 K presently. The 33 K difference is attributed to the greenhouse effect.

Let us make an illustrative calculation to quantify this greenhouse effect. At a temperature of 288 K, the surface emits E = 390 Wm^{-2}. Satellites tell us that only 237 Wm^{-2} espace to space (which is coherent with $S_0 = 1368$ Wm^{-2} and $\alpha = 0.307$ in (1)). If we call it F, the energy trapped in the atmosphere is given by :

$$G = E - F \tag{2}$$

(2) defines the greenhouse effect. It is thus the difference between the surface emission and the total energy loss. It is presently 153 Wm^{-2}. Any change in E and/or F, like the only due to the increase in atmospheric concentration of the greenhouse gases for example, leads to a perturbation of the greenhouse effect, ΔG, as it will be explained in section 7.

B can be characterised also by an effective transmissivity factor τ of the atmosphere by relating the absorbed solar radiation to the Earth's surface temperature through :

$$\frac{S_0}{4}(1-\alpha) - \epsilon \, \tau \, \sigma \, T_s^4 = 0 \tag{3}$$

assuming the Earth's surface emission is close to that of a blackbody (i.e. emissivity, ϵ, is close to 1). Therefore, (3) gives $\epsilon\tau = 0.6$. (3) shows also that a more efficient trapping (i.e. a lower infrared transmissivity) of the atmosphere will automatically result in a higher surface temperature for a fixed S_0 and α.

In order to illustrate further this greenhouse effect, let us consider Venus. For Venus, $S_0 = 2620$ Wm^{-2} and $\alpha = 0.8$. Hence Venus absorbs only 130 Wm^{-2}, only 55 % as much as the Earth despite it receives twice as much solar radiation at the top of its atmosphere as does the Earth. However, Venus has a much hotter surface than the Earth ($T_s = 750$ K) which emits about 17,900 Wm^{-2}. Thus its atmosphere traps nearly two orders of magnitude greater than the Earth's greenhouse effect. This suggests that there is no conceivable saturation point for the atmospheric greenhouse effect which is limited only by the concentration of gases in the atmosphere. It is also worth to note that because Venus is closer to the Sun, saturation in water vapor was never achieved allowing temperature to run away. On the Earth, the increase of surface temperature halted when the water vapor pressure began to be equal to the saturated vapor pressure and freezing or condensation occured.

4. THE PHYSICAL PROCESSES OF THE GREENHOUSE EFFECT

The physical processes which explain the trapping G defined by (2) are as follows.

1. The atmosphere is quite transparent to solar energy. Various empirical estimates give an atmospheric absorption of solar radiation of 68 Wm^{-2}, the remaining 169 Wm^{-2} being absorbed at the surface.

2. The infrared trapping by the atmopshere is due to greenhouse gases which are primarily water vapor, clouds and CO_2 (Annex 1), with a smaller 5 % contribution from O_3, N_2O and CH_4. Several anthropogenic gases, however, such as the chlorofluorocarbons, like $CFCl_3$ and CF_2 Cl_2, are now beginning to make an appreciable contribution (Hansen et al., 1989).

3. For G to be positive, the temperature must decrease with altitude in the region of the infrared-absorbing gas (Raval and Ramanathan, 1989). Because tropospheric temperatures decrease with increasing altitude, the active atmospheric constituants absorb more upward radiative flux than it emits upwards. The net result of these absorption and emission processes is that part of the infrared radiation emitted by the surface is trapped. If we consider a simple 2-level radiative model such as in Annex 2, we can see that the ground temperature would be 335 K and the calculated radiative temperature profile would be unstable. Thus, a particle disturbed from a location close to the surface would rise and carry energy upwards. The resulting convection currents would mix the atmosphere and alter the temperature profile until the atmosphere is driven toward a neutral thermal lapse rate.

Heating the lower boundary of a fluid while cooling its interior is the classical mechanism for inducing convective instability and turbulence. In the Earth's troposphere, turbulent transfer of heat and condensation of water evaporated from the surface make up for the atmosphere's radiative energy deficit, the combination of these nonradiative processes being basely called convective heat transport. The stratosphere, however, is the region in which the radiative equilibrium lapse rate agrees with the observed lapse rate. Once the lapse rate is prescribed, the surface temperature is therefore the only degree of freedom for the troposphere; it is determined by the net flux of the solar and infrared radiation at the tropopause (the fundamental climate-forcing term).

The radiation fluxes at the upper boundary are influenced strongly by internal parameters such as the distribution of water vapour, clouds and other gases; by the lapse rate; by the surface properties such as ice and snow cover, vegetation types and soil moisture. The dependance of these parameters on the surface temperature T_s gives rise to several feedback loops, of which the interaction between water vapour and T_s is the best understood and that between clouds and T_s the least understood.

It is therefore important to differentiate between what is meant by the greenhouse effect, climate forcing and climate feedback.

5. CLIME FORCING AND CLIMATE FEEDBACKS

The French physicist, Jean-Baptiste Fourier, was probably the first person in 1827 to allude to the greenhouse effect and to suggest that human activities could influence the climate (Ramanathan, 1988, Jones and Henderson-Sellers, 1990).

In the latter half of the nineteenth century, Tyndall (1861) described the greenhouse effect caused by atmospheric water vapour, pointing out that water vapour transmits a large fraction of the incident solar radiation but strongly absorbs infrared radiation emitted by the Earth's surface. Later, Arrhenius (1896) suggested that a climate change may be induced primarily by a change of CO_2 concentration in the atmosphere. One century later, the development of the greenhouse theory took a new dimension. Plass (1956) calculated that the mean global surface temperature would increase by 3.6°C if atmospheric carbon dioxide doubled. Möller (1963) provided the first model attempt and suggested that water vapour might also act as an amplifying climate feedback mechanism. In 1967, Manabe and Wetherald provided quantitative results for carbon dioxide induced warming on the basis of a one-dimensional radiative-convective model. Perhaps, one of the most significant advances in the carbon warming was the development by 1975 of a three-dimensional global climatic model reported by Manabe and Wetherald. Since then, the model groups have increased the complexity and hopefully the reliability of their general circulation models (Mitchell, 1989).

In 1989, Raval and Ramanathan cleverly employed satellite measurements to quantify the greenhouse effect and to demonstrate the positive water-vapour feedback.

This provides a convenient means of making the conventional interpretation of climate change as a two stage processes : forcing and response (Cess, 1989).

Let us consider the energy budget,H, of the whole Earth system :

$$H = \frac{S_0}{4}(1 - \alpha) - F \tag{4}$$

For an increase in atmospheric CO_2, the global mean direct radiative forcing of the surface-atmosphere system is the reduction in the top-of-the-atmosphere infrared flux caused solely by the CO_2 increase; it is thus evaluated by holding all the other climate parameters fixed. When the CO_2 increases in the atmosphere, trapping is more efficient and F decreases. Radiative calculations (Dickinson and Cicerone, 1986) has lead to a logrithmic expression of ΔF :

$$\Delta F = -\beta\, ln \frac{[CO_2]}{[CO_2]_0} \tag{5}$$

where β is equal to 6.1 ± 0.4 Wm^{-2}. This means for a 2 x CO_2 : $\Delta F = - 4.2 \pm 0.3$ Wm^{-2}.

If we could immobilize the atmosphere and suddently double its concentration the long wave flux F would decrease by about 4 Wm^{-2} at the tropopause so that the heating increases by 4 Wm^{-2} ($\Delta\ H = 4\ Wm^{-2}$). According to the zero-dimensional climate model, the global situation will restore the radiation energy balance. In other words, the climate system will force H to zero. The planet's surface and troposphere could warm up until it radiates to space the excess 4 Wm^{-2}. The consequent increase in F effected by such as higher temperature balances the decrease in F caused by the increase in CO_2 concentration. The response within which climate feedback mechanisms are contained, is thus the ensuing change in climate that is required to restore the top-of-the-atmosphere radiation balance and corresponds to $\Delta\ H = -\ 4\ Wm^{-2}$ (Ramanathan et al., 1989a).

The discussions here ignore the stratosphere (we consider only that part of the atmosphere where the temperature decreases), which in fact will cool because of the increased CO_2 infrared emission.

The infrared emission F is a function of CO_2 and temperature, but also of water vapour because of the evaporation feedback. As the Earth's surface warms, water evaporates more rapidly from the surface. To keep the process near equilibrium, more water must condense, but the net result is increased water vapor in the atmosphere. This vapour will further decrease F and increase H. For these simple models, it is generally assumed that humidity is only a function of temperature. Therefore, (4) becomes :

$$H = \frac{S_0}{4}(1 - \alpha) - F\,(CO_2,\, T,\, e(T)) \tag{6}$$

This energy balance equation changes to become a sum of 5 terms :

$$\Delta H = \frac{1-\alpha}{4}\Delta S_0 - \frac{S_0}{4}\frac{d\alpha}{dt}\Delta T - \frac{\partial F}{\partial C}\Delta C - \frac{\partial F}{\partial T}\Delta T - \frac{\partial F}{\partial e}\frac{de}{dt}\Delta T \tag{7}$$

The first term expresses the possible change in the solar constant, the second is a function of the albedo-temperature feedback, the third the initial radiative forcing, the fourth one is the direct response and the fifth is the indirect response related to the evaporation-temperature feedback.

One fundamental inference from this model is that climate should be extremely sensitive to small variations in radiative forcing. For example, a 1 % increase in the solar irradiance will increase the absorbed solar radiation by 2.4 Wm^{-2}.

When the system reaches equilibrium, the radiation balance perturbation vanishes (Δ H = 0). Assuming Δ $S_0 = 0$, the final temperature change is therefore :

$$\Delta T = \frac{- \partial F / \partial C \; \Delta C}{\frac{dF}{dT} + \frac{S_0}{4} \frac{d\alpha}{dt}} \tag{8}$$

where $\frac{dF}{dT} = \frac{\partial F}{\partial T} + \frac{\partial F}{\partial e} \frac{de}{dT}$.

This relation is often rewritten in terms of the forcing, ΔQ, and the feedback parameter, λ, such that :

$$\Delta T = \frac{\Delta Q}{\lambda} \tag{9}$$

The same physical idea has been expressed in different ways, (Manabe, 1983) in particular by using a gain factor (Schlesinger, 1985; Berger and Tricot, 1988).

6. THE FEEDBACK PARAMETER

An upper hypothetical limit of λ (3.7 Wm^{-2} K^{-1}) could be obtained by assuming the climate system is devoid of all feedbacks other than IR radiative damping and that the Earth emits IR radiation as a blackbody with an equilibrium temperature of 255 K :

$$F = \sigma T_e^4 \rightarrow \lambda = \frac{\partial F}{\partial T} = 4 \sigma T_e^3 \tag{10}$$

Current three-dimensional climate models yield global warming by amounts in the range of 1.9 - 5 K (Mitchell et al., 1989; Mitchell, 1989; Schlesinger, 1989). As for a doubling of CO_2, the model estimate of ΔQ is about 4 Wm^{-2}, the theoretical value of λ lies in the range of 0.8 - 2.1 Wm^{-2} K^{-1}.

There have been many empirical estimates of λ from satellite measurements of Earth's radiation budget (Ramanathan, 1987). These lie between 0.7 and 2 Wm^{-2} K^{-1} and are therefore consistent with those estimated from the models. In general, these values derived from observations use the latitudinal and seasonal changes in the observed F, α, and T. This consistency would thus be a satisfactory proof of the models, only if the seasonal climate variations mimics a climate change caused by CO_2. Moreover, the sensitivity of climate to small variations in radiative forcing poses very stringent accuracy requirements on observations (a 1% increase in solar irradiance would lead to a warming of 1.1 to 3°C according to the λ values from GCMs), .

Thus, the measurement of the radiation budget has been a story of increasingly sophisticated instruments and rigorous data processing. After two decades of progress in satellite instrumentation, the Earth Radiation Budget Experiment began in the 1980s. ERBE instruments are carried on three satellites : the Earth Radiation Budget Satellite, NOAA-9 and NOAA-10. A unique feature of ERBE is that it separates the top-of-the-atmopshere fluxes for clear skies from fluxes from cloudy skies, which allows to obtain the greenhouse effect of the atmosphere and that of the clouds separately. Such measurements of F were used recently by Raval and Ramanathan (1989) to quantify the atmospheric greenhouse effect G over the year 1985.

To better estimate the emission E from the surface, they restricted their study to the open oceans. Overall, they expected the error (systematic plus random) in the monthly and regional mean values of G to be 5 to 10 Wm^{-2}.

Globally, for April 1985, the surface emission was 421 $\mathrm{Wm^{-2}}$ and the top-of-the-atmosphere emission was 243 $\mathrm{Wm^{-2}}$, resulting in a total trapping of 178 $\mathrm{Wm^{-2}}$. Of this, the atmopsheric greenhouse gases trap 146 $\mathrm{Wm^{-2}}$, whereas clouds trap the remaining 32 $\mathrm{Wm^{-2}}$.

On the other hand, estimates of G over the open oceans for a cloudless atmosphere revealed significant regional variations, generally decreasing from Equator to pole. But the most significant result was that this clear-sky G has a strong positive correlation with sea surface temperature, a correlation that according to Raval and Ramanathan (1989), gives direct evidence of the water vapour feedback.

In order to demonstrate this, they first attempted to eliminate the temperature dependence of G by defining a normalized greenhouse effect $g = \frac{G}{\sigma T^4}$. This definition $g = \frac{G}{E}$ leads to $F = (1-g)E$.

Their test rested then on three pieces of evidence :

(i) the normalized greenhouse effect increases linearly with temperature :

$$g = g(T_s) = -0.658 + 0.00342\, T_s \tag{11}$$

which for present day surface temperature gives $g = 0.327$. This feedback is clearly positive as if T_s increases, g and therefore G increases. In fact, E increases more than F with T_s. Moreover, $\frac{dF}{dT_s}$ given by :

$$\frac{dF}{dT_s} = 4\,\sigma\, T_s^3\,(1.658 - 0.004275 T_s)$$

is smaller (2.31 $\mathrm{Wm^{-2}\,K^{-1}}$) than without the water vapour feedback. For this latter case, g being kept constant to its present day value, we have indeed:

$$\frac{dF}{dT_s} = \frac{\partial F}{\partial T_s} = 4\,\sigma\, T_s^3\,(1-g) \simeq 3.65\ Wm^{-2}K^{-1}$$

(ii) the logarithmic of the measured water vapour concentration varies linearly with surface tempeature, just a dependence that one would calculate from the Clausius-Clapeyron equation governing the saturation vapour pressure.

(iii) g increases logarithmically with the water vapour concentration.

Conclusively, the analysis strongly indicates the presence of the water vapour feedback, which is further supported by the good agreement:

(i) between the sensitivity $\frac{dG}{dT_s}$ of the NCAR Community model and the observed one :

$$\frac{dG}{dT} = 4\,\sigma\, T_s^3\,(-0.658 + 0.004275\, T_s) \sim 3.1\ Wm^{-2}\ K^{-1}$$

(ii) between the value of the feedback parameter $\frac{dF}{dT_s} = 2.31\ Wm^{-2}\ K^{-1}$ obtained from ERBE for clear sky conditions and the averages for the 14 GCMs analysed by Cess et al. (1989) : 2.38 ± 0.16 $\mathrm{Wm^{-2}\,K^{-1}}$, although significant disagreements amongst the models' global mean $\frac{dF}{dT_s}$ occur when clouds are taken into account.

Water vapour feedback is thus clearly detectable from ERBE observations and it can account for most of the observed variation of G with surface temperature. Moreover, the greenhouse perturbation by human activities might be detected by ERBE in the near future (Raval and Ramanathan, 1989). Indeed, the increase in trace gases, if it continues unabated, will globally increase G by 9 to 15.5 Wm^{-2} over the next 50 years (for a direct forcing of 2.5 Wm^{-2} the globe is expected to warm by 2 to 4°C which would lead to a further increase in G of 6.5 to 13 Wm^{-2} due to water vapour feedback).

In summary :

1. $(\frac{\partial F}{\partial T_s})_{g\ fixed} = \frac{dF}{dT_s} = (1-g)\ 4\ \sigma\ T_s^3 = 3.65\ Wm^{-2}K^{-1}$

   This is clearly the feedback related to the direct response already defined in terms of the temperature at the top of the atmosphere in (10). In such a case,

   $$\Delta T = \frac{-\partial F/\partial C\ \Delta C}{\frac{\partial F}{\partial T}} \tag{12}$$

   and the rate at which the emission increases with increasing temperature governs the temperature change.

2.

   $$(\frac{dF}{dT_s})_{g\ variable} = 4\ \sigma\ T_s^3\ (1.658\ -\ 0.004275\ T_s) \tag{13}$$

   This expression which contains both $\frac{\partial F}{\partial T}$ and $\frac{\partial F}{\partial e}\ \frac{de}{dT}$ as shown in (8), allows to determine the water vapour feedback contribution per se by substracting (12) from (13) :

   $$\frac{\partial F}{\partial e}\ \frac{de}{dT_s} = 4\ \sigma\ T_s^3\ (0.985\ -\ 0.004275\ T_s) \tag{14}$$

   which for all $T_s > 230\ K$ is clearly negative, leading to a smaller value of λ and therefore a positive feedback.

3. Finally, the albedo-temperature feedback is also positive:

   $$\frac{S_0}{4}\ \frac{d\alpha}{dT} = -\ 0.4\ Wm^{-2}K^{-1} \tag{15}$$

   an increase in T causes indeed a melting of sea ice and snow cover; the decrease in the area of ice and snow lowers the albedo and thereby increases the absorbed sunlight, the whole process amplifying the surface warming.

7. THE RESPONSE TO A 2 X CO_2

A simple calculation can easily show how the climate system is restoring the equilibrium at the top of the atmosphere when it has been forced by doubling the CO_2 concentration in the atmosphere. Because Raval and Ramanathan (1989) refers to clear-sky condition, Cess (1989) has proposed to consider a cloud free Earth with a surface temperature

Table 1: Response of the hypothetical planet's climate system to a 4 Wm^{-2} direct forcing (Cess, 1989)

Process	$\Delta T_s(K)$	$\Delta G(Wm^{-2})$	$\Delta F(Wm^{-2})$
direct forcing (1)	0	4	-4
response with g fixed (2)	1.1	1.9	4
global response (3)	1.7	9.5	0
additional response with g variable (4) ((4) = (3)-(2))	0.6	3.6	0

of 288 K, where absorption of solar radiation by the surface-atmosphere system is invariant to climate change and no other feedback than water vapour is considered.

Table 1 summarizes the results in 3 steps. The direct infrared forcing simultaneously reduces F and increases G so that $H = 4\ Wm^{-2}$. This imbalance at the top of the atmosphere causes a global warming which is 1.09 K without water vapour feedback. Indeed for g prescribed to its present-day value 0.327 (process 2 in Table 1), we have :

$$\Delta F \;=\; 4 \;=\; (1-g)\,\Delta E \;\rightarrow\; \Delta E \;=\; 5.94\ Wm^{-2} \tag{16}$$

which implies, through $\Delta E \;=\; 4\,\sigma\,T_s^3\,\Delta\,T_s$, $\Delta\,T_s \;=\; 1.09\ K$ and $\Delta\,G \;=\; g\,\Delta\,E \;=\; 1.9\ Wm^{-2}$.

If the water vapour feedback is considered (process 3) :

$$\Delta F \;=\; 4 \;=\; (1-g)\,\Delta E \;-\; E\,\Delta g \tag{17}$$

which gives - through $E \;=\; \sigma\,T_s^4$ and g given by (11) : $\Delta T_s = 1.73K$
- through $G \;=\; \sigma\,T_s^4 - F\;:\;\Delta G = 9.4 - 4 = 5.4\ Wm^{-2}$

This simple illustration demonstrates how the direct greenhouse forcing of 4 Wm^{-2} is first amplified to 5.9 Wm^{-2} through temperature feedback and then to 9.5 Wm^{-2} by water vapour feedback, the further response to variable g being thus 3.6 Wm^{-2}. The combined forcing and feedbacks thus increase the clear sky greenhouse effect from its initial value of 146 Wm^{-2} to nearly 156 Wm^{-2}. Moreover, water vapour feedback amplifies the direct surface warming of 1.1 K by roughly 60 per cent leading to a 1.7 K global warming.

The role of the water vapour feedback has also been described through 3 processes involving ocean-atmosphere thermal interactions as shown in Figure 3 (Ramanathan, 1981 and 1988). For the case of a doubling of CO_2, out of the 4 Wm^{-2} of CO_2 heating, roughly 1 Wm^{-2} is deposited at the surface as increased emission from CO_2 (process 1). The balance, 3 Wm^{-2}, is trapped in the troposphere (process 2). This increase in the infrared energy warms the troposphere and so the surface, including the oceans. More moisture evaporates; the latent heat is released as moisture condenses through precipitation. The warmer troposphere, as a result of the direct greenhouse heating and the release of latent heat holds more water vapour because it is observed that the atmopshere tends to conserve its relative humidity with a change in temperature. The enhanced water vapour in turn traps more infrared radiation and amplifies the greenhouse effect (process 3). In one-dimensional climate models, Ramanathan (1981) has shown that for a global warming of 2.2 K, the 3 processes are responsible for a temperature increase of respectively 0.17, 0.33 and 1.7 K, which shows that the water vapour feedback amplifies the surface warming by a factor of ~ 3.