THE SIGNIFICANCE OF RADIATIVE TRANSFER AND ITS ROLE IN THE ATMOSPHERIC GENERAL CIRCULATION

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1. INTRODUCTION

The energy source for the Earth's climate system is the absorption of shortwave radiation from the sun. On average, this is balanced by the emission of longwave (thermal) radiation back to space. Figure 1 shows a schematic of the terms in the global energy balance at the top of the atmosphere, within the atmosphere and at the surface. The effect of clouds can be seen by comparing with the values in parentheses, which are for clear-sky conditions (Hartmann 1993). Minor liberties have been taken with the accepted values to ensure that the various terms balance exactly. The only non-radiative terms which appear in such an energy balance are the sensible and latent heat fluxes from the surface to the atmosphere, associated with convection.

Of fundamental importance is the fact that the atmosphere is much more transparent in the shortwave than in the longwave. About 70% of the solar heating takes place at the surface, whereas much of the compensating longwave cooling to space takes place from the (cooler) atmosphere. The system thus emits less energy to space than if there had been no atmosphere, giving rise to the 'greenhouse effect'. The net radiative heating of the surface leads to convection, which transfers the energy vertically to offset the net radiative cooling of the atmosphere.

The energy balance of the surface is:

$$\begin{array}{ccccc} \text{Shortwave heating} & = & \text{Net longwave cooling} & + & \text{Convective cooling} \\ & & [390 - 327] & & \\ 169 & = & 63 & & +16 \quad +90 \end{array} \qquad (1)$$

The energy balance of the atmosphere is:

$$\begin{array}{ccccc} \text{Net longwave cooling} & = & \text{Shortwave heating} & + & \text{Convective heating} \\ [237 + 327 - 390] & & & & \\ 174 & = & 68 & & +16 \quad +90 \end{array} \qquad (2)$$

Comparison of the various terms in Figure 1 and in these equations leads one to the conclusion that the

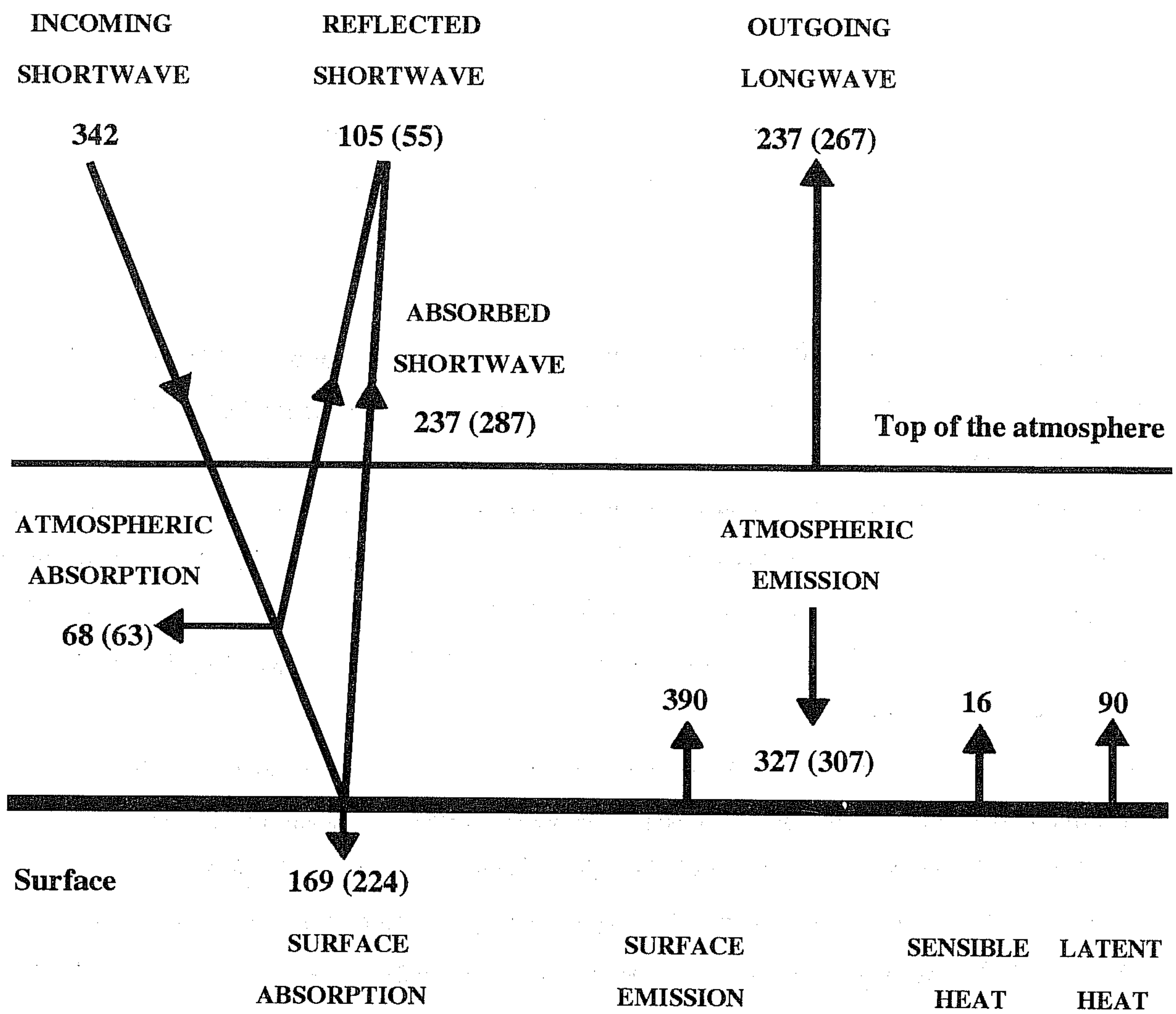

Fig. 1 Schematic of the global and annual mean fluxes (Wm^{-2}) in the energy budget of the climate system. Values for clear skies are shown in parentheses. The surface longwave emission is calculated from the Planck function for a mean surface temperature of 15°C. The mean surface latent heat flux, or evaporation, is equal to the mean precipitation, assumed to be 3.1 mm/day.

most important contributors to the energy balance are firstly the surface, followed by the clear atmosphere and clouds. In this seminar we shall briefly discuss some contemporary issues relating to the radiative properties of these components and of their interactions with the general circulation.

2. SURFACE REFLECTIVITY

All NWP and climate models use radiation codes which are formulated in terms of the upward and downward fluxes, integrated over each hemisphere. The lower boundary condition for the shortwave codes is the surface albedo, which is assumed to be constant or to vary in a simple way with the solar zenith angle. This is in marked contrast with the approach followed by the remote sensing community, which usually deals with radiances, for example as observed by satellite sensors. In this case it is necessary to specify the highly anisotropic angular scattering patterns of real surfaces. These patterns have the grand title of Bidirectional Reflectance Distribution Functions (BRDFs) and are the subject of much research at the present time. BRDFs for vegetated surfaces are dominated by two features; the 'bowl shape' and the 'hot spot'. A bowl-shaped BRDF corresponds to the surface appearing darkest from above in the nadir direction and brightest towards the horizon (i.e. there is limb brightening). It is due to being able to see furthest into the surface (where it is darkest) when looking straight down and is strongest at high solar zenith angles because this accentuates the contrast between the relatively bright top of the canopy and the shaded layers beneath. The hot spot corresponds to looking down onto a surface in the same direction as the incident illumination, so that no shadows are visible.

GCMs clearly cannot represent all the details of surface BRDFs, but they need to include more realistic albedos which at least depend on the solar zenith angle. It is a challenge to both the GCM and remote sensing communities to ensure that GCM albedos are as consistent as possible with those used in remote sensing studies. For an example of the status of modelling of the BRDF see Verstraete et al. (1990).

3. CLEAR ATMOSPHERE

The majority of the Earth's greenhouse effect is due to emission and absorption by water vapour. Recent papers have investigated the dependence of the clear-sky greenhouse effect on water vapour and temperature (Webb et al. 1993, Bony and Duvel 1994, Raval et al. 1994) and the 'super greenhouse effect' at low latitudes (Hallberg and Inamdar 1993, Inamdar and Ramanathan 1994).

Examination of the spectral distribution of the longwave cooling by water vapour reveals that the bulk of the cooling in the middle and upper troposphere takes place in the far-infared rotation band, at wavenumbers below about 600 cm^{-1}, corresponding to wavelengths greater than about 15 μm (Clough et al. 1992). This region of the infrared spectrum is thus of great importance in understanding the atmospheric radiative cooling, and hence the operation of the greenhouse effect. However, remote sensing at these wavelengths is in its infancy, mainly because of technical problems up to now in fabricating suitable optics and detectors. As a result, there are no global measurements available of the atmospheric emission in this region. Fortunately, the weaker middle and upper tropospheric cooling on the other side of the atmospheric window is well sampled by water vapour imaging channels at around 6.7 µm wavelength. Data from such channels have been used to derive upper tropospheric humidity products, for example from METEOSAT (Schmetz and Turpeinen 1988) and GOES (Soden and Bretherton 1994). The latter paper demonstrates the potential of such products for validating GCMs.

The greenhouse effect of other trace gases must also be taken into account of course, both in extended range weather prediction and in climate modelling. Apart from carbon dioxide and ozone, it is now recognised that minor trace gases such as methane, nitrous oxide and the chlorofluorocarbons must be included, as these can contribute 4-5 Wm^{-2} to the global mean outgoing longwave radiation. Aerosols have also become a subject of intense interest, because of their potential for cooling the climate system (Charlson et al. 1992). These and other aspects of changes in the radiative forcing are comprehensively covered in IPCC (1994).

4. CLOUDY ATMOSPHERE

The reflectivity of a cloud R in the visible region of the shortwave spectrum is approximately given by:

$$R = \frac{(1-g)(\tau/\mu_0)}{2 + (1-g)(\tau/\mu_0)} \quad (3)$$

where g is the asymmetry parameter, τ is the optical depth and μ_0 is the cosine of the solar zenith angle. The optical depth of the cloud τ is approximately given by:

$$\tau = \frac{3}{2\rho}\frac{W}{r_E} \quad (4)$$

where W is the (liquid or ice) water path, ρ is the density of water and r_E is the 'effective radius', which is a measure of the mean particle size as seen by the radiation fields (for water clouds r_E is easily defined, but it is still unclear how best to define such a quantity for ice clouds, which are of course composed of non-spherical particles so that the concept of effective radius may be invalid).

The important lesson from equations 3 and 4 is that r_E is as important in determining the cloud radiative properties as is the water content. If r_E were constant that would not pose a problem, but there is ample evidence that it varies with the airmass, according to the concentration of cloud condensation nuclei

(CCN). Taylor and McHaffie (1994) summarise data on r_E obtained from a large number of flights with the Meteorological Research Flight C-130. The variation in the measured value of r_E is large, which suggests that some means must be found for simulating this quantity in GCMs. Evidence for significant geographical variations in r_E is also provided by satellite retrievals (Han et al. 1994). The challenge for GCMs is thus to represent aerosol and its impact on r_E. Preliminary attempts have been reported by Jones et al. (1994) and Boucher and Lohmann (1995). The motivation in both of these papers was to be able to make estimates of the effect of anthropogenic sulphate aerosols on cloud albedo and hence climate.

Validation of calculations of cloud radiative properties remains an important task for experimental studies with research aircraft. This task is made very difficult by the inhomogeneous nature of most real clouds. Nevertheless, even for cirrus, that most inhomogeneous of cloud types, it is occasionally possible to show that theory and measurement are at least consistent (Francis et al. 1994), if only for the separate upward and downward broad-band fluxes. What is unfortunately not possible to verify is the calculated cloud absorption, because this is the divergence of the net flux and the experimental errors in estimating this are far too large. This is one reason why speculation that real clouds absorb more solar radiation than theory would suggest ('anomalous absorption') has been hard to prove or disprove. This possibility has recently been resurrected by Ramanathan et al. (1994) and Cess et al. (1994).

5. INTERACTIONS WITH THE GENERAL CIRCULATION

Some aspects of the interaction between radiation and the general circulation have been touched on in the preceding sections. Given the magnitude of the clear-sky greenhouse effect and the dominant role of water vapour, a more complete understanding of the factors which control the vertical and horizontal distibution of water vapour is a pre-requisite to a more complete understanding of the greenhouse effect. In the middle and upper troposphere of the tropics the distribution of water vapour is presumably intimately related to the amount of moisture detrained by deep convection and its transport by the tropical circulation. It is therefore not surprising that our understanding of this distribution is so crude, given our rudimentary understanding of the distribution of cumulus detrainment. Indeed, it might be profitable to work backwards from the observed distribution of the clear-sky longwave fluxes at the top of the atmosphere to learn about cumulus detrainment than vice versa.

Other interactions which are important include the pervasive impact of aerosols on both clear-sky and cloudy radiative transfer and the role of cloud radiative feedbacks in the energy balance of the warm pool (Ramanathan et al. 1994). The above study asserts that the absorption of solar radiation by clouds is much larger than is generally calculated by models. This would modify significantly the numbers in Figure 1 for the clear-sky shortwave radiation absorbed within the atmosphere and at the surface. Not surprisingly, this is a contentious issue and will certainly stimulate a great deal of both theoretical and experimental research.

6. ACKNOWLEDGEMENTS

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