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2. Climate Forcings and Feedbacks

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Overview

Global temperature has increased significantly during the past century (IPCC, 1990; Hansen and Lebedeff, 1987; Jones *et al.*, 1986), as illustrated in Fig. 2.1. Understanding the causes of observed global temperature change is impossible in the absence of adequate monitoring of changes in global climate forcings and radiative feedbacks. Climate forcings are changes *imposed* on the planet's energy balance, such as change of incoming sunlight or a human-induced change of surface properties due to deforestation. Radiative feedbacks are radiative changes induced by climate change, such as alteration of cloud properties or the extent of sea ice.

Monitoring of global climate forcings and feedbacks, if sufficiently precise and long-term, can provide a *very strong constraint* on interpretation of observed temperature change. Such monitoring is essential to eliminate uncertainties about the relative importance of various climate change mechanisms including tropospheric sulfate aerosols from burning of coal and oil (Charlson *et al.*, 1992), smoke from slash and burn agriculture (Penner *et al.*, 1992), changes of solar irradiance (Friis-Christensen and Lassen, 1991), changes of several greenhouse gases, and many other mechanisms.

The considerable variability of observed temperature (Fig. 2.1), together with evidence that a substantial portion of this variability is unforced (Barnett *et al.*, 1992; Manabe *et al.*, 1990; Hansen *et al.*, 1988; Lorenz, 1963), indicates that observations of climate forcings and feedbacks must be continued for decades. Since the climate system responds to the time integral of the forcing, a further requirement is that the observations be carried out continuously.

However, precise observations of forcings and feedbacks will also be able to provide valuable conclusions on shorter time scales. For example, knowledge of the climate forcing by increasing CFCs relative to the forcing by changing ozone is important to policymakers, as is information on the forcing by CO_2 relative to the forcing by sulfate aerosols. It will also be possible to obtain valuable tests of climate models on short time scales, if there is precise monitoring of all forcings and feedbacks during and after events such as a large volcanic eruption or an El Nino.

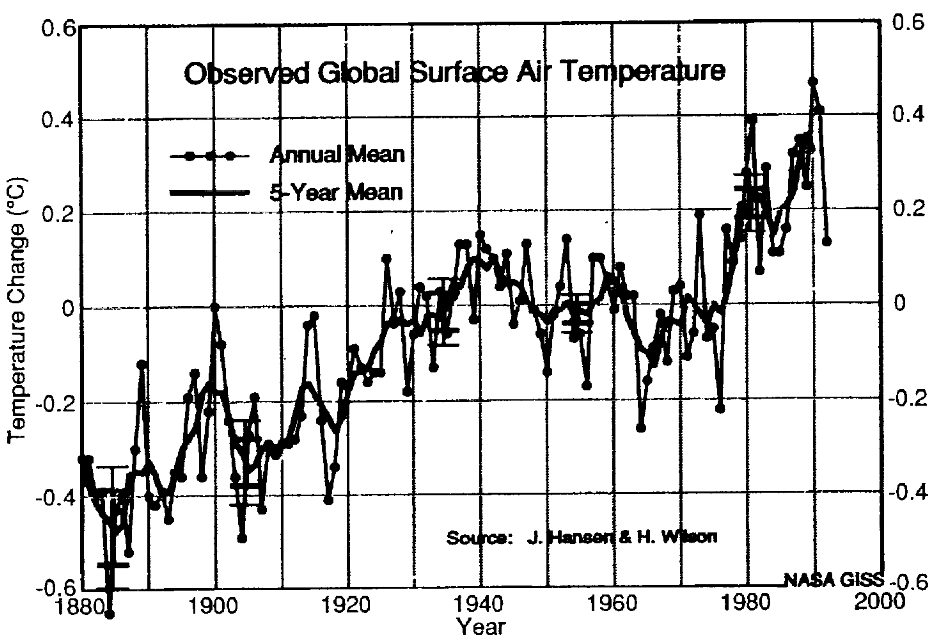

Fig. 2.1. Global surface air temperature change during the past century as extracted from measurements at meteorological stations (update of Hansen and Lebedeff, 1987).

Forcings and Feedbacks

Greenhouse gases. The measured increase of homogeneously mixed greenhouse gases since the beginning of the industrial revolution causes a climate forcing of about 2 W/m^2 (IPCC, 1992; Hansen and Lacis, 1990; Dickinson and Cicerone, 1986; Ramanathan *et al.*, 1985; Wang *et al.*, 1976), as illustrated in Fig. 2.2. However, there is major uncertainty about the total anthropogenic greenhouse forcing, especially because of uncertain changes of the ozone profile (IPCC, 1992; Ramaswamy *et al.*, 1992; Lacis *et al.*, 1990). Stratospheric water vapor may be increasing because of oxidation of increasing methane (Ellsaesser, 1983; Le Texier *et al.*, 1988), but other mechanisms are capable of influencing stratospheric water vapor, so in the absence of adequate monitoring its net climate forcing is very uncertain.

Climate forcing due to ozone change is complicated because ozone influences both solar heating of the Earth's surface and the greenhouse effect. These two mechanisms influence surface temperature in opposite directions and their relative importance depends on the altitude of the ozone change. Figure 2.3 illustrates the equilibrium response of a GCM to specific ozone changes. (a) Ozone loss in the upper stratosphere warms the Earth's surface, because of increased ultraviolet heating of the troposphere. (b) Added ozone in the troposphere warms the surface moderately. (c) Ozone loss in the tropopause region causes a strong cooling because the low temperature at the tropopause maximizes the ozone's greenhouse effect. (d) Coincidentally, removal of all ozone causes only a moderate surface cooling.

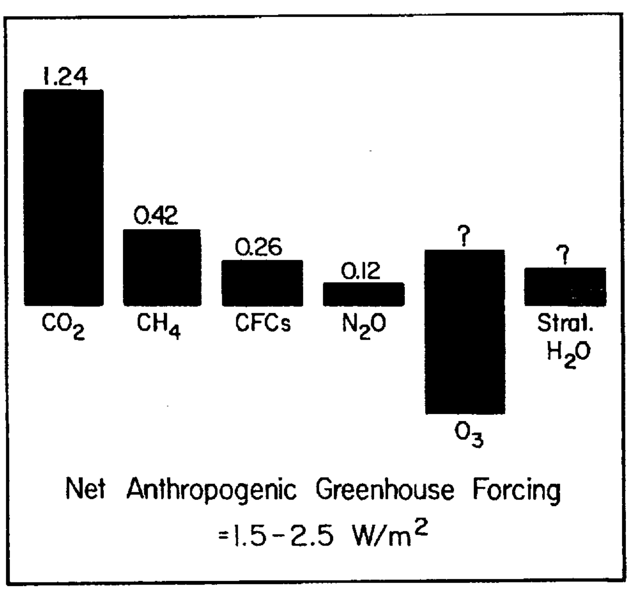

Fig. 2.2. Anthropogenic greenhouse climate forcings (W/m^2) due to measured or estimated trace gas changes between 1850 and 1990. The forcing is calculated as the change in net radiative flux at the tropopause caused by the change in atmospheric composition.

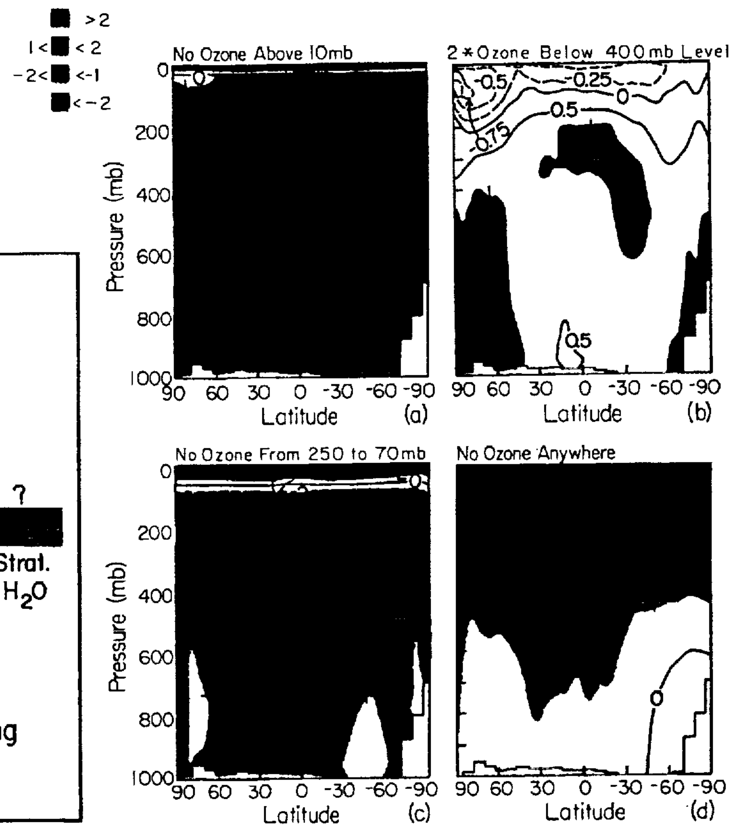

Fig. 2.3. Zonal mean equilibrium temperature change estimated for several arbitrary changes of the ozone distribution. Results were obtained from 50 year runs of the GISS GCM.

The ozone changes that had been predicted for many years on the basis of homogeneous (gas phase) chemistry models included upper stratospheric ozone loss and tropospheric ozone increase, shown by the dashed curves in Fig. 2.4. Both of those ozone changes would cause surface heating. But limited ozone measurements in the 1970s (Tiao *et al.*, 1986; Reinsel *et al.*, 1984), shown by the histograms in Fig. 2.4, suggested the possibility that upper tropospheric ozone and lower stratospheric ozone may be decreasing. Discovery of the Antarctic ozone hole in the 1980s (Farman *et al.*, 1985) and analysis of the mechanisms involved in the ozone depletion led to the realization of the effectiveness of heterogeneous loss processes in the 15-25 km region (WMO, 1990). Satellite data for the 1980s (Stolarski *et al.*, 1991; McCormick *et al.*, 1992) have shown that the lower stratospheric ozone loss in not confined to the Antarctic.

Lower stratospheric ozone loss can be a significant climate forcing. This is illustrated (Fig. 2.5) by comparison of the simulated global warming due to all the homogeneously mixed greenhouse gases (HMGG) with the simulated warming when ozone loss is also included. The ozone loss is that reported by Stolarski *et al.* (1991), with the assumption that the entire change is in the 70-250 mb region. The latter assumption probably maximizes the cooling effect of the ozone loss. Despite the large natural variability in the results of a single GCM experiment, or even the mean of 5 experiments, it is apparent that the ozone change is a significant contributor to the total greenhouse effect. Indeed, it will not be possible to accurately evaluate the total anthropogenic greenhouse effect unless ozone change is monitored as a function of altitude, latitude and season. Useful ozone profile data are presently supplied by the SAGE II instrument on the ERB satellite, which is over eight years old. This data record can be extended and enhanced by flight of a proposed improved version of the instrument (SAGE III) with greater sensitivity, higher spectral resolution, and increased spatial sampling. Although total ozone abundance is being monitored by flights of the TOMS and SBUV instruments, there are no plans to fly SAGE III before 2002.

Aerosols. Perhaps the greatest uncertainty in climate forcing is that due to tropospheric aerosols (Charlson *et al.*, 1992). Aerosols cause a direct climate forcing, by reflecting sunlight to space, and an indirect climate forcing, by altering cloud properties. Existence of the latter effect is supported by satellite observations of increased cloud brightness in ship wakes (Coakley *et al.*, 1987), satellite observations of land-ocean and hemispheric contrasts of cloud droplet sizes (Han 1992), and

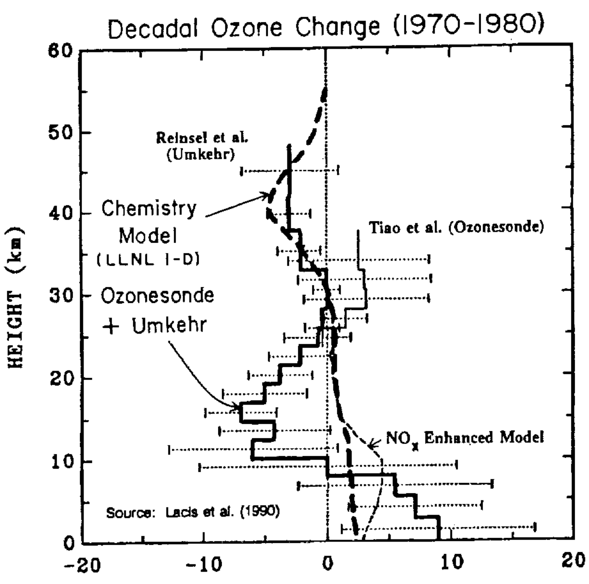

Fig. 2.4. Ozone changes predicted on the basis of homogeneous chemistry and ozone changes measured in the 1970s (figure reproduced fromLacis *et al.*, 1990).

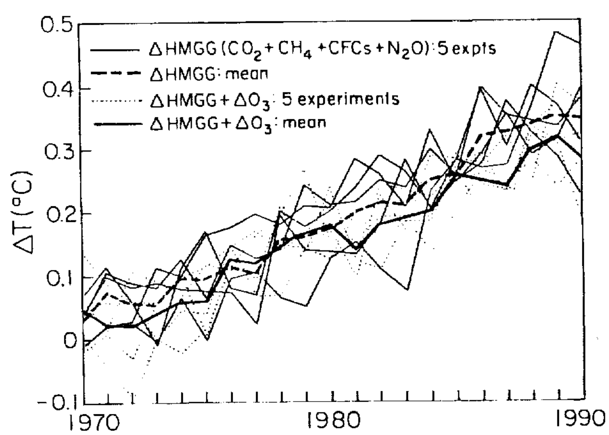

Fig. 2.5. Transient global temperature change due to changing greenhouse gases, as simulated with the GISS GCM (Hansen, 1991). Five experiments were run with only four homogeneously mixed greenhouse gases increasing (ΔHMGG), and five additional experiments with ozone also changing (ΔHMGG + ΔO_3). The ozone loss reported by Stolarski *et al.* was used with the loss placed entirely in the 70-250 mb region.

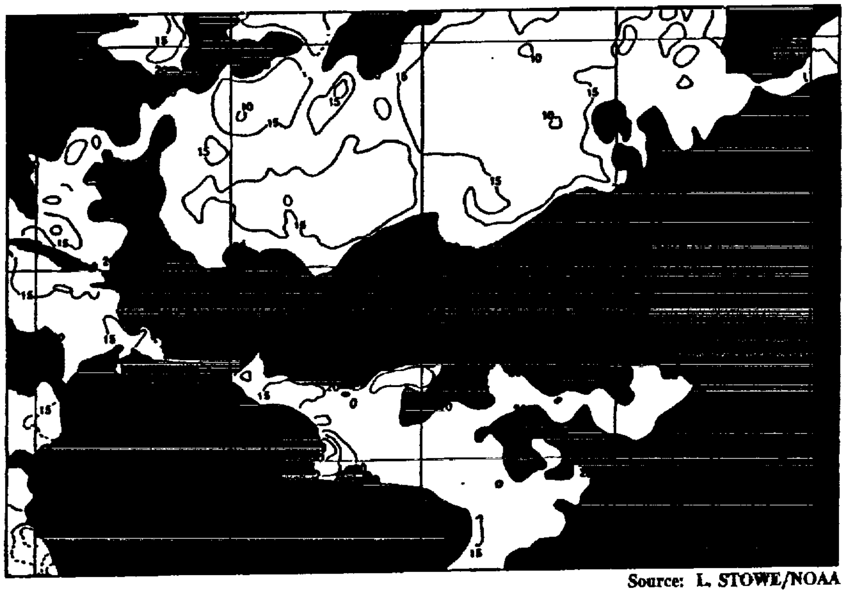

Fig. 2.6. Estimate of aerosol optical depth (×100) for June 18-25, 1987, based on reflected radiances measured by the AVHRR instrument on operational weather satellites (Rao *et al.*, 1988).

in situ data concerning the influence of the aerosol condensation nuclei on the clouds (Radke *et al.*, 1989). Sulfate aerosols originating in fossil fuel burning may produce a global climate forcing of order 1 W/m^2 (Charlson *et al.*, 1991), and aerosols from biomass burning conceivably produce a comparable forcing (Penner *et al.*, 1992). Wind-blown desert dust has long been suspected of being an important forcing on regional climates (Tanre *et al.*, 1984; Joseph, 1984; Coakley and Cess, 1985). It has also been suggested (Jensen and Toon, 1992; Sassen, 1992) that volcanic aerosols sedimenting into the upper troposphere may alter cirrus cloud microphysics, thus producing a possibly significant climate forcing. Unfortunately, no global data exist that are adequate to define any of these aerosol climate forcings.

Aerosols can be seen in present satellite measurements (Rao *et al.*, 1988; Jankowiak and Tanre, 1992), as indicated by Fig. 2.6, which shows an estimate of aerosol optical depth based on the imaging instrument on an operational meteorological satellite. Sahara dust spreading westward from Africa is apparent, as well as sulfate aerosols moving eastward from the United States. However, the nature and accuracy of these data are inadequate to define the climate forcing, and, indeed, the optical depths in Fig. 2.6 are probably in part thin cirrus clouds. The climate forcing issue requires aerosol data of much higher precision, including information on aerosol altitude and aerosol physical properties such as size and refractive index. Cloud properties, including optical depth, particle size and phase must be monitored simultaneously to very high precision, so that the temporal and spatial variations of aerosols and clouds can be used to help define the indirect aerosol climate forcing.

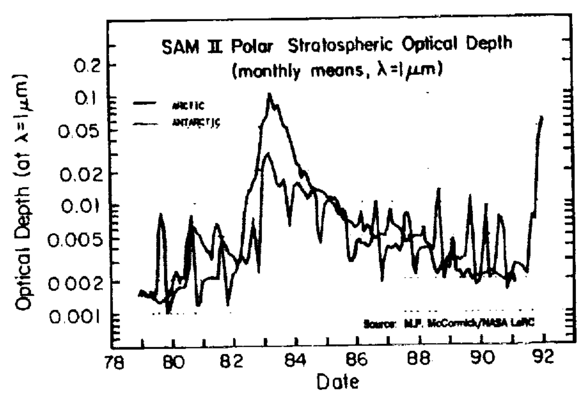

Fig. 2.7. Stratospheric aerosol optical depth at 1 μm wavelength in the polar regions measured by a solar occultation instrument on the Nimbus-7 spacecraft (M.P. McCormick, private communication).

Stratospheric aerosol optical depth has been monitored in the polar regions since late 1978 by a solar occultation instrument on the Nimbus-7 spacecraft (McCormick, *et al.*, 1979), as illustrated in Fig. 2.7. The record reveals seasonal polar stratospheric (condensation) clouds, especially in Antarctica, as well as the influence of aperiodic volcanic sulfuric acid aerosols, especially the El Chichon

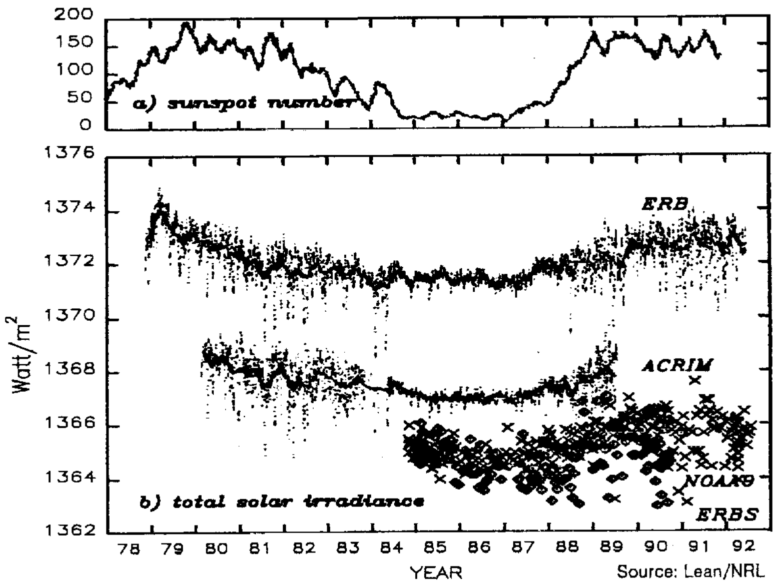

Fig. 2.8. Solar irradiance variations measured for the past solar cycle (J. Lean, private communication). The ACRIM results from the SMM and UARS missions, the latter not shown here, also have an offset from each other.

eruption in 1982 and the Mt. Hudson and Mt. Pinatubo eruptions in 1991. The approximate 50 percent increase of "background" aerosol optical depth between 1979 and 1990 is thought by some (e.g., Hofmann, 1990) to be a result of anthropogenic impact on the sulfur cycle, perhaps due to aircraft emissions.

The global radiative forcing of the El Chichon aerosols reached a maximum of about 2 W/m^2 (Hansen and Lacis, 1990), approximately the same as the forcing by all anthropogenic greenhouse gases, but opposite in sign. Although the aerosol forcing is more short-lived, it must be monitored if global temperature changes are to be interpreted. Nimbus-7 is nearing the end of its long life (launched in 1978), and it recently lost the ability to obtain occultation measurements in the Arctic. SAGE II has been obtaining data at low and middle latitudes from the ERB spacecraft since 1984, but that spacecraft is also showing signs of age and is already well beyond its design life. Flight of SAGE III is not planned before 2002.

Solar irradiance. Another potentially important climate forcing is change of solar irradiance. The spectrally integrated irradiance has been monitored for the past decade (Fig. 2.8), showing a decline of about 0.1 percent between 1979 and 1986, followed by at least a partial recovery. If this measured variability were spectrally uniform, it would imply a climate forcing of about 0.3 W/m^2 of absorbed solar energy. Solar variability of a few tenths of a percent could cause a global temperature change of the magnitude of the observed cooling between 1940 and 1970, and there have been suggestions that the sun may be responsible for the warming trend of the past century (Friis-Christensen and Lassen, 1991). Thus we need to monitor solar irradiance on longer time scales, including the spectral distribution of changes, because the climate forcing varies strongly depending on the altitude of absorption. Note that there are offsets of the absolute irradiance even among the best calibrated instruments (Fig. 2.8), which implies the necessity of overlapping coverage by successive instruments for successful monitoring. There is no approved plan to continue monitoring of solar irradiance beyond the current UARS instrument (launched in late 1991 with an expected lifetime of 3-5 years).

Surface reflectivity. The next climate forcing mechanism likely to be rediscovered as a competitor to increasing greenhouse gases is change of the Earth's surface reflectivity. Sagan *et al.* (1979) argued that anthropogenic deforestation and desertification could have reduced the planetary albedo sufficiently to cause a cooling of about 1°C over the past few millennia, and may have been

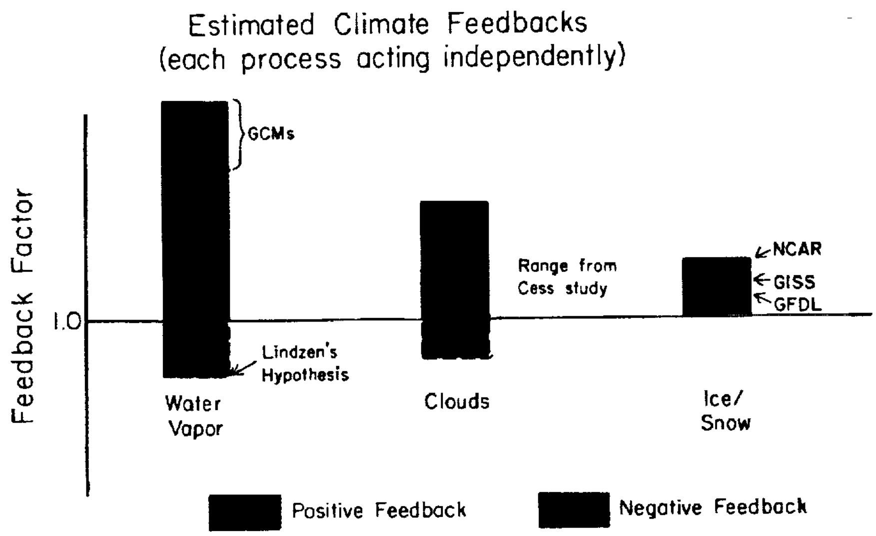

Fig. 2.9. Schematic indication of the radiative feedback factors which have been found to determine the global sensitivity of the general circulation models to climate forcings such as doubled atmospheric CO_2.

responsible for the observed global cooling after 1940. Potter *et al.* (1981) calculated a smaller global cooling, 0.2°C, with a two-dimensional climate model, but nevertheless surface albedo change is a potentially significant climate forcing. For example, a change of mean land albedo from 0.15 to 0.16 would cause a global climate forcing of about 0.5 W/m^2, comparable in magnitude to the forcing due to expected increases of anthropogenic greenhouse gases during the next two decades. Although a global mean change that large may be unlikely, regional effects could be substantial and the global effects need to be quantified.

Operational meteorological satellites currently measure the Earth's surface reflectivity at one or two wavelengths, but the instruments are not calibrated well enough to provide reliable long-term data (Brest and Rossow, 1992). However, it is not difficult to obtain both higher accuracy and precision than that of the meteorological instruments, which were not designed for long-term climate monitoring.

Radiative feedbacks. There are many feedback processes, some known and others yet to be discovered, which alter the climate system's ultimate response to a climate forcing. In studies with current GCMs, it has been found that the net response of global temperature to a forcing such as doubled carbon dioxide can be separated quantitatively into contributions arising from the forcing plus three major radiative feedbacks: changes of atmospheric water vapor, clouds and the area of ice and snow cover (Cess *et al.*, 1989, 1990, 1991; Schlesinger and Mitchell, 1987; Hansen *et al.*, 1984). For example, for doubled CO_2 the no-feedback climate sensitivity of 1.2-1.3°C is increased to about 2-5°C in the GCM simulations, with the latter value depending upon the strength of these three feedbacks in each global model.

As indicated by the schematic Fig. 2.9, the largest feedback in the GCMs is caused by water vapor. Lindzen (1990) maintains that the models exaggerate the water vapor feedback and has argued that the feedback could be negative. Although there is theoretical and empirical evidence against Lindzen's hypothesis of a negative feedback (Betts, 1991; DelGenio *et al.*, 1991; Rind *et al.*, 1991; Raval and Ramanathan, 1989), this does not diminish the importance of changes of the water vapor profile in determining the magnitude of the water vapor feedback. Cloud feedbacks are probably the most uncertain, with the range from GCMs including negative as well as positive feedbacks (Cess *et al.*, 1989, 1990). The ice/snow feedback also shows a wide variation among models.

Climate feedbacks are the cause of large uncertainty about climate sensitivity to a specified forcing. Continued efforts to improve the representation of the feedback processes in climate models are important and are receiving much attention, but it seems unlikely that general agreement on the magnitude of global climate feedbacks can be obtained on the basis of models alone. Thus it is crucial that observations of current and future climate change be accompanied by measurements of the feedbacks to an accuracy sufficient to define their contribution to observed climate change. As we demonstrate below, it is possible to obtain the required accuracies with existing technology.

Summary Caveat

It is appropriate to ask whether there are other important climate forcings or feedbacks, in addition to those which the scientific community has already identified. Although the processes that have been considered account for all the major mechanisms for exchange of energy with space, it is very likely that there will be future surprises in our understanding of both climate forcings and feedbacks. Therefore, it is very important that a monitoring strategy include measurements covering practically the entire spectra of both the solar and thermal radiation emerging from the Earth, because all radiative forcings and feedbacks operate by altering these spectra. Although efforts to measure integrated reflected solar and emitted thermal fluxes are underway (Kandel, 1990), measurement of changes in the spectral distribution of the radiation are required to provide diagnostic information about causes of flux changes.