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Global Indirect Radiative Forcing Caused by Aerosols

IPCC (2007) and Beyond

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Abstract

Anthropogenic aerosols are thought to exert a significant indirect radiative forcing because they act as cloud condensation nuclei in warm cloud-forming processes and ice nuclei in cold cloud-forming processes. Although many of the processes associated with the perturbation of cloud microphysics by anthropogenic aerosols were discussed, IPCC (2007) provided only an estimate of full quantification of the radiative forcing attributable to the first indirect effect (which they referred to as the cloud albedo effect). Here we explain that this approach is necessary if one is to compare the radiative forcing from the indirect effect of aerosols with those from other radiative forcing components such as that from changes in well-mixed greenhouse gases. We also highlight the problems in assessing the effect of anthropogenic aerosols upon clouds under the strict definitions of radiative forcing provided by the IPCC (2007). Although results from global climate models, at their current state of development, suggest that an analysis of indirect aerosol effects in terms of forcing and feedback is possible, a key rationale for the IPCC's definition of radiative forcing, a straightforward scaling between an agent's forcing and the temperature change it induces, is significantly compromised. Feedbacks from other radiative forcings are responses to radiative perturbations, whereas feedbacks from indirect aerosol effects are responses to both radiative and cloud microphysical perturbations. This inherent difference in forcing mechanism breaks down the consistency between forcing and temperature response. It is likely that additional characterization, such as climate efficacy, will be required when comparing indirect aerosol effects with other radiative forcings. We suggest using the radiative flux perturbation associated with a change from preindustrial to present-day composition,

calculated in a global climate model using fixed sea surface temperature and sea ice, as a supplement to IPCC forcing.

The Concept of Radiative Forcing

In the latest IPCC report, Forster et al. (2007) define the concept of radiative forcing as follows:

> The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in the net irradiance at the tropopause *after* allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.

Over the last couple of decades, radiative forcing has proved to be a useful concept because the global mean near surface temperature response, dT, to a particular radiative forcing, dF, may be related to the climate sensitivity, λ, via the relationship:

$$dT = \lambda dF. \qquad (19.1)$$

Generally, studies suggest that this relationship appears to be approximately independent of the forcing mechanism (e.g., Meehl et al. 2004; Matthews et al. 2004), which means that the relative importance of many different forcing mechanisms may be quantified and compared.

While λ is approximately independent of the forcing mechanism, it may be quite strongly model-dependent. Additionally, some recent studies have suggested that λ may not be entirely independent of the forcing mechanism, as they may induce different feedbacks, which may lead to a modification of Equation 19.1 via the climate forcing efficacy, ε, (Joshi et al. 2003; Hansen and Nazarenko 2004):

$$dT = \varepsilon_i \lambda_{CO2} dF \qquad (19.2)$$

where ε_i is defined as λ_i/λ_{CO2}. The inter-forcing mechanism differences in ε_i appear to be greatest for absorbing aerosols, where absorption of solar radiation induces the so-called "semi-direct effect," but large-scale dynamic feedbacks differ in the models used in assessing ε_i. This results in values that are either larger (e.g., Jacobson 2001) or smaller (e.g., Roberts and Jones 2004; Hansen et al. 2005; Jones et al. 2007) than unity with values that typically range from 0.7–1.3 (Forster et al. 2007).

It is important to realize that to diagnose an indirect radiative forcing that may be compared to other forcing mechanisms, it is the *global* radiative forcing that is related to the *global* temperature change in Equation 19.1 and 19.2. A local radiative forcing does not correspond to a local temperature change because of the myriad of local-, regional-, and global-scale feedback processes that vary over the different regions of the Earth.

Now that the IPCC (2007) definition of radiative forcing and its limitations have been presented, we will discuss the specifics of the indirect aerosol radiative forcing via interactions with clouds.

Radiative Forcing and the Aerosol Indirect Effects

Aerosol particles act as cloud condensation nuclei and can thereby modify the microphysical, macrophysical, and optical properties of clouds. Figure 19.1 summarizes schematically the processes considered in assessing aerosol indirect radiative effects. As depicted, unperturbed clouds reflect a proportion of incident solar radiation back to space; when anthropogenic aerosols are introduced under the assumption of constant cloud liquid water, the cloud is made up of a larger number of smaller droplets, as represented by the albedo effect/1st indirect effect/Twomey effect (Twomey 1977). The change in the cloud droplet radius affects the cloud development in a number of complex ways, some of which are shown in Figure 19.1. Smaller cloud drops may lead to a decrease in the coalescence rate and thus reduce rainfall: decreased rainfall will increase the cloud liquid water content, leading to more developed and therefore deeper clouds (e.g., Pincus and Baker 1994). Reduced rainfall and the increase in cloud liquid water content may also lead to an increase in the lifetime of clouds (Albrecht 1989). All of these effects were considered by Forster et al. (2007) to be encompassed by the labels "cloud lifetime effect/2nd indirect effect/Albrecht effect" in Figure 19.1. Furthermore, two other effects are represented in Figure

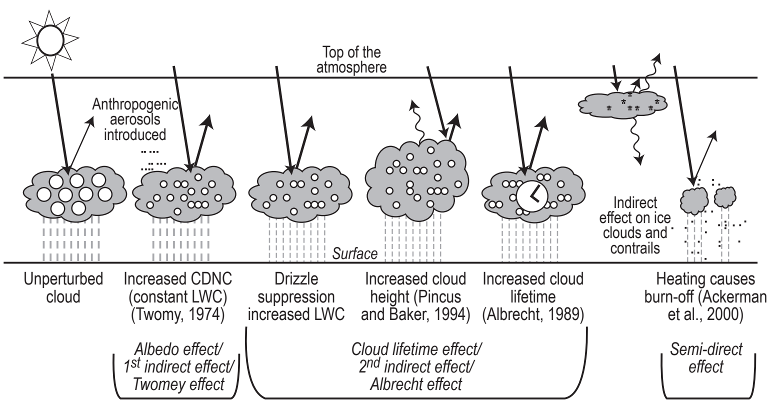

Figure 19.1 A schematic diagram representing the processes considered in assessing aerosol direct and indirect radiative effects (modified from Haywood and Boucher 2001).The small black dots represent anthropogenic aerosols, and the large/small open circles depict large/small cloud droplets, respectively. Ice particles are represented by stars. Solar fluxes are represented by arrows, and the magnitude of the fluxes represented by the width of the arrows. Wavy lines represent infrared fluxes. Precipitation is depicted by dashed vertical gray lines. CDNC: cloud droplet number concentration; LWC: liquid water content.

19.1: the effect of anthropogenic aerosols as ice nuclei and the semi-direct effect, whereby additional solar absorption by anthropogenic aerosols causes heating of the ambient environment and reduces the ambient relative humidity, thereby changing the cloud amount.

Much higher-resolution models, such as cloud-resolving models (CRMs) or large eddy simulation models, are better able to represent the microphysical and dynamical interaction of aerosols and clouds, but they still require subgrid-scale parameterizations of some processes (e.g., entrainment). Their limited domains mean that they are currently only capable of estimating the local indirect radiative forcing for specific case studies. Thus, only general circulation models (GCMs) or chemical transport models (CTMs) are suitable for quantifying the *global* indirect radiative forcing, which can then be compared with other forcing mechanisms such as that attributable to changes in well-mixed greenhouse gases.

The History of Aerosol Indirect Radiative Forcing

In the mid-1990s, when global simulations of aerosol interactions with clouds were in their infancy, a compromise between CTM and GCM modeling efforts was devised to investigate aerosol indirect forcing. CTMs generally did not include realistic radiative transfer codes, which need accurate representation of absorbing gases, treatment of scattering, and accurate representation of surface reflectance, emissivity, and temperature profiles. Similarly, GCMs did not include the detailed chemical processes that were necessary to represent the emission, formation, transportation, microphysical processes, and wet and dry deposition of aerosols and their precursors. Therefore, CTMs were frequently used to model the particulate mass mixing ratios for preindustrial and present-day conditions. These CTM-derived mass mixing ratios were used by the GCMs to simulate the effect of aerosols upon the cloud effective radius by using parameterizations based on either Köhler theory or aircraft observations (e.g., Leaitch et al. 1992; Hegg et al. 1993; Martin et al. 1994). These GCM parameterizations related the particle number or mass concentration to the number of cloud droplets, which itself is related to cloud effective radius. Typically, GCMs diagnosed the first indirect radiative forcing by making two calls to the radiation code: the first call used preindustrial particle concentrations and the second used present-day particle concentrations. "Preindustrial" was used for advancing the model physics at each radiation time-step and the top-of-the-atmosphere (TOA) outgoing shortwave radiation, $SW_{TOA}{}^{\uparrow}{}_{PREIND}$, was diagnosed. "Present-day" was used to modify the cloud effective radius at each radiation time step and determined the TOA outgoing shortwave radiation perturbed by anthropogenic aerosols, $SW_{TOA}{}^{\uparrow}{}_{PRESENT.}$ The first indirect effect can then be simply diagnosed as $SW_{TOA}{}^{\uparrow}{}_{PREIND}$ - $SW_{TOA}{}^{\uparrow}{}_{PRESENT}$. Because increased concentrations of anthropogenic aerosol reduce the effective radius of cloud particles and smaller cloud particles reflect more radiation back to space, $SW_{TOA}{\uparrow}_{PREIND}$ - $SW_{TOA}{\uparrow}_{PRESENT}$ is negative, and the first indirect effect leads to a cooling of the climate system according to Equation 19.1.

There are two contraventions to the definition of radiative forcing of Forster et al. (2007), namely that the change in the net irradiance is frequently derived at the TOA rather than at the tropopause, and the definition does not account for stratospheric adjustment. Neglecting these effects makes very little difference to the derived first indirect radiative forcing when it is derived diagnostically. It is important to realize that the present-day call to the radiative transfer code does not affect the atmospheric heating rates in the model in any way, and therefore the model evolution is entirely unaffected by the perturbation to the particle concentrations. This means that feedback processes are not induced, and cloud, precipitation, sensible and latent heat fluxes, etc. are not affected in diagnosing the first indirect effect in this manner.

GCMs and CTMs have continued their development, and increases in computing power mean that they have to some extent merged: GCMs are now capable of including detailed parameterizations for many types of aerosol which account for the emissions, gas and aqueous phase formation, transportation, and wet and dry deposition of aerosols and their precursors. Therefore, GCMs no longer rely on the off-line particle mass mixing ratios generated by CTMs. As a result, deriving the first aerosol indirect forcing in the manner described above has fallen out of favor. This is because global climate simulations are now driven by emissions, and they explicitly model (albeit in a highly parameterized way) the effect of aerosols upon the microphysical properties of clouds in a far more complete way, and account for the host of second indirect effects, shown schematically in Figure 19.1. Once this approach is taken, diagnosis of the first indirect effect by itself is difficult because separation of the first from the second indirect effects is difficult to achieve in a consistent way. Although the first indirect effect can be approximated by global models without inducing any feedbacks to the climate system (using two calls to the radiation code), when the second indirect effects are invoked, there are necessarily significant fast feedbacks that come into play. For example, each of the second indirect effects represented schematically in Figure 19.1 and represented by GCMs show perturbations to the precipitation. Therefore the state of the atmosphere is not held fixed because surface and tropospheric temperatures respond to changes in, for example, the surface sensible and latent heat flux perturbations caused by the perturbation to the aerosol. Thus, the definition of radiative forcing of Forster et al. (2007) is further compromised. Because we wish, however, to quantify approximately the potential global climatic impact of the second indirect effects, a so-called *quasi-* or *pseudo-indirect forcing* is frequently diagnosed (e.g., Rotstayn and Penner 2001). This “quasi-forcing” is diagnosed in a very different way to the first indirect effect. The TOA net flux (the sum of the short- and longwave fluxes, $SW_{TOA}{\uparrow}$ and $LW_{TOA}{\uparrow}$) in two separate parallel global GCM simulations is diagnosed. The first simulation uses preindustrial aerosol emissions while the second simulation uses present-day aerosol emissions, and the total indirect "quasi-forcing" is diagnosed as the difference between the net top of atmosphere fluxes. Importantly, the simulations are generally carried out in atmosphere-only GCMs with fixed SSTs and sea-ice extents; this means that the temperature response of the model and slow feedbacks associated with changes in global temperatures are inhibited, but the atmospheric state is no longer strictly held fixed (Hansen et al. 2002). Further methods for diagnosing the radiative forcing have been proposed where the land-surface temperatures are also held fixed (e.g., Shine et al. 2003).

At this point, it is worth considering whether the "quasi-forcing" provides an adequate representation of the strict definition of radiative forcing, as defined by Forster et al. (2007). Figure 19.2a (after Ming et al. 2005), shows the radiative forcing from the cloud albedo effect calculated using this definition in the GFDL AM2 (GFDL 2004). To obtain the forcing in Figure 19.2a, a simulation is run with preindustrial aerosols. The fields from this simulation are used to calculate a second set of TOA radiative fluxes, with the only change being the replacement of preindustrial by present-day aerosols in the radiation code. The difference between fluxes with present-day and preindustrial aerosols (the IPCC forcing) is shown in Figure 19.2a. Figure 19.2b shows the "quasi-forcing" from the cloud albedo effect, obtained by integrating AM2 with preindustrial aerosols but using present-day aerosols for purposes of radiative transfer only. The simulation in Figure 19.2b is a preindustrial simulation, except that the cloud albedo corresponds to present-day aerosols. We use this simulation to illustrate the effect of the preindustrial to present-day change in aerosols on cloud albedo while modeling all other cloud processes for preindustrial aerosols. The "quasi-forcing" in Figure 19.2b includes feedbacks caused by radiative, but not microphysical, perturbations associated with anthropogenic aerosols. Many features of the forcing and "quasi-forcing" patterns are similar. Although the amplitudes of the features tend to be larger for the "quasi-forcing," the global means are almost the same. The feedbacks, which are included in the "quasi-forcing," are responses to a radiative perturbation only. This is also true of the feedbacks, which occur in response to forcing by changes in well-mixed greenhouse gases. For cloud-albedo feedback, then, "quasi-forcing" and forcing behave similarly, at least for the GFDL AM2.

The use of the radiative forcing concept becomes problematic when one considers feedbacks associated with microphysical aspects of the aerosol indirect effect. We refer to these feedbacks here as non-albedo effects. Figure 19.2c shows non-albedo "quasi-forcing," obtained by integrating AM2 with present-day aerosols but using preindustrial aerosols for purposes of radiative transfer only. The simulation in Figure 19.2c models all cloud processes, except albedo, using present-day aerosols. We use this simulation to illustrate the effects of the preindustrial to present-day change in aerosols on all cloud processes except albedo, which corresponds to preindustrial aerosols. The most important point is that the magnitude of the non-albedo "quasi-forcing" is a

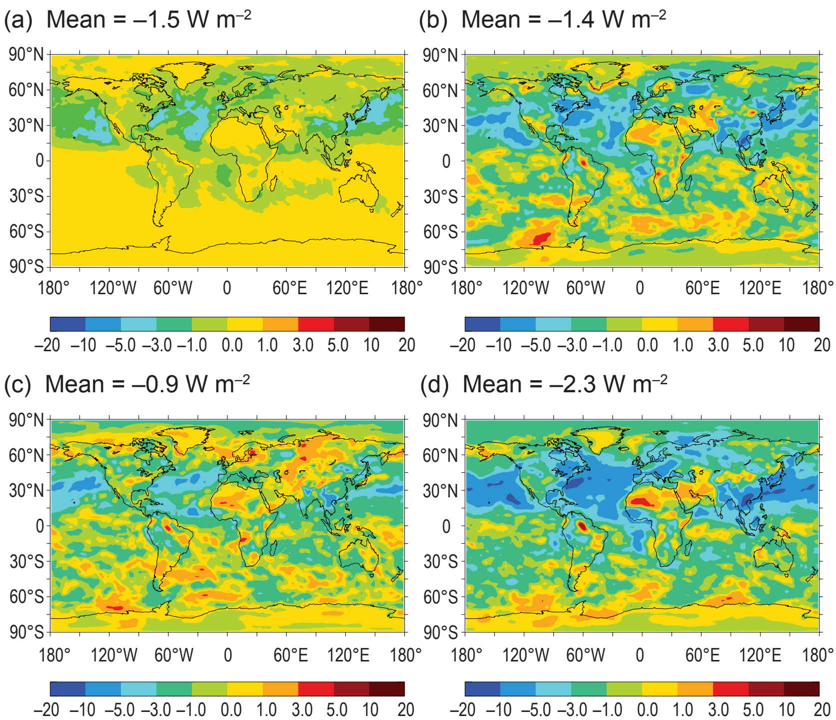

Figure 19.2 (a) Indirect forcing (by cloud albedo effect) using the definition of Forster et al. (2007); (b) quasi-forcing by cloud albedo effect only; (c) quasi-forcing by non-albedo effects only; and (d) quasi-forcing by all indirect effects. The quasi-forcings are derived from ten-year means from parallel GCM simulations where the sea surface temperatures are held fixed. Simulations use the GFDL AM2 model. Figure 19.2a modified from Ming et al. (2005).

large fraction of the magnitude of the albedo forcing, and this is apparent in Figure 19.2d, which shows the total indirect-effect "quasi-forcing." Given the nonlinear nature of the forcing mechanisms, the near additivity of the albedo and non-albedo forcings is noteworthy; at this point we have no way of knowing whether this result is general or particular to this model. The microphysical feedbacks, which produce the "quasi-forcing" in Figure 19.2c are unique among the forcings considered by IPCC and are not associated with instantaneous forcing, as defined by Forster et al. (2007). The relationship between forcing and "quasi-forcing" (and thus between forcing and temperature change) at the global mean will differ for indirect aerosol effects from the relationship for changes in well-mixed greenhouse gases or aerosol direct effects.

A key rationale for use of forcings by IPCC is to scale temperature changes among various agents of climate change. Aerosol indirect effects will not fit into this scaling because unique microphysical feedback mechanisms operate, and the magnitude of the microphysical feedbacks is large relative to the radiative feedbacks.

Rationale of IPCC (2007) for Including Only the First Indirect Effect

IPCC (2007) continues to adopt the approach that only the first aerosol indirect effect can be rigorously defined as a forcing because, in determining any of the second indirect effects, cloud feedbacks necessarily come into play in the climate system. The second indirect effects are therefore considered as feedbacks (responses to the initial anthropogenic perturbation of aerosol via the first indirect effect) to the climate system rather than as radiative forcings. IPCC (2007) continues to rely on global climate models for these estimates, as they are the only tool presently capable of providing global estimates. Arguably, satellite retrievals could provide global estimates of the indirect effects of aerosols (e.g., Nakajima et al. 2001; Brenguier et al. 2000) but an unambiguous determination of a change in cloud reflectance when influenced by anthropogenic aerosols is hampered by large natural variability and/or artifacts in retrievals of cloud liquid water path and/or cloud effective radius caused by absorbing aerosol above cloud (e.g., Haywood et al. 2004). As with all such satellite-based approaches, there is also the question of the degree to which modern-day "clean" conditions are representative of global preindustrial conditions. Figure 19.3 shows the first indirect radiative forcing determined by IPCC (2007), ranging from –0.2 to –1.8 W m^{-2}.

It may be argued that the second indirect effects have to be comprehensively quantified if we are to understand fully the effects of aerosols upon clouds. While there is no doubt that clouds remain one of the most challenging aspects in accurate simulations of climate change, the following argument shows that there is some wisdom in not (yet) including the second indirect effects as radiative forcing mechanisms. This statement stems from the different behavior of the second aerosol indirect effect when assessed by GCM schemes compared with more detailed microphysical large eddy models (LEMs). In GCM parameterizations, the second indirect effect leads to a decrease in precipitation efficiency and therefore increases in cloud water path and fraction. In LEM simulations, however, the response to increases in particle concentration depends on precise details of the situation. In studies of tradewind cumuli, Xue and Feingold (2006) and Xue et al. (2008) found that the competing effects of aerosol-induced precipitation suppression and evaporation enhancement determined whether aerosols increased or decreased cloud fraction, and could be quite regime-dependent. Detailed modeling studies of stratiform clouds by Ackerman et al. (2004) and Wood (2007) showed that the second indirect effect can operate either to enhance or reduce cloud amount, again depending on the precise conditions that prevail (humidity above cloud and cloud-base

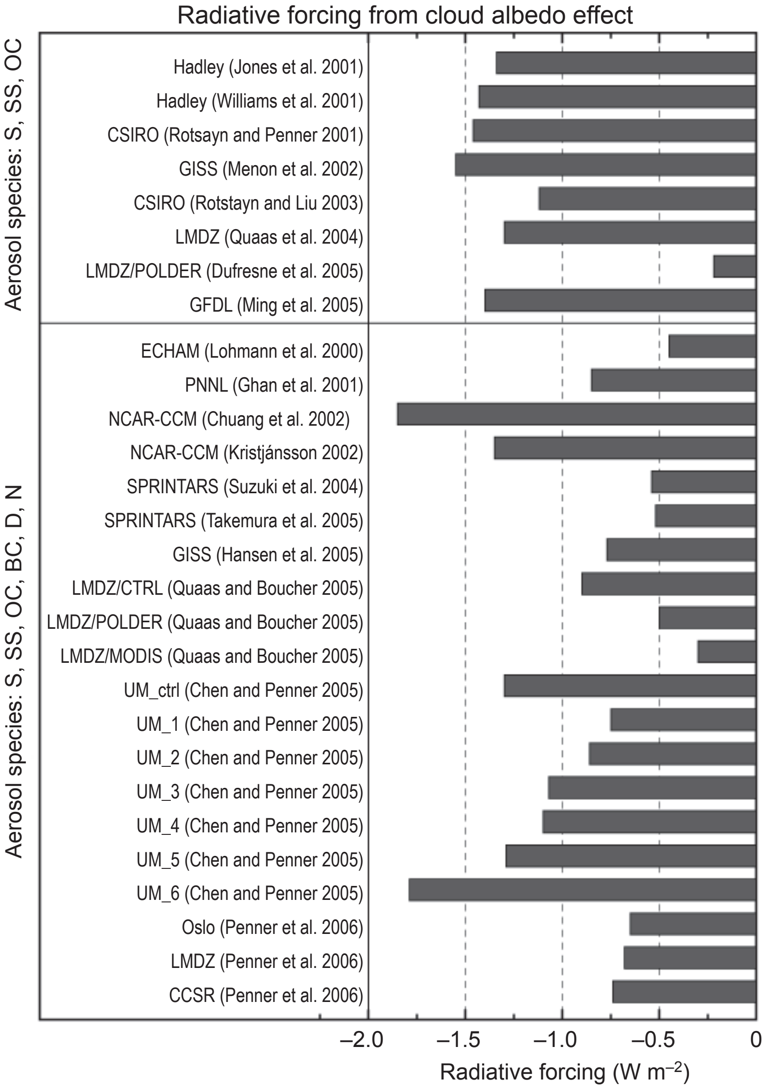

Figure 19.3 Assessment of the first indirect effect. Modified from Forster et al. (2007). BC: black carbon; D: dust; N: nitrate; OC: organic carbon; S: sulfate; SS: sea salt.

height being two of the conditions identified). Studies with CRMs for deep convection indicate that increasing aerosols can either increase or decrease precipitation (van der Heever et al. 2006; Khain and Pokrovsky 2004; Khain et al. 2004; Khain et al. 2005; Lynn et al. 2005), depending on the stability and moisture structure of the flow in which convection develops.

Although global climate models appear to simulate the first-order effect of aerosols on cloud droplet number and precipitation fairly well, the climate impact of this change depends on a host of feedback processes, some of which have only crudely been modeled. This means that in GCMs, which are the only tool available at present for diagnosing the second indirect effect on a global basis, cloud water path or fraction always increases with particle concentration, leading to a cooling of the Earth–atmosphere system. Analysis of the results presented in Forster et al. (2007) shows that in all of the climate models studied, the total indirect effects were more negative than the first indirect effect alone, indicating that the second indirect effect in all the models operated in this manner. In more detailed models, which represent the microphysical, dynamic, and radiative properties of both clouds and aerosols far more explicitly, the second indirect effect can operate in either direction, suggesting that the global impact on the Earth–atmosphere system is unclear.

Limitations of Forcing as a Measure of Indirect Effects

In the previous section, we made a case for viewing forcing as IPCC has traditionally construed it; that is, as an instantaneous flux change produced by a specified change in atmospheric composition. Here, we consider further characteristics of cloud–aerosol interactions which may limit the interpretation of forcing when applied to aerosol indirect effects.

Figure 19.1 presented a traditional view of aerosol direct and indirect effects in GCMs. As noted above, process-level models (e.g., LEM) raise the possibility that, as clouds evolve from an initial state with increased aerosol, evaporation may compete with reduced precipitation and break the sequence depicted in Figure 19.1. A concern for GCM development is that current cloud parameterizations are not able to capture processes in LEMs that could fundamentally alter the response of clouds to aerosols. However, even with current state-of-the-science GCM cloud parameterizations, the response of clouds to increased aerosols can differ fundamentally, depending on atmospheric state. Figure 19.4 shows the change in cloud liquid profiles over two days of integration at high and low particle concentrations, using the single-column model for the GFDL AM2 (GFDL 2004). (A simplified radiation parameterization has been used in these calculations.) For the moist sounding, the clouds and aerosols interact as depicted in Figure 19.1. For the dry sounding, Figure 19.5 shows that the interaction sequence is broken after drizzle is suppressed and liquid water content increased; this, in turn, results in an increase in cloud-top longwave cooling. The associated instability leads to increased entrainment of dry air into the planetary boundary layer and subsequent increased evaporation. Cloud lifetime *decreases* with increasing aerosol particle concentrations, and the sign of the cloud lifetime effect is changed. Figure 19.6 summarizes the sequences of interactions between clouds and radiation occurring in Figure 19.1 and 19.5. The mechanisms shown in Figures 19.5 and 19.6 are by no means the only possibilities for reducing cloud liquid water at high particle concentration.

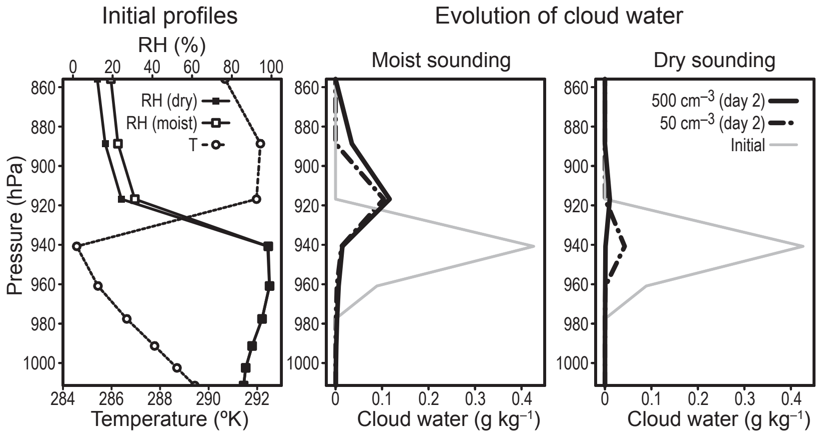

Figure 19.4 Evolution of cloud liquid over two days at high and low aerosol concentrations for two initial relative humidity (RH) profiles (otherwise identical soundings) in the GFDL AM2 single-column model. Cloud liquid is a grid mean, i.e., the product of cloud fraction and in-cloud water mixing ratio.

Among other possibilities is turbulence that results from precipitation suppression (Ackerman et al. 2004; Wood 2005), and all such mechanisms are not included in current GCM parameterizations.

A change in the sign of the cloud lifetime effect does not, by itself, negate the case made earlier about the utility of the forcing concept. The cloud lifetime effect acts as a feedback. Whether the feedback is positive or negative depends on the moisture structure of the atmosphere in which the clouds form in the illustrative case we have just discussed, and probably on additional

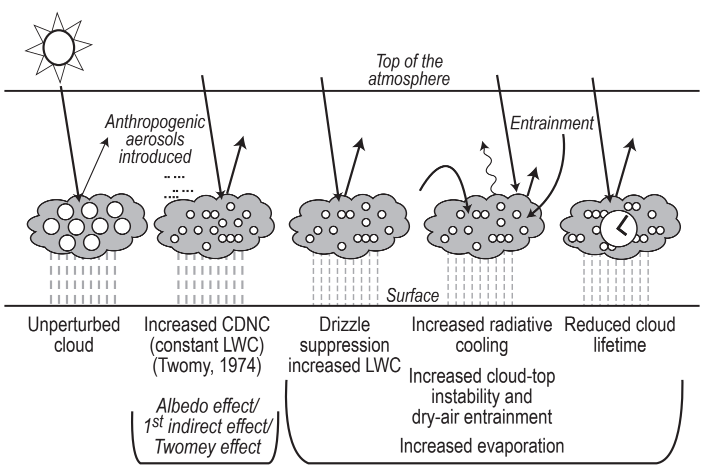

Figure 19.5 A schematic diagram showing how the sequence of indirect effects depicted in Figure 19.1 can change if drier air overlies the planetary boundary layer. Curved lines represent entrainment, while other notation follows Figure 19.1.

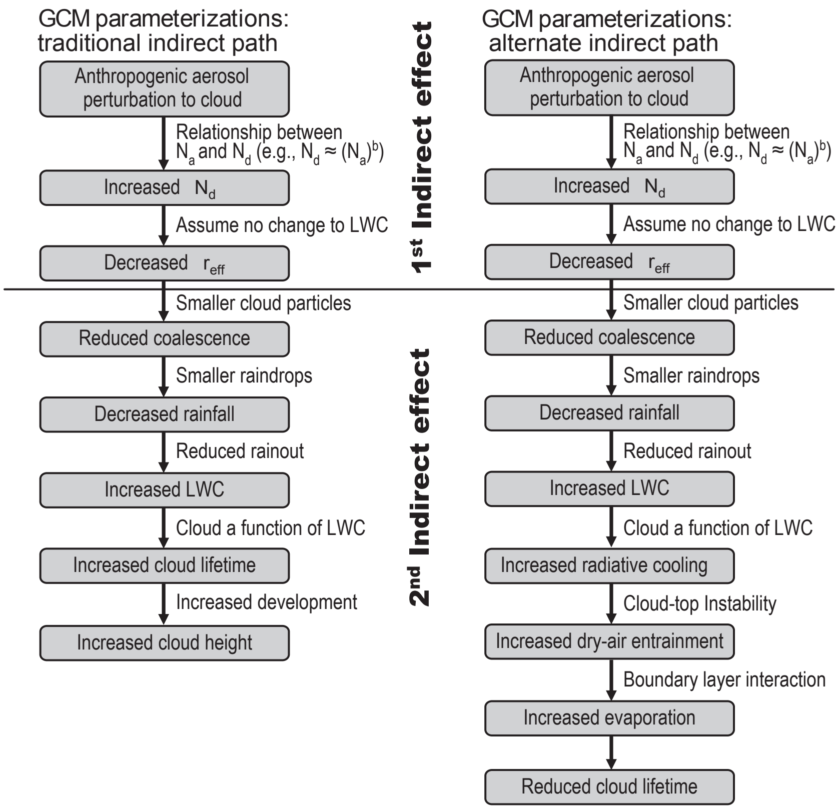

Figure 19.6 Sequence of feedbacks in GCMs in response to increasing aerosol concentration. The GCM paths on the left and right correspond to Figure 19.1. LWC: liquid water content.

factors in other cases. A more interesting situation would arise were a negative cloud lifetime effect to reduce cloud lifetime sufficiently rapidly so that the resulting reduction in reflected shortwave radiation exceeded the increase in reflected shortwave radiation associated with the first indirect effect. In this case, the combination of oppositely signed albedo and lifetime effects would have a net effect of opposite sign to the forcing. This certainly is not consistent with the general view of a feedback amplifying or damping a forcing, although it would still fit within the framework of Equation 19.1 or 19.2, but only if *negative* climate sensitivities or efficacies are allowed. Much of the IPCC rationale for using forcing is that it scales with temperature response in a fairly straightforward manner. The relationship between forcing and temperature response is not straightforward if the magnitude of a cloud lifetime effect exceeds that of an oppositely signed cloud albedo effect.

The use of "quasi-forcing" avoids issues of this type but is likely to exhibit considerable model-dependence. It also clearly (and undesirably) includes some but not all feedbacks operating in the climate system. As a practical matter, the relative merits of forcing and "quasi-forcing" would depend on the prevalence of situations where indirect non-albedo cloud effects oppose the indirect cloud albedo effect and the relative magnitudes of albedo and non-albedo effects. If the prevalence is low or the albedo effects are much larger than the non-albedo effects, the advantages of clear separation of forcing from feedback using the current IPCC approach are very evident. As noted, Forster et al. (2007) report that climate models developed thus far, which include indirect effects, exhibit same-signed global-mean indirect albedo and non-albedo effects. This is true for the GFDL AM2 (Ming et al. 2005), as is evident in Figure 19.2, even though its parameterizations allow oppositely signed non-albedo and albedo effects. The current state of climate modeling of indirect effects, then, does not make the case for departing from the current approach to forcing for indirect aerosol effects. However, a major caveat lies in the poorly developed state of many of the cloud parameterizations on which indirect effects depend. The case shown in Figures 19.1, 19.4, and 19.5 depends strongly on the treatment of cloud radiation and boundary-layer turbulence, both of which are probably represented with limited realism in GCMs. The preliminary conclusions about relative magnitudes and signs of indirect cloud–albedo and non-albedo effects may change with further GCM development.

Conclusion

Indirect aerosol effects challenge the traditional view of forcing in climate models. For liquid clouds alone, several aerosol effects are likely. In state-of-the-science GCMs, these effects can be considered in terms of traditional forcing–feedback analysis, since the global responses to changes in droplet size, which produce the indirect cloud albedo effect, amplify the albedo effect. The concept remains useful if indirect non-albedo effects are oppositely signed to the albedo effects, at least if the magnitude of these effects remains smaller than the cloud albedo effect. (If not, quantities such as climate sensitivity and forcing efficacy need not even remain positive for indirect forcing.)

Even though forcing–feedback analysis remains a viable tool for considering indirect aerosol effects, much of its attractiveness in earlier applications disappears. For example, the climate sensitivity for forcing by indirect effects of aerosols in Equation 19.1 will almost certainly take values considerably different than for forcing by changes in well-mixed greenhouse gases, at least for some models. Although this can be formally treated using the climate forcing efficacy in Equation 19.2, substantial departures of the forcing efficacy from unity are quite possible for indirect forcing. Given the range of results in Figure 19.3, substantial variation of the climate forcing efficacy among models is also likely, at least at the present stage of model development. Note here that feedbacks for well-mixed greenhouse gases are also important. The limitations on the utility of the forcing concept arise because the nature of the feedbacks differs for perturbations of clouds by aerosols and perturbations in well-mixed greenhouse gases.

The case of indirect forcing by aerosols simulated by the GFDL AM2, shown in Figure 19.2, provided an illustrative example. Although it exhibited qualitative similarities in the regional patterns of flux changes for forcing and "quasi-forcing," the regional and global mean magnitudes differed appreciably. These differences are attributable to the presence of strong microphysical feedbacks that result from changes in the sizes of cloud droplets when aerosols increase. Direct aerosol forcing and forcing by changes in well-mixed greenhouse gases are assumed to have feedbacks that respond only to radiative perturbations, whereas both radiative and microphysical feedbacks occur with aerosol indirect effects. The large magnitude of the non-albedo (microphysical) "quasi-forcing" indicates that the temperature response to a forcing whose feedbacks result from a purely radiative perturbation will differ from a forcing whose feedbacks result from both radiative and microphysical perturbations.

As a result, the chief rationale for using forcings in IPCC—to compare cleanly the relative importance of perturbations in atmospheric composition—is likely to be limited for indirect aerosol effects. At least, the climate forcing efficacy will require consideration, along with forcing, to compare indirect aerosol effects with other forcing. This situation introduces complexity but is an inevitable consequence of the vast difference between the forcing mechanism associated with indirect aerosol effects and other forcing mechanisms considered by the IPCC. Although changes in greenhouse gases or direct aerosol effects are assumed to force the atmosphere by changing its radiative properties, indirect aerosol effects force the atmosphere by changing both its radiative and microphysical properties. Feedbacks occur in all cases but can operate through more processes in response to indirect aerosol effects.

"Quasi-forcing" or pseudo-indirect forcing is a strong candidate to supplement IPCC forcing. Its chief drawback is probably the confusion which using the term "forcing" produces. Given that "quasi-forcing" is, in fact, the TOA radiative flux perturbation produced by integrating an atmospheric GCM from preindustrial to present-day composition with fixed SSTs and sea-ice extents, we recommend using the term *radiative flux perturbation* instead. Radiative flux perturbations are likely to scale more closely with global mean surface temperature change than IPCC forcings and, like forcings, remain reasonably easy to calculate, relative to fully coupled GCMs. In addition to incorporating aerosol indirect effects, recent results from Gregory and Webb (2008) suggest that the radiative flux perturbations will include fast cloud feedbacks as well. Invariably, intermodel spread in radiative flux perturbations is likely to be greater than the spread in forcings. Thus, radiative flux perturbation would more accurately capture uncertainty associated with indirect effects than forcing.

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References

Ackerman, A. S., M. P. Kirkpatrick, D. E. Stevens, and O. B. Toon. 2004. The impact of humidity above stratiform clouds on indirect aerosol climate forcing. *Nature* **432**:1014–1017.

Albrecht, B. 1989. Aerosols, cloud microphysics and fractional cloudiness. *Science* **245**:1227–1230.

Brenguier, J. -L., H. Pawlowska, L. Schueller et al. 2000. Radiative properties of boundary layer clouds: Droplet effective radius versus number concentration. *J. Atmos. Sci.* **57**:803–821.

Chen, Y., and J. E. Penner. 2005. Uncertainty analysis of the first indirect aerosol effect. *Atmos. Chem. Phys.* **5**:2935–2948.

Chuang, C. C., J. E. Penner, J. M. Prospero et al. 2002. Cloud susceptibility and the first aerosol indirect forcing: Sensitivity to black carbon and aerosol concentrations. *J. Geophys. Res.* **107(D21)**:4564.

Dufresne, J.-L., J. Quaas, O. Boucher, S. Denvil, and L. Fairhead. 2005. Contrasts in the effects on climate of anthropogenic sulfate aerosols between the 20th and the 21st century. *Geophys. Res. Lett.* **32**:L21703.

Forster, P., V. Ramaswamy, P. Artaxo et al. 2007. Radiative forcing of climate change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning et al. pp. 129–234. New York: Cambridge Univ. Press.

GFDL Global Atmosphere Model Development Team. 2004. The GFDL new global atmosphere and land model AM2/LM2: Evaluation with prescribed SST simulations. *J. Climate* **17**:4641–4673.

Ghan, S., N. Laulainen, R. Easter et al. 2001. Evaluation of aerosol direct radiative forcing in MIRAGE. *J. Geophys. Res.* **106(D6)**:5295–5316.

Gregory, J., and M. J. Webb. 2008. Tropospheric adjustment induces a cloud component in CO_2 forcing. *J. Climate* **19(1)**:39.

Hansen, J., and L. Nazarenko. 2004. Soot climate forcing via snow and ice albedos. *PNAS* **101**:423–428.

Hansen, J., M. Sato, L. Nazarenko et al. 2002. Climate forcings in Goddard Institute for Space Studies SI2000 simulations. *J. Geophys. Res*. **107**:D184347.

Hansen, J., M. Sato, R. Ruedy et al. 2005. Efficacy of climate forcings. *J. Geophys. Res*. **110**:D18104.

Haywood, J. M., S. R. Osborne, and S. J. Abel. 2004. The effect of overlying absorbing aerosol layers on remote sensing retrievals of cloud effective radius and cloud optical depth. *Q. J. Roy. Meteor. Soc.* **130**:779–800.

Hegg, D. A., R. J. Ferek, and P. V. Hobbs. 1993. Light scattering and cloud condensation nucleus activity of sulfate aerosol measured over the Northeast Atlantic Ocean. *J. Geophys. Res.* **98**:14,887–14,894.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. S. Solomon, D. Qin, M. Manning et al. New York: Cambridge Univ. Press.

Jacobson, M. Z. 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* **409**:695–697.

Jones, A., D. L. Roberts, and M. J. Woodage. 2001. Indirect sulphate aerosol forcing in a climate model with an interactive sulphur cycle. *J. Geophys. Res*. **106(D17)**:20,293–20,301.

Jones, A., J. M. Haywood, and O. Boucher. 2007. Aerosol forcing, climate response and climate sensitivity in the Hadley Centre climate model. *J. Geophys. Res*. **112**:D20211.

Joshi, M., K. Shine, M. Ponater et al. 2003. A comparison of climate response to different radiative forcings in three general circulation models: Towards an improved metric of climate change. *Climate Dyn*. **20**:843–854.

Khain, A., A. Pokrovsky, M. Pinsky, A. Seifert, and V. Phillips. 2004. Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed phase cumulus cloud model. Part I: Model description and possible applications. *J. Atmos. Sci.* **15**:2963–2982.

Khain, A., and A. Pokrovsky. 2004. Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part II: Sensitivity study. *J. Atmos. Sci.* **24**:2983–3001.

Khain, A., D. Rosenfeld, and A. Pokrovsky. 2005. Aerosol impact on the dynamics and microphysics of deep convective clouds. *Q. J. Roy. Meteor. Soc*. **131**:2639–2663.

Kristjánsson, J. E., A. Staple, J. Kristiansen, and E. Kaas. 2002. A new look at possible connections between solar activity, clouds and climate. *Geophys. Res. Lett*. **29(23)**:2107.

Leaitch, W. R., G. A. Isaac, J. W. Strapp, C. M. Banic, and H. A. Wiebe. 1992. The relationship between cloud droplet number concentration and anthropogenic pollution: Observations and climatic implications. *J. Geophys. Res*. **97**:2463–2474.

Lohmann, U., J. Feichter, J. E. Penner, and W. R. Leaitch. 2000. Indirect effect of sulfate and carbonaceous aerosols: A mechanistic treatment. *J. Geophys. Res*. **105(D10)**:12,193–12,206.

Lynn, B. H., A. P. Khain, J. Dudhia et al. 2005. Spectral (bin) microphysics coupled with a mesoscale model (MM5). Part I: Model description and first results. *Mon. Wea. Rev.* **133**:44–58.

Martin, G. M., D. W. Johnson, and A. Spice. 1994. The measurement and parameterisation of effective radius of droplets in warm stratocumulus clouds. *J. Atmos. Sci*. **51**:1823–1843.

Matthews, H. D., A. J. Weaver, K. J. Meissner, N. P. Gillett and M. Eby. 2004. Natural and anthropogenic climate change: Incorporating historical land cover change, vegetation dynamics and the global carbon cycle. *Climate Dyn.* **22**:461–479.

Meehl, G. A., W. M. Washington, C. M. Ammann et al. 2004. Combinations of natural and anthropogenic forcings in twentieth-century climate. *J. Climate* **17**:3721–3727.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo. 2002. Climate effects of black carbon aerosols in China and India. *Science* **297**:2250–2253.

Ming, Y., V. Ramaswamy, P. A. Ginoux, L. W. Horowitz, and L. M. Russell. 2005. Geophysical Fluid Dynamics Laboratory general circulation model investigation of the indirect radiative effects of anthropogenic sulphate aerosol. *J. Geophys. Res.* **110**:D22206.

Nakajima, T., A. Higurashi, K. Kawamoto, and J. Penner. 2001. A possible correlation between satellite-derived cloud and aerosol microphysical parameters. *Geophys. Res. Lett*. **28**:1171–1174.

Pincus, R., and M. B. Baker. 1994. Effect of precipitation on the albedo susceptibility of clouds in the marine boundary layer. *Nature* **372**:250–252.

Quaas, J., O. Boucher, and F.-M. Breon. 2004. Aerosol indirect effects in POLDER satellite data and the Laboratoire de Météorologie Dynamique-Zoom (LMDZ) general circulation model. *J. Geophys. Res*. **109**:D08205.

Quaas, J., and O. Boucher. 2005. Constraining the first aerosol indirect radiative forcing in the LMDZ GCM using POLDER and MODIS satellite data. *Geophys. Res. Lett.* **32**:L17814.

Penner, J. E., J. Quaas, T. Storelvmo et al. 2006. Model intercomparison of indirect aerosol effects. *Atmos. Chem. Phys. Discuss.* **6**:1579–1617.

Ramaswamy, V., O. Boucher, J. Haigh et al. 2001. Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, ed. J. T. Houghton et al. pp. 349–416. New York: Cambridge Univ. Press.

Roberts, D. L., and A. Jones. 2004. Climate sensitivity to black carbon aerosol from fossil fuel combustion. *J. Geophys. Res*. **109**:D16202.

Rotstayn, L., and J. E. Penner. 2001. Indirect aerosol forcing, quasi forcing, and climate response. *J. Climate* **14**:2960–2975.

Rotstayn, L. D., and Y. Liu. 2003. Sensitivity of the first indirect aerosol effect to an increase of the cloud droplet spectral dispersion with droplet number concentration. *J. Climate* **16**:3476–3481.

Shine, K. P., J. Cook, E. J. Highwood, and M. M. Joshi. 2003. An alternative to radiative forcing for estimating the relative importance of climate change mechanisms. *Geophys. Res. Lett*. **30**:2047.

Suzuki, K., T. Nakajima, A. Numaguti et al. 2004. A study of the aerosol effect on a cloud field with simultaneous use of GCM modeling and satellite observation. *J. Atmos. Sci.* **61**:179–194.

Takemura, T., T. Nozawa, S. Emori, T. Y. Nakajima, and T. Nakajima. 2005. Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. *J. Geophys. Res.* **110**:D02202.

Twomey, S. A. 1977. The influence of pollution on the shortwave albedo of clouds. *J. Atmos. Sci*. **34**:1149–1152.

van den Heever, S. C., G. G. Carrio, W. R. Cotton, P. J. DeMott, and A. J. Prenni. 2006. Impacts of nucleating aerosol on Florida Storms. Part I: Mesoscale Simulations. *J. Atmos. Sci.* **63**:1752–1775.

Williams, K. D., A. Jones, D. L. Roberts, C. A. Senior, and M. J. Woodage. 2001. The response of the climate system to the indirect effects of anthropogenic sulfate aerosols. *Clim. Dyn*. **17(11)**:845–856.

Wood, R. 2005. Drizzle in stratiform boundary layer clouds. Part I. Vertical and horizontal structure. *J. Atmos. Sci.* **62**:3011–3033.

Wood, R. 2007. Cancellation of aerosol indirect effects in marine stratocumulus through cloud thinning. *J. Atmos. Sci*. **64**:2657–2669.

Xue, H., and G. Feingold. 2006. Large-eddy simulations of trade wind cumuli: Investigation of aerosol indirect effects. *J. Atmos. Sci*. **63**:1605–1622.

Xue, H., G. Feingold, and B. Stevens. 2008. Aerosol effects on clouds, precipitation, and the organization of shallow cumulus convection. *J. Atmos. Sci.* **65**:392–406.