Clouds in the Perturbed Climate System

Their Relationship to Energy Balance, Atmospheric Dynamics, and Precipitation

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Introduction

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Clouds populate the Earth's atmosphere from the surface, as fog, to the mesosphere, as noctilucent clouds (cf. Table 1.1). They form whenever air is cooled sufficiently for its relative humidity to exceed 100%. Such cooling occurs, for example, when air is lofted upward or when a volume of air loses energy by radiating longwave radiation. Clouds can form at temperatures greater than 0°C (so-called "warm clouds") or below 0°C, and they can exist for lengthy periods of time as supercooled water droplets or as ice, either frozen droplets or crystals grown from the vapor phase. Since cooling can occur at almost any altitude and in myriad meteorological circumstances, clouds take on a nearly indescribable range of physical appearances, ranging from massive cumulus that dominate the sky to wispy veils that may even be too thin to be seen with the naked eye.

Clouds, however, constitute the largest source of uncertainty in the climate system, and there are solid reasons why our knowledge of clouds and their related processes is very limited. To approach these issues, this *Ernst Strüngmann Forum* was convened to assess the limits of current knowledge and to offer new approaches to the understanding of cloud-related issues in the Earth system.

Perturbations of Clouds and Related Aerosols

Humankind is perturbing the Earth's cloud system through its actions (e.g., emissions and surface changes). Contrails, which result from aircraft emissions, represent the most obvious (but not necessarily most relevant) and easily perceived evidence of regional perturbations. Other anthropogenic cloud perturbations in the form of ship tracks, found in persistent low marine clouds, are clearly visible from space. Table 1.2 lists the primary mechanisms of

Table 1.1 Range of typical cloud properties. LWC/IWC = liquid water content/ice water content; $N_{\text{hydrometeors}}$ = number of cloud particles per volume of air.

Location	Height (km)	Type	Temperature (°C)	LWC/IWC (mg m^{-3})	$N_{\text{hydrometeors}}$ (cm^{-3})
Surface	0	Fog	≈ 0	10–100	1–100
Lower troposphere	1–5	Cumulus	10 to ≈ –35	100–1000	10–1000
Lower troposphere	1–3	Stratus	10 to ≈ –35	100–500	10–1000
Troposphere	1–15	Cumulo-nimbus	0 to –60	1000–10,000	100–1000
Upper troposphere	7–15	Cirrus	–40 to –90	1–10	0.01–10
Stratosphere	15–25	Polar stratospheric clouds	< –80	0.001–0.01	1–10
Mesosphere	80–85	Noctilucent clouds	≈ –120	0.00001–0.0001	25–500

anthropogenic perturbations of clouds recognized today (for a detailed discussion, see Chapters 6, 15–17).

Anderson et al. (Chapter 6) devoted considerable time to the discussion of confounding meteorological influences, which makes it difficult to test hypotheses of anthropogenic effects on clouds. They offer strategies for separating aerosol and meteorological effects in view of the classical "null" hypothesis combined with specific atmospheric settings in which potential anthropogenic cloud changes should be sought.

The observed and hypothesized perturbations of clouds listed in Table 1.2 require a comparison to long-term trends in observed clouds over the past several decades—a period marked by rapidly rising temperatures and changes in the Earth's radiation budget. The radiation budget controls the formation of clouds and is also strongly influenced by their existence, as discussed in Chapter 2. Here, Norris and Slingo review multidecadal variations in various cloud and radiation parameters, documented in previous studies; they argue that no conclusive results are yet available. Problems include the lack of global and quantitative surface measurements, the shortness of the available satellite record, the inability to determine correctly cloud and aerosol properties from satellites, many different kinds of inhomogeneities in data, and insufficient precision to measure the small changes in cloudiness and radiation, which nevertheless can significantly impact the Earth's climate. Their recommendations to improve this situation include (a) processing the available historical measurements as a means of mitigating inhomogeneities, (b) providing better

Table 1.2 Observed and hypothesized anthropogenic perturbations of clouds. CCN = cloud condensation nuclei; IN = ice nuclei; LWC = liquid water content; PBL = planetary boundary layer.

Cloud type	Perturbation	Potential mechanism
Contrails	+ Albedo	Water vapor and anthropogenic CCN/IN[1]
Contrails	– Daily temperature range	Change in air traffic in connection with 9/11[2]
Ship trails	+ Albedo	Anthropogenic water vapor, and CCN[3]
Continental stratocumulus	+ Albedo	Anthropogenic CCN[4]
Continental stratocumulus	+ Cloud-top temperature	Anthropogenic CCN[5]
Continental stratocumulus	– Precipitation	Anthropogenic CCN[6]
Global PBL stratocumulus	+ Albedo	Anthropogenic CCN[7]
Continental rain clouds	– Precipitation	Anthropogenic CCN[8]
Continental deep convection	+ Freezing level	Anthropogenic CCN[9]
Continental low clouds	+ Precipitation	Cloud seeding with CCN or IN[10]
Continental low clouds	± Cloudiness	Surface flux change attributable to vegetation change[11]
Marine PBL clouds	– “Effective radius”	Anthropogenic CCN[12]
PBL stratocumulus	– LWC	Anthropogenic soot[13]
Cloud formation	+ Atmospheric heating	Anthropogenic greenhouse gases[14]
Global cloud cover	+ Cloudiness	Cosmic radiation, ions, anthropogenic CCN[15]
Regional weather	± Synoptic weather systems	Anthropogenic energy release or redirection[16]

[1]Scorer 1955, Meerkötter et al. 1999; [2]Travis et al. 2002; [3]Twomey 1974, Coakley et al. 1987; [4]Twomey 1974, Krüger and Graßl 2002; [5]Devasthale et al. 2005; [6]Albrecht 1989, Rosenfeld 1999, Rosenfeld 2000; [7]Twomey 1974, Nakajima et al. 2003, Sekiguchi et al. 2003; [8]Bell et al. 2008; [9]Andreae et al. 2004; [10]Garstang et al. 2004; [11]Pitman et al. 1999, Ray et al. 2003; [12]Twomey 1974, Albrecht 1989, Han et al. 1994; [13]Ackerman et al. 2000; [14]Douville et al. 2002, Wetherald and Manabe 2002; [15]Marsh and Svensmark 2000; [16]Hoffman 2002

retrievals of cloud and aerosol properties, and (c) extending the record farther back in time. In addition, they advocate an observation system with sufficient stability and longevity to measure long-term variations in cloudiness and the radiation budget with improved precision and accuracy. Unfortunately, as they note, there is currently little prospect in enhancing the present system, which is, moreover, in danger of deterioration since there are no definite commitments to replace several critical instruments when the current satellite missions end.

Clouds consist of particles of condensed water that have grown from either a cloud condensation nucleus (CCN) or an ice nucleus (IN), which caused either a supercooled water droplet to freeze by means of several possible mechanisms or water vapor to deposit directly to form solid water ice. Because CCN and IN are found in the form of aerosol particles, and because almost all aerosol particles can become CCN and some of them are inherently IN, understanding how and why clouds form and what properties they have requires us first to understand the nature and amounts of aerosol particles. The atmospheric aerosol spans a range of four orders of magnitude in particle size and seven orders of magnitude in number concentration (cf. Figure 1.1); CCNs are a subpopulation of this aerosol. Figure 1.1 illustrates the size and concentration ranges that typically act as CCN. Again, complexity arises because of the myriad sorts of aerosol particles, deriving from a host of natural and anthropogenic aerosol sources, that produce the starting material for the formation of cloud particles.

In Chapter 3, Kinne (Part 1) and Pöschl et al. (Part 2) discuss climatologies of cloud-related aerosols in terms of particle number, size, and hygroscopic properties. To date, the high temporal and spatial variability of concentration, size, and composition of atmospheric aerosols has been mapped, based largely on insufficiently evaluated datasets of model simulations or satellite retrievals. Their approach merges data from ground-based remote-sensing networks into multi-model, median background fields that yield global monthly maps of columnar particle properties. The vertical distribution of aerosol characteristics is derived from global modeling. Applying the argument that hygroscopic growth of atmospheric aerosol particles is relatively well-constrained, global

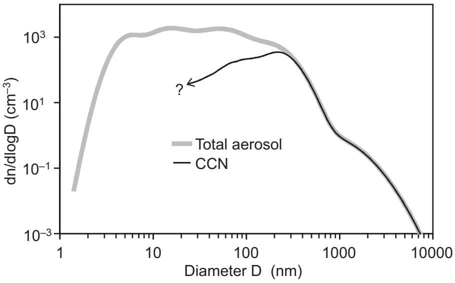

Figure 1.1 Typical near-surface nonurban continental number-size distribution of atmospheric particles (Birmili et al. 1999; Heintzenberg et al. 1998). The typical size distribution of cloud condensation nuclei (CCN) is illustrated by the drop-scavenged fraction according to counterflow virtual impactor (CVI) data from Mertes et al. (2005). The CVI-scavenging data are extrapolated from their upper limit at D = 900 nm to the value of one at 10,000 nm. The question mark indicates the lack of data for smaller particles.

monthly maps for concentrations of CCN are presented. The uncertainty of these results is not known.

Cloud characteristics have vertical and geographical variations, which are important but poorly constrained by present experimental methods. Isaac and Schmidt (Chapter 4) describe the *in-situ* and remote-sensing instrumentation currently available, as well as potential problems in discerning cloud properties. They discuss the necessity to measure parameters on the scales of interest and to present those measurements in proper units. Recommendations for future action include improvements in the accuracy of cloud measurements, global cloud data sets, and better collaborations between those who make and those who use *in-situ* and remote-sensing measurements.

Variability and potential trends of cloud properties affect not only the global radiation budget but also the global hydrological cycle through precipitation (e.g., rain and snow). Precipitation is difficult to assess on large scales. Based on recent developments in passive and active remote sensing, Takayabu and Masunaga (Chapter 5) review current understanding of extreme rainfall, as well as the statistics of light rain and rain from shallow clouds. They find a "butterfly" geographical pattern of shallow rainfall across the equator over both the tropical Pacific and Atlantic oceans. It is not fully understood why this quasi-symmetric pattern appears, as the tropical convergence zones, which geographically constrain deep convective rainfall, are highly asymmetric around the equator. The nature of extreme precipitation varies, depending on the timescale of interest, and is discussed in terms of hourly and daily extremes. Satellite observations imply that the global distribution of extreme precipitation shows a systematic difference from the total rainfall map in terms of, for example, the contrast between land and ocean. Results suggest that the realistic reproduction in models of synoptic systems as well as proper representations of shallow convection and its interaction with the synoptic-scale systems are indispensable for adequate reproduction of extreme daily precipitation.

Anderson et al. (Chapter 6) confirm the findings of the authors of Chapter 5 and emphasize that the most uncertain aspects in current knowledge concern ice microphysics and ice nucleation. Particular difficulties exist because of the confounding effects of built-in correlations of aerosols, clouds, and the meteorological fields in which they are found. These discussions strongly confirm the necessity of understanding and quantifying aerosol and cloud effects as a prerequisite to a full explanation of the climatic records of the twentieth century. Of considerable interest to the entire Forum was the conclusion that observational evidence for large-scale impacts of aerosols on cloud albedo, cloud amount, and precipitation remain ambiguous. Despite this ambiguity, participants were convinced that the emerging trend of warming over the past few decades makes it imperative to look for and quantify coincident changes in clouds. They emphasize the serious need for long-term planning of satellites to monitor the Earth's radiation budget and propose suggestions for new technologies and new orbits (e.g., at the Lagrange point L1 in space).

Cloud-controlling Factors

Since the atmosphere allows only the observation of clouds and does not permit us to control the initial and/or boundary conditions, laboratory studies are important tools for the examination and understanding of microphysical cloud processes under well-defined and repeatable conditions. Stratmann et al. (Chapter 7) provide an overview of the capabilities and limitations of laboratory facilities (ranging in scales from bench-top instruments to vertical mine shafts), wherein clouds are generated artificially and studied under controlled conditions. In this context, hygroscopic growth and activation of aerosol particles, droplet dynamic growth, ice nucleation, and droplet–turbulence interactions can be investigated. Stratmann et al. offer suggestions for future research topics, including investigations into particle hygroscopic growth and activation, the accommodation coefficients of water vapor on liquid water and ice, aerosol effects on primary ice formation in clouds, aerosol-based parameterizations of cloud ice formation, secondary ice formation/multiplication, the production and characterization of particles suitable for cloud simulation experiments, and experiments which combine turbulence and microphysics. The latter is emphasized because of the potential importance of interactions between the microphysical (activation, growth, freezing) and turbulent transport processes within clouds, and the difficulty of studying these through any other approach.

Stevens and Brenguier (Chapter 8) review how meteorological and aerosol factors determine the statistics and climatology of layers of shallow (boundary layer) clouds, with an emphasis on factors that may be expected to change in a fluctuating climate. They identify the paramount role of theory, both to advance our understanding and to improve our modeling and attribution of specific cause and effects. In particular, they argue that limits to current understanding of meteorological controls on cloudiness make it difficult, and in many situations perhaps impossible, to attribute changes in cloudiness to perturbations in the aerosol. Suggestions for advancing our understanding of low cloud-controlling processes include renewing our focus on theory, model craftsmanship, and increasing the scope and breadth of observational efforts.

In Chapter 9, Grabowski and Petch address deep convection, which plays a key role in the Earth's atmospheric general circulation and is often associated with severe weather. They argue that an understanding of the role of deep convection in the climate system, as well as in predictions of climate change, necessitates modeling efforts across all scales, from the micro- to global scale, using a variety of models. Traditional atmospheric general circulation models, in which representation of deep convection and how it may change in the perturbed climate is highly uncertain, are not sufficient. Grabowski and Petch review the relevant aspects of the problem, highlight limitations of current modeling and observational approaches, and suggest areas for future research.

Bretherton and Hartmann (Chapter 10) emphasize current limits in modeling accurately the interaction of clouds and dynamics in the present-day climate.

To guide thinking about the real atmosphere, they demonstrate that horizontal gradients in top-of-the-atmosphere cloud radiative forcing act as atmospheric circulation feedbacks, and that cloud shading helps regulate sea surface temperatures. This relates closely to our lack of fundamental understanding of the empirical controls on tropical deep and low cloud forcing. Bretherton and Hartmann advocate the use of new high-resolution modeling tools, discussed elsewhere in the volume (Chapters 8, 9, and 18) and suggest that new observations may lead to progress if cleverly applied. They caution that scientists should tread carefully and test comprehensively when adding components to general circulation models, such as aerosols and soluble trace gases which interact closely with clouds.

Clouds in the upper troposphere and tropopause region that lack a liquid water phase are called cirrus. They represent a special cloud type, not only because of their formation mechanisms and characteristics but also because of their evident anthropogenic perturbations in terms of contrails. Factors controlling cirrus clouds comprise small- and large-scale atmospheric dynamics, ice nucleation behavior of natural and anthropogenic particles, and interaction with terrestrial and solar radiation. Current understanding of these factors is summarized by Kärcher and Spichtinger in Chapter 11. Key uncertainties in this active area of research are outlined, along with viable approaches to minimize them. These areas of concern include relative humidities in the cirrus regions, vertical velocities, the understanding of ice initiation and growth processes, and accurate data on small ice particles.

Siebesma et al. (Chapter 12) address the shortcomings that arise in atmospheric models attributable to the interactions between resolved and unresolved (i.e., parameterized) cloud-related processes. These problems occur because it is necessary to consider simultaneously a wide range of scales of cloud-related processes, from molecular to global (cf. Figures 12.1 and 12.2). One way to do this is to use smaller-scale process models to improve the representation of clouds in climate models. However, problems and questions arise in deciding just what level of complexity is needed in global models. Siebesma et al. suggest three different pathways to improve the representation of cloud-related processes in future climate models. They recognize that there are many open issues concerning the description of cloud particle formation, right down to questions about the behavior of the water molecule during phase transitions. They echo statements made by Anderson et al. (Chapter 6), in terms of the difficulties in describing the ice phase; however, they add the case of mixed-phase clouds as another cloud process with a serious knowledge deficit. In terms of observations, Siebesma et al. note that polar-orbiting satellites, which are necessary for global, high-resolution coverage with some classes of instruments, do not provide adequate information about the diurnal variations of clouds (e.g., the mid-day convection maximum).

Extent and Nature of Anthropogenic Perturbations of Clouds

Starting with the characteristic parameters of cloud particle precursors and the sensitivities of warm and cold cloud formation to these characteristics, Kreidenweis et al. (Chapter 13) discuss changes to these parameters and propose recommendations for future closure exercises between modeled and experimentally characterized cloud formation processes.

Feingold and Siebert (Chapter 14) extend the microphysical interaction of aerosols and cloud processes to the cloud scale, which involves vertical motions and turbulent mixing processes inside clouds as well as at their borders. Many uncertainties remain on this scale. In particular, there is scant observational evidence of aerosol effects (positive or negative) on surface precipitation. In addition, clouds and precipitation modify the amount of aerosol through both physical and chemical processes so that a three-way interactive feedback between aerosol, cloud microphysics, and cloud dynamics must be considered. Feingold and Siebert demonstrate the dubious utility of simple constructs to separate aerosol effects from the rest of the cloud system. Both observations and modeling suggest that the magnitude (as well as perhaps the sign) of these effects depend on the larger-scale meteorological context in which aerosol–cloud interactions are embedded. They also consider alternate approaches and the possibility of self-regulation processes, which may act to limit the range over which aerosol significantly affects clouds.

The most obvious, yet controversial, perturbation of clouds through willful human intervention—cloud seeding—is addressed in Chapter 15 by Cotton. Here, he reviews research that confirms or refutes the existing concepts for increasing rainfall, decreasing hail damage, and reducing hurricane intensity, and provides a critical overview of the existing atmospheric concepts for climate engineering to counter greenhouse warming.

The physical hypothesis that air pollution in the form of small particles should lead to less efficient formation of precipitation has been established for several decades and is considered by some to be scientifically sound. Ayers and Levin (Chapter 16) provide strong arguments that there is as yet no convincing proof that such a microphysical control of precipitation efficiency has been the prime cause of rainfall reduction in any area of the globe. They emphasize the need for new experimental designs to test this hypothesis in a holistic way, taking into account all possible confounding influences on rainfall trends in a climate that is clearly nonstationary in the face of global warming and natural decadal variability.

Nakajima and Schulz (Chapter 17) broaden the scope of anthropogenic perturbations of clouds to the global scale, using satellite data and global models. Recent observations have detected what appear to be signatures of large-scale changes in the atmospheric aerosol amount and associated changes in cloud fraction and microphysical structures on a global scale. Models can simulate these signatures fairly well, but problems still exist, thus necessitating further improvements. Fields of anthropogenic aerosol optical depth from several atmospheric models have been found to be consistent with the spatial pattern obtained from satellite-derived products. Further studies are needed (a) to improve our ability to differentiate between natural and anthropogenic aerosols, (b) to interpret observed temporal and regional trends in aerosol parameters, and (c) to interpret the extent to which the covariation of satellite-derived aerosol and cloud characteristics can be utilized to advance understanding of aerosol–cloud interactions.

Chuang et al. (Chapter 18) emphasize the daunting task of identifying the myriad effects which must be considered, and the consequences of these for relevant cloud-related processes. These effects include those on microphysics, radiation (both reflected short wave and emitted longwave), precipitation (both rain and snow), dynamics (attributable to the redistribution of energy by clouds), and on chemical processes in clouds and on the composition of precipitation. Three sorts of perturbations are noted: those attributable to aerosols, perturbations of greenhouse gases (which involve changes in dynamics), and changes in the land surface. Three categories of gaps in understanding are identified: conceptual gaps, knowledge or data gaps (which are deficits that could be filled using present-day instruments and data, but for some reason, e.g., lack of resources, have not), and tool gaps or deficits in our ability to make relevant measurements. However, some points seem clear. For example, Chuang et al. emphasize the need to consider multiple scales. The constraints imposed by limitations of available observations were exemplified by the present impossibility to measure small supersaturations in the field (cf. Grabowski and Petch, Chapter 9, who state that it is possible to generate accurately known supersaturations in the laboratory). In addition, Chuang et al. discuss the apparent constancy of global albedo over the past ca. 10 millennia in the context that this stability implies constancy of cloud properties. The possibility exists that as yet unidentified feedbacks might be responsible for such stasis. The difficulty of understanding and quantifying cloud fraction (i.e., the fractional area of a region or the globe covered by clouds) was highlighted as a key problem. Once again, Chuang et al. identified the need for longevity of satellite observations of 30+ years, as well as the need for new sorts of instruments in new orbits (e.g., L1 satellite).

Current Understanding and Quantification of the Effects of Clouds in the Changing Climate System and Strategies to Reduce the Critical Uncertainties

Anthropogenic aerosols are thought to exert a significant indirect radiative forcing because they act as CCN in warm cloud formation and as ice nuclei in cold cloud-forming processes. Haywood et al. (Chapter 19) address this issue by comparing 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. They highlight problems in assessing the effect of anthropogenic aerosols upon clouds under the strict definitions of radiative forcing provided by the IPCC (2007). Straightforward scaling between forcing and the temperature change it induces is significantly compromised in the case of aerosols, where feedbacks from indirect aerosol effects are responses to both radiative and cloud microphysical perturbations. Haywood et al. argue that additional characterization, such as climate efficacy, is required when comparing indirect aerosol effects with other radiative forcings. They suggest using the *radiative flux perturbation* associated with a change from preindustrial to present-day composition, calculated in a global climate model with fixed sea-surface temperature and sea ice, as a supplement to IPCC's definition of forcing.

Collins and Satoh (Chapter 20) discuss the differences of cloud responses to increasing greenhouse gas concentrations using global cloud-resolving models (GCRMs) in comparison to conventional global climate models with cloud parameterization. They demonstrate that high clouds behave differently within these models, suggesting the questions: How is high cloud amount sensitive to cloud processes such as cloud generation, precipitation efficiency, or sedimentation of cloud ice? How are model results of high clouds comparable to current satellite observations such as CloudSat and CALIPSO? How can we understand the change in dynamic fields such as narrowing the precipitation regions, increase in transport of water, and relative humidity?

Strategies to reduce critical uncertainties in our understanding of inadvertent anthropogenic perturbations of clouds are discussed on micro- to mesoscales by Brenguier and Wood (Chapter 21). They emphasize that the challenge is to establish the links between two contrasting forcings, i.e., to understand how clouds respond to changes in the general circulation in order to quantify how this response might be modulated by changes in their microphysical properties. The two generic classes of micro- to mesoscale observational strategies, the Eulerian column closure and the Lagrangian cloud system evolution approaches, are described using examples of low-level cloud studies, and recommendations are made on how they should be combined with large-scale information to address this issue.

Illingworth and Bony (Chapter 22) extend this strategic discussion from the mesoscale to larger scales, where the response of clouds to climate change remains very uncertain because of an incomplete knowledge of the cloud physics and the difficulties in simulating the different properties of clouds. They propose an observational strategy to improve the representation of clouds in large-scale models and reduce uncertainties in the future change of cloud properties. This consists first in determining what key aspects of the simulation of clouds are the most critical with respect to future climate changes, and then in using specific methodologies and new datasets to improve the simulation of these aspects in large–scale models.

A critical review of the representation of clouds in large-scale models by Lohmann and Schwartz (Chapter 23) reveals a major unresolved problem. This is attributable to the high sensitivity of radiative transfer and water cycle to cloud properties and processes, an incomplete understanding of these processes, and the wide range of scales over which these processes occur. Small changes in the amount, altitude, physical thickness, and/or microphysical properties of clouds which result from human influences can exert changes in the Earth's radiation budget that are comparable to the radiative forcing by anthropogenic greenhouse gases, thus either partly offsetting or enhancing greenhouse warming. Because clouds form on aerosol particles, changes in the amount and/or composition of aerosols affect clouds in a variety of ways. Because of the forcing of the radiation balance that results from aerosol–cloud interactions, major uncertainties exist and must be addressed before accurate results can be obtained.

Quaas et al. (Chapter 23) focus on the necessity of models at all scales, especially global, and note the apparent lack of progress in quantifying the cloud–albedo–climate feedback, even though this problem has been identified for more than two decades. Substantial discussion centers on our need for present-day observational proxies to extrapolate future cloud perturbations. In addition, Quaas et al. emphasize the role of small-scale models to describe processes in large-scale models. Substantial effort seems to be required if we are to be able to identify and isolate key cloud-related processes. Quass et al. discuss the problem of applying the concept of climate forcing (Wm^{-2}) to systems in which the fast response of the system via feedbacks changes the initial forcing itself. They recommend the use of a different terminology (i.e., the term *radiative flux perturbation*) to avoid misapplication of the concept of forcing. This new forcing concept, however, could be defined in an even more rigorous way, with explicit statements about the maximum response time of system adjustments in the models that are allowed. Quaas et al. note the necessity of developing process-based evaluation of large-scale models: What aspects of clouds do we need to represent to achieve an accurate assessment of aerosol–cloud interactions? Is it possible to design an observational program to detect and quantify aerosol indirect effects?

Describing the Response of Clouds to Changing Climate: The Need for Multiple Indices of Climate Change

Although there is no question that clouds must have changed as a result of forced climate change and because of the impositions of anthropogenic aerosol on the atmosphere, major questions and uncertainties remain in terms of the details: How have clouds changed? How much have they changed? How will they change in the future? The simplest climate models of the 1960s, as well as the zero-dimensional model of Arrhenius (1896), projected increased

Table 1.3 Indices of climate change.

Index of change	Symbol, unit
Global mean surface temperature	Δ T
Ocean heat content	Joules
Change in regional-scale surface temperature	Δ T
Change in global- or regional-scale atmospheric water content	B_{H2O}, g m^{-2} B_{H2O} region
Total greenhouse absorption	LW_{abs} W m^{-2}
Global or regional mean radiative forcing	Δ F, W m^{-2}
Global or regional mean precipitation	mm
Atmospheric GHG concentration or concentration change	e.g., Δ CO_2
Ocean pH	–
Global or regional mean albedo	Δ A
Sea level change	meters
Global or regional change in solar irradiance at the surface	W m^{-2}
Change in cloud cover, type of cloud, height of cloud, etc.	–

anthropogenic water vapor as a result of global warming. Yet the simplicity of this phenomenon (attributable to consideration of the accurately known and strong dependence of water vapor pressure on temperature change) belies the complexity of responses via a multitude of cloud processes and feedbacks. Indeed, *temperature change* is a misleadingly simple index of the known and suspected changes in clouds, cloud processes, and cloud functions.

Temperature change is the only "gold standard" index of forced climate change and natural variability. However, because this parameter does not capture the essence of changes in clouds and cloud functions (e.g., their role in planetary albedo or the amount, location, and timing of precipitation), we suggest that other indices can and should be used to describe more fully and quantify the consequences of change in the atmosphere caused by human activity (see Table 1.3). Of these, several indices pertain to the known or suspected changes of clouds in the perturbed climate system. In Table 1.3, we include regional-scale variables because regional changes are generally more important to society than global mean changes and because regional-scale changes in cloud-related parameters may, in some cases, be easier to detect and attribute than global-scale changes.

Context of this Forum: The Urgency of Current Demands by the Policy Community on the Scientific Community and the Need for High Scientific Standards

Given the various forecasts of impending climatic catastrophes, there can be little doubt that the issue of "global warming" has captured world attention. Such forecasts range from modest increases of global mean temperature to severe climatic shifts, flooding coastlines, crop failures, and beyond. Yet the term "global warming" is also a source of some ambiguity insofar as the verb "to warm" has both transitive and intransitive meanings.

There is no scientific doubt that the increase in manmade greenhouse gases (e.g., CO_2) has created a warming of the lower layers of the atmosphere in the sense that these gases have caused heat to be added to the air (the transitive meaning). However, substantial uncertainty exists as to how much warming (in the intransitive sense) can be expected as a result of this additional heat energy, not least because the sensitivity of the climate to such perturbations is itself uncertain. Indeed, the sensitivity of global mean surface temperature to a given change in the content of greenhouse gases is uncertain to at least a factor of two and perhaps a factor of three (Schwartz 2008). A large portion of this uncertainty in climate sensitivity, and hence uncertainty in the climate forecast, stems from the uncertainty in the numerous effects of clouds and associated aerosols.

This high degree of uncertainty regarding clouds, combined with the urgency for societies to make firm decisions on the emissions of greenhouse gases (most especially on the continued combustion of fossil carbon fuels), places a great burden on our scientific community. Because we are the only group trained to study the details of clouds and climate, we must do our utmost to reduce the uncertainties and clarify the details of the climate forecast. In doing so, we assume the awesome obligation to communicate our research to the policy community in ways that are impeccably honest and forthright, so that the uncertainties that will always remain and which will, by nature, constrain the confidence that can be taken regarding policy decisions are understood. Just a few decades ago, our fields of science contributed far less to policy making, and we enjoyed the freedom to speculate openly about the physics of clouds and aerosols. Today, however, what we say does count, and a very attentive audience is listening. We must therefore hold ourselves and our findings to an ever-higher standard of scientific proof and be candid about what we have and have not found.

Reducing the uncertainty of climate sensitivity requires vast improvements in the ways that clouds and aerosols are understood and described in the models used by decision makers. What is literally at stake is the ability of the global society to plan rationally ways to conduct its business. As stated by Schwartz (2008):

> This uncertainty in climate sensitivity, which gives rise to a comparable uncertainty in the shared global resource of the amount of fossil fuel that can be burned consonant with a given increase in global mean surface temperature, greatly limits the ability to effectively formulate strategies to limit climate change while meeting the world's energy requirements.

It is of crucial importance for us to find answers to the many puzzles posed by clouds in the perturbed climate system.

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