Climate Processes: Clouds, Aerosols and Dynamics (B6)

Steven C. Sherwood, M. Joan Alexander, Andy R. Brown, Norm A. McFarlane, Edwin P. Gerber, Graham Feingold, Adam A. Scaife, and Wojciech W. Grabowski

Abstract Physical processes not well resolved by climate models continue to limit confidence in detailed predictions of climate change. The representation of cloud and convection-related processes dominates the model spread in global climate sensitivity, and affects the simulation of important aspects of the present-day climate

[AU1] S.C. Sherwood (✉)
Climate Change Research Centre and ARC Centre of Excellence for Earth Systems Science, University of New South Wales, Sydney, NSW 2052, Australia
e-mail: ssherwood@alum.mit.edu

M.J. Alexander
NorthWest Research Associates, 3380 Mitchell Lane, Boulder, CO 80301, USA
e-mail: alexand@cora.nwra.com

A.R. Brown • A.A. Scaife
Met Office, Hadley Centre, FitzRoy Road, Exeter, Devon EX1 3PB, UK
e-mail: andy.brown@metoffice.gov.uk; adam.scaife@metoffice.gov.uk

N.A. McFarlane
Canadian Centre for Climate Modelling and Analysis, University of Victoria, PO Box 3065 STN CSC, Victoria, BC V8W 3V6, Canada
e-mail: Norm.McFarlane@ec.gc.ca

E.P. Gerber
Center for Atmosphere Ocean Science, Courant Institute of Mathematical Sciences, New York University, 251 Mercer Street, New York, NY 10012, USA
e-mail: gerber@cims.nyu.edu

G. Feingold
Chemical Sciences Division, NOAA Earth System Research Laboratory, 325 Broadway R/CSD2, Boulder, CO 80305, USA
e-mail: Graham.Feingold@noaa.gov

W.W. Grabowski
Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307-300, USA
e-mail: grabow@ucar.edu

G.R. Asrar and J.W. Hurrell (eds.), *Climate Science for Serving Society: Research, Modeling and Prediction Priorities*, DOI 10.1007/978-94-007-6692-1_4,

especially in the tropics. Uncertainty in aerosol radiative effects complicates the interpretation of climate changes in the observational and paleoclimate records, in particular limiting our ability to infer climate sensitivity. Dynamical uncertainties, notably those involving teleconnections and troposphere-stratosphere interaction, also affect simulation of regional climate change especially at high latitudes. In response, targeted field programs, new satellite capabilities, and new computational approaches are promoting progress on these problems. Advances include recognition of the likely importance of non-greenhouse gas forcings in driving recent trends in the general circulation, compensating interactions and emergent phenomena in aerosol-cloud-dynamical systems, and the climatic importance of cumulus entrainment. Continued progress will require, among other things, more integrative analysis of key processes across scales, recognizing the complexity at the local level but also the constraints and possible buffering operating at larger (system) scales.

Keywords Clouds • Atmospheric convection • Aerosols • Cloud-aerosol interaction • Atmospheric dynamics • Climate feedbacks • Climate modeling

1 Introduction

Cloud, aerosol, and dynamical processes remain at the core of uncertainties about atmospheric aspects of climate and continue to be the subject of detailed research. This research encompasses observations, process modeling, and the analysis of global climate models (GCMs) to examine the possible broader consequences of the processes. While aerosols play an important role in air quality and visibility, this paper will consider only their climatic consequences; similarly, our discussion of cloud and dynamical issues will be oriented toward WCRP science objectives rather than purely weather-related or highly localized phenomena.

Anthropogenic aerosols are now cooling the climate by an amount that remains difficult to quantify accurately, but could be comparable to the warming effect of anthropogenic carbon dioxide. Moreover, because aerosols are highly nonuniform and therefore warm the atmosphere and cool the surface non-uniformly over the Earth, they can drive changes to the atmospheric circulation that may affect patterns of rainfall (Rotstayn and Lohmann 2002) or cloud (e.g., Allen and Sherwood 2010) independently of any impact on global-mean temperature.

Clouds remain the greatest source of spread in model predictions of future climate. Much of this spread comes from low clouds, but other cloud types also contribute and/or may be more important than suggested by their contribution to this among present models. Cirrus clouds, for example, are not well represented in models and exert a net warming effect that is comparable to the net cooling effect of low clouds; models are beginning to hint at the potential importance of this for climate change. Convective clouds interact with the circulation and tend to amplify or organize many tropospheric circulations, playing a central role, for example, in tropical intraseasonal variability and helping to drive the general circulation at low latitudes (Slingo and Slingo 1991). Polar clouds interact not only with atmospheric dynamics, but also with sea ice. See Heintzenberg and Charlson (2009) for a thorough review of our understanding of how clouds respond to both aerosols and climate changes, and Rosenfeld et al. (this volume) for a more focused perspective on current ideas about aerosol impacts on clouds.

Dynamical processes at all scales modulate how global heat inputs are expressed regionally, and affect global-mean climate indirectly through their role in transporting energy to where it can be radiated to space. The dynamical processes considered here are not comprehensive but include motions from the cloud-system scale upward, that appear to be important for climate or inadequately understood. While it is often assumed that global-scale circulations are fully captured by existing climate models, this is not necessarily the case as shown by recent examinations of varying circulations in different model designs as described in Sect. 2.3. Also, even if global models do capture a phenomenon correctly there are typically intellectual and practical advantages to achieving a more fundamental or heuristic understanding (see, e.g., Held 2005). Rosenlof et al. (this volume) discuss global-scale dynamical changes more extensively, including their ocean and surface components.

2 Recent Scientific Advances

2.1 Clouds and Convection

The representation of clouds in climate models continues to exhibit mean biases that have been brought into sharper focus by the data from active remote sensors on board the CloudSat and CALIPSO satellites. These sensors reveal more clearly the vertical distribution of cloudiness, confirming that many climate models generate too much cloud in upper levels and too little at middle and low levels (e.g., Chepfer et al. 2008).

2.1.1 Boundary Layer Clouds and Dynamics

Field programs have shed new light on the strong and varied dynamical and microphysical interactions in maritime shallow convection and marine stratus clouds (Wood 2012). In many cases these systems are remarkably robust, but occasionally exhibit rapid transitions from open-celled to closed-celled morphologies, with substantially different albedos and rainfall characteristics. The role of aerosol-cloud interactions in these transitions is discussed further in Sect. 2.2.3.

Recent progress in the representation of boundary layer clouds in climate models has been brought about through both parameterization improvements and in many cases the use of higher vertical resolution. Other recent parameterization developments include: (i) Non-local boundary layer schemes with explicit entrainment, which typically lead to improved stratocumulus (e.g. Lock et al. 2000); (ii) Eddy diffusion mass flux schemes, which seek to unify turbulence and cumulus parameterizations (e.g. Siebesma et al. 2007).

Improved community coordination through groups that bring together observationalists, process modelers and parameterization developers, such as GCSS (Global Cloud System Studies group, now being subsumed into a new program called GASS that also includes land processes), has been a positive development in recent years. GCSS and CFMIP (Cloud Feedback Model Intercomparison Project) efforts have additionally engaged members of the climate feedback community. Observation sites that monitor detailed surface and remotely sensed information on turbulent fluxes, boundary layer depth, and cloud properties have been linked to create improved networks through programs like CLOUDNET and ARM.

2.1.2 Deep Convection and Its Dynamical Coupling to Larger Scales

There is now evidence that phenomena such as the Madden Julian Oscillation (MJO) and other tropical wavelike phenomena are sensitive to aspects of convective behavior (Hannah and Maloney 2011; Raymond and Fuchs 2009). Raising barriers to deep convection, either through more stringent triggering conditions or greater entrainment, generally improves the representation of the MJO. However these changes usually affect other aspects of simulations adversely, and are not a modeling panacea. It now appears that the eastward propagation of the MJO, previously attributed either to dynamical/wavelike propagation or to a wind-surface flux feedback, may actually arise from simple advection of mid-level moisture (Maloney et al. 2010). This accounts for the importance of convective sensitivity to this variable in reproducing the phenomenon in models.

After a long period of relative apathy since the early 1990s, the last few years have seen renewed interest in developing new parameterizations for deep convection and in cloud dynamics generally. This has been motivated partly by negative drivers such as the significant failure of many existing schemes to properly respond to atmospheric humidity variations (Derbyshire et al. 2004) or simulate realistic diurnal and intraseasonal variations, but also by positive drivers such as the advent of new computational approaches and the spread of cloud-resolving models. Some recent studies have questioned the centrality of thermodynamic, parcel-based reasoning in theories of convection, emphasizing the additional role of mesoscale dynamical constraints in influencing convective growth (Robinson et al. 2008, [AU2] 2011). At the same time climate models with "superparameterizations," or explicit convection models in place of the usual convective and cloud parameterizations (Randall et al. 2003), have also come into wider use and global models have appeared at resolutions better than 10 km (Satoh et al. 2008). These models are too expensive to run as conventional climate models themselves, but are beginning to provide insights that may help improve standard parameterizations; for example, convective mass fluxes from these simulations can be used in parameterizations of aerosol physics (Gustafson et al. 2008; Wang et al. 2003).

As model grid sizes decrease, traditional assumptions of grid independence and statistically equilibrated cloud fields used in convective parameterizations appear increasingly unjustifiable. Two alternative strategies gaining attention are the inclusion of evolving mesoscale structure, and some elements of stochasticity. While only one convective scheme (Donner 1993) accounts for mesoscale motions explicitly, several new strategies capture in other ways the qualitative evolution of convective events, and seem to improve both diurnal and intraseasonal variability. One such strategy is to add prognostic parameters representing the evolving degree of convective organization (Mapes and Neale 2011) or boundary-layer forcings (Rio et al. 2009), while another is to represent transitions between convective stages or regimes in a population of clouds (e.g. Frenkel et al. 2011a, b; Khouider and Majda 2008). Stochastic parameterizations are also being tested for many model physical schemes, the basic idea being to predict a range of possible outcomes (or one chosen at random) from the inputs to the scheme. One advantage of this is to create a more physical way of generating ensemble forecasts; another is to "smooth" the behavior of the physical scheme with respect to resolved state variables. It is as yet unclear whether stochastic physics will improve climate simulations, or whether any of these strategies will systematically improve the simulated mean climate or cloud feedbacks.

2.1.3 Microphysics

More climate models are beginning to include multiple-moment cloud microphysical schemes to represent both liquid and ice particles. This allows prediction of cloud droplet sizes as well as bulk condensate amounts, and makes possible the computation of more aerosol indirect effects.

However, the fundamental problem with applying more sophisticated cloud microphysics schemes in models that rely on cloud parameterizations is that microphysics is tightly coupled to the cloud dynamics, with the latter unresolved when clouds are parameterized. Arguably, some bulk aspects of convective clouds (such as their total water content profiles) may be well constrained by the mass flux quantities that convective schemes predict. However, predicting sizes of cloud and precipitation particles requires additional assumptions. For instance, in shallow convective clouds in the tropics and subtropics, activation of cloud condensation nuclei strongly depends not only on aerosol characteristics, but also on the vertical velocity field. Some recent cloud parameterizations include information about the vertical velocity in order to provide an estimate of the droplet concentration (Chen et al. 2010; Golaz et al. 2011; Ghan et al. 2011).

2.1.4 Trends, Variations and Feedbacks

While absolute trends in cloud cover have always been difficult to verify due to calibration difficulties, Bender et al. (2012) found evidence in multiple observing systems of a poleward shift of storm-track clouds, that is relative increases at high latitudes and decreases in the subtropics. This shift is qualitatively consistent with poleward shifts of the general circulation reported on the basis of other indices (Sects. 2.3.1 and 2.3.4), and on its own would imply a significant increase in net radiative heating of the planet in recent decades. This phenomenon contributes strongly to a net positive cloud-amount feedback in GCMs (Zelinka and Hartmann 2010).

Climate models, process models, and observations show that upper-level clouds at a given latitude rise or fall roughly in accord with upper-tropospheric isotherms, as predicted by Hartmann and Larson (2002) (Zelinka and Hartmann 2011). This produces a positive feedback on global temperature that accounts for most of the overall mean positive cloud feedback in the CMIP3 collection of climate models (Zelinka and Hartmann 2010).

In general, cloud fields in models change in roughly the same way that the relative humidity field changes (Sherwood et al. 2010). However the exception is boundary-layer clouds, which are crucial to the spread in model predictions. Boundary-layer relative humidity changes are small generally in models. Instead these clouds appear to be sensitive to subtle perturbations in radiation, subsidence and surface fluxes (Zhang and Bretherton 2008; Colman and McAvaney 2011).

2.2 Aerosols and Aerosol-Cloud Interactions

2.2.1 Sources, Ageing and Sinks of Aerosols in the Atmosphere

Volkamer et al. (2006) identified evidence that the natural production of secondary organic aerosol (SOA) is much larger than expected, perhaps by an order of magnitude. This aerosol forms from organic precursor gases such as VOCs (volatile organic compounds) emitted from vegetation and other sources. Recent studies have explored this discrepancy and are suggesting that it is not quite as large as previously thought, but still evident in model-observation comparisons (Spracklen et al. 2011; Hodzic et al. 2009). It is not yet clear whether the main problem is insufficient sources, or incorrect sinks in models.

Aerosol sinks are not as well understood as sources, but some progress is being made. The crucial importance of wet scavenging of CCN aerosols in the dynamics of shallow cloud systems is now recognized (see Sect. 2.2.3). Sinks of organic aerosols are not fully understood, and may include unexpected processes such as fragmentation (Kroll et al. 2009). Aerosol ageing is a complex process especially for organics, but recent work suggests possible simplifications in how this can be described (Heald et al. 2010).

A significant problem affecting aerosol-cloud interactions is that currently IN concentrations are poorly quantified, and we still don't have a very good idea which substances are the most important IN, or what fraction of IN are anthropogenic. An important factor determining IN concentrations in the atmosphere appears to be the overall number concentration of aerosol particles at sizes greater than 0.5 μ diameter (Demott et al. 2010), but there are still large variations in the ratio of IN to other aerosol. While primary organic aerosol such as pollen do not appear to be dominant sources of IN in clouds, organic residues on dust and in soils do appear to contribute significantly to the ice-nucleating ability of these substances (Conen et al. 2011) but in ways that vary mysteriously from one region to another. Most IN are undoubtedly natural; the most likely anthropogenic IN would either be black carbon (whose ability to nucleate ice is still in question) or additional dust emissions arising from human land use changes or other activity (which are hard to isolate from the much greater quantities of natural dust).

2.2.2 Direct and Indirect Radiative Effects of Aerosols on Climate

Aerosols exert a direct cooling effect on climate by reflecting sunlight to space, although dark carbonaceous aerosols can exert either warming or cooling effects because they absorb as well as scatter sunlight. Quantifying these effects from observations alone is difficult, as some type of model is needed to establish the radiative balance that would have occurred in the absence of whatever aerosol is present. Some kind of model is also needed to establish how much of the observed aerosol is anthropogenic, given that global observations are unable to distinguish aerosol types sufficiently for this purpose, except via crude assumptions. Interest in aerosol effects on climate has been enhanced by proposals to disperse aerosols in boundary layer clouds and in the stratosphere as a geoengineering strategy for cooling the planet.

The most straightforward and long-established aerosol impact on cloud albedo comes through the so-called Twomey (sometimes known as cloud-albedo) effect, whereby more droplets are nucleated by greater aerosol counts, increasing the surface area and thus albedo of a given total cloud water content. Model estimates of the magnitude of this forcing over time have changed little. Additional indirect effects due to changes in cloud lifetime or cover, or arising from changes to atmospheric circulations arising from aerosol thermal and microphysical effects, are increasingly being considered but are much more difficult to quantify. There is some suggestion in recent studies that as new effects are added, compensation occurs with existing effects such that the total impact on cloud albedo and/or precipitation doesn't change as much as might have been expected (see Sect. 2.2.3). However, rapid transitions can be triggered in stratocumulus such that changes in cloud amount and thickness strongly amplify the Twomey effect (see Rosenfeld et al. this volume).

A number of GCMs equipped with aerosol physics now predict the radiative effects of anthropogenic aerosol. Model predictions of both the direct (Myhre 2009; Bellouin et al. 2008) and aerosol-cloud related (Storelvmo et al. 2009) cooling effects have decreased somewhat in more recent studies, with estimates of total forcing (not including ice processes) now near -1.5 W m^{-2}; a few models with ice effects tend to show greater cooling. Considering only the albedo effect, estimates of forcing constrained by satellite observations show significantly less cooling than those predicted by models alone: from -0.5 W m^{-2} to near zero. This may mean models are still overestimating the albedo effect, though it is also possible that observations of aerosol in the vicinity of clouds, and methodologies for averaging data from the satellite pixel scale to model grid-box scale, bias the strength of the cloud-aerosol relationships used to constrain climate models (McComiskey and Feingold 2012). Inter-model estimates of aerosol-cloud forcing that allow for dynamical feedbacks tend to be more variable than estimates of the albedo effect alone because of the greater range of processes considered. However there are some indications, from both observations and small-scale models, that compensating factors may be at play in real cloud systems, and that the higher negative forcing estimates are a result of the inability of climate models to resolve small spatiotemporal scale cloud, and aerosol-cloud interaction processes (see Sect. 2.2.3). This is an active area of research.

There are several reasons why model estimates of aerosol forcing have dropped. Perhaps the most important is increased estimates of the absorbing effect of black carbon (Myhre 2009; Chung et al. 2005), which offsets the cooling effect of aerosol scattering and can warm climate further by settling on ice surfaces where it is a particularly efficient absorber. Also, new observations are showing somewhat greater natural contributions to the observed aerosol burden (see Sect. 2.2.1).

There is growing evidence that decadal changes in aerosols may be responsible for the observed phenomenon of global dimming (the reduction of sunlight observed at the surface) prior to about 1990 and global brightening since, although changes in cloudiness (whether due to aerosols or not) play a large role especially on a regional basis (Wild 2009). Background stratospheric aerosol and water vapor may also vary on decadal or longer time scales, making some contribution to radiative forcing (Solomon et al. 2010, 2011). Aerosols may also drive interdecadal climate variations in the Atlantic basin (Booth et al. 2012).

New research highlights the possibility of IN effects on cirrus or mixed-phase cloud properties, which has even been suggested as another geoengineering strategy (Mitchell and Finnegan 2009). The main anticipated mechanism for IN to affect clouds is by causing the earlier nucleation of smaller numbers of ice particles at temperatures between −10 and −40° C in deep convective clouds. These early-initiators would grow rapidly and become efficient collectors, leading (in principle) to optically thinner deep-cloud outflows. However the complexity of mixed-phase cloud systems means that currently such mechanisms are hypothetical; indeed some simulations show IN leading to increased cirrus (Zeng et al. 2009). See Rosenfeld et al. (this volume) for more details.

2.2.3 Microphysical Effects of Aerosols on Precipitation and Vice Versa

A long history of efforts to ascertain the influence of CCN aerosol on warm clouds (Gunn and Phillips 1957; Warner 1968) have indicated a likely suppression of rainfall, although there exists no definitive, statistically-sound, observational proof of this. The proposed mechanism is that by nucleating more droplets, droplets do not grow as fast, fall speeds are reduced, and the formation of rain by collision and coalescence is delayed or prevented. However this suppression of precipitation will lead to more evaporation in the free troposphere, destabilization and deepening of subsequent clouds, and the potential for more rain. Dynamical feedbacks of this kind make it particularly difficult to untangle aerosol effects on precipitation (e.g., Stevens and Feingold 2009). The net effect of aerosol on cloud albedo is a complex function of small-scale processes and feedbacks that occur at a range of scales. As a result it is likely cloud-regime-dependent. When averaged over multiple regimes, it may be significantly less than would be expected from consideration of the simple microphysical response in isolation (Stevens and Feingold 2009).

Recent work shows that the knock-on effects from the initial modification of clouds are sometimes "absorbed" by the cloud system, but other times are more profound. Observations of shallow convective cloud layers confirm strong connections between aerosol loading, precipitation and cloud morphology, with precipitating portions of marine cloud decks appearing nearly devoid of aerosols (Sharon et al. 2006; Wood 2012). This suggests a strong positive feedback where precipitation removes aerosol, leading to more efficient formation of precipitation, a feedback thought to shift closed-cellular to open-cellular convection, in sub-regions that are non-raining and raining respectively (Stevens et al. 2005; Sharon et al. 2006). Both A-Train observations (Christensen and Stephens 2011) and large eddy simulation (e.g., Wang et al. 2003; Ackerman et al. 2004; Xue et al. 2008; Wang and Feingold 2009) show that the aerosol increases cloud amount and cloud water in clean, open-cell regions and decreases cloud amount in non-precipitating, closed-cell regions.

It is now argued that as coupled cloud systems evolve, they tend to prefer certain modes (e.g., non-precipitating closed cells and precipitating open cells) that are resilient to change due to internal compensating processes (Stevens and Feingold 2009; Koren and Feingold 2011). However under certain conditions, e.g., very low aerosol concentrations, instability sets in and the closed-cell, stable system may transfer to the precipitating open-cell system. The open cells appear to constantly rearrange themselves as precipitation-driven outflows collide and drive new convection, which forms new precipitation, and so on (Feingold et al. 2010).

A weakness of the detailed process-level large eddy simulation is that it is rather idealized. Cloud resolving and regional models allow for a much broader range of scale interactions and timescales and are increasingly being used to explore aerosol-cloud interactions (e.g., Grabowski 2006). Modeling of deep convective cloud systems suggests that the average impact of added aerosol is very short-lived, with a slight delay in the initial development of rainfall but no effect on the integrated rainfall amounts over times approaching a day or longer (Morrison and Grabowski 2011; Seifert et al. 2012). Similarly, under conditions of radiative-convective equilibrium van den Heever et al. (2011) have shown that aerosol perturbations have little influence on domain-averaged precipitation and cloud fraction. However this is a result of compensation between the responses of shallow and deep convective clouds, in keeping with the idea that while average aerosol influences may be small, local influences may be significant.

In addition to their potential to study aerosol-cloud interactions, cloud resolving and regional models show that gradients in the aerosol may generate changes in circulation patterns via changes in heating rates (Lau et al. 2006), radiative properties of cloud anvils (van den Heever et al. 2011), or in the spatial distribution of precipitation (Lee 2012).

2.2.4 Advances in Parameterizing Aerosols

Aerosol treatments in global climate models remain fairly crude, although this could be said of all model parameterizations. Studies using chemical transport models driven by observational estimates of wind fields have proven useful in constraining and refining the schemes for predicting poorly-constrained natural sources of aerosols such as sea-salt and organic aerosol precursors (Lapina et al. 2011).

Aerosol effects on clouds are being treated in more models, and are beginning to include effects on convective clouds including secondary effects although this involves massive uncertainties. Mass fluxes obtained from explicit simulations are being used to implement aerosol effects on convective clouds (see Wang et al. 2003).

2.3 Dynamics from Small to Global Scales

2.3.1 Gravity Waves

Small scale atmospheric gravity waves (or internal waves), produced by flow over topography, convection, and imbalances in the geostrophic flow, influence climate through their effects on the large-scale circulation, which in turn affect synoptic and planetary wave propagation and dissipation (e.g. Alexander et al. 2010). With important horizontal and vertical scales as small as 5 km and 1 km, respectively, much of the gravity wave spectrum remains unresolved at current climate model resolution. Mountain wave drag reduces westerly biases in zonal winds near the tropopause, and parameterized mountain wave drag settings in climate models can affect high-latitude climate change response patterns in surface pressure (Sigmond and Scinocca 2010). The changes in wind shear that occur with tropospheric warming and stratospheric cooling alter the altitude and strength of mountain wave drag; this affects planetary wave propagation and associated surface pressure patterns, strengthening aspects of the Brewer-Dobson circulation such as poleward stratospheric transport and upwelling and downwelling near the tropical and polar tropopause respectively.

Trends in upwelling near the tropical tropopause have been related to changes in stratospheric water vapor, an important greenhouse gas (Solomon et al. 2010). An increasing trend in twenty-first century upwelling is predicted in models that resolve the stratospheric Brewer-Dobson circulation (Butchart et al. 2006). This wave-driven transport circulation responds to changes in forcing by planetary-scale and gravity waves, and many models ascribe a large fraction of the trend to changes in parameterized orographic gravity wave drag (Li et al. 2008; McLandress and Shepherd 2009; Butchart et al. 2010). Cooling in the stratosphere and warming in the troposphere associated with greenhouse gas (GHG) trends lead to stronger subtropical jets, and these changes in the winds explain the changes in the parameterized drag.

An early focus on different dissipation mechanisms within non-orographic gravity wave parameterizations has given way in recent years to a focus on defining wave sources and the properties of the waves emitted. This has followed from research demonstrating effective equivalence of different parameterization methods in climate model applications (McLandress and Scinocca 2005). For climate prediction, the sources of non-orographic gravity waves should respond to climate changes, but in most current models wave sources are simply prescribed. A few models do include multiple wave sources like convection and fronts in addition to orography (e.g. Richter et al. 2010; Song et al. 2007). However, the underlying processes remain rather poorly understood and the parameterizations are largely based on two-dimensional theoretical models.

Recent global simulations at very-high resolution capable of resolving many (though not all) scales of gravity waves have advanced our understanding of the processes important for improving parameterizations (e.g. Sato et al. 2009; Watanabe et al. 2008), and comparisons of these with observations are assessing their ability to realistically represent the resolvable portions of the wave spectrum (Shutts and Vosper 2011).

2.3.2 Blocking Events

Atmospheric blocking is characterized by abnormally persistent (i.e. time scales of 1–2 weeks) high pressure systems which steer, or "block," the usual propagation of midlatitude cyclones, and thus play a critical role in intraseasonal variability and extreme events in the extratropics. Limitations in the ability of climate-models to capture these important synoptic scale features were described in the IPCC's AR4, and appear to persist in more recent models. Since the 1980s many authors reported an upscale feedback of eddy vorticity that helps to maintain blocking highs (e.g. Shutts 1986; Lau 1988). Recently this has been verified in models and analyses, and the self-maintaining nature of blocking eddies has been confirmed (e.g. Kug and Jin 2009).

Despite this, it is not yet clear what resolution is required to successfully model enough of the vorticity flux to give reasonable blocking statistics. Traditionally, models have under-represented the frequency of blocking (D'Andrea et al. 1998) in a way consistent with their limited resolution. Some studies have shown an increase in blocking when either horizontal resolution (Matsueda et al 2009) or vertical resolution (Scaife and Knight 2008) is increased. This is consistent with the idea of an upscale feedback from poorly resolved eddies. Evidence has also emerged that climate models are systematically westerly biased (Kaas and Branstator 1993), which can greatly bias blocking frequencies diagnosed via standard measures (Doblas-Reyes et al. 1998), even if the simulated variability appears adequate (Scaife et al. 2010). In coupled models, the westerly bias and blocking deficit over the Atlantic may be associated with errors in the simulated Gulf Stream (Scaife et al. 2011).

2.3.3 Widening of the Tropics

On planetary scales, evidence for a widening of the Hadley circulation, or tropical belt, in the last decades of the twentieth century has been deduced from various data sources, and model simulations show that GHG increases cause widening (e.g., Schneider et al. 2010). This has potential connections to important changes in global precipitation patterns and other climate variables (e.g. Seidel et al. 2008). How the width of the Hadley cell is controlled is however unclear. Both thermodynamic changes at low latitudes and eddy flux changes in the subtropics and extratropics likely play a role. Indeed, Son et al. (2008) show that changes in polar stratospheric ozone influence the width of the Hadley Cell, most likely by displacing the midlatitude jets and so modifying eddy momentum fluxes in the subtropics. Based on model simulations, the expansion of the Hadley cell has been ascribed to radiative forcing associated with changes in GHG and stratospheric ozone depletion (Lu et al. 2007) or absorbing aerosols or ozone in the troposphere (Allen et al. 2012), and is consistent with poleward shifts of the subtropical jet streams (Yin 2005). However changes in tropical tropopause heights that have been associated with the Hadley cell widening (Seidel and Randel 2007) are also strongly affected by changes in the Brewer-Dobson circulation (Birner 2010) and therefore coupled to changes in the extra-tropical circulation in the stratosphere.

2.3.4 Impact of the Stratosphere on the Large-Scale Circulation

Observational evidence for a significant impact of stratospheric ozone loss on the tropospheric circulation emerged prior to the IPCC's AR4 (e.g., Thompson and Solomon 2002). To date, the largest change in the midlatitude jet streams and storm tracks is observed in the Southern Hemisphere in summer, following the annual formation of the ozone hole, and climate model studies have verified the critical role of ozone in these changes (e.g. Arblaster and Meehl 2006; Polvani et al. 2011). However some of the CMIP3 models used in the last assessment ignored ozone changes, and most represented the stratosphere poorly in general. Understanding of the connection between twenty-first century ozone recovery and SH climate projections has advanced very recently. Son et al. (2008) showed that models with realistic ozone recovery predict a weak equatorward shift in the summertime extra-tropical jet in the twenty-first century, while models with constant ozone predict a poleward shift in the jet due to GHG increases. These trends in jet position project strongly onto the Southern Annular Mode (SAM). While GHG trends lead to a year-round positive trend in the SAM, some models including ozone recovery with a well-resolved stratosphere predict a large negative trend in the SAM in summer (e.g. Perlwitz et al. 2008). Seasonally dependent trends in SAM could influence carbon uptake in the Southern Ocean (Lenton et al. 2009) and may further couple with Antarctic sea ice trends (Turner et al. 2009).

New work shows the stratosphere plays another important role in climate change independent of ozone changes. In models with good representation of the stratosphere, regional climate changes, particularly those associated with ENSO teleconnection to European winter climate, can propagate through a stratospheric pathway (Ineson and Scaife 2009; Cagnazzo and Manzini 2009), and even long-term predictions of precipitation and wind patterns in models lacking a well-resolved stratosphere can suffer from first order errors compared to those of models that better resolve the stratosphere (Scaife et al. 2012). These changes often project onto the North Atlantic Oscillation (NAO) and the Northern Annular Mode (NAM), a primary mode of northern hemisphere climate variability. Gerber et al. (2012) review the current understanding of stratospheric effects on surface weather and climate. Roughly ten models in the CMIP5 will include a better represented stratosphere, compared to almost no models in CMIP3, so these issues should become clearer in the IPCC's AR5 report.

2.3.5 Impact of Warming on Rainfall Extremes, Cyclones, and Severe Storms

Infrequent, intense weather events are part of a stable climate system, and involve many scales, from isolated convective cells on the order of kilometers to planetary scale features such as the Madden Julian Oscillation. Evidence of increases in certain extremes is beginning to emerge in the observational record (Zwiers et al. this volume), though attribution to specific aspects of climate change is difficult, especially for individual events (Stott et al. this volume). While model predictions of extremes remain dubious, certain expectations follow from our understanding of basic physical processes and are being investigated by process models.

Dynamical responses in the atmosphere to the warming climate lie behind changes in likelihood of some "extreme" weather events and therefore understanding and quantifying these is a basic step in determining changes in extremes. Poleward shifts of the extra-tropical jet stream with associated migrations of storm tracks and changes in the intensity of the storms may be accompanied by changes in weather patterns and associated extremes (Gastineau and Soden 2009, 2011). Expansion of sub-tropical dry zones at the edges of the widening Hadley circulation may be accompanied by pronounced changes in precipitation patterns and associated desertification (Johanson and Fu 2009).

Assessing the response of tropical circulations and associated weather extremes to changes in GHG forcing using climate models has proved to be difficult because of the lack of agreement among models (Kharin et al. 2007) and their general inability to consistently represent some key physical features such as the observed mean precipitation regimes of the Asian summer monsoon (Stowasser et al. 2009). Such deficiencies are in large part associated with resolution constraints and associated inadequate parameterization of unresolved small scale processes. Large-scale increases in tropical sea surface temperatures (SSTs) associated with a warming climate do not necessarily translate directly into local increases in precipitation intensity associated with enhanced deep moist convection. In fact model results suggest that precipitation may decrease in regions such as the equatorial Indian

Ocean in association with uniform increases in SSTs. However modeling results do indicate that intensified deep convection with higher precipitation is more likely to occur where SSTs are locally larger than their surroundings (Stowasser et al. 2009; Neelin and Held 1987). Only a few of the coupled models used in AR4 simulate a qualitatively realistic climatology of the Asian monsoon (Annamalai et al. 2007; Stowasser et al. 2009); under global warming, these models predict an increase in monsoon rainfall over southern India, despite weakened cross-equatorial flow (Stowasser et al. 2009).

3 Current Scientific Gaps and Open Questions

3.1 Clouds and Convection

Observational capabilities for clouds have improved significantly with the launch of MODIS, CloudSat/CALIPSO and other satellite sensors. However we lack good data on the detailed motions at the convective scale that would be beneficial for testing the assumptions of cloud models and in particular for constraining processes such as entrainment. Also, observations of precipitation still have large errors even from the best spaceborne sensors, particularly for light rain.

Many GCMs still have difficulty in successfully simulating transitions between different cloud regimes (e.g., stratocumulus to cumulus). Most deep convective schemes used in global models appear to make the transition from shallow to deep convection much too quickly, which among other problems leads to inaccurate diurnal cycles. A possibly related problem is that convection in models is insufficiently sensitive to humidity above the cloud base (Derbyshire et al. 2004). This problem is well-recognized by model developers but a fundamental basis for redeveloping the convective schemes is currently lacking, such that most approaches to address the problem have so far been convenient fixes that don't come to grips with underlying problems.

While recent research (e.g. through GEWEX) has focused particularly on low clouds due to their role as a "known unknown," (e.g., Soden and Vecchi 2011), the representation of upper-level and cirrus clouds in GCMs is a source of concern as it is highly simplified, and models currently underpredict mid-level cloud which begs the question of whether feedbacks by these clouds might be missing or underrepresented. Cirrus clouds have also been hypothesized as playing a role in polar amplification of warmer past climate states (Sloan and Pollard 1998) but this has not been reproduced by climate models so far.

Models still have difficulty representing tropical variability (Lin et al. 2006). Convective parameterizations tend to well represent either the mean climate or the variability, but not both. Convectively coupled equatorial waves (CCEWs) control a substantial fraction of tropical rainfall variability. CCEWs have broad impacts within the tropics, and their simulation in general circulation models is still problematic, although progress has been made using simpler models. A complete understanding of CCEWs remains a challenge in tropical meteorology (Kiladis et al. 2009).

Cloud microphysics remains a great challenge, with most work so far limited to liquid clouds, which have still proven difficult to model. For ice clouds the situation is even more difficult because of complications of ice initiation (i.e., homogeneous versus heterogeneous activation) and subsequent growth. Only about 1 in 10^5 aerosol particles are active as heterogeneous ice nuclei, they are hard to measure, and the detailed nature of the freezing mechanisms is uncertain. Cloud physics has struggled with representation of ice processes in detailed models for decades, so it should not be surprising that representation of such processes in large-scale models remains highly uncertain. In summary, parameterizing cloud microphysics in models with parameterized clouds is extremely difficult. Arguably explicitly cloud-resolving approaches are a significant improvement, but often not at an affordable cost for many applications.

The modeling of clouds is badly hampered by the poor state of understanding of basic cloud physics and dynamics, and the inability to represent all scales of cloud motion and entrainment. Fundamental uncertainties about entrainment and mixing may significantly affect our ability to quantify aerosol impacts on cloud radiative forcing (e.g., Jeffery 2007).

Some researchers are calling for greater emphasis on basic cloud physics in the context of aerosol effects (e.g. Stevens and Feingold 2009), on the grounds that we cannot fully understand or quantify how clouds are modified by aerosols before we are able to predict what clouds do in the absence of aerosol perturbations. While that article focuses mainly on warm boundary layer clouds, an equally or stronger case can be made for mixed-phase stratus clouds (Morrison et al. 2011) or cirrus clouds, where even the relative importance of homogeneous vs. heterogeneous nucleation is still unknown let alone the cloud dynamics or evolution of ice particles after they have formed. An alternative view however, is advanced by Rosenfeld (this volume) on the basis that aerosol impacts on clouds can be observed even if we don't have complete theories of cloud behavior.

3.2 Aerosols and Aerosol-Cloud Interactions

The discrepancy between model and observational estimates of aerosol cloud-mediated forcings (Sect. 2.2.2) is a significant issue. It is not yet clear whether biases lie predominantly with the observations or with the models. If satellite-derived estimates are correct, most GCMs are probably overestimating the cooling effect of aerosols during the twentieth century.

The quantitative study of aerosols is greatly hampered by the complexity of aerosol structures in the atmosphere and the limited compositional information provided by most observing systems, especially satellite sensors. It is evident that most aerosols are inhomogeneous mixtures, with optical and hygroscopic properties that depend on how they are mixed. One upshot is that particles not normally thought to be effective CCN may become effective after a modification through the deposition of other materials while the particle is airborne (Ervens et al. 2010). The reverse may be true for IN because their effectiveness is reduced by the addition of soluble material. There are also many forms of organic aerosol with different source and deposition properties. Economically describing or categorizing such a rich spectrum of possible aerosol types, mixtures, and sizes is a significant observational and modeling challenge.

Relatively little research has gone into quantifying aerosol sinks, in comparison to sources (e.g., Lee and Feingold 2010). The measurement of dry deposition of aerosols is difficult in many cases, and measurements are currently too scarce to constrain models. The processing of secondary organic aerosols through aqueous chemistry is also not well understood. It is possible that poor representation of sinks may be affecting model simulations of aerosol distribution as much as inaccurate sources.

Aerosol modeling is also affected by transport issues. Models typically make naive assumptions about vertical redistribution of aerosols by boundary layer motions and deep convective mixing. Aerosol effects on clouds are quite sensitive to mixing assumptions and the science is currently hampered by basic questions of how to model turbulent entrainment and mixing within clouds noted above. Vertical distributions of aerosol vary significantly with region and aerosol type, and are of concern in interpreting both satellite observations and in-situ near-surface observations.

Observational studies of aerosol impacts on clouds have long been plagued by a problem of correlation vs. causality, since clouds strongly affect aerosols as well as the reverse, and both are affected by meteorology. Satellite-based aerosol observations are mainly provided by polar orbiters, but these only give snapshots, providing little traction against the causality dilemma. Geostationary satellites can provide crucial temporal information but produce relatively poor aerosol and cloud products compared to polar orbiting satellites.

It continues to be difficult to unambiguously distinguish aerosol and cloud in remote sensing observations, because of a combination of factors, including aerosols becoming hydrated and growing in size with decreasing distance to clouds, cloud fragments, and enhanced scattering of photons between clouds (Wen et al. 2007). Since even in principle there is no clear distinction between a hydrated CCN aerosol and an incipient cloud droplet, it may for some purposes be better not to attempt to distinguish aerosol and clouds at all (Koren et al. 2007; Charlson et al. 2007).

Ice nuclei remain a particularly puzzling aspect of the global aerosol burden. Progress in predicting IN concentrations appears to be hampered by the incomplete understanding of why some substances nucleate ice well and others poorly. It is hard to see how aerosol-cloud radiative effects modulated by deep convection, and subsequently affecting anvils and cirrus, will be properly understood or quantified while issues surrounding ice nucleation and growth remain so unresolved.

Aerosol-cloud related forcings remain poorly quantified. Even in the relatively well-studied case of shallow clouds, it remains unclear whether secondary effects globally tend to cancel (e.g., Stevens and Feingold 2009) or reinforce (e.g., Rosenfeld et al. this volume) the primary (“Twomey”) effect, since both outcomes are possible depending on circumstances. The prevalence and areal coverage of the sign and magnitude of these responses would seem to be an important line of enquiry. Aerosol effects on ice-containing clouds are likely in opposition to those on shallow clouds, and climate model simulations suggest that radiative forcings involving these are potentially larger than those of liquid-phase clouds, and involve large infrared forcing effects. While this result is highly uncertain, it highlights the need for progress on mixed-phase cloud microphysics, and points to large uncertainties in model-based "forward" estimates of indirect forcing; it also leaves open the possibility that a modest net aerosol-cloud forcing represents a near-balance between opposing large ones from deep and shallow clouds (Rosenfeld et al. this volume).

Studies attempting to back out aerosol forcing from the observed temperature record ("inverse estimates") must consider not only uncertainties in climate sensitivity and ocean heat uptake, but also the role of other forcings such as tropospheric ozone, stratospheric water vapor, and land use changes. Recent studies also show that aerosol impacts on surface temperature can be highly non-local, nonlinear, and can include impacts on the general circulation. This complicates attribution efforts, as for example changes in tropical aerosol may have affected the extratropical temperatures in either hemisphere and may not be strictly additive with other forcings.

3.3 Dynamics from Small to Global Scales

The push toward higher horizontal resolution leads to resolution of more gravity waves in climate and NWP models. Observational verification of these waves and their effects on general circulation is needed. Evidence in the tropics suggests that higher vertical resolution is more urgently needed to properly simulate large-scale equatorially trapped modes (e.g. Evan et al. 2012) important to driving the QBO (e.g. Scaife et al. 2000; Giorgetta et al. 2002). Even at NWP resolutions, short horizontal wavelength gravity waves with substantial momentum fluxes and inferred large effects on circulation remain unresolved (e.g. Alexander et al. 2009). Improvements in the parameterization of gravity wave sources is needed to properly simulate gravity wave effects in future climate scenarios.

Higher resolution also impacts the representation of synoptic scale variability in climate models. It is still unclear what resolution is required to accurately represent atmospheric blocking. Further work is needed to understand the role of mean state errors in blocking statistics and how blocking might be improved in models. The organization of synoptic scale heat and momentum fluxes in the planetary scales generates the midlatitude jet streams. There are substantial biases in the location of austral jets in almost all CMIP3 models, which are associated with errors in their intraseasonal variability and sensitivity to climate forcing (e.g. Kidston and Gerber 2010). While these processes are nominally resolved by all CMIP3 models, simply increasing the resolution appears to help correct (but not eliminate) biases (Arakelian and Codron 2012). Further work is need to understand how errors in marginally resolved mesoscale processes are scattering back and biasing the resolved variability.

The issue of resolved vs. unresolved scales is a more pressing problem in tropical meteorology, where key processes must be parameterized. The interactions of unresolved cloud and convective processes with resolved waves and vortices is a critical area of current research (e.g. Khouider et al. 2013). This coupling across scales (or lack thereof) is likely behind the most persistent problems in climate model's representation of tropical variability, including convective coupled waves and the Madden–Julian oscillation (e.g. Lin et al. 2006). Poor tropical variability in turn affects both the mean climate (i.e. the double inter-tropical convergence zone problem; Lin 2007) and the frequency of high- and low-intensity rainfall events (e.g., Stephens et al. 2011).

Although the simulated pattern of sea-surface temperature response to global warming includes an El Nino-like component, the extratropical atmospheric responses occur in a somewhat opposite fashion to the El Nino teleconnection pattern (Lu et al. 2008). Understanding the difference between the response to El Nino (jets shift equatorward) and global warming (jets shift poleward) may provide important clues to understanding mechanisms for the poleward shift of the jet and widening of the Hadley cell in climate change scenarios.

A common theme in many of these gaps in our understanding is the relationship between natural, or internal variability, and the mean climate. One can view the climate as a stochastically forced system, and formulate the questions: what does climate "noise" tell us about the system and its response to external forcing, and how does noise at unresolved scales scatter back to resolved scales? To account for unresolved variability, new stochastic parameterizations are being developed to explicitly introduce uncertainty in subgrid scale processes (e.g. in the sources of non-orographic gravity waves; Berner et al. 2009; Eckermann 2011). To account for resolved variability, modeling groups are turning to large ensemble forecasts, as is routinely done in numerical weather prediction. Properly accounting for natural variability is also extremely important for predicting changes in the extremes and making regional climate forecasts, where the signal to noise ratio is smaller (e.g. Deser et al. 2012).

Another general issue which affects all research areas covered in this article is the limited size of the community involved in model development (e. g., Jakob 2010). A relatively large community of researchers use global and regional climate models, or study the processes that are not well represented. Some of this work gets as far as proposing parameterization improvements. However, there is a large and separate task of improving the GCMs, which is crucial, but in which there are only a relatively small number of people participating. The problem is exacerbated by current funding models which tend to separate basic research (largely at universities) from model development (largely at big modeling centers) with too little support or incentive to link these activities. Further, scientific achievement is measured by counting papers, which may be harder for hands on-model developers to do in quantity. Finally, model development is a challenging undertaking for a postgraduate student or short-term postdoc, really requiring longer-term support and a team environment; this will become more true as models become more complex and parameterizations more interconnected.

4 Strategic Opportunities and Recommendations

After decades of effort it remains evident that no current model can reliably simulate both individual clouds and the climate at the same time. Yet the cloud and climate scales cannot be decoupled. One question that then arises is how to best harness high-resolution computations, and whether they can ultimately bridge the gap and render parameterization unnecessary? Second, how can observations be used to help make progress? The complexity of the system makes it very difficult either to durably improve models by haphazard experimentation, or to diagnose their problems directly from discrepancies with observations, although these activities must continue. Nor is there evidence that numerical cloud models, even at extreme resolutions, converge to solutions that are insensitive to parameterizations. These difficulties highlight the need for better fundamental understanding. We believe this applies equally to aerosol and dynamical research.

4.1 Research Foci, Strategies and Resources

While there is a wide array of diverging views on the best paths forward, we see several promising opportunities, as well as important assets that must be protected and nourished.

4.1.1 Confront Two-Way Integration Across Scales

A recurring theme in cloud, aerosol and dynamics research is the tight connections between behavior across scales. It is becoming evident for example that the immediate response of a cloud to an aerosol perturbation, in the absence of any interactions or feedbacks from the larger environment, may differ dramatically from what happens in a more realistic setting where the cloud interacts with others dynamically. Thus role of clouds in climate may be as difficult to discern from traditional small-scale (e.g. cloud-scale) studies—where dynamical adjustments and feedbacks from remote processes cannot occur—as from global studies that cannot resolve the clouds. Numerical (e.g. LES) simulations may capture some, but not all of these adjustments. A similar limitation affects observational analyses based on local relationships between variables that do not account for the fact that the putative causal agent (e.g., aerosol) can effect the target quantity (e.g., clouds) nonlocally.

A key research priority should be the development and implementation of strategies to couple large-scale responses into process modeling efforts, and the application of this to interpretation of observations. One approach is simply to perform extremely large and expensive computations; another has been “superparameterization/” The latter approach could for example be extended to resolve gravity wave propagation into the stratosphere. However, other, more affordable and widely adoptable strategies are needed.

A useful prototype strategy is to run process models in a "weak temperature gradient" setup (Sobel and Bretherton 2000) that allows some idealized feedback from larger scales in a Tropical setting. Development and standardized use of a small set of analogous strategies or testbeds, perhaps involving the coupling of multiple process models, would fill a crucial gap. Another strategy for combining models and observations is to exploit emergent behavior or other non-traditional measures of the behavior of a tightly coupled aerosol-cloud-dynamical system, rather than trying to isolate deterministic impacts of one part of the system on the others (e.g., Harte 2002; Koren and Feingold 2011; Bretherton et al. 2010; Morrison et al. 2011). A prototype for this strategy is the longstanding effort to explain convectively-coupled wave activity in the tropics, with models of varying complexity and design, to see what is needed to get it right.

4.1.2 Emphasize Fundamental Science and Model Development

Our perception is that the amount of effort being expended toward the proper development of atmospheric model "physics" (cumulus and other parameterizations) is too small relative to the expanding use of the models for predictions and demands from users for greater regional accuracy, which in most cases the models cannot yet deliver (Jakob 2010). While there are significant model development efforts at some centers, more often the development is driven toward short-term model improvement rather than identifying and resolving fundamental problems. A larger, vibrant community working on the development of more solid theory through basic research into poorly understood processes and, crucially, the transfer of this to practical applications in more comprehensive models, is essential to sustained improvement in global and regional simulations. This probably requires more durable institutional support for broadly engaged model development teams, as well as promotion of stronger links between basic research and model development.

4.1.3 Explore Hierarchical Modeling Approaches

While adding new processes to models has value, there is equal value (but currently less effort) in simplifying models—even in highly idealized ways—in order to reveal deeper aspects of system behavior, narrow down possible explanations for phenomena or for model differences, or identify misconceptions (see Bony et al. this volume). One specific example could be the use of aquaplanets or other even more idealized configurations to explore the cloud-mediated effects of aerosols or other forcings; another could be switching off selected processes in GCMs systematically as part of future intercomparisons. Single-column versions of GCMs are a potentially valuable resource that is currently underutilized outside model development centers.

4.1.4 Integrate the Whole Atmosphere, Ocean and Surface

The recent reorientation of SPARC toward troposphere-stratosphere coupling is already a good development in light of new awareness that such interactions may be more important than previously thought. This accompanies a growing development of "high-top" atmosphere models. However, as the stratosphere, cryosphere and ocean each have more "memory" than the troposphere, they may be capable of interactions (through the troposphere) that would only be resolved by fully coupled high-top models. Such models barely exist at present; more should be pursued. One area of attention would be the impact of solar variability on climate.

4.1.5 Plan for the High-Resolution Future

Advancing computer power will inevitably lead to higher resolution global and process models, a potential boon for atmospheric physics research but one not without problems. First, performance does not always increase, and can even drop, when resolution rises beyond those for which parameterizations were optimized. It is thus becoming clear that physical parameterizations in models should be "scale aware"—their behavior should depend on the grid size, and in particular, they should gradually stop acting if and when the grid size shrinks to where it can explicitly resolve the parameterized phenomenon. Second, data transfer and storage technologies are not keeping pace with CPU power, and data analysis software is typically not parallelized, with the result that the analyses needed to take full advantage of large simulations will continue to become more difficult. Traditional practices of dumping output and then analyzing it may become increasingly impractical. Modeling, IT and theory communities should together devise strategies to maximize the practical scientific utility of state-of-the-art computations.

Similar issues exist for more modest but more numerous CRM and LES computations, which have entered a rapid-growth phase, and could benefit from the adoption of canonical test cases (analogous to CO_2-doubling, 1 %/year and twentieth century hindcasts for GCMs) and standardized output quantities and formats. Moves in this direction are already occurring in GEWEX and e.g. CGILS. These studies are often based on observed cases, but simpler, idealized cases also have a role to play in testing hypotheses and understanding key processes and how best to represent them in larger-scale models.

4.1.6 Bring Weather to Climate

The experience of the weather forecasting community, which routinely runs at high resolution, could be better utilized by climate modelers. Efforts to examine the behavior of climate models on short time scales in a variety of different environments, and the climatic behavior of forecast models, should be encouraged as possible pathways to better understanding. For example, idealized studies with simplified GCMs suggest a connection between the internal variability and the response to external forcing (Ring and Plumb 2008; Gerber et al. 2008). Other evidence is that strong connections are found between biases in the time-averaged position of the extratropical jets in different GCMs, the time scales of their natural weather variability, and biases in blocking (e.g. Kidston and Gerber 2010; Barnes and Hartmann 2010). The similarity of short-term and long-term errors in model forecasts from a specified initial state also suggests the utility of this approach for climate (Brown et al. 2012). Related to this is a need for more statistical rigor, and perhaps opportunities from new statistical approaches, in many aspects of climate and climate-process research.

4.1.7 Sustain and Improve Observations

Last but not least, new observational capabilities are needed to address key weaknesses, and existing capabilities should be protected and kept as homogeneous and continuous as possible. Experience has shown the importance of sustained observations in order to capture crucial variability on decadal and multi-decadal time scales, and how sensitive this can be to gaps or too-short overlaps in satellite records. Continuation of existing cloud- and aerosol-observing capabilities is not assured, as few new missions are in the pipeline; plans to incorporate process- and climate-oriented observations into operational satellites in the US in particular have largely fallen by the wayside.

New observables that would be particularly useful include better fine-scale observations of clouds on a range of scales, better information on vertical velocities in clouds (promised by the EarthCare satellite scheduled to launch in 2015), measurements of aerosols and water vapor underneath clouds, better characterization of cloud microphysics and water content, more accurate global measurement of light and/or shallow precipitation, and better monitoring of spectral solar variability (Harder et al. 2009). Some of these could potentially be provided from space by multiangular, multispectral sensors, by GPS technologies or by new active sensors.

New observational opportunities need not be limited to big satellite missions or traditional aircraft observations, but could also include unattended aerial observations that can dwell over a single scene (Stevens and Feingold 2009). Expansion of inexpensive radar networks or cameras, perhaps combined with advanced data-mining/reduction techniques to cope with the large amount of information potentially available, is another possibility. The network of DOE ARM (Atmospheric Radiation Measurement) and similar European sites will prove the more valuable as record lengths grow, and their value could be further augmented by expanding the network to new sites and/or better integrating modeling and observations at such sites, as described by Neggers et al. (2012).

4.2 *Research Coordination*

Existing projects under the WCRP are well structured to improve the problem associated with lack of resources for model development. Examples include WGNE/WGCM model development and testing; GCSS/GABLS (now GASS) looking at details of boundary layer/clouds/convection; SPARC DynVar for defining necessary improvements in representation of the stratosphere (Gerber et al. 2012); CFMIP for representation of cloud feedbacks. In addition, recent efforts to improve the links between the groups (and the proposed new modeling council) should provide further support. Important links to THORPEX (subseasonal prediction) and WGSIP and WGCM (seasonal to centennial prediction) and through WGNE to the numerical weather prediction (NWP) community will also assist in the effort to achieve 'seamless science'.

Similar programs or efforts would be very useful, however, for aerosol and aerosol-cloud interactions. While all GCMs include similar cloud types and processes, different models include different types of aerosol-cloud effects (lifetime, semi-direct, cumulus, IN etc.) and this makes it difficult to compare these effects between models, or distinguish the impacts of different aerosol predictions from those of different aerosol sensitivities (e.g., Quaas et al. 2009). It is also difficult to distinguish the impacts of aerosol physics and cloud microphysical assumptions in assessing behavioral differences among models. Finally, although the AEROCOM program evaluates global models (Textor et al. 2006), no systematic program is in place to use available field data from observational case studies to evaluate detailed aerosol process models in the manner analogous to GCSS intercomparisons of cloud process models. Such a program could be helpful in identifying the root causes of model-observation discrepancies and could draw on the testbed established by Fast et al. (2011) for this purpose.

5 Summary

In this paper we have attempted to summarize a broad sweep of issues relating to atmospheric physical processes and their impact on our understanding and simulation of climate. Significantly, recent work has highlighted that some important aspects of climate change, including global cloud feedbacks and regional climate changes, may be modulated by shifts of the atmospheric general circulation that are not thought to depend in particular on small-scale processes. These shifts are evident in observations and qualitatively in models, but not all are fundamentally understood or well simulated. Some involve interactions with the stratosphere, which may be more important to tropospheric climate than previously assumed, and was given short shrift in most climate models until very recently. These findings represent a real advance in terms of confidence in model predictions, but do not resolve long-standing problems in how to model the smaller-scale processes, which remain broadly important.

Progress on smaller-scale processes, as well as the larger-scale issues, is being driven by results of new observing campaigns, growing awareness of key unexplained phenomena, targeted research initiatives e.g. through the WCRP, and advancing computational resources. We have identified key problems and presented a number of suggestions for emphasis in coming years. Chief among these is the need for research approaches that confront the interactions on a wide array of scales from the process scale out to (potentially) near-global scales. Such approaches must treat the complexity at the local process level but also account for feedbacks from remote dynamical adjustments, which may occur at any scale, and which could either buffer, enhance, or qualitatively modify local changes. This requires novel modeling, theoretical or observational analysis approaches because traditional numerical models will not be able to span the full range of scales required in the foreseeable future, for many key applications.

The evolution of scientific efforts will continue to be shaped by rapidly advancing information technology. Applications of this should not be limited to bigger computations alone, although these will be carried out. Equally important is facilitating intercomparison and hypothesis-testing efforts via greater accessibility of the complete spectrum of modeling approaches and results to the greater scientific community, members of which are always generating the new ideas that may eventually become the basis for new and deeper understanding of atmospheric physical phenomena.

Acknowledgments AAS was supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). EPG is supported by the US National Science Foundation under grant AGS- 0938325. GF acknowledges NOAA's Climate Goal.

References

Ackerman AS, Kirkpatrick MP, Stevens DE, Toon OB (2004) The impact of humidity above stratiform clouds on indirect aerosol climate forcing. Nature 432(7020):1014–1017

Alexander MJ, Eckermann SD, Broutman D, Ma J (2009) Momentum flux estimates for South Georgia Island mountain waves in the stratosphere observed via satellite. Geophys Res Lett 36:L12816. doi:10.1029/2009GL038587

Alexander MJ, Coauthors (2010) Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models. Q J R Meteorol Soc 136:1103–1124

Allen RJ, Sherwood SC (2010) The aerosol-cloud semi-direct effect and land-sea temperature contrast in a GCM. Geophys Res Lett 37:L07702

Allen RJ, Sherwood SC, Norris JR, Zender CS (2012) Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. Nature 485:350–354

Annamalai H, Hamilton K, Sperber KR (2007) South Asian Monsoon and its relationship with ENSO in the IPCC-AR4 simulations. J Clim 20:1071–1092

Arakelian A, Codron F (2012) Southern hemisphere jet variability in the IPSL GCM at varying resolutions. J Atmos Sci 69(12):3788–3799 [AU3]

Arblaster JM, Meehl GA (2006) Contributions of external forcings to Southern annular mode trends. J Clim 19:2896–2905

Barnes EA, Hartmann DL (2010) Dynamical feedbacks and the persistence of the NAO. J Atmos Sci 67:851–865

Bellouin N et al (2008) Updated estimate of aerosol direct radiative forcing from satellite observations and comparison against the Hadley Centre climate model. J Geophys Res Atmos 113:D10205

Bender FA et al (2012) Changes in extratropical storm track cloudiness 1983–2008: observational support for a poleward shift. Clim Dyn 38:2037–2053

Berner J, Shutts GJ, Leutbecher M, Palmer TN (2009) A spectral stochastic kinetic energy backscatter scheme and its impact on flow-dependent predictability in the ECMWF ensemble prediction system. J Atmos Sci 66:603–626

Birner T (2010) Recent widening of the tropical belt from global tropopause statistics: sensitivities. J Geophys Res 115:D23109. doi:10.1029/2010JD014664

Booth BBB, Dunstone NJ, Halloran PR, Andrews T, Bellouin N (2012) Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. Nature 484:228–232. doi:10.1038/nature10946

Bretherton CS, Uchida J, Blossey PN (2010) Slow manifolds and multiple equilibria in stratocumulus-capped boundary layers. J Adv Model Earth Syst 2, Art.#14. doi:10.3894/JAMES.2010.2.14

Brown A, Milton S, Cullen M, Golding B, Mitchell J, Shelly A (2012) Unified modeling and prediction of weather and climate: a 25 year journey. Bull Am Meteorol Soc 93:1865–1877. doi:10.1175/BAMS-D-12-00018.1

Butchart N, Scaife AA, Bourqui M, de Grandpre J, Hare SHE, Kettleborough J, Langematz U, Manzini E, Sassi F, Shibata K, Shindell D, Sigmond M (2006) Simulations of anthropogenic change in the strength of the Brewer-Dobson circulation. Clim Dyn 27:727–741

Butchart N, Cionni I, Eyring V, Waugh DW, Akiyoshi H, Austin J, Brühl C, Chipperfield MP, Cordero E, Dameris M, Deckert R, Frith SM, Garcia RR, Gettelman A, Giorgetta MA, Kinnison DE, Li F, Mancini E, McLandress C, Pawson S, Pitari G, Plummer DA, Rozanov E, Sassi F, Scinocca JF, Shepherd TG, Shibata K, Tian W (2010) Chemistry–climate model simulations of 21st century stratospheric climate and circulation changes. J Clim 23:5349–5374

Cagnazzo C, Manzini E (2009) Impact of the stratosphere on the winter tropospheric teleconnections between ENSO and the North Atlantic and European Region. J Clim 22:1223–1238

Charlson RJ, Ackerman AS, Bender FA-M, Anderson TL, Liu Z (2007) On the climate forcing consequences of the albedo continuum between cloudy and clear air. Tellus B 59:715–727. doi:10.1111/j.1600-0889.2007.00297.x

Chen WT, Nenes A, Liao H, Adams P, Seinfeld JH (2010) Global climate response to anthropogenic aerosol indirect effects: present day and year 2100. J Geophys Res 115:D12207. doi:10.1029/2008JD011619

Chepfer H, Bony S, Winker D, Chiriaco M, Dufresne, JL, Seze G (2008) Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model. Geophys Res Lett 35, Art. L15 704. doi:10.1029/2008GL034207

Christensen MW, Stephens GL (2011) Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: evidence of cloud deepening. J Geophys Res Atmos 116:D03201. doi:10.1029/2010JD014638

Chung CE, Ramanathan V et al (2005) Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations. J Geophys Res Atmos 110(D24):D24207

Colman R, McAvaney BJ (2011) On tropospheric adjustment to forcing and climate feedbacks. Clim Dyn 36:1649–1658

Conen F et al (2011) Biological residues define the ice nucleation properties of soil dust. Atmos Chem Phys Discuss 11:16585

D’Andrea F et al (1998) Northern hemisphere atmospheric blocking as simulated by 15 atmospheric general circulation models in the period 1979–1998. Clim Dyn 14:385–407. doi:10.1007/s003820050230

Demott P et al (2010) Predicting global atmospheric ice nuclei distributions and their impacts on climate. Proc Natl Acad Sci 107(25):11217–11222. doi:10.1073/pnas.0910818107

Derbyshire SH, Beau I, Bechtold P, Grandpeix J-Y, Piriou J-M, Redelsperger J-L, Soares PMM (2004) Sensitivity of moist convection to environmental humidity. Q J R Meteorol Soc 130:3055–3079

Deser D, Knutti R, Solomon S, Phillips AS (2012) Communication of the role of natural variability in future North American climate. Nat Clim Change 2:775–779

Doblas-Reyes FJ, Deque M, Valero F, Stephenson DB (1998) North Atlantic wintertime intraseasonal variability and its sensitivity to GCM horizontal resolution. Tellus Ser A 50:573–595

Donner LJ (1993) A cumulus parameterization including mass fluxes, vertical momentum dynamics, and mesoscale effects. J Atmos Sci 50:889–906

Eckermann SD (2011) Explicitly stochastic parameterization of nonorographic gravity wave drag. J Atmos Sci 68:1749–1765

Ervens B, Cubison MJ, Andrews E, Feingold G, Ogren JA, Jimenez JL, Quinn PK, Bates TS, Wang J, Zhang Q, Coe H, Flynn M, Allan JD (2010) CCN predictions using simplified assumptions of organic aerosol composition and mixing state: a synthesis from six different locations. Atmos Chem Phys 10:4795–4807. doi:10.5194/acp-10-4795-2010

Evan S, Alexander MJ, Dudhia J (2012) Model study of intermediate-scale tropical inertia-gravity waves and comparison to TWP-ICE campaign observations. J Atmos Sci 69:591–610. doi:10.1175/JAS-D-11-051.1

Fast JD, Gustafson WI Jr, Chapman EG, Easter RC Jr, Rishel JP, Zaveri RA, Grell G, Barth M (2011) The Aerosol Modeling Testbed: a community tool to objectively evaluate aerosol process modules. Bull Am Meteorol Soc 92(3):343–360. doi:10.1175/2010BAMS2868.1

Feingold G, Koren I, Wang H, Xue H, Brewer WA (2010) Precipitation-generated oscillations in open cellular cloud fields. Nature 466:849. doi:10.1038/nature09314

Frenkel Y, Khouider B, Majda A (2011a) Simple multicloud models for diurnal cycle of precipitation. Part I.: Formulation and the tropical ocean. J Atmos Sci 68(10 (October 2011)):2169–2190

Frenkel Y, Khouider B, Majda A (2011b) Simple multicloud models for diurnal cycle of precipitation. Part II: The continental regime. J Atmos Sci 61(17 (September 2004)):2188–2205

Gastineau G, Soden BJ (2009) Model projected changes of extreme wind events in response to global warming. Geophys Res Lett 36:L10810

Gastineau G, Soden BJ (2011) Evidence for a weakening of tropical surface wind extremes in response to atmospheric warming. Geophys Res Lett 38:L09706

Gerber EP, Coauthors (2012) Assessing and understanding the impact of stratospheric dynamics and variability on the Earth system. Bull Am Meteorol Soc 93(6):845–859

Gerber EP, Voronin S, Polvani LM (2008) Testing the annular mode autocorrelation timescale in simple atmospheric general circulation models. Mon Wea Rev 136:1523–1536

Ghan SJ, Abdul-Razzak H, Nenes A, Ming Y, Liu X, Ovchinnikov M (2011) Droplet nucleation: physically-based parameterizations and comparative evaluation. J Adv Model Earth Syst 3:M10001

Giorgetta MA, Manzini E, Roeckner E (2002) Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves. Geophys Res Lett 29(8):1245. doi:10.1029/2002GL014756

Golaz J-C, Salzmann M, Donner LJ, Horowitz LW, Ming Y, Zhao M (2011) Sensitivity of the aerosol indirect effect to subgrid variability in the cloud parameterization of the GFDL atmosphere general circulation model AM3. J Clim 24:3145–3160

Grabowski WW (2006) Indirect impact of atmospheric aerosols in idealized simulations of convective–radiative quasi equilibrium. J Climate 19:4664–4682

Gunn R, Phillips BB (1957) An experimental investigation of the effect of air pollution on the initiation of rain. J Meteorol 14:272–280

Gustafson WI Jr, Berg LK, Easter RC, Ghan SJ (2008) The Explicit-Cloud Parameterized-Pollutant hybrid approach for aerosol-cloud interactions in multiscale modelling framework models. Environ Res Lett 3:Art. 025005. doi:10.1088/1748-9326/3/2/025005

Hannah WM, Maloney ED (2011) The role of moisture-convection feedbacks in simulating the Madden-Julian oscillation. J Clim 245:2754–2770

Harder JW, Fontenla JM, Pilewskie P, Richard EC, Woods TN (2009) Trends in solar spectral irradiance variability in the visible and infrared. Geophys Res Lett 36:L07801

Harte J (2002) Towards a synthesis of the Newtonian and Darwinian worldviews. Phys Today 55:29–34

Hartmann DL, Larson K (2002) An important constraint on tropical cloud – climate feedback. Geophys Res Lett 29(20):1951–1954

Heald CL, Kroll JH, Jimenez JL, Docherty KS, DeCarlo PF, Aiken AC, Chen Q, Martin ST, Farmer DK, Artaxo P (2010) A simplified description of the evolution of organic aerosol composition in the atmosphere. Geophys Res Lett 37:L08803. doi:10.1029/2010GL042737

Heintzenberg J, Charlson RJ (eds) (2009) Clouds in the perturbed climate system: their relationship to energy balance, atmospheric dynamics, and precipitation. Struengmann Forum Report. MIT Press, Cambridge, pp 197–215

Held IM (2005) The Gap between simulation and understanding in climate modeling. Bull Am Meteorol Soc 86:1609–1615. doi:10.1175/BAMS-86-11-1609

Hodzic A et al (2009) Modeling organic aerosols during MILAGRO: importance of biogenic secondary organic aerosols. Atmos Chem Phys 9:6949–6982

Ineson S, Scaife AA (2009) The role of the stratosphere in the European climate response to El Nino. Nat Geosci 2:32–36

Jakob C (2010) Accelerating progress in global atmospheric model development through improved parameterizations: challenges, opportunities and strategies. Bull Am Meteorol Soc 91: 869–875

Jeffery CA (2007) Inhomogeneous cloud evaporation, invariance, and Damkohler number. J Geophys Res 112:D24S21. doi:10.1029/2007JD008789

Johanson CM, Fu Q (2009) Hadley cell widening: model simulations versus observations. J Clim 22(10):2713–2725

Kaas E, Branstator G (1993) The relationship between a zonal index and blocking activity. J Atmos Sci 50:3061–3077. doi:10.1175/1520-0469(1993)050<3061:TRBAZI>2.0.CO;2

Kharin VV, Zwiers FW, Zhang X, Hegerl GC (2007) Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. J Clim 20:1419–1444

Khouider B, Majda AJ (2008) Equatorial convectively coupled waves in a simple multicloud model. J Atmos Sci 65:3376–3397

Khouider B, Majda AJ, Stechmann SN (2013) Climate science in the tropics: waves, vortices, and PDEs, Nonlinearity 26:R1–R68

Kidston J, Gerber EP (2010) Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology. Geophys Res Lett 37:L09708. doi:10.1029/2010GL042873

Kiladis GN, Wheeler MC et al (2009) Convectively coupled equatorial waves. Rev Geophys 47:RG2003

Koren I, Feingold G (2011) Aerosol-cloud-precipitation system as a predator-prey problem. Proc Natl Acad Sci U S A 108(30):12227–12232

Koren I, Remer LA, Kaufman YJ, Rudich Y, Martins JV (2007) On the twilight zone between clouds and aerosols. Geophys Res Lett 34:L08805. doi:10.1029/2007GL029253

Kroll JH, Smith JD et al (2009) Measurement of fragmentation and functionalization pathways in the heterogeneous oxidation of oxidized organic aerosol. Phys Chem Chem Phys 11(36): 8005–8014

Kug J-S, Jin F-F (2009) Left-hand rule for synoptic eddy feedback on low-frequency flow. Geophys Res Lett 36:L05709. doi:10.1029/2008GL036435

Lapina K, Heald CL, Spracklen DV, Arnold SR, Allan JD, Coe H, McFiggans G, Zorn SR, Drewnick F, Bates TS, Hawkins LN, Russell LM, Smirnov A, O'Dowd CD, Hind AJ (2011) Investigating organic aerosol loading in the marine environment. Atmos Chem Phys 11:8847–8860. doi:10.5194/acp-11-8847-2011

Lau N-C (1988) Variability of the observed midlatitude storm tracks in relation to low-frequency changes in the circulation pattern. J Atmos Sci 45:2718–2743

Lau KM, Kim MK, Kim KM (2006) Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. Clim Dyn 26(7–8):855–864

Lee S-S (2012) Effect of aerosol on circulations and precipitation in deep convective clouds. J Atmos Sci 69:1957–1974. http://dx.doi.org/10.1175/JAS-D-11-0111.1

Lee S, Feingold G (2010) Precipitating cloud-system response to aerosol perturbations. Geophys Res Lett 37:L23806. doi:10.1029/2010GL045596

Lenton A, Codron F, Bopp L, Metzl N, Cadule P, Tagliabue A, Le Sommer J (2009) Stratospheric ozone depletion reduces ocean carbon uptake and enhances ocean acidification. Geophys Res Lett 36:L12606. doi:10.1029/2009GL038227

Li F, Austin J, Wilson J (2008) The strength of the Brewer–Dobson circulation in a changing climate: coupled chemistry – climate model simulations. J Clim 21:40–57

Lin J-L (2007) The double-ITCZ problem in IPCC AR4 coupled GCMs: ocean–atmosphere feedback analysis. J Clim 20:4497–4525. http://dx.doi.org/10.1175/JCLI4272.1

Lin J-L, Kiladis GN, Mapes BE, Weickmann KM, Sperber KR, Lin W, Wheeler MC, Schubert SD, Del Genio A, Donner LJ, Emori S, Gueremy J-F, Jourdin F, Rasch PJ, Roeckner E, Scinocca JF (2006) Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: Convective signals. J Clim 19:2665–2690

Lock AP, Brown AR, Bush MR, Martin GM, Smith RNB (2000) A new boundary layer scheme for the unified model. Part I: Scheme description and single-column model tests. Mon Wea Rev 128:3187–3199

Lu J, Vecchi GA, Reichler T (2007) Expansion of the Hadley cell under global warming. Geophys Res Lett 34:L06805. doi:10.1029/2006GL028443

Lu J, Chen G, Frierson DMW (2008) Response of the zonal mean atmospheric Circulation to El Nino versus global warming. J Clim 21:5835–5851

Maloney ED, Sobel AH, Hannah WM (2010) Intraseasonal variability in an aquaplanet general circulation model. J Adv Model Earth Syst 2, Art. #5. doi:10.3894/JAMES.2010.2.5

Mapes BE, Neale RB (2011) Parameterizing convective organization to escape the entrainment dilemma. J Adv Model Earth Syst 3:M06004. doi:10.1029/2011MS000042

Matsueda M, Mizuta R, Kusunoki S (2009) Future change in wintertime atmospheric blocking simulated using a 20-km-mesh atmospheric global circulation model. J Geophys Res 114:D12114. doi:10.1029/2009JD011919

McComiskey A, Feingold G (2012) The scale problem in quantifying aerosol indirect effects. Atmos Chem Phys 12:1031–1049. doi:10.5194/acp-12-1031-2012

McLandress C, Scinocca JF (2005) The GCM response to current parameterizations of nonorographic gravity wave drag. J Atmos Sci 62:2394–2413

McLandress C, Shepherd TG (2009) Simulated anthropogenic changes in the Brewer–Dobson circulation, including its extension to high latitudes. J Clim 22:1516–1540

Mitchell DL, Finnegan W (2009) Modification of cirrus clouds to reduce global warming. Environ Res Lett 4(4):045102

Morrison H, Grabowski WW (2011) Cloud-system resolving model simulations of aerosol indirect effects on tropical deep convection and its thermodynamic environment. Atmos Chem Phys 11:10503–10523

Morrison H, DeBoer G, Feingold G, Harrington JY, Shupe M, Sulia K (2011) Resilience of persistent Arctic mixed-phase clouds. Nat Geosci 5:11–17. doi:10.1038/ngeo1332

Myhre G (2009) Consistency between satellite-derived and modeled estimates of the direct aerosol effect. Science 325(5937):187–190

Neelin JD, Held IM (1987) Modeling tropical convergence based on the moist static energy budget. Mon Wea Rev 115(1):3–12

Neggers RAJ, Siebesma AP, Heus T (2012) Continuous single-column model evaluation at a permanent meteorological supersite. Bull Am Meteorol Soc 93(9):1389–1400

Perlwitz J, Pawson S, Fogt R, Nielsen JE, Neff W (2008) The impact of stratospheric ozone hole recovery on Antarctic climate. Geophys Res Lett 35:L08714. doi:10.1029/2008GL033317

Polvani LM, Waugh DW, Correa GJP, Son S-W (2011) Stratospheric ozone depletion: the main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. J Clim 24:795–812

Quaas J, Ming Y, Menon S, Takemura T, Wang M, Penner JE, Gettelman A, Lohmann U, Bellouin N, Boucher O, Sayer AM, Thomas GE, McComiskey A, Feingold G, Hoose C, Kristjansson JE, Liu X, Balkanski Y, Donner LJ, Ginoux PA, Stier P, Grandey B, Feichter J, Sednev I, Bauer SE, Koch D, Grainger RG, Kirkevag A, Iversen T, Seland O, Easter R, Ghan S, Rasch P, Morrison H, Lamarque J, Iacono M, Kinne S, Schulz M (2009) Aerosol indirect effects – general circulation model intercomparison and evaluation with satellite data. Atmos Chem Phys 9:8697–8717

Randall D, Khairoutdinov M, Arakawa A, Grabowski W (2003) Breaking the cloud-parameterization deadlock. Bull Am Meteorol Soc 84:1547–1564

Raymond DJ, Fuchs Z (2009) Moisture modes and the Madden-Julian oscillation. J Clim 22:3031–3046

Richter JH, Sassi F, Garcia RR (2010) Toward a physically based gravity wave source parameterization in a general circulation model. J Atmos Sci 67:136–156

Ring MJ, Plumb RA (2008) The response of a simplified GCM to axisymmetric forcings: applicability of the fluctuation–dissipation theorem. J Atmos Sci 65:3880–3898

Rio C, Hourdin F, Grandpeix J-Y, Lafore J-P (2009) Shifting the diurnal cycle of parameterized deep convection over land. Geophys Res Lett 36:L07809. doi:10.1029/2008GL036779

Robinson FJ, Sherwood SC, Li Y (2008) Resonant response of deep convection to surface hot spots. J Atmos Sci 65:276–286

Robinson FJ, Sherwood SC, Gerstle D, Liu C, Kirshbaum DJ (2011) Exploring the land-ocean contrast in convective vigor using islands. J Atmos Sci 68:602–618

Rotstayn LD, Lohmann U (2002) Tropical rainfall trends and the indirect aerosol effect. J Clim 15(15):2103–2116

Sato K, Watanabe S, Kawatani Y, Tomikawa Y, Miyazaki K, Takahashi M (2009) On the origins of gravity waves in the mesosphere. Geophys Res Lett 36:L19801. doi:10.1029/2009GL039908

Satoh M, Matsuno T, Tomita H, Miura H, Nasuno T, Iga S (2008) Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations. J Comput Phys 227:3486–3514

Scaife AA, Knight JR (2008) Ensemble simulations of the cold European winter of 2005/2006. Q J R Meteorol Soc 134:1647–1659

Scaife AA, Butchart N, Warner CD, Stainforth D, Norton WA, Austin J (2000) Realistic Quasi-Biennial Oscillations in a simulation of the global climate. Geophys Res Lett 27:3481–3484

Scaife AA, Woollings T, Knight J, Martin G, Hinton T (2010) Atmospheric blocking and mean biases in climate models. Bull Am Meteorol Soc 23:6143–6152. doi:10.1175/2010JCLI3728.1

Scaife AA, Copsey D, Gordon C, Harris C, Hinton T, Keeley S, O'Neill A, Roberts M, Williams K (2011) Improved Atlantic winter blocking in a climate model. Geophys Res Lett 38:L23703. doi:10.1029/2011GL049573

Scaife AA, Spangehl T, Fereday D, Cubasch U, Langematz U, Akiyoshi H, Bekki S, Braesicke P, Butchart N, Chipperfield M, Gettelman A, Hardiman S, Michou M, Rozanov E, Shepherd TG (2012) Climate change and stratosphere-troposphere interaction. Clim Dyn 38:2089–2097. doi:10.1007/s00382-011-1080-7

Schneider T, O'Gorman PA, Levine XJ (2010) Water vapor and the dynamics of climate changes. Rev Geophys 48:RG3001. doi:10.1029/2009RG000302

Seidel DJ, Randel WJ (2007) Recent widening of the tropical belt: evidence from tropopause observations. J Geophys Res 112:D20113. doi:10.1029/2007JD008861

Seidel DJ, Fu Q, Randel WJ, Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nat Geosci 1:21–24

Seifert A, Köhler C, Beheng KD (2012) Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model. Atmos Chem Phys 12:709–725

Sharon TM, Albrecht BA, Jonsson HH, Minnis P, Khaiyer MM, Van Reken TM, Seinfeld J, Flagan R (2006) Aerosol and cloud microphysical characteristics of rifts and gradients in maritime stratocumulus clouds. J Atmos Sci 63:983–997

Sherwood SC, Ingram W, Tsushima Y, Satoh M, Roberts M, Vidale PL, O'Gorman PA (2010) Relative humidity changes in a warmer climate. J Geophys Res 115:D09104

Shutts GJ (1986) A case study of eddy forcing during an Atlantic blocking episode. Adv Geophys 29:135–162. doi:10.1016/S0065-2687(08)60037-0

Shutts GJ, Vosper SB (2011) Stratospheric gravity waves revealed in NWP model forecasts. Q J R Meteorol Soc 137:303–317

Siebesma AP, Soares PM, Teixeira J (2007) A combined eddy-diffusivity mass-flux approach for the convective boundary layer. JAS 64:1230–1248

Sigmond M, Scinocca JF (2010) The influence of the basic state on the Northern Hemisphere circulation response to climate change. J Clim 23:1434–1446

Slingo JM, Slingo A (1991) The response of a general circulation model to cloud longwave radiative forcing. II: Further studies. Q J R Meteorol Soc 117:333–364

Sloan LC, Pollard D (1998) Polar stratospheric clouds: a high latitude warming mechanism in an ancient greenhouse world. Geophys Res Lett 25(18):3517–3520

Sobel AH, Bretherton CS (2000) Modeling tropical precipitation in a single column. J Clim 13:4378–4392

Soden BJ, Vecchi GA (2011) The vertical distribution of cloud feedback in coupled ocean-atmosphere models. Geophys Res Lett 38:L12704

Solomon SK et al (2010) Contributions of stratospheric water vapor to decadal changes in the rate of global warming. Science 327(5970):1219–1223

Solomon S et al (2011) The persistently variable "background" stratospheric aerosol layer and global climate change. Science 333(6044):866–870

Son S-W, Coauthors (2008) The impact of stratospheric ozone recovery on the Southern Hemisphere westerly jet. Science 320:1486–1489

Song I-S, Chun H-Y, Garcia RR, Boville BA (2007) Momentum flux spectrum of convectively forced internal gravity waves and its application to gravity wave drag parameterization: Part II: Impacts in a GCM (WACCCM). J Atmos Sci 64:2286–2308

Spracklen V, Jimenez JL, Carslaw KS, Worsnop DR, Evans MJ, Mann GW, Zhang Q, Canagaratna MR, Allan J, Coe H, McFiggans G, Rap A, Forster P (2011) Aerosol mass spectrometer constraint on the global secondary organic aerosol budget. Atmos Chem Phys Discuss 11:5699–5755

Stephens GL, Ecuyer TL, Forbes FR, Gettelman A, Golaz JC, Bodas-Salcedo A, Suzuki K, Gabriel P, Haynes J (2011) Dreary state of precipitation in global models. J Geophys Res 115:D24211

Stevens B, Feingold G (2009) Untangling aerosol effects on clouds and precipitation in a buffered system. Nature 461(7264):607–613

Stevens B, Vali G, Comstock K, Wood R, van Zanten MC, Austin PH, Bretherton CS, Lenschow DH (2005) Pockets of open cells and drizzle in marine stratocumulus. Bull Am Meteorol Soc 86(1):51–57

Storelvmo T, Lohmann U, Bennartz R (2009) What governs the spread in shortwave forcings in the transient IPCC AR4 models? Geophys Res Lett 36, L01806

Stowasser M, Annamalai H, Hafner J (2009) Response of Asian summer monsoon to global warming: mean and synoptic systems. J Clim 22:1014–1036

Textor C, Schulz M, Guibert S, Kinne S, Balkanski Y, Bauer S, Berntsen T, Berglen T, Boucher O, Chin M, Dentener F, Diehl T, Easter RC Jr, Feichter H, Fillmore D, Ghan SJ, Ginoux P, Gong S, Grini A, Hendricks J, Horrowitz L, Huang P, Isaksen I, Iversen T, Kloster S, Koch D, Kirkevag A, Kristjansson JE, Krol M, Lauer A, Lamarque JF, Liu X, Montanaro V, Myhre G, Penner JE, Pitari G, Reddy S, Seland O, Stier P, Takemura T, Tie X (2006) Analysis and quantification of the diversities of aerosol life cycles within AeroCom. Atmos Chem Phys 6(7):1777–1813

Thompson DWJ, Solomon S (2002) Interpretation of recent southern hemisphere climate change. Science 296:895–899

Turner J, Coauthors (2009) Nonannular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett 36:L08 502. doi:10.1029/2009GL037524

van den Heever SC, Stephens GL, Wood NB (2011) Aerosol indirect effects on tropical convection characteristics under conditions of radiative-convective equilibrium. J Atmos Sci 68(4):699–718

Volkamer R, Jimenez JL, San Martini F, Dzepina K, Zhang Q, Salcedo D, Molina LT, Worsnop DR, Molina MJ (2006) Secondary organic aerosol formation from anthropogenic air pollution: rapid and higher than expected. Geophys Res Lett 33:L17811. doi:10.1029/2006GL026899

Wang H, Feingold G (2009) Modeling Mesoscale Cellular Structures and Drizzle in Marine Stratocumulus. Part I: Impact of drizzle on the formation and evolution of open cells. J Atmos Sci 66(11):3237–3256

Wang M, Ghan S, Ovchinnikov M, Liu X, Easter R, Kassianov E, Qian Y, Marchand R, Morrison H (2003) Aerosol indirect effects in a multi-scale aerosol-climate model PNNL-MMF. Atmos Chem Phys 11:5431–5455. doi:10.5194/acp-11-5431-2011

Wang S, Wang Q, Feingold G (2003) Turbulence, condensation and liquid water transport in numerically simulated nonprecipitating stratocumulus clouds. J Atmos Sci 60:262–278

Warner J (1968) A reduction in rainfall associated with smoke from sugar-cane fires: an inadvertent weather modification? J Appl Meteor 7:247–251

Watanabe S, Kawatani Y, Tomikawa Y, Miyazaki K, Takahashi M, Sato K (2008) General aspects of a T213L256 middle atmosphere general circulation model. J Geophys Res 113:D12110. doi: 10.1029/2008JD010026

Wen G, Marshak A, Cahalan RF, Remer LA, Kleidman RG (2007) 3-D aerosol-cloud radiative interaction observed in collocated MODIS and ASTER images of cumulus cloud fields. J Geophys Res 112:D13204. doi:10.1029/2006JD008267

Wild M (2009) Global dimming and brightening: a review. J Geophys Res 114:D00D16. doi:10.1029/2008jd011470

Wood R (2012) Stratocumulus clouds, Mon Wea Rev, 140:2373–2423

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

Yin JH (2005) A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophys Res Lett 32:L18701. doi:10.1029/2005GL023684

Zelinka MD, Hartmann DL (2010) Why is longwave cloud feedback positive? J Geophys Res 115:D16117. doi:10.1029/2010jd013817

Zelinka MD, Hartmann DL (2011) The observed sensitivity of high clouds to mean surface temperature anomalies in the tropics. J Geophys Res 116, D23103

Zeng XP et al (2009) An indirect effect of ice nuclei on atmospheric radiation. J Atmos Sci 66:41–61

Zhang M, Bretherton CS (2008) Mechanisms of low cloud climate feedback in idealized single-column simulations with the Community Atmospheric Model (CAM3). J Clim 21:4859–4878

Author Query

Chapter No.: 4 0001973456

Query	Details Required	Author's Response
AU1	Please confirm the corresponding author and also affiliation of all authors.	
AU2	Citations Robinson et al. (2010), Donner (2003), Zelinka and Hartmann (2011), Wang et al. (2003), Doblas-Reyes et al. (2002), Son et al. (2009), Polvani (2011), Stephens et al. (2010), Eckermann (2012), Stevens and Feingold (2010) have been changed to Robinson et al. (2011), Donner (1993), Zelinka and Hartmann (2010), Wang et al. (2011), Doblas-eyes et al. (1998), Son et al. (2008), Polvani et al. (2011), Stephens et al. (2011), Eckermann (2011), Stevens and Feingold (2009) as per the reference list. Please check.	
AU3	Please confirm the inserted volume number and page range is appropriate for references Arakelian and Codron (2012), Deser et al. (2012), Feingold et al. (2010), Gastineau and Soden (2009, 2011), Gerber et al. (2012), Held (2005), Neggers et al. (2012), Scaife et al. (2012), Wild (2009), Zelinka and Hartmann (2010), Brown et al. (2012), Chung and Ramanathan et al. (2005), Hartmann and Larson (2002), Kiladis and Wheeler et al. (2009).	