Climate Processes: Clouds, Aerosols and Dynamics (B6)

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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 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 troposphere-stratosphere exchange, also affect simulation of regional climate change especially at high latitudes. Targeted field programs, new satellite capabilities, and new computational approaches are promoting progress on these problems however. Recent 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, recognising the complexity at the local level but also the constraints and possible buffering operating at larger (system) scales.

1. Introduction

Aerosol, cloud 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 direct observations, process modelling, 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 localised 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 (Rotstyn 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. The chief source of spread is from low clouds, but this does not mean that other types of clouds are completely in hand. 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 organise 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 Heitzenberg 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 issue) for a more focussed 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 Section 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 issue) 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. 2010).

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 2011). These clouds 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 Section 2.2.3.

Recent progress in the representation of boundary layer clouds in climate models has been brought about through both parametrization improvements and in many cases the use of higher vertical resolution. Other recent parametrization 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 parametrizations (e.g. Siebesma et al 2007).

Improved community coordination through groups that bring together observationalists, process modellers and parametrization developers, such as GCSS (Global Cloud System Studies group, now being subsumed into 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 brought in 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 in 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 and other tropical wavelike phenomena are sensitive to aspects of convective behaviour (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 modelling 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 1990‘s, the last few years have seen renewed interest in developing new parametrizations for deep convection. This has been motivated partly by 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. Some recent studies have questioned the centrality of thermodynamic, parcel-based reasoning in theories of convection, emphasising the additional role of mesoscale dynamical constraints in influencing convective growth (Robinson et al. 2008, 2010). At the same time climate models with “superparametrizations,” or explicit convection models in place of the usual convective and cloud parametrizations (Randall et al. 2003), have also come into wider use. These models are too expensive to run as conventional climate models themselves, but are beginning to provide insights that may help improve standard parametrizations; for example, convective mass fluxes from these simulations can be used in parametrizations of aerosol physics (Gustafson et al. 2008; M. Wang et al. 2011).

As model grid sizes decrease, traditional assumptions of grid independence and statistically equilibrated cloud fields used in convective parametrizations—if they were ever adequate—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 2003) 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 instraseasonal variability. One such strategy is to formulate an additional prognostic parameter representing the evolving degree of convective organisation (Mapes and Neale 2011), while another is to represent transitions between convective stages or regimes in a population of clouds (e.g. Frenkel et al. 2011a,b; Khouder and Majda 2008). Stochastic parametrizations 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 behaviour 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 and schemes with explicit representation of 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 the clouds (such as their total water content profiles) may be well constrained by the mass flux quantities that most 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. 1997).

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. (2011) 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 (Sections 2.3.1, 2.3.4), and on its own would imply a significant increase in net radiative heating of the planet in recent decades.

Climate models now exhibit a consensus that upper-level clouds will rise roughly in accord with the lifting of upper-tropospheric isotherms in warmer climates, as predicted by Hartmann and Larson (2002). This produces a positive feedback that accounts for most of the overall mean positive feedback in the CMIP3 collection of climate models (Zelinka and Hartmann 2010). Additional positive feedback comes from robust reductions in mid-level cloud (Zelinka et al. 2011a).

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 interaction

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 recognised (see 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. The main factor determining IN concentrations in the atmosphere is the overall number concentration of aerosol at size greater than 0.5 micron 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 Section 2.2.3). However, rapid transitions can be triggered in stratocumulus such that cloud amount and thickness changes strongly amplify the Twomey effect (see Rosenfeld et al., this issue).

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 indirect

(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. Importantly, estimates constrained by satellite observations show significantly less cooling than those predicted by models alone, from −0.5 W m^{-2} to near zero. While this may mean models are still overestimating aerosol effects, it is also likely that satellite resolutions are inadequate for them to properly quantify cloud-free aerosol effects on cloud microphysics or that they may not control properly for non-aerosol cloud effects (McComiskey and Feingold 2008).

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 Section 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 vapour may also vary on decadal or longer time scales, making some contribution to radiative forcing (Solomon et al. 2010, 2011).

New research highlights the possibility of IN effects on cirrus 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 −40C 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).

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).

Recent work shows that the knock-on effects from the initial modification of clouds are profound, but may also be self-limiting or produce interesting coherent variations in a cloud system. 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 2011). 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; Xue et al. 2008; Stevens and Savic-Jovcic 2008;

Wang and Feingold 2009).

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).

Research over recent decades has clarified that the net effect of aerosols on cloud albedo, when averaged over large cloud systems, may be significantly less than would be expected from considering the perturbation of a single cloud in isolation (Stevens and Feingold 2009) as would happen in a limited cloud simulation or observed local cloud behaviour near isolated aerosol sources.

This situation applies equally to deep convective systems. Recent model studies suggest that the 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. 2011).

2.2.4 *Advances in parameterising aerosols*

Aerosol treatments in global climate models remain fairly crude, though this could be said of all model parametrizations. 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 indirect effects 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 M. Wang et al. 2011).

2.3 Dynamics from small to global scales

2.3.1 *Widening of the Tropics*

Evidence for widening of the Hadley circulation or tropical belt in the later decades of the 20th 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 (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. (2009) 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 greenhouse gases and stratospheric ozone depletion (Lu et al. 2007) 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.

2.3.2 *Large-scale circulation*

Observational evidence for the importance of the development of the stratospheric ozone hole on late 20th century Southern Hemisphere climate emerged prior to the IPCC's AR4 (Thompson and Solomon 2002), and the dominance of stratospheric ozone in driving these changes was verified in climate model studies. However many 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 21st 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 extratropical jet in the 21st century, while models with constant ozone predict a poleward shift in the jet due to greenhouse gas (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). Seasonal 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).

The stratosphere is now recognised to play 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. 2011a). 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 10 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.

2.3.3 *Gravity waves*

Gravity waves influence climate through their effects on the large-scale circulation, which in turn affects planetary wave propagation and reflection—yet much of the gravity wave spectrum remains unresolved at current climate model resolution (e.g. Alexander et al. 2010). Mountain wave drag reduces westerly biases in zonal winds near the tropopause, and parametrized 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 vapour, an important greenhouse gas (Solomon et al. 2010). An increasing trend in 21st 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 parametrized 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 GHG trends lead to stronger subtropical jets, and these changes in the winds explain the changes in the parametrized drag.

An early focus on different dissipation mechanisms within non-orographic gravity wave parametrizations 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 parametrization 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 parametrizations 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 parametrizations (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).

2.3.4 *Blocking events*

Limitations in climate-model representation of the frequency and duration of blocking events were described in the IPCC's AR4, and these persist. 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. 2002) even if the simulated variability appears adequate (Scaife et al 2010). In coupled models, the westerly bias and blocking deficit over the Atlantic in coupled models may be associated with errors in the simulated Gulf Stream (Scaife et al. 2011b).

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

Infrequent, intense weather events are part of a stable climate system. It is now well recognised that climate changes will almost certainly drive changes in the characteristics of “rare” or “extreme” weather related events. Evidence of such changes in the observational record is beginning to emerge (Zwiers et al., this issue), though attribution to specific aspects of climate change is difficult especially for individual events (Stott et al., this issue). 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 parametrization 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 modelling 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

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. Also, observations of precipitation still have large errors even from the best spaceborne sensors, particularly for light rain.

Many models 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-recognised 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 ad-hoc.

The modelling 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 (Jeffery 2007).

Continuing uncertainty remains over the true sign and magnitude of the boundary layer cloud feedback (which itself is a big player in overall cloud feedback) under climate change (e.g. Bony et al. 2005). While recent research (e.g. through GEWEX) has focused particularly on low clouds for this reason, 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 hypothesised 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 parametrizations 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. Ice clouds are typically between ice and water saturation, and the relative humidity not only affects the growth of ice crystals, but also depends on the past growth. For instance, clouds with low vertical velocity are expected to be below water saturation and feature ice crystals grown by the diffusion of water vapor. If the vertical velocity is large, however, water saturation can be reached and supercooled water will appear. In such a situation, ice crystals will also grow by accretion of the supercooled water, and homogeneous freezing of supercooled droplets may take place at sufficiently low temperatures. Cloud physics has struggled with representation of ice processes in cloud models for decades, so it should not be surprising that representation of such processes in large-scale models remains highly uncertain. In summary, parametrizing cloud microphysics in models with parameterized clouds seems extremely difficult. Arguably more advanced approaches (such as superparametrization, Randall et al. 2003; or convection-permitting models) provide significantly better alternatives but often not at an affordable cost for many applications.

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 issue) on the basis that aerosol impacts on clouds can be observed directly even if we don't have complete theories of cloud behaviour.

3.2 Aerosols and aerosol-cloud interactions

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 now 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 categorising such a rich spectrum of possible aerosol types, mixtures, and sizes is a significant modelling 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 modelling 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 in clouds are quite sensitive to mixing assumptions and the science is currently hampered by basic questions in 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 lack of a basic theory of ice nucleation, i.e. an understanding of why some substances nucleate ice well and others poorly. It is hard to see how indirect cloud radiative effects modulated by deep convection, and subsequently affecting anvils and cirrus, will be properly understood or quantified while issues surrounding ice nucleation remain so obscure.

Indirect aerosol 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 issue) the primary ("Twomey") effect, since both outcomes are possible depending on circumstances. Indirect effects on ice-containing clouds are likely in opposition to those on shallow clouds, and climate model simulations suggest that indirect 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 indirect forcing represents a near-balance between opposing large ones from deep and shallow clouds (Rosenfeld et al., this issue).

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 increasingly recognised role of other forcings such as tropospheric ozone, stratospheric water vapour, 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

The jury is still out on what resolution is required to accurately represent atmospheric blocking and the role of mean state errors in biasing blocking statistics and how blocking might be improved in models.

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 parametrization of gravity wave sources is needed to properly simulate gravity wave effects in future climate scenarios.

Although the simulated pattern of sea-surface temperature response to global warming includes an El Nino-like component, the extratropical atmospheric responses occurs 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.

The extratropical jets are driven by synoptic eddies, something we can certainly simulate with some fidelity in climate models. However, there are substantial biases in the location of jets in almost all CMIP3 models that are associated with errors in the persistence of the annular modes (e.g. Kidston and Gerber 2010) and blocking event frequencies.

A general urgent issue is the limited size of the community involved in model development (e.g., Jakob 2010). Persistent problems in climate models include poor resolution of boundary layer and cloud processes, the representation of Madden–Julian oscillation and other modes of tropical variability (e.g., Lin et al. 2006), and the incorrect representation of the frequency of occurrence of high- and low-intensity rainfall events (e.g., Stephens et al. 2010). A relatively large community of researchers use climate models or study processes relevant to improving climate models. Some of this work gets as far as proposing parametrization 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 like to support new and cutting edge research rather than traditional and unglamorous model development. Further, scientific achievement is measured by counting papers, which may be harder for hands on model developers to do in quantity.

4. Strategic opportunities and recommendations

4.1 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 modelling council) should provide further support. Important links to THORPEX (subseasonal prediction) and WGSIP and WGCM (seasonal to multiannual 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 indirect effects (lifetime, semi-direct, cumulus, IN etc.) and this makes it difficult to compare aerosol indirect 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 behavioural differences among models. Finally, although the AEROCOM program evaluates global models (Textor et al. 2006), no systematic programme 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.

4.2 Research foci and strategies

A recurring theme in cloud, aerosol and sometimes dynamics research is the tight connections between behaviour 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, is not very informative as to what will happen in a more realistic setting where a cloud interacts with others. In this situation, the initial changes are often strongly buffered by responses from larger scales. Addressing clouds as a system is far more appropriate. Likewise, the role of clouds in dynamics at larger scales is very difficult to discern from small-scale studies although some strategies such as the “weak temperature gradient” setup (Sobel and Bretherton 2000) do allow some feedback from larger scales in an idealised setting. There appear to be significant discrepancies between inferred aerosol-cloud effects from LES or other process models, and in GCMs. While LES provides detailed, local assessments of aerosol effects on clouds, the small domain size does not allow for the important feedbacks with larger scales. At the other extreme, GCMs integrate a great deal of physics globally, but fail to represent the processes in sufficient detail, thus undermining confidence in results.

A key research strategy should therefore be to find better ways to integrate across scales, combining the ability of local process models to represent important details with the ability of a larger-scale model to represent the important interactions over distances and enforce global conservation constraints. One approach to this is “superparametrization,” where cloud-permitting models run in each grid box of a global model. There are likely to be other approaches that may be more economical for examining key mechanisms and interactions. Observational studies should similarly consider the nonlocal impact of aerosol perturbations, if possible, which may cancel out local effects. Another strategy for combining models and observations is to exploit emergent chaotic behaviour or other non-traditional measures of the behaviour 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). This may be thought of as a generalisation of longstanding efforts to explain convectively-coupled wave activity in the tropics, to non-wavelike emergent phenomena.

It is also the perception of the authors that the amount of effort being expended toward the proper development of atmospheric model "physics" (cumulus and other parametrizations) is too small relative to the growing breadth of use of the models 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 centres, more often the development is driven mainly by ad-hoc approaches. A larger vibrant community working on the development of more solid theory and, crucially, the transfer of this to practical applications in more comprehensive models is crucial if we want continued improvement in global simulations.

It is becoming clear that physical parametrizations in models should be "scale aware"—their behaviour should depend on the grid size, and in particular, they should gradually stop acting as the grid size shrinks to where it can explicitly resolve the phenomenon in question. The experience of the weather forecasting community could be better utilised by climate modellers, since the former typically run at much smaller resolutions than the latter and (at least for convection) have mostly chosen different parametrizations from those favoured by the latter.

A better understanding of interactions across scales is also needed to improve simulation of large-scale climate variability and trends. In contrast to cloud and aerosol interactions, however, current models do resolve the primary scales in question. For example, the planetary scale mid-latitude jet streams are generated by momentum fluxes of synoptic scale baroclinic eddies, all features clearly resolved in CMIP3 models. Nonetheless, nearly all models placed the Southern Hemisphere westerly jets too far equatorward, sometimes by 10 degrees (e.g. Kidston and Gerber 2010). While there is considerable qualitative understanding on eddy-mean flow interactions, there is no theory that tells us exactly where the jets should be. We must therefore rely on simulations, and correcting these model biases has significant implications for global climate, as surface wind biases impact carbon uptake (e.g. Swart and Fyfe 2012). As discussed in the context of problems in capturing blocking features in section 2.3.4, the key may be in how smaller scale dissipative processes impact the energy containing synoptic scales. Lessons from NWP experience suggest that improvements in the representation of blocking events and the jet streams may occur with further systematic study of performance of climate models as a function of resolution.

There is also hope that we could improve climate forecasts by paying more attention to the temporal variability in climate models. Idealised studies, based on models with fully resolved numerics, but simplified climate physics, suggest a connection between the internal variability and the response to external forcing (Ring and Plumb 2008; Gerber et al. 2008a): models with enhanced persistence tend to be more sensitive to external forcing, qualitatively consistent with the Fluctuation-Dissipation relationship exhibited by simpler systems (e.g. Leith 1977). There are strong connections between biases in the position of the extratropical jets and the time scales of the annular modes in CMIP3 models, as well as biases in blocking, and some indication that these biases could affect the response of the extratropical jets to anthropogenic forcing (e.g. Kidston and Gerber 2010; Barnes and Hartmann 2010). Increasing model resolution can improve the annular mode time scale (Gerber et al. 2008b), more evidence that smaller scale dissipative processes need to be accurately modeled to capture synoptic and planetary scale features.

Climate model representations of the jet streams and blocking events are also sensitive to background errors that may originate in the ocean simulations. Trenberth and Fasullo (2010) highlight the impact of substantial biases in the energy budget of the Southern Ocean on the austral storm track. These biases may ultimately stem from the poor representation of clouds in climate models, linking problems in dynamics to problems with cloud and aerosol interactions.

5. Summary

In this paper we have attempted to summarise a broad sweep of issues relating to atmospheric processes and their impact on our understanding and simulation of climate. While cloud- and aerosol-related process uncertainties are long-recognised, recent work has highlighted that many aspects of climate change, including important cloud feedbacks, may be modulated by global-scale dynamical shifts that are not thought to depend in particular on cloud or aerosol processes. These shifts are evident in observations and qualitatively in models, but not all are fundamentally understood or well simulated. Most involve interactions with the stratosphere, which is more important to tropospheric climate than previously assumed and was given short shrift in most climate models until very recently.

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 presented a number of suggestions for emphasis in coming years. Chief among these is the need for research approaches that acknowledge the importance of interactions on a wide array of scales from the process scale out to near-global scales. Such approaches must treat the complexity at the process level but also account for feedbacks from dynamical adjustments at much larger scales that could buffer or enhance local changes. This requires novel modelling or theoretical approaches because traditional numerical models cannot span the full range of scales required.

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