Chapter 1
Numerical Resolution and Modeling of the Global Atmospheric Circulation: A Review of Our Current Understanding and Outstanding Issues

Kevin Hamilton

Summary This chapter presents a survey of published literature related to the issue of how the simulation of climate and atmospheric circulation by global models depend on numerical spatial resolution. To begin the basic question of how the zonal-mean tropospheric circulation in atmospheric general circulation models (AGCMs) vary with changing horizontal and vertical grid spacing is considered. The appropriate modification of subgrid-scale parameterizations with model resolution is discussed. Advances in available computational power have recently spurred work with quite fine resolution global AGCMs, and the issue of how well such models simulate mesoscale aspects of the atmospheric circulation is considered. Experience has shown that the AGCM simulated circulation is particularly sensitive to resolution in the stratosphere and mesosphere, and so studies related to the middle atmospheric circulation are considered in some detail. Finally, the significance of atmospheric model resolution for coupled global ocean–atmosphere models and the simulated climate sensitivity to large-scale perturbations is discussed.

1.1 Introduction – Global Atmospheric Simulations

The first attempt at integrating a multilevel comprehensive atmospheric general circulation model (AGCM) including treatment of the hydrological cycle was that of Manabe et al. (1965). This employed coarse resolution in both the horizontal ($\sim$500 km grid spacing) and the vertical (nine levels from the ground to the model top near 10 hPa). For many research applications (and also for very long timescale climate forecasts), a majority of projects in subsequent decades have employed AGCMs with typically only about twice the horizontal and vertical resolution of this original Manabe et al. model. Until recently, research groups typically devoted their ever increasing computer power principally to making longer integrations and incorporating more sophisticated parameterizations into their AGCMs.

Most of the early efforts to run global models with particularly fine resolution were undertaken by major operational forecasting centers, which generally have state-of-the-art computing facilities and also a strong practical incentive to fully use their resources in producing the best possible deterministic short-range predictions. The horizontal and vertical resolutions used in the global deterministic forecast runs at two leading operational centers, those of the USA (currently the National Centers for Environmental Prediction, NCEP) and Europe (European Center for Medium Range Weather Forecasts, ECMWF) are regularly increased as computational resources permit. Horizontal resolution has improved by roughly a factor of 10 in these runs over the last two decades while vertical resolution has improved by about a factor of 5. Given that time steps for integration are usually scaled with the horizontal resolution, this represents about a 5,000-fold increase in the computational burden over about 20 years. Currently the operational model at the ECMWF uses a triangularly truncated spectral representation (T799) with smallest wavelength resolved of about 40 km, corresponding to an effective horizontal grid spacing of about 20 km.

On the climate side, a pioneering effort to apply substantial supercomputer resources to integration of a very fine resolution AGCM was begun in the 1980s at the Geophysical Fluid Dynamics Laboratory (GFDL). Mahlman and Umscheid (1987) describe simulations with a version of the GFDL "SKYHI" grid-point model with $\sim$100 km horizontal resolution and 40 levels in the vertical. This effort continued over the next decade with simulations performed using grid spacing as fine as 35 km and with versions with up to 160 levels (Hamilton and Hemler, 1997; Hamilton et al., 1999, 2001; Koshyk and Hamilton, 2001).

Recently the efforts to run global AGCMs at fine resolution have attracted interest and participation from a wider range of research groups and have been assisted by substantial investments in development of major supercomputers. Conaty et al. (2001) discuss aspects of the synoptic and mesoscale circulation features appearing in a seasonal integration with a version of a global AGCM with $\sim$100 km grid spacing. In a recent chapter Shen et al. (2006) discuss several 5-day integrations with a $1/8°$ version of the NASA finite-volume GCM. The Atmospheric Model for the Earth Simulator (AFES) is a spectral AGCM which has been adapted to run very efficiently on the Earth Simulator. Ohfuchi et al. (2004, 2005) report on brief ($\sim$2 weeks) simulations performed using AFES versions with triangular-1,259 truncation (corresponding roughly to 10 km grid spacing) and 96 levels in the vertical. A global version of the GFDL:ZAETAC nonhydrostatic grid-point model with $\sim$10 km horizontal resolution was integrated for 24 h at GFDL (Orlanski and Kerr, 2007). Finally, in a very ambitious project, Tomita et al. (2005) report on brief integrations using the Earth Simulator of a nonhydrostatic AGCM with roughly 3.5 km horizontal grid spacing.

There have been increasing efforts at using high-resolution models even for long-period climate change predictions. In the current round of very extensive integrations from coupled global models submitted for consideration in the IPCC Fourth Assessment Report the horizontal resolution of the atmospheric components of the models ranges up to T106. Mizuta et al. (2005) discuss an even more ambitious experiment conducted on the Earth Simulator. They performed both a 10-year present-day control simulation and a 10-year late-twenty-first century time-slice global warming simulation using a T959 atmospheric global model in which the sea surface temperatures (SSTs) were taken from comparable periods of a low-resolution coupled GCM global warming scenario experiment.

This chapter is an informal review of research on the question of how horizontal and vertical resolution affects the simulation of the global atmospheric circulation. The focus is on the ability of models to simulate realistic circulations when run from essentially arbitrary initial conditions (i.e., in “climate mode”). Not covered here are related questions concerning the effects of model resolution on the performance of short-range weather forecasts. Mullen and Buizza (2002) and Roebber et al. (2004), among others, provide discussions of the role of model resolution in practical short-range weather forecasts.

The outline of this chapter is as follows. Section 1.2 reviews the results obtained by various groups concerning the basic dependence of the simulated large-scale circulation on horizontal model resolution. In this section only results relevant to the troposphere will be considered. Section 1.3 reviews the rather less extensive published work on the dependence of the basic tropospheric simulation on vertical model resolution. Historically, most of the studies of resolution-dependence of simulated circulation have been performed with model suites that extend up to only relatively modest horizontal resolution (typically grid spacings larger than 100 km). However, the recent efforts at running significantly finer-resolution models raise other issues of convergence, namely whether these mesoscale-resolving (or mesoscale “permitting” to adapt a term from ocean modeling, e.g., Griffies and Hallberg, 2000) global models are producing realistic mesoscale motions. The explicit simulation of the tropospheric mesoscale within global models is reviewed in Sect. 1.4. Section 1.5 reviews the somewhat limited literature related to appropriate scaling of parameterizations with changing model spatial resolution. Section 1.6 considers the dependence of the simulated circulation on resolution for the stratosphere and mesosphere. Section 1.7 reviews the literature on the effect of model resolution on coupled atmosphere–ocean global simulations and on modeled climate sensitivity to large-scale radiative perturbations. Conclusions are summarized in Sect. 1.8.

Throughout this chapter, for simplicity, the effective horizontal grid resolution of a spectral model with triangular truncation at total spherical wavenumber n is taken to roughly the circumference of the earth divided by $2n$. Lander and Hoskins (1997) offer a more detailed discussion of the effective equivalent resolution in grid and spectral representations.

1.2 Effect of Horizontal Resolution on Simulations of Tropospheric Circulation

A basic issue in global modeling is how the overall large-scale and regional features of the simulated climate depend on numerical resolution. This issue has been investigated systematically for a range of horizontal resolution in a number of studies using a variety of models. Held and Suarez (1994), Boer and Denis (1997), and Pope and Stratton (2002) discussed the convergence of the results from idealized dry-dynamical core (DDC) models. The DDC models have no topography, no moisture, and employ radiative heating specified as a function of the latitude, height, and local temperature. Such studies have also been performed with several full AGCMs employing either spectral dynamics (Boer and Lazare, 1988; Boville, 1991; Boyle, 1993) or grid-point dynamics (Hamilton et al., 1995, 2001; Pope and Stratton, 2002). A common result in all the spectral model studies is that even the largest scales of the mean circulation change very significantly as spectral resolution is increased from ~T21 to ~T42, notably with increased poleward eddy fluxes of eastward momentum along with increased midlatitude surface westerlies and corresponding meridional surface pressure gradients. As horizontal resolution is increased still further, these changes in the zonal-mean circulation continue, but at a much slower rate. Similar trends are observable in grid-point model simulations. The changes seem not to have completely converged even at the highest resolution considered in these studies (e.g., T63 for Boville, 1991; T106 for Boyle, 1993; ~35 km grid spacing for Hamilton et al., 2001; ~90 km grid spacing for Pope and Stratton, 2002). Continuing modest changes in the zonal-mean winds and temperatures and also in eddy statistics such as the zonal-mean of the eddy kinetic energy are apparent in these studies, even as the model resolution reaches these relatively fine values.

Williamson (1999) compared some aspects of simulations in a conventional spectral AGCM run at T63 and T106 horizontal resolution in the full model, and in versions in which the subgrid-scale physics parameterizations were performed on a reduced T42 grid. That is, the full resolution spectral fields produced by the dynamical model were truncated to T42, the tendencies due to physics parameterizations were then computed on the appropriate T42 transform grid and expanded into the spectral space. The resulting tendencies were then applied in the full model dynamics. Williamson notes that the strength of the tropical Hadley circulation does not converge in the standard model (even at T170 resolution), but there is convergence when the resolution of the subgrid-scale physics is held at T42. By contrast, the statistical properties of the extratropical storm tracks do change significantly between T63 and T106, even in the version with fixed resolution for the subgrid-scale physics.

A more complex issue is the dependence of simulated regional climatology in realistic models as resolution is improved. One complication is that higher horizontal resolution models typically employ finer-scale topography, and by itself this may be expected to change the simulations. The overall impression obtained by reviewing the studies cited above is that increasing horizontal resolution generally leads to improved regional climatology for such quantities as seasonal-mean sea level pressure or seasonal-mean precipitation. An interesting example is provided by Hamilton et al. (1995) who evaluated the boreal summer and boreal winter precipitation simulations obtained with the GFDL SKYHI grid-point AGCM when run with ~300, ~200, and ~100 km grid spacing. The seasonal-mean results in each case were averaged on $5^\circ \times 5^\circ$ latitude–longitude areas and correlated with observed climatology over the globe. Although the precipitation simulations had some fairly obvious deficiencies (e.g., in the summer South Asian monsoon) at all three resolutions, the objective measure of pattern correlation with observations was reasonably high (∼0.7–0.8) and it increased with improved model resolution. A similar conclusion concerning the global correlation of simulated and observed rainfall patterns was reached by Kobayashi and Sugi (2004) in simulations with different resolution versions of the Japan Meteorological Agency (JMA) spectral AGCM. Pope and Stratton (2002) calculate the rms differences from observations in December–February mean sea level pressure simulated by their grid-point model when run at ∼275 km resolution versus ∼90 km resolution. They find that the rms error drops very substantially from 3.5 to 2 hPa at the higher resolution. They also ran a version of their high-resolution model with the low-resolution topography, and find that much (but not all) of the improvement in the simulation of sea level pressure at high resolution can be attributed to the finer topography rather than simply the improved resolution of the atmospheric dynamics.

There have been some systematic studies of the horizontal resolution dependence of the AGCM simulation of Asian monsoon circulations and associated rainfall. Sperber et al. (1994) find significant deficiencies in the T42 simulation of the monsoon by the ECMWF model, some of which are alleviated at T106 resolution. Stevenson et al. (1998) compare summer monsoon simulations in T21, T31, T42, and T63 versions of an AGCM. Stevenson et al. found that the large-scale features such as the lower tropospheric westerly jet, the upper tropospheric tropical easterlies, the Tibetan High were simulated by the model at all resolutions. As the resolution was increased the core of the low-level westerly jet moved toward Somalia and became more realistic. However, the model simulated excessive rainfall over the equatorial Indian Ocean and over the southern slopes of the Tibetan plateau, and these errors actually became accentuated at finer resolution. Kobayashi and Sugi (2004) examine the Asian monsoon simulation in prescribed SST simulations with the JMA Global Spectral Model model with horizontal resolution varied between T42 and T213, all L40. Even a large-scale feature such as the seasonal-mean Tibetan High is stronger (and more realistic) at T213. Many smaller scale climatological features are better represented at high resolution as well, notably the location and strength of associated precipitation of the Baiu front.

We can conclude that, while there have been a number of studies addressing the issue of how simulated tropospheric circulation changes with model horizontal resolution, there is nothing definitive that allows a determination of the resolution needed for a particular degree of convergence in the simulated climate. There has been little work along these lines performed at finer model resolution (say effective horizontal grid spacings significantly less than 100 km). The possibility that employing still finer horizontal resolution may significantly improve global model simulations of the mean tropospheric climate cannot be discounted.

1.3 Effects of Vertical Resolution on Simulations of Tropospheric Circulation

The issue of appropriate scaling of the vertical and horizontal resolution of numerical models of the atmospheric circulation has been a concern for some decades, but a clear and general determination of how simulations are affected by the vertical resolution has not been achieved. Lindzen and Fox-Rabinovitz (1989) argued that in order to simulate quasigeostrophic motions in the troposphere, a model should employ a ratio of horizontal grid spacing (Δx) to the vertical grid spacing (Δz) of the order of 300 in the extratropics and at least an order of magnitude larger near the equator. In practice, various atmospheric simulation models have been designed with an enormous range of ratios of the horizontal to vertical grid spacing, almost all significantly smaller than those advocated by Lindzen and Fox-Rabinovitz. For typical global climate GCMs we may have $\Delta x \sim 300$ km and $\Delta z \sim 1$–2 km in the midtroposphere (enhanced vertical resolution near the ground is common of course) for a ratio of ∼150–300. The operational global forecast models referred to in Sect. 1.1 have finer horizontal and vertical resolutions, but all have $\Delta x/\Delta z$ ratios of this order, as well. In limited-area mesoscale models the $\Delta x/\Delta z$ ratio is typically much smaller; for example Janjic et al. (2001) describe simulations with a nonhydrostatic mesoscale model with $\Delta x \sim 8$ km and $\Delta z \sim 0.5$ km, or a ratio of ∼15. In cloud-resolving calculations it is sometimes the case that Δx will be taken to be almost as small as Δz and so the ratio can be ∼1. In general these choices seem to be motivated by a widespread belief that once Δz is down to ∼0.5–1 km there is more to be gained by increasing the horizontal resolution than in reducing Δz further. The empirical and theoretical basis for this belief appears not to be as developed as one may like, but there have been a few published relevant studies of how the vertical resolution affects AGCM simulations which seem to support this view.

Boville (1991) discussed a set of simulations with an AGCM run at T21 horizontal resolution and vertical level spacings varied from ∼2.8 km down to ∼0.7 km. He found little difference in these simulations except in the behavior of vertically propagating equatorial waves (more of an issue for the stratosphere than the lower atmosphere). Some more recent results studying models with different vertical resolution suggest that the largest sensitivity may be in the tropics and may be most significant for the simulation of upper tropospheric water vapor. Tompkins and Emanuel (2000) studied results of a single-column atmospheric model formulated with equal pressure difference between model levels; this model was run to a radiative–convective equilibrium for tropical conditions. They found that the vertical structure of temperature and water vapor was sensitive to improving vertical resolution at least until the level spacing was reduced to ∼25 hPa (corresponding to $\Delta z \sim 500$ m in the midtroposphere). Inness et al. (2001) analyzed control climate simulations performed with 19 and 30 level versions of an AGCM. They find modest, but significant, differences between the simulations in terms of the mean temperature and humidity structure and also in the behavior of tropical intraseasonal oscillations.

Roeckner et al. (2006) have performed a systematic investigation of the global rms errors in seasonal-mean fields in an array of simulations with the ECHAM5 AGCM as the resolution varies from T21L19 to T159L31. Consistent with earlier studies, the authors find that at L19 vertical resolution there is an improvement in the simulation with increasing horizontal resolution up to T42, but little improvement beyond that. With the L39 vertical resolution, however, the improvement of the simulation with horizontal resolution in most respects continues through T159 truncation.

These AGCM studies have dealt with modest horizontal resolution models only, and the question of optimum vertical resolution for very fine horizontal resolution global models has not been systematically addressed. This issue also obviously is connected with the performance of subgrid-scale parameterizations, notably those for cloud processes and turbulence.

1.4 Explicit Simulation of Mesoscale Phenomena

While increasing resolution past a certain point may lead to only modest changes in the large-scale circulation, higher resolution models have at least the possibility to explicitly simulate mesoscale circulations. Such features may be very significant for both weather forecasting and climate applications. As climate model simulations are run at ever finer resolution it will become more important to evaluate the mesoscale aspects of these simulations.

Perhaps the most basic question is whether the mesoscales in the simulated flow are realistically energized. It has been known that moderate resolution AGCMs can simulate a realistic spectrum of horizontal variance of the horizontal wind and temperature. These are often referred to as the kinetic energy (KE) and available potential energy (APE) spectra, respectively (Boer and Shepherd, 1983; Boville, 1991; Koshyk et al., 1999). Model results can be projected onto spherical harmonics and horizontal spectra then expressed as a function of total wavenumber, n, of the spherical harmonic (a rough equivalent wavelength is 40,000 km$/n$). Observations of tropospheric circulation show a kinetic energy spectrum with a broad peak around $n \sim 5$ and then a roughly n^{-3} regime out to $n \sim 80$. Most AGCMs are truncated within this n^{-3} regime, but observations show that past $n \sim 80$ (or horizontal wavelengths shorter than about 500 km) the kinetic energy spectrum becomes much shallower (e.g., Nastrom and Gage, 1985; Lindborg, 1999).

The simulated horizontal KE spectrum has been examined in a number of earlier studies using relatively modest horizontal resolution AGCMs (Boville, 1991; Koshyk et al., 1999). These studies showed that GCMs can reproduce a realistic n^{-3} regime in the troposphere but, due to the limited horizontal resolution, these models did not allow simulation of a significant range of the shallower mesoscale regime.

It appears that various current very high-resolution AGCMs perform rather differently in terms of their ability to simulate a realistically shallow mesoscale kinetic energy spectrum. Palmer (2001) notes that the ECMWF GCM, when run at fine resolution, actually simulates flow with a KE spectrum that steepens rather than shallows in the mesoscale. However, Koshyk and Hamilton (2001) found that the SKYHI AGCM can simulate a realistically energized mesoscale. In particular, they analyzed results from a control simulation with a $\sim$35 km horizontal resolution, 40-level version of the SKYHI model and found that their fields did reproduce the shallow horizontal KE spectra observed by Nastrom and Gage (1985) in the upper troposphere, down to the smallest model-resolved wavelength ($\sim$70 km). Recently Takahashi et al. (2006) analyzed results from T639 AFES model control simulations. With an appropriate choice of subgrid-scale mixing parameter the model can reproduce quite well the observed upper troposphere KE and APE spectra. The experiment was also repeated in a DDC version of the model. This version also simulated a shallow mesoscale range, supporting the view that the mesoscale regime in the atmosphere is energized, at least in part, by a predominantly downscale nonlinear spectral cascade.

Hayashi et al. (1997) examined the space–time structure of low-latitude precipitation in versions of a grid-point AGCM run with horizontal grid spacings of $\sim$50, $\sim$100, and $\sim$300 km. At the finer horizontal resolutions, grid-scale precipitation, which is thought to roughly represent the precipitation associated with cloud clusters, is organized into larger-scale superclusters. The westward propagation of cloud clusters and eastward propagation of superclusters is much more apparent in the high-resolution experiments. These basic conclusions are also found from the results of Yamada et al. (2005), who examined the space–time spectra of equatorial precipitation in versions of a global spectral AGCM with horizontal resolutions varying from T39 to T159 and L48 in the vertical. Yamada et al. considered a simplified "aquaplanet" case with all ocean surface and prescribed SSTs a function only of latitude. They found that as resolution is increased the eastward-propagating precipitation clusters and westward-propagating organizing structures become more clearly defined.

In addition to the analysis of overall energy content in mesoscale motions, there have been efforts aimed at characterizing the simulation of particular features in the circulation. One important challenge has been the simulation of the quasipermanent Baiu frontal zone that appears over East Asia and the far western Pacific region in the May–July period. This is a case where a reasonable simulation of local weather variability requires a good representation of the fairly narrow frontal zone and the mesoscale weather systems that disturb it. A number of studies have demonstrated the difficulty in simulating this feature realistically with moderate resolution global models (Yu et al., 2000; Zhou and Li, 2002; Kang et al., 2002). Kawatani and Takahashi (2003) had some success in Baiu front simulation with a T106 AGCM, but many more details of the front and typical disturbances were successfully captured by Ohfuchi et al. (2004) with their T1279L96 AGCM.

One aspect of mesoscale meteorology in global models that has attracted considerable attention is their ability to simulate tropical cyclones. The great practical interest in forecasting how global change may affect the climatology of tropical cyclone numbers, tracks and intensities is one of the main motivations for pursuing very fine resolution AGCM modeling. It has been known for some time that global AGCMs run in climate mode will spontaneously generate tropical depressions and tropical cyclones. Of course, mature intense tropical cyclones (hurricanes and typhoons) in the real world have rather small sizes (peak winds typically ∼50 km from the center) and cannot be adequately resolved except by a very fine scale model. However, the ability of AGCMs with various horizontal resolutions to simulate a somewhat realistic climatology of tropical cyclone occurrence and motion has been documented (e.g., Bengtsson et al., 1995; Tsutsui, 2002). While moderate resolution models may be able to reproduce some aspects of the observed tropical cyclone climatology, they are unable to simulate the most intense storms observed in the real atmosphere. For example, in multiyear control simulations using global models with ∼300 km grid spacing described by Broccoli and Manabe (1990) and Tsutsui (2002), the deepest central surface pressures in the tropical cyclones that develop are about 980 hPa. In a control simulation using a global model with ∼100 km effective grid spacing reported by Bengtsson et al. (1995) the most intense tropical cyclone appearing had a minimum central pressure of 953 hPa and peak surface winds of ∼45 m s^{-1}. Peak surface winds of somewhat less than ∼50 m s^{-1} are also apparent in the 10-year control run performed using a model with ∼100 km effective grid spacing described by Sugi et al. (2002). Hamilton and Hemler (1997) described results from a single season of control integration with a global grid-point atmospheric model with spacing about 35 km. They reported one Pacific typhoon with minimum pressure of 906 hPa and peak winds in the lowest model level ∼70 m s^{-1}, comparable to the strongest typhoon that might typically be observed in a given year, but still weaker than the strongest typhoon ever observed (Typhoon Tip in 1979 which had an estimated central pressure as low as 870 hPa according to Dunnavan and Dierks, 1980).

Ohfuchi et al. (2004) and Yoshioka et al. (2005) discuss some aspects of tropical cyclones seen in brief integrations of a T1279L96 AGCM. Ohfuchi et al. (2004) discuss the properties of four west Pacific typhoons in their simulation. Yoshioka et al. (2005) use the fine resolution simulation of intense tropical cyclones to examine the interaction between tropical cyclones and the diurnal cycle. A full global model is needed for first-principles simulation of the atmospheric tidal response to diurnal heating (e.g., Zwiers and Hamilton, 1986; Tokioka and Yagai, 1987) and very fine horizontal resolution is needed to provide a first-principles simulation of intense tropical cyclones, so only recently have models appropriate for study of this interaction been available.

Oouchi et al. (2006) examined the tropical cyclones simulated in 10 years of integration with a T959 AGCM using SSTs taken from the control run of a much lower version of the AGCM coupled to a fully interactive ocean. The model is able to generate a few tropical storms with maximum winds of nearly 50 m s^{-1}. Overall the number and distribution of tropical cyclone occurrences in the model simulation is reasonably realistic, although there is a significant underprediction (factor of ∼2) of the number of tropical cyclones in western North Pacific and an overprediction of the occurrence of South Indian Ocean tropical cyclones.

1.5 Changing Subgrid-Scale Parameterizations with Model Resolution

It is generally appreciated that the subgrid-scale parameterizations need to be adjusted as the explicit resolution of a model in changed. Overall, however, this is not an area that has been very deeply explored. One issue that has forced itself on the modeling community is the scaling of subgrid-scale horizontal mixing parameterizations with horizontal resolution. Smagorinsky (1963) proposed a second-order mixing parameterization in which the eddy diffusivity (and eddy viscosity) varied as the inverse square of the model horizontal grid spacing. In more recent times higher order hyperdiffusion (and hyperviscosity) formulations have generally been favored. For idealized one-layer quasigeostrophic models Yuan and Hamilton (1994) found that a simple scaling of the fourth-order (biharmonic) viscosity and diffusivity parameters with the fourth power of the grid spacing worked well (i.e., keeping the diffusion timescale of the smallest resolved scale constant), and led to simulations in which the horizontal variance spectra of the winds appeared consistent as model resolution is changed. However, when the same scaling was used in a one-layer primitive equation (shallow water) model the results were not satisfactory, in the sense that the horizontal variance spectra of the winds was not consistent as the model resolution was changed.

In many studies with full AGCMs the investigators seem to have chosen horizontal diffusivities in a somewhat arbitrary manner. Two studies that tried systematically to examine the dependence of the appropriate diffusivity as a function of resolution are those of Boville (1991) and Takahashi et al. (2006). Both studies used rather standard spectral AGCMs with fourth-order hyperdiffusivity and hyperviscosity parameterizations. Boville examined results with simulations performed at T21, T42, and T63 resolution, while Takahashi et al. considered simulations at T39, T79, T159, T319, and T639. In each a case the diffusivity parameter was adjusted by trial-and-error to produce results in which the end of the horizontal velocity variance spectra follows a power law and in which the spectra were consistent as the model resolution was changed. Both Boville and Takahashi et al. found that the diffusivity coefficient needs to be scaled at about the inverse third power of the spectral truncation (i.e., the diffusion timescale of the smallest resolved scale must drop with finer resolution).

While the need to change the horizontal subgrid-scale mixing parameterizations with model resolution is well appreciated and has attracted some systematic investigation, the comparable issue with vertical subgrid mixing has been less studied. Typically the vertical mixing in AGCMs depends on some measure of the vertical stability based on resolved vertical gradients of temperature (or virtual temperature) and horizontal wind, and most modelers have not seen any necessity to scale this with the vertical grid spacing. One exception is the work of Levy et al. (1982) who developed a scheme in which the mixing across numerical levels mixing depends on the resolved Richardson number in the expected manner, namely that the mixing becomes very strong rapidly as the Richardson number falls below some threshold. They note that in the real world subgrid-scale variability would introduce smaller scale variations in the Richardson number. Thus some mixing would be expected to occur even before the resolved-scale Richardson number appears to be unstable. Levy et al. noted that the modification to the Richardson number dependence to account for this effect should itself depend on the explicit vertical resolution, and they derive a proposed vertical resolution scaling of the Richardson number criterion, based on observations of typical vertical variability at small scales.

A particularly problematic issue in subgrid-scale parameterization is the treatment of moist convective processes. It is has been shown that the space–time variability of simulated precipitation in moderate-resolution AGCMs depends strongly on which parameterization scheme is used for moist convection (Ricciardulli and Garcia, 2000). One might naively expect that, as model resolution is made finer, the results obtained with different subgrid-scale schemes will converge and converge toward a realistic result. Unfortunately what evidence exists suggests that the differences in the behavior among convective parameterization schemes, and some unrealistic aspects of convective simulation, may actually be exacerbated at fine model resolution. Ricciardulli and Sardeshmukh (2002) find that the moist convective adjustment scheme employed in the $\sim$35 km grid version of the SKYHI model produced an unrealistically noisy tropical precipitation field. Enomoto et al. (2007) discuss results obtained with different schemes in the AFES with fine resolution. They note that for resolutions finer than about T639 the Arakawa–Schubert (Arakawa and Schubert, 1974) scheme behaves very unrealistically in that it produces very little convective rain, and the model nonconvective parameterization takes over the production of tropical rain. Enomoto et al. (2007) find a better behavior at fine resolution when employing a version of the Emanuel scheme (Emanuel and Zivkovic-Rothman, 1999). Of course, as grid spacing becomes smaller there are potential conceptual problems with at least some convective parameterizations as currently formulated. The parameterizations are generally regarded as describing the statistical effects of a collection individual convective updrafts and downdrafts assumed to occupy the grid box. As the box becomes smaller such a statistical treatment may not make sense. For example Enomoto et al. (2007) note that the Arakawa–Schubert scheme assumes that (at most) a small fraction of a grid-box is occupied by strong convective updrafts. This is a reasonable assumption for large grid-boxes, but Enomoto et al. question whether it is still appropriate for grid boxes of the order of 10 km horizontal dimension.

Yamada et al. (2005) examined the vertical resolution dependence of the tropical rainfall in their aquaplanet simulations. Interestingly, they find significant differences in the rainfall behavior even between two versions with modest horizontal (T39) and reasonably fine vertical resolution, L48 and L96. In particular, they find that the rainfall rates are typically weaker but more widespread in the L96 version, possibly because the fine resolution opens up additional possibilities for very thin convectively unstable regions to form.

As resolution is increased to a sufficiently fine degree it may be reasonable to expect models to explicitly resolve individual convective updrafts and downdrafts. Certainly there have been some impressive successes with such “cloud-resolving” or “cloud system resolving” limited area models (e.g., Randall et al., 2003a). Typically such models employ roughly 1 km grid spacing in the horizontal, or even finer resolution (Randall et al., 2003a). The very recent work by Tomita et al. (2005), mentioned earlier, showed that reasonable results for organized convection (in many respects, at least) can be obtained with a sufficiently fine resolution global nonhydrostatic model without any convective parameterization, just bulk microphysics parameterizations. Such a model would presumably have no need to change the cloud-related parameterizations with resolution.

Another approach to the sub-grid scale cloud problem is so-called superparameterization, in which limited area fine resolution models with bulk microphysics parameterizations are run embedded in each AGCM gird box. As noted by Randall et al. (2003b) one advantage of this approach is that no adjustment in the parameterization as a function of AGCM resolution should be needed, and that in the limit of very small AGCM grid spacing this model should seamlessly evolve into a global explicit cloud-resolving model. Of course, such a seamless evolution only occurs with particular formulations of the superparameterization. Notably it requires superparameterization schemes that fill each GCM grid box with a full 3D cloud-resolving model, rather than 2D arrays (which is the approach that actually has been applied most extensively so far).

1.6 Middle Atmosphere

While the simulated zonal-mean circulation in the troposphere is only moderately sensitive to the horizontal and vertical resolution employed, it appears that the zonal-mean simulation in the middle atmosphere can be much more sensitive to numerical resolution even as the resolution becomes quite fine. Mahlman and Umschied (1987) noted that the simulation of the basic extratropical stratospheric mean temperature and wind structure in the SKYHI improved dramatically as the latitude–longitude grid resolution was enhanced from $9° \times 10°$ to $5° \times 6°$, to $3° \times 3.6°$ and $1° \times 1.2°$. The high latitude winter stratospheric temperatures were much too cold in the low-resolution versions and this "cold pole bias" problem became less severe as resolution was improved. Jones et al. (1997) and Hamilton et al. (1999) show that this improvement continues even as the resolution is reduced to $0.33° \times 0.4°$. It seems that vertical eddy transports of zonal momentum by gravity waves drive a meridional circulation that warms the winter pole in the stratosphere and reduces the strength of the westerly polar night jet (e.g., Garcia and Boville, 1994; Hamilton, 1996). Coarse-resolution models are not able to explicitly resolve all the gravity waves that are important in the real world, and this leads to a winter cold pole bias, unless the model includes a parameterization of expected gravity wave effects on the mean flow. As the resolution is improved, more of the spectrum can be explicitly resolved and the drag on the mean flow, and consequent dynamical warming at high latitudes are larger (Hayashi et al., 1989; Hamilton et al., 1995, 1999). These issues in the winter polar stratosphere have a counterpart in the summer hemisphere, where the unrealistically weak eddy forcing of the mean upwelling circulation leads to a simulated polar mesopause that is too warm (Hamilton 1996; Hamilton et al., 1995, 1999).

In the tropical stratosphere it appears that the zonal-mean circulation is much less sensitive to changes in the horizontal resolution, but may depend critically on the vertical resolution employed. Historically most AGCMs have simulated winds in the tropical stratosphere that are much too steady, notably lacking the strong interannual quasibiennial oscillation (QBO). The first study to show that an AGCM could simulate a strong mean flow oscillation with the descending intense vertical shear zones that are a prominent feature of the observed QBO was that of Takahashi (1996). He took a standard T21 AGCM and reduced the vertical level spacing to about 500 m as well as reducing the subgrid-scale horizontal diffusivity. He found that an oscillation in the zonal-mean wind developed with a period of about 1.5 years. In the middle stratosphere the amplitude was comparable to that of the observed QBO, but the simulated amplitude was unrealistically weak in the lower stratosphere. Horinouchi and Yoden (1998) and Hamilton et al. (1999, 2001) found similar results, i.e., global AGCMs with fine enough vertical resolution, small enough subgrid-scale viscosity and enough resolved gravity wave flux in the tropics can produce large amplitude, low frequency mean flow oscillations in the tropical stratosphere that clearly resemble the QBO but may differ by having somewhat different periods or vertical structures (referred to now as QBO-like oscillations).

An example of how the mean flow structure in the tropical middle atmosphere changes with vertical resolution is provided by the case of the SKYHI model discussed in Hamilton et al. (2001). SKYHI when run with 40 vertical levels (L40) between the ground and the mesopause (this configuration has about 1.5 km level spacing in the lower-middle stratosphere) lacks any semblance of a QBO. The picture changes dramatically when the vertical resolution is increased to L80 or L160. In these higher-resolution versions of the model the mean flow in the stratosphere is dominated by downward propagating easterly and westerly wind regimes separated by intense shear zones in a QBO-like oscillation. In the stratosphere, the peak equatorial shears in the L40 simulation (run at about 100 km horizontal grid spacing) are $\sim 0.004\,\mathrm{s}^{-1}$. In the L160 simulation they are roughly five times as large ($\sim 0.02\,\mathrm{s}^{-1}$) and are comparable to those seen in monthly mean observations near the equator in the real stratosphere (e.g., Naujokat, 1986; Baldwin et al., 2001). The dramatic change with resolution is presumably related to the ability of fine vertical resolution models to more adequately represent the interaction of the mean flow with a broad spectrum of vertically propagating gravity waves. It is important to note that simply increasing vertical resolution does not seem to initiate QBO-like variability in the tropical stratosphere of all models, however (e.g., Boville and Randel, 1991; Hamilton and Yuan, 1992). Indeed Takahashi (1996) noted that his model produced a QBO-like oscillation only when a moist convective adjustment parameterization was employed. Apparently there needs to be enough resolved gravity wave momentum flux in the appropriate frequency and wavenumber ranges to actually generate the needed mean flow accelerations, and this is controlled to some degree by the convective parameterization employed in a given model.

None of the Takahashi (1996), Horinouchi and Yoden (1998), and Hamilton et al. (1999, 2001) models had a parameterization of nontopographic subgrid-scale gravity wave effects. The QBO has also been successfully simulated in AGCMs that do include a parameterization of the effects the nontopographic gravity waves that are thought to be important in the tropical stratosphere. For example Giorgetta et al. (2002) simulated a rather realistic mean flow QBO in a model that included a Doppler-spread parameterization of nonstationary gravity waves (Manzini et al., 1997). These authors find that their model with T42 horizontal resolution and roughly 500 m level spacing in the stratosphere did produce a nice QBO, but that the same model run with level spacings of more than 1 km did not. They found that in the version with the QBO, roughly half the forcing of mean flow accelerations came from resolved waves and half from parameterized waves (with the role of resolved waves being more important in the lowermost stratosphere).

All these studies have shown that the explicitly resolved upward gravity field emerging from the troposphere plays a critical role in the simulation even of the largest scale features of the middle atmospheric circulation. This raises the question of the validity of the gravity wave field simulation itself. A detailed comparison with observations is complicated by two problems. One is that no current instrument or analysis system can produce an instantaneous global picture of the flow on the horizontal scales of the relevant gravity waves (tens to hundreds of km). Comparisons can be made of statistics of gravity wave variances, covariances, etc. with single station observations (balloons, rockets, radars, lidars) or limited horizontal track data (from aircraft and space shuttle flights) or limited satellite swath data. Each technique has its own bias in terms of the part of the spectrum that can be efficiently detected. Unfortunately, as noted e.g., by Hamilton (1993), the most easily detected parts of the spectrum are the most energetic, which may not correspond to those with the largest eddy fluxes of momentum. Among the limited comparisons that have been published are those of variations in AGCMs with the (1) rocket soundings (Hamilton, 1989), (2) lidars (Hamilton, 1996), and (3) the Kyoto University MU radar (Sato et al., 1999). These comparisons have been fairly encouraging and suggest that current AGCMs with reasonably fine horizontal and vertical resolution may be able to reasonably simulate at least the most basic aspects of the observed gravity wave field in the middle atmosphere. Much more work on this issue needs to be performed, however.

1.7 Coupled Global Ocean–Atmosphere Model Simulations and Climate Sensitivity

How the resolution of global atmospheric AGCMs affects the simulation in coupled ocean–atmosphere global climate models is an issue of obvious importance for climate studies, but one that has thus far received only modest attention from researchers.

Emanuel (2001) noted that tropical cyclones induce strong vertical mixing within the upper ocean, leaving cold wakes that are restored to normal conditions to a large extent by surface fluxes from the atmosphere. This restoration is associated with net heating of the ocean column, which is balanced by oceanic heat transport out of the regions affected by the storms. The power input into the ocean from wind (which determines the strength of the vertical ocean mixing) varies as the cube of the surface wind speed. Thus the effects of very intense storms are particularly pronounced. As noted above, the intensity of the strongest storms simulated by AGCMs is a strong function of horizontal resolution, at least down to $\sim$10 km grid spacing. So if the effect Emanuel identifies is significant for the global heat budget, then we should anticipate systematic biases in the simulated climate in a coupled model without extremely fine resolution.

Gualdi et al. (2005) performed a series of 6-month ensemble forecasts using the 19-level ECHAM4 AGCM coupled to a global ocean model, with a focus on the accuracy of forecasts of the development of the El Nino/Southern Oscillation (ENSO) phenomenon in the tropical Pacific. Many of the forecasts were repeated with both T42 and T106 versions of the ECHAM4 atmospheric component, with everything else (initial conditions, ocean model resolution, atmospheric vertical resolution) kept the same. The differences in the forecasts were considerable, particularly for the growing phase of El Nino or La Nina events. At T42 resolution the initial perturbation of the coupled system decays quickly, while the T106 model can sustain the growth of disturbances, leading to significant improvement in the forecasts.

A key application of coupled climate models is to determine the response of climate to imposed natural or anthropogenic perturbations, such as increasing concentrations of greenhouse gases. In an early study Senior (1995) examined the role of model horizontal resolution in determining the equilibrium response to a doubling of atmospheric carbon dioxide content in an AGCM coupled to a mixed layer ocean model. He found nearly identical global mean surface warming in versions of the model with roughly 500 and 250 km horizontal grid spacings. However, the latitudinal variation of warming was somewhat different, with the lower-resolution version displaying a greater intensification of the warming at high latitudes. Senior attributed this difference to the much more realistic representation of storm tracks in the higher-resolution version, which allows the eddy fluxes to respond more effectively to the reduced equator-pole temperature gradient.

The sensitivity of a model climate to large-scale perturbations is determined by the strengths of various feedback processes in the model. It is fairly clear now that the important feedback that is most uncertain in current models is the cloud feedback, particularly in the tropics and subtropics (Cess et al., 1990; Stowasser et al., 2006). Among current global models even the sign of this feedback is not consistent, and this uncertainty leads to a variation in simulated sensitivity of the global mean surface temperature of a factor of 2–3 (e.g., Stowasser et al., 2006). An interesting question is how the simulated cloud feedbacks depend on model resolution. Stowasser and Hamilton (2006) examined a related issue, namely how the simulated monthly mean cloud fields in the tropics and subtropics vary in relation to the interannual fluctuations of the large-scale circulation. In particular, they examined the connection between cloud forcing and monthly mean meteorological fields in a large number of the global coupled climate models included in the preparation of the IPCC Fourth Assessment Report. They found a very wide range of results for the various models. It was interesting that no systematic variation in the results as a function of the spatial resolution of the models was apparent. In fact, Stowasser and Hamilton (2006) examined results from two versions of the Japanese MIROC (Model for Interdisciplinary Research on Climate) model, one run at T42L20 and the other at T106L56, and the results were very similar. The implication seems to be that, at least in the range of resolutions considered, the cloud and convection parameterizations are much more important than the numerical resolution in determining how the cloud feedbacks are simulated in a global model.

Ingram (2002) investigated the water vapor feedback operating in climate change experiments in several versions of an AGCM with widely different vertical model resolutions. He found that the feedbacks were insensitive to the vertical resolution once some modest threshold was passed (i.e., results were very similar for models with 19, 38 and 100 total model levels).

1.8 Summary

A numerical AGCM is a finite numerical approximation to the continuous differential equations governing atmospheric circulation. With current resources it is generally not possible to show that our AGCM solutions have completely converged, and at least modest changes in the statistical properties AGCM simulated circulation seem to occur with improving horizontal and vertical resolution. One issue that has been fairly extensively addressed is the dependence of the zonal-mean climatological circulation on the horizontal grid spacing or (for spectral models) horizontal wavenumber truncation. For the troposphere it seems that such changes are quite important up to about T42, and still significant, if more modest, at higher resolutions. For the stratosphere and mesosphere it appears that model results for the zonal-mean simulation may depend more dramatically on the resolution. In particular, the overall structure of the extratropical middle atmosphere in coarse or moderate resolution AGCMs tends to be unrealistically close to radiative equilibrium (too cold in the high latitude winter and too warm in the high latitude summer), and this problem is progressively alleviated as horizontal resolution is improved.

Zonal-mean tropospheric simulations appear not to be strongly dependent on vertical resolution, but the zonal-mean circulation in the tropical stratosphere, in some models at least, has a very strong dependence on vertical resolution. With vertical level spacings of $\sim$1 km or more in the stratosphere it appears that most (perhaps all) AGCMs will simulate nearly steady prevailing winds in the tropical stratosphere, a very unrealistic representation of the most basic aspect of the general circulation in this region of the atmosphere. When model vertical grid spacing is reduced to about

0.5 km or finer, some models display strong interannual oscillations of the zonal-mean wind in the tropical stratosphere with the alternating downward-propagating shear zones that are well-known features of the observed QBO.

In the last few years there has been considerable development in high-performance computing facilities available for atmospheric simulation, notably with the 2002 inauguration of the Earth Simulator in Japan. This has made possible global atmospheric simulations at unprecedented fine resolution. This raises issues of evaluation of the very complex and detailed simulations that result. It has been shown that at least some fine resolution models simulate a flow with realistic horizontal energy spectra. A number of studies have examined the tropical cyclone simulations within global models. These show that even modest resolution models can spontaneously simulate a climatology with a reasonable number of tropical cyclones, but that simulation of storm intensity become much more realistic as model horizontal resolution is improved.

It is understood that the model simulations will have deficiencies simply associated with the fact that components of the real circulation will not be explicitly resolved in the finite numerical approximation employed. As explicit model resolution is changed, the parameterizations used to incorporate subgrid-scale effects must also be modified. For example it is known that subgrid-scale diffusivity and viscosity coefficients must be lowered as horizontal resolution is improved. Presumably some similar scaling should apply to vertical subgrid-scale mixing, but little work on this problem seems to have been published. The effects of resolution on the performance of moist convection parameterizations are a complicated issue, and at least some published studies suggest that the performance of models with state-of-the-art convection schemes may not converge toward realistic results.

Experience with limited-area models suggests that model performance may pass a threshold when horizontal grid spacings are reduced to $\sim$1 km or less. At this point the explicit dynamics along with a bulk microphysics parameterization may realistically represent many features of moist convection and clouds. Recent work with the NICAM global model run on the Earth Simulator has approached within a factor of 3 of this hypothesized horizontal resolution threshold, and initial results are encouraging that such global models can simulate realistic mesoscale organization of cloud-scale features.

Acknowledgments This work was supported by NSF Award ATM02-19120 and by JAMSTEC through its sponsorship of the International Pacific Research Center.

References

Arakawa, A. and W.H. Schubert, 1974: Interaction of cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.*, **31**, 671–701.

Baldwin, M., L. Gray, T. Dunkerton, K. Hamilton, P. Haynes, W. Randel, J. Holton, M. Alexander, I. Hirota, T. Horinouchi, D. Jones, J. Kinnersley, C. Marquardt, K. Sato and M. Takahashi, 2001: The Quasi-biennial Oscillation. *Rev. Geophys.*, **39**, 179–229.

Bengtsson, L., M. Botzet and M. Esh, 1995: Simulation of hurricane-type vortices in a general circulation model. *Tellus*, **47A**, 175–196.
Boer, G.J. and B. Denis, 1997: Numerical convergence of the dynamics of a GCM. *Clim. Dyn.*, **13**, 359–374.
Boer, G.J. and M. Lazare, 1988: Some results concerning the effect of horizontal resolution and gravity-wave drag on simulated climate. *J. Clim.*, **1**, 789–806.
Boer, G.J. and T.G. Shepherd, 1983: Large-scale two-dimensional turbulence in the atmosphere. *J. Atmos. Sci.*, **40**, 164–184.
Boville, B.A., 1991: Sensitivity of simulated climate to model resolution. *J. Clim.*, **4**, 469–485.
Boville, B.A. and W.J. Randel, 1991: Equatorial waves in a stratospheric GCM: Effects of vertical resolution. *J. Atmos. Sci.*, **49**, 785–801.
Boyle, J.S., 1993: Sensitivity of dynamical quantities to horizontal resolution for a climate simulation using the ECMWF (cycle 33) model. *J. Clim.*, **6**, 796–815.
Broccoli, A. and S. Manabe, 1990: Can existing climate models be used to study anthropogenic changes in tropical cyclone climate. *Geophys. Res. Lett.*, **17**, 1917–1920.
Cess, R.D. et al., 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models.*J. Geophys. Res.*, **95**, 16601–16615.
Conaty, A.L., J.C. Jusem, L. Takacs, D. Keyser and R. Atlas, 2001: The structure and evolution of extratropical cyclones, fronts, jet streams, and the tropopause in the GEOS General Circulation Model. *Bull. Am. Meteor. Soc.*, **82**, 1853–1867.
Dunnavan, G.M. and J.W. Dierks, 1980: An analysis of Supertyphoon Tip (October 1979). *Mon. Weather Rev.*, **108**, 1915–1923.
Emanuel, K., 2001: Contribution of tropical cyclones to meridional heat transport by the oceans, *J. Geophys. Res.*, **106**, 14771–14782, doi:10.1029/2000JD900641.
Emanuel, K. and M. Zivkovic-Rothman, 1999: Development and evaluation of a convective scheme for use in climate models. *J. Atmos. Sci.*, **56**, 1766–1782.
Enomoto, T., A. Kuwano-Yoshida, N. Komori and W. Ohfuchi, 2007: Description of AFES 2: Improvements of high-resolution and coupled simulations. *High Resolution Numerical Modelling of the Atmosphere and Ocean*, (W. Ohfuchi and K. Hamilton, eds.), Springer Publications, Chapter 5.
Garcia, R.R. and B.A. Boville, 1994: "Downward control" of the mean meridional circulation and temperature distribution of the polar winter stratosphere. *J. Atmos. Sci.*, **51**, 2238–2245.
Giorgetta M.A., E. Manzini and E. Roeckner, 2002: Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves. *Geophys. Res. Lett.*, **29**, 1245, doi:10.1029/2002GL014756.
Griffies, S.M. and R.W. Hallberg, 2000: Biharmonic friction with a Smagorinsky-like viscosity for use in large-scale eddy-permitting ocean models. *Mon. Weather Rev.*, **128**, 2935–2946.
Gualdi, S., A. Alessandri and A. Navarra, 2005: Impact of atmospheric horizontal resolution on El Nino/Southern Oscillation forecasts. *Tellus*, **57A**, 357–374.
Hamilton, K., 1989: Evaluation of the gravity wave field in the middle atmosphere of the GFDL "SKYHI" general circulation model. *World Meteorological Organization Technical Document #273*, pp. 264–271.
Hamilton, K, 1993: What we can learn from general circulation models about the spectrum of middle atmospheric motions. *Coupling Processes in the Lower and Middle Atmosphere* (E. Thrane, T. Blix and D. Fritts, eds.), Kluwer Academic Publishers, pp. 161–174.
Hamilton, K., 1996: Comprehensive meteorological modelling of the middle atmosphere: A tutorial review. *J. Atmos. Terr. Phys.*, **58**, 1591–1628.
Hamilton, K. and R.S. Hemler, 1997: Appearance of a super-typhoon in a global climate model simulation. *Bull. Am. Meteor. Soc.*, **78**, 2874–2876.
Hamilton, K. and L. Yuan, 1992: Experiments on tropical stratospheric mean wind variations in a spectral general circulation model. *J. Atmos. Sci*, **49**, 2464–2483.
Hamilton, K., R.J. Wilson, J.D. Mahlman and L.J. Umscheid, 1995: Climatology of the SKYHI troposphere–stratosphere–mesosphere General Circulation Model. *J. Atmos. Sci.*, **52**, 5–43.
Hamilton, K., R.J. Wilson and R.S. Hemler, 1999: Middle atmosphere simulated with high vertical and horizontal resolution versions of a GCM: Improvement in the cold pole bias and generation of a QBO-like oscillation in the tropics. *J. Atmos. Sci.*, **56**, 3829–3846.

Hamilton, K., R.J. Wilson and R.S. Hemler. 2001: Spontaneous stratospheric QBO-like oscillations simulated by the GFDL SKYHI General Circulation Model. *J. Atmos. Sci.*, **58**, 3271–3292.
Hayashi, Y., D. G. Golder, J. D. Mahlman and S. Miyahara, 1989: The effect of horizontal resolution on gravity waves simulated by the GFDL "SKYHI" general circulation model. *Pure Appl. Geophys.*, **130**, 421–443.
Hayashi, Y., D.G. Golder and P.W. Jones, 1997: Tropical gravity waves and superclusters simulated by high-horizontal-resolution SKYHI general circulation models. *J. Meteor. Soc. Jpn.*, **75**, 1125–1139.
Held, I.M. and M.J. Suarez, 1994: A proposal for the intercomparison of the dynamical cores of atmospheric General Circulation Models. *Bull. Am. Meter. Soc.*, **75**, 1825–1830.
Horinouchi T. and S. Yoden, 1998: Wave-mean flow interaction associated with a QBO-like oscillation simulated in a simplified GCM. *J. Atmos. Sci.*, **55**, 502–526.
Ingram, W.J., 2002: On the robustness of the water vapor feedback: GCM vertical resolution and formulation. *J. Clim.*, **15**, 917–921.
Inness, P.M., J.M. Slingo, S.J. Woolnough, R.B. Neale and V.D. Pope, 2001: Organization of tropical convection in a GCM with varying vertical resolution; implications for the simulation of the Madden–Julian Oscillation. *Clim. Dyn.*, **17**, 777–793.
Janjic, Z.I., J.P. Gerrity Jr., and S. Nickovic, 2001: An alternative approach to nonhydrostatic modeling. *Mon. Weather Rev.*, **129**, 1164–1178.
Jones, P.W., K. Hamilton and R.J. Wilson, 1997: A very high-resolution general circulation model simulation of the global circulation in austral winter. *J. Atmos. Sci.*, **54**, 1107–1116.
Kang, I.-S., K. Jin, B. Wang, K.-M. Lau, J. Shukla, V. Krishnamurthy, S. Schubert, D. Wailser, W. Stern, A. Kitoh, G. Meehl, M. Kanamitsu, V. Galin, V. Satyan, C.-K. Park, and Y. Liu., 2002: Intercomparison of the climatological variations of Asian summer monsoon precipitation simulated by 10 GCMs. *Clim. Dyn.*, **19**, 383–395.
Kawatani, Y. and M. Takahashi, 2003: Simulation of the Baiu front in a high-resolution AGCM. *J. Meteor. Soc. Jpn.*, **81**, 113–126.
Kobayashi C. and M. Sugi, 2004: Impact of horizontal resolution on the simulation of the Asian summer monsoon and tropical cyclones in the JMA global model. *Clim. Dyn.*, **23**, 165–176.
Koshyk, J.N. and K. Hamilton, 2001: The horizontal kinetic energy spectrum and spectral budget simulated by a high-resolution troposphere–stratosphere–mesosphere GCM. *J. Atmos. Sci.*, **58**, 329–348.
Koshyk, J.N., B.A. Boville, K. Hamilton, E. Manzini and K. Shibata, 1999: The kinetic energy spectrum of horizontal motions in middle atmosphere models. *J. Geophys. Res.*, **104**, 27177–27190.
Lander, J. and B.J. Hoskins, 1997: Believable scales and parameterizations in a spectral model. *Mon. Weather Rev.*, **125**, 292–303.
Levy, H., J.D. Mahlman and W.J. Moxim, 1982: Tropospheric N2O variability. *J. Geophys. Res.*, **87**, 3061–3080.
Lindborg, E., 1999: Can the atmospheric kinetic energy spectrum be explained by two-dimensional turbulence? *J. Fluid Mech.*, **388**, 259–288.
Lindzen, R.S. and M. Fox-Rabinovitz, 1989: Consistent vertical and horizontal resolution. *Mon. Weather Rev.*, **117**, 2575–2583.
Mahlman, J.D. and L.J. Umscheid, 1987: Comprehensive modeling of the middle atmosphere: The influence of horizontal resolution. *Transport Processes in the Middle Atmosphere* (G. Visconti and R. Garcia, eds.), Reidel Publishing, pp. 251–266.
Manabe, S., J. Smagorinsky and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Weather Rev.*, **93**, 769–798.
Manzini, E., N.A. McFarlane and C. McLandress, 1997: Impact of the Doppler spread parameterization on the simulation of the middle atmosphere circulation using the MA/ECHAM4 general circulation model. *J. Geophys. Res.*, **102**, 25751–25762.
Mizuta, R., T. Uchiyama, K. Kamiguchi, A. Kitoh and A. Noda, 2005: Changes in extremes indices over Japan due to global warming projected by a global 20-km-mesh atmospheric model. *SOLA*, **1**, 153–156.

Mullen, S.L. and R. Buizza, 2002: The impact of horizontal resolution and ensemble size on probabilistic forecasts of precipitation by the ECMWF Ensemble Prediction System. *Weather Forecast.*, **17**, 173–191.

Nastrom, G.D. and K.S. Gage, 1985: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft. *J. Atmos. Sci.*, **42**, 950–960.

Naujokat, B., 1986: An update of the observed Quasi-Biennial Oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci.*, **43**, 1873–1877.

Ohfuchi, W., H. Nakamura, M.K. Yoshioka, T. Enomoto, K. Takaya, X. Peng, S. Yamane, T. Nishimura, Y. Kurihara, and K. Ninomiya, 2004: 10-km mesh meso-scale resolving simulations of the global atmosphere on the earth simulator – preliminary outcomes of AFES (AGCM for the Earth Simulator). *J. Earth Simulator*, **1**, 8–34.

Ohfuchi, W., H. Sasaki, Y. Masumoto and H. Nakamura, 2005: Mesoscale-resolving simulations of the global atmosphere and ocean on the Earth Simulator. *Eos*, 86, 45–46.

Oouchi, K., J. Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki and A. Noda, 2006: Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analyses. *J. Meteor. Soc. Jpn.*, **84**, 259–276.

Orlanski, I. and C. Kerr, 2007: Project TERRA: A glimpse into the future of weather and climate. *High Resolution Numerical Modelling of the Atmosphere and Ocean*, (W. Ohfuchi and K. Hamilton, eds.), Springer Publications, Chapter 3.

Palmer, T.N., 2001: A nonlinear dynamical perspective on model error: A proposal for non-local stochastic-dynamic parameterization in weather and climate prediction models. *Q. J. R. Meteor. Soc.*, **127**, 279–304.

Pope, V. and R. Stratton, 2002: The processes governing horizontal resolution sensitivity in a climate model. *Clim. Dyn.*, **19**, 211–236.

Randall, D., S. Krueger, C. Bretherton, J. Curry, P. Duynkerke, M. Moncrieff, B. Ryan, D. Starr, M. Miller, W. Rossow, G. Tselioudis and B. Wielicki, 2003a: Confronting models with data: The GEWEX Cloud Systems Study. *Bull. Am. Meter. Soc.*, **84**, 455–469.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003b: Breaking the cloud parameterization deadlock. *Bull Amer Met Soc.*, **84**, 1547–1564.

Ricciardulli, L. and R.R. Garcia, 2000: The excitation of equatorial waves by deep convection in the NCAR Community Climate Model (CCM3). *J. Atmos. Sci.*, **57**, 3461–3487.

Ricciardulli, L. and P.D. Sardeshmukh, 2002: Local time- and space scales of organized tropical deep convection. *J. Atmos. Sci.*, **59**, 2775–2790.

Roebber, P.J., D.M. Schultz, B.A. Colle and D.J. Stensrud, 2004: Towards improved prediction: High-resolution and ensemble modeling systems in operations. *Wea. Forecasting*, **19**, 936–949.

Roeckner, E., R. Brokopf, M. Esch, M. Giorgetta, S. Hagemann, L. Kornblueh, E. Manzini, U. Schlese and U. Schulzweida, 2006: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. *J. Clim.*, **19**, 3771–3791.

Sato, K., T. Kumakura and M. Takahashi. 1999: Gravity waves appearing in a high-resolution GCM simulation. *J. Atmos. Sci.*, **56**, 1005–1018.

Senior, C.A., 1995: The dependence of climate sensitivity on the horizontal resolution of a GCM. *J. Clim.*, **8**, 2860–2880.

Shen, B.-W., R. Atlas, J.-D. Chern, O. Reale, S.-J. Lin, T. Lee and J. Chang, 2006: The 0.125 degree finite-volume general circulation model on the NASA Columbia supercomputer: Preliminary simulations of mesoscale vortices. *Geophys. Res. Lett.*, **33**, doi:10.1029/2005GL024594.

Smagorinsky, J., 1963: General circulation experiments with the primitive equations. I. The basic experiment. *Mon. Weather Rev.*, **91**, 99–164.

Sperber, K.R., S. Hameed, G.L. Potter and J.S. Boyle, 1994: Simulation of the northern summer monsoon in the ECMWF model: sensitivity of horizontal resolution. *Mon. Weather Rev.*, **122**, 2461–2481.

Stevenson, D.B., F. Chauvin and J.-F. Royer, 1998: Simulation of the Asian summer monsoon and its dependence on model horizontal resolution. *J. Meteor. Soc. Jpn.*, **76**, 237–265.

Stowasser, M. and K. Hamilton, 2006: Relationships between cloud radiative forcing and local meteorological variables compared in observations and several global climate models. *J. Clim.*, **19**, 4344–4359.

Stowasser, M., K. Hamilton and G.J. Boer, 2006: Local and global climate feedbacks in models with differing climate sensitivities. *J. Clim.*, **19**, 193–209.

Sugi, M., A. Noda and N. Sato, 2002: Influence of global warming on tropical cyclone climatology: An experiment with the JMA global model. *J. Meteor. Soc. Japan*, **80**, 249–272.

Takahashi, M., 1996: Simulation of the stratospheric quasi-biennial oscillation using a general circulation model. *Geophys. Res. Lett.*, **23**, 661–664.

Takahashi, Y.O., K. Hamilton and W. Ohfuchi, 2006: Explicit global simulation of the mesoscale spectrum of atmospheric motions. *Geophys. Res. Lett.*, **33**, L12812, doi:10.1029/2006GL026429.

Tokioka, T. and I. Yagai, 1987: Atmospheric tides appearing in a global atmospheric general circulation model. *J. Meteor. Soc. Japan*, **65**, 423–438.

Tomita, H., H. Miura, S. Iga, T. Nasuno and M. Satoh, 2005: A global cloud-resolving simulation: Preliminary results from an aqua-planet experiment, *Geophys. Res. Lett.*, **32**, L08805, doi:10.1029/2005GL022459.

Tompkins, A.M and K.A. Emanuel, 2000: The vertical resolution sensitivity of simulated equilibrium tropical temperature and water vapour profiles. *Q. J. R. Meteor. Soc.*, **126**, 1219–1238.

Tsutsui, J., 2002: Implications of anthropogenic climate change for tropcial cyclone activity. A case study with the NCAR CCM2. *J. Meteor. Soc. Japan*, **80**, 45–65.

Williamson, D.L., 1999: Convergence of atmospheric simulations with increasing horizontal resolution and fixed forcing scales. *Tellus*, **51A**, 663–673.

Yamada, Y., T. Sampe, Y.O. Takahashi, M.K. Yoshioka, W. Ohfuchi, M. Ishiwatari, K. Nakajima and Y.-Y. HayashiI, 2005: A resolution dependence of equatorial precipitation activities represented in a general circulation model. *Theor. Appl. Mech. Jpn.*, **54**, 289–297.

Yoshioka, M.K., Y. Kurihara and W. Ohfuchi, 2005: Effect of the thermal tidal oscillation of the atmosphere on tropical cyclones. *Geophys. Res. Lett.*, **32**, L16802, doi:10.1029/2005GL022716.

Yu, R.C., W. Li, X. Zhang, Y.M. Liu, Y.Q. Yu, H.L. Liu and T.J. Zhou., 2000: Climatic features related to eastern China summer rainfalls in the NCAR CCM3. *Adv. Atmos. Sci.*, **17**, 503–518.

Yuan, L. and K. Hamilton, 1994: Equilibrium dynamics in a forced-dissipative f-plane shallow water model. *J. Fluid Mech.*, **280**, 369–394.

Zhou, T.J. and Z.X. Li, 2002: Simulation of the east Asian summer monsoon by using a variable resolution atmospheric GCM. *Clim. Dyn.*, **19**, 167–180.

Zwiers, F. and K. Hamilton, 1986: The Simulation of atmospheric tides in the Canadian Climate Centre general circulation model. *J. Geophys. Res.*, **91**, 11877–11898.