High Resolution Numerical Modelling of the Atmosphere and Ocean

Kevin Hamilton · Wataru Ohfuchi
Editors

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Springer

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Introduction

Numerical simulation models of atmospheric and oceanic circulation are simply finite numerical approximations to the continuous governing differential equations. In many branches of applied mathematics, researchers will routinely show that their finite numerical solutions to a particular problem have converged with increasing resolution. In the study of atmospheric and oceanic circulation one rarely has the luxury of such straightforward demonstrations of convergence. The standard practice for attacking difficult problems has been to truncate the model employed at some finite horizontal, vertical, and time resolution, and perform time integrations for a specified period. In operational forecast applications the final state is the prediction, which will eventually be verified against simultaneous observations. In climate applications typically the statistical properties of the flow over the period simulated are analyzed. In either case, it is understood that the model integrations will have deficiencies simply associated with the fact that significant aspects of the real circulation will be unresolved in the finite numerical approximation employed.

Much effort has been expended on parameterizing the effects of subgrid-scale motions on the larger-scale flow, but it has also been a goal of researchers to explicitly resolve as many scales of the actual circulation as possible. For example, in studies of the global ocean circulation, a long-standing concern has been the issue of adequately resolving eddies that have horizontal scales of the order of the Rossby radius (the oceanic analogues of synoptic scale waves in the midlatitude atmosphere). In global and regional atmospheric models, a key issue has been resolving the mesoscale circulations that organize moist convection. With the recent advent of a new generation of high-performance computing systems such as the Earth Simulator, some notable thresholds in terms of model resolution have been approached or, in some cases, surpassed. For example, very recently the first long integrations with genuinely eddy-resolving, or at least eddy-permitting, global ocean models have been reported. On the atmospheric side, decadal integrations using global models with effective horizontal resolution of $\sim$20 km have now become possible, and very short integrations of models that explicitly resolve scales approaching those of individual convective elements have just been reported. These developments in global models have been paralleled by rising research activity with increasingly fine resolution regional atmospheric models for both climate and short-range forecasting applications. It is thus an opportune time to review progress in the field and consider outstanding issues and the prospects for further advances.

An international workshop to address issues in high-resolution modeling was held on September 21–22, 2005 at the home of the Earth Simulator supercomputer, the JAMSTEC (Japan Agency for Marine–Earth Science and Technology) Yokohama Institute for Earth Sciences. Twenty-two speakers were invited from Australia, Canada, Japan, the UK and the USA, and more than 60 scientists attended the workshop. Following the workshop the speakers and some other selected colleagues were invited to submit papers related to the topic of high-resolution modeling of the atmosphere and ocean (but not limited to the material discussed in the workshop) to the present volume. The papers submitted spanned a variety of topics and described ocean, atmosphere, and coupled models with both global and regional domains.

The first group of papers in this volume relate to various aspects of high-resolution global atmospheric modeling. First, Hamilton reviews previous results concerning the dependence of atmospheric simulation on the horizontal and vertical resolution employed. He notes that even the very large-scale aspects of the simulated flow have not necessarily completely converged even at horizontal resolutions of approximately tens of kilometers, both in the troposphere and, more particularly, in the middle atmosphere. Encouragingly, some recent high-resolution simulations have successfully represented many observed features in the mesoscale circulation and, importantly, a realistic overall energy level of mesoscale motions. Hamilton notes some critical open questions relating to the appropriate scaling of physical subgrid scale parameterizations with the model numerical truncation.

Orlanski discusses the relevance of fine numerical resolution to simulation of large-scale atmospheric dynamics. He particularly concentrates on simulation of the extratropical circulation and points out the critical importance of adequately representing the interaction of the mesoscale and synoptic scales. In a companion paper, Orlanski and Kerr discuss results of a brief (24 h) experimental integration of a global version of the Geophysical Fluid Dynamics Laboratory nonhydrostatic zeta-coordinate model.

McGregor and Dix report recent technical improvements to, and simulations with, the finite difference Conformal-Cubic Atmospheric Model (CCAM) that has been developed at the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO). Developing such a model may provide one approach for ultra-high-resolution models to avoid the high computational cost of Legendre transforms used in conventional spectral atmospheric general circulation models (AGCMs), and also to avoid the singularity at the poles in conventional latitude–longitude finite difference AGCMs. McGregor and Dix describe in detail technical aspects, such as the implementation of the semi-Lagrangian scheme and grid decomposition for parallel computing, and they show results from idealized and realistic simulations with CCAM.

Enomoto et al. describe the second generation of the AFES (AGCM for the Earth Simulator) global atmospheric model. The first version of the AFES has been applied in a number of published studies in configurations with resolution up to T1279L96 (i.e., triangular truncation at total spherical wavenumber 1,279, and 96 levels in the vertical). The new version differs from the original AFES notably in incorporating upgrades to the radiation scheme, the convective scheme and the cloud scheme. Enomoto et al. show the effects these changes make on the long-term climate simulated by T79L48 versions of the model. They also include a discussion of the technicalities involved in the calculation of accurate Legendre transforms at very high order. They note that previous methods of this calculation become problematical at about T1800 and higher truncation limits, and they advance their own solution to this problem which may allow the standard pseudospectral models to be efficiently extended to very high truncation limits.

Satoh et al. discuss results of brief integration of a global atmospheric model with 3.5 km horizontal resolution. This study employed the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) that was developed mainly at the Frontier Research Center for Global Change (FRCGC) of JAMSTEC specifically for such ultra-fine-resolution global simulations. The model is run without a convective parameterization and the main focus in the initial analysis of the results is in seeing how the model flow interacts with, and acts to organize, tropical convection. Results are compared with high spatial resolution rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) satellite.

One of main goals for the Earth Simulator was to provide sufficient computing resources to allow projections of future global warming that might represent a qualitative improvement over other current forecasts in the explicit representation of key processes. Noda et al. give a summary of their recent studies of twenty-first century global warming using time-slice experiments with a 20-km mesh AGCM. With this ultrahigh resolution, they can reasonably simulate some mesoscale phenomena, such as tropical cyclones (TCs) and the Baiu front, though their model employs the hydrostatic approximation and cumulus convection parameterization. They obtained the difference in sea surface temperatures (SST) between 1979–1998 and 2080–2099 from a warming projection performed using with the Japan Meteorological Agency Meteorological Research Institute coupled GCM with a much coarser horizontal resolution. The ultrahigh resolution present-day time slice was run for a decade with observed SST averaged from 1982 to 1993. Then the warmed time slice was run for a decade with the SST used for the present-day run superimposed with the SST difference described above. Noda et al. report that in the warmed climate the number of TCs decreases but their intensity increases. Also the Baiu front lasts longer and the strength of the mesoscale disturbances associated with this front intensify in the twenty-first century integration.

The next group of papers discusses limited-area high-resolution atmospheric models. Yoshizaki et al. apply regional nonhydrostatic models (NHMs) on the Earth Simulator for both weather forecast-type and climate change-type simulations. For the former, they use an NHM with horizontal resolution of 1 km (2,000 × 2,000 grid points) and 38 vertical levels, covering the Sea of Japan. This short-term simulation reproduces the detailed structures of the Japan Sea polar air mass convergence zone. For the climate change application, Yoshizaki et al. use an NHM with horizontal resolution of 5 km (800 × 600 grid points) and with 48 vertical levels, covering the Japan area. They utilize the result from time-slice global warming projection reported in the above Noda et al. paper by employing a spectral boundary coupling method. June and July cases are simulated for both present-day and globally warmed conditions. Yoshizaki et al. conclude that in the warmed climate the activity of Baiu front will increase over southern Japan and the frequency of heavy rainfall will generally increase over all of Japan.

Tsuboki gives a brief description of a nonhydrostatic regional atmospheric model, CReSS (Cloud Resolving Storm Simulator), developed by his group at Nagoya University, and discusses results of some simulations. CReSS has been optimized for the Earth Simulator and now is capable of large-scale simulations. Tsuboki concentrates on short-term (typically a day or so) simulations of high-impact weather events, such as localized heavy rainfalls, tropical cyclones, and snowstorms, using resolutions of 300–1,000 m (typically of order of 1,500 × 1,500 grid points) and 50–400 m (∼40–70 vertical levels) in horizontal and vertical directions, respectively. These high-impact weather systems have hierarchical structures from about 100–1,000 km for the whole system down to about 1–10 km. Tsuboki demonstrates the capability of CReSS to simulate the multiscale structures.

While it is easy to see small features of the real atmospheric circulation in satellite and radar imagery, it is very difficult to observe detailed features of the ocean interior because electromagnetic waves do not propagate efficiently in sea water. Thus there may be a particular need for models that can credibly simulate the small-scale features of the ocean circulation. The next four papers discuss fine structures of the ocean currents simulated by ocean models. Sasaki et al. discuss results obtained with the OFES (Ocean GCM for the Earth Simulator), an ocean model specifically developed to run efficiently on the Earth Simulator. They show results from a hindcast experiment forced by daily atmospheric reanalysis data covering the second half of the twentieth century. The domain is quasi-global, from 75° S to 75° N, and this version is run with horizontal resolution of 0.1° and with 54 vertical levels. This experiment was designed to see how well the observed oceanic circulation variations from intraseasonal to decadal timescales are reproduced in a model with realistic time-varying forcing. The analysis considers the simulation of El Niño and the Indian Ocean Dipole events, the Pacific and the Pan-Atlantic Decadal Oscillations, and the intraseasonal variations in the equatorial Pacific and Indian Oceans, among other phenomena. Comparisons are made with an earlier experiment in which the same model was forced with climatological (but still seasonally varying) atmospheric forcing.

Richards et al. report on the spatial and temporal structures of jets and waves simulated in the ocean interior of fine resolution global ocean models. These jets have elongated structures in the longitudinal direction, but a rather small latitudinal scales of ∼300–500 km. These features seem rather robust in high-resolution but low-dissipative ocean models and have been increasingly recognized in satellite altimeter data and also by in situ measurements. Richards et al. discuss possible wave-mean interactions that may define the spatial and temporal structures of the jets and waves, and implications for tracer transport.

Tanaka et al. discuss results from very fine resolution simulations in an ocean model with domain confined to the Southern Ocean (from 20° S to 75° S). They consider results from several different horizontal resolution versions, with the finest being $1/12 \times 1/8$ degrees latitude–longitude. It is fair to say that this very fine resolution permits, if not completely resolves, the midlatitude eddies that are ocean counterparts of atmospheric synoptic-scale cyclones and anticyclones. In more moderate resolution ocean models, the effects of these eddies on resolved-scale momentum and energy have been treated via a parameterization, such as the widely used Gent-McWilliams scheme. Tanaka et al. use their finest resolution simulation to estimate the diffusion coefficient of isopycnal thickness appropriate for low-resolution ocean models. They note that the areas with large inferred effective diffusivity coefficient correspond well with those with strong baroclinic eddies.

Kagimoto et al. introduce the Kuroshio forecast system with about 10 km horizontal resolution, named the Japan Coastal Ocean Predictability Experiment (JCOPE). The forecast is conducted with a limited-area ocean model covering about 60° longitude by 50° latitude. They show, in particular, one very successful forecast of the development of a large Kuroshio meander with about a month lead time. Kagimoto et al. describe not only specific forecast cases but also the detailed technical aspects of the forecast system. They also report on a preliminary study aimed at further downscaling their results for application to coastal ocean areas.

Finally two papers discuss high-resolution coupled global ocean–atmosphere models. Komori et al. describe the CFES (Coupled GCM for the Earth Simulator) model which couples versions of the AFES model with an extended version of the OFES model which includes a sea ice component. CFES uses a novel approach to coupling the ocean, sea ice, and atmospheric simulations and this minimizes communication overhead in the parallel computing environment of the Earth Simulator. Komori et al. discuss preliminary results from a multiyear CFES integration conducted at much finer resolution than has been typical in coupled global GCMs, specifically T239L48 in the atmosphere and 1/4 degree in the ocean. Results are encouraging in that the climate spins up to a realistic state including a reasonable representation of the seasonal cycle of the ocean circulation.

The paper by Takahashi et al. describes the formulation of nonhydrostatic atmospheric and oceanic models which can be run in coupled mode. Their formulation is sufficiently flexible that higher-resolution regional models can be nested within the global model. It is particularly exciting that the code allows either regional atmosphere, ocean, or coupled regional models to be nested. So far the nesting is one-way, but the authors note that they are working on implementing a two-way nesting. The paper goes on to discuss results from some preliminary integrations – short forecasts with the atmosphere-only model run at 5.5 km horizontal resolution, a 15-year run of the ocean-only model (for the North Pacific basin) with observed atmospheric forcing, and then another short forecast run of the coupled ocean–atmosphere model (with an enhanced grid around Japan).

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

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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° × 5° 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 ($\sim$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 $\sim$275 km resolution versus $\sim$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 $\Delta x \sim 300\,\mathrm{km}$ and $\Delta z \sim 1$–$2\,\mathrm{km}$ in the midtroposphere (enhanced vertical resolution near the ground is common of course) for a ratio of $\sim$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 $\Delta x \sim 8\,\mathrm{km}$ and $\Delta z \sim 0.5\,\mathrm{km}$, or a ratio of $\sim$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 $\sim$1. In general these choices seem to be motivated by a widespread belief that once Δz is down to $\sim$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 $\sim$2.8 km down to $\sim$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 $\sim$25 hPa (corresponding to $\Delta z \sim 500\,\mathrm{m}$ 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 $\sim$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 $\sim$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 $\sim$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 $\sim$45 m s^{-1}. Peak surface winds of somewhat less than $\sim$50 m s^{-1} are also apparent in the 10-year control run performed using a model with $\sim$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 $\sim$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 $\sim$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 $9^\circ \times 10^\circ$ to $5^\circ \times 6^\circ$, to $3^\circ \times 3.6^\circ$ and $1^\circ \times 1.2^\circ$. 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 $0.33^\circ \times 0.4^\circ$. 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