A Global Version of the PSU–NCAR Mesoscale Model

JIMY DUDHIA AND JAMES F. BRESCH

National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 18 September 2001, in final form 4 June 2002)

ABSTRACT

A global version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (PSU–NCAR MM5) is described. The new model employs two polar stereographic projection domains centered on each pole. These domains interact at their equators, thereby eliminating the need for a lateral boundary condition file.

This paper describes the method, and contrasts this fully compressible nonhydrostatic Eulerian global model with other global models. There are potential advantages over spherical polar grids in the resolution distribution and the treatment of curvature forces near the poles. The model also selectively damps acoustic modes, which appears to have some benefits in real-data initialization. The split-explicit time steps are different from the semi-implicit schemes used in several global nonhydrostatic models, and this localized scheme avoids the need for global elliptic solvers, making it particularly adept for distributed-memory platforms and the use of composite meshes.

Tests of the model show that acoustic and gravity waves as well as advective features propagate across the equator without distortion. A trial 100-day perpetual January simulation shows realistic rain patterns as compared to climatology with no evidence of equatorial effects. Nesting is also available to focus on areas of interest, and this is demonstrated with a 72-h nested forecast over North America.

While the time step is shorter than that typically used in semi-Lagrangian global models with a comparable resolution, the model is efficient enough to have allowed the running of daily 120-km grid forecasts on non-dedicated computers as small as four-processor workstations since October 1999. Results from this real-time application of the model to 5-day forecasts are shown, and demonstrate that the model performs well at this scale.

The model is consistent with the regular regional MM5 and shares dynamics and physics packages without modification. It can also make use of pre- and postprocessing packages developed for the MM5 system. This tight linkage between a regional and global model will have a clear benefit as future global models move toward higher resolutions. It allows current mesoscale numerical weather prediction research to directly feed into the next generation of global models.

1. Introduction

The fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (PSU–NCAR MM5) is a research tool supported at NCAR for numerical weather prediction research and mesoscale modeling applications. Since Anthes and Warner (1978) described an early version, it has steadily grown into a widely used model with many physical parameterization options. The introduction of nonhydrostatic dynamics by Dudhia (1993) extended its range of applicability to fine scales, 1–5-km grids, by removing the restriction of the hydrostatic approximation.

The former clear separation of global and mesoscale regional models has become blurred by advances in computer technology. There is a current trend toward covering larger areas with mesoscale models, while global models are starting to have mesoscale resolutions. If computer performance is doubling every 2 yr, as is often assumed (e.g., see MacDonald et al. 2000), an order of magnitude reduction in grid size is achievable every 20 yr, or conversely, the grid resolution applied to the scale of the contiguous United States can be applied globally after 10 yr, given that a U.S. domain is about 3% of the global area.

In mesoscale modeling, the incentive to cover larger areas comes from the need to avoid boundary influences in the region of interest (Warner et al. 1997), because boundary conditions are often provided by global analyses with poor time resolutions, typically every 6 h. It is well known that the advective timescale for a given domain size is a good indicator of the timescale on which the boundary conditions become the primary determining factor in a forecast’s evolution. While a mesoscale model can add detail to a forecast by a global model, it cannot correct for large-scale phase or amplitude errors that enter its boundaries, or that arise from...
crude time interpolation at the boundaries or from the low spatial resolution of boundary features (e.g., see Laprise et al. 2000). Relocation of the boundaries farther upstream helps in resolving some of these problems, and can help distinguish better between causes of forecast errors, such as model error or initialization, as opposed to boundary conditions, particularly for longer-range forecasts. Making this distinction is important to research in model development or data assimilation.

Mesoscale applications are also becoming common in which long-term simulations are required in regional domains. These are seasonal or annual runs that are used for regional climate studies, or to generate mesoscale-resolution four-dimensional datasets for air quality models. In such applications it is vital that the model biases are not large enough to cause severe drifts in the model "climate." However, to investigate model biases on the long term (weeks to months) requires a large-area domain, and ideally a global domain, to remove influences of the boundaries that would otherwise hide some of the bias due to the advective timescale limitation. So a global model is a valuable tool for investigating long-term biases in physical parameterizations such as convective/radiative equilibrium or land surface processes, or biases in the dynamics such as jet streams and large-scale circulations.

A global version of the model has uses in real-time forecasting too. It requires only initial conditions to run and can, therefore, be started from a current analysis alone, without having to wait for boundary conditions from a prior global model run as required by regional models. Furthermore, with a global data assimilation system, the model could be initialized from a previous MM5 global forecast requiring only observations for initialization, and no other external datasets. The model can be run 5–10 days in forecast mode before assumptions, such as using a constant sea surface temperature, become a limitation. However, with medium-range predictability limited by data density and the natural timescales of growth of atmospheric waves, the model has adequate physics for state-of-the-art medium-range forecasts, particularly with the recent addition of the National Centers for Environmental Prediction–Oregon State University Land-Surface Model (NCEP–OSU LSM) (Chen and Dudhia 2001) that allows for evolving soil moisture and snow cover.

Such a model will allow users to investigate problems in medium-range predictability, general circulation dynamics, and global data assimilation, which have so far been beyond the scope of the MM5 research community. Problems in scale interaction can also be addressed, making use of MM5’s nesting capabilities that would separate it from other global models. With this extension, a single model can be used to cover scales from 10,000-km planetary waves and continents to 1-km clouds and topographic features.

In this paper, we will outline the method used to make MM5 global, and describe how it differs from other global models in many respects. We will show some results that demonstrate that the method works, and conclude with remarks about the potential uses of this model.

2. Equations

MM5 has equations for a fully compressible, non-hydrostatic atmosphere with the only approximation being the neglect of the heating term in the pressure prediction equation (Dudhia 1993). The numerical method is that of time splitting following the semi-implicit technique of Klemp and Wilhelmson (1978) and a leapfrog time step. The vertical coordinate is a sigma-type terrain-following coordinate based on reference pressure, and has similarity to height-based terrain-following coordinates. The grid is staggered with horizontal velocities at the corners of grid boxes, and scalars at the center (Arakawa B grid). The vertical velocity is at full levels, while the scalars and horizontal velocities are at half levels. The spatial finite differencing is centered and second order.

Since 1998 MM5 has had a complete set of curvature terms, which we document here in the equations for the substantial derivatives of the three momentum components:

\[ \frac{Du}{Dt} = -\frac{m \frac{\partial p'}{\partial x}}{\rho} + \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) v - \frac{ew \cos \alpha - \frac{uv}{r}}{1 + \sin \lambda} + D_{v}, \]  
\[ \frac{Dw}{Dt} = -\frac{m \frac{\partial p'}{\partial y}}{\rho} - \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) u + \frac{ew \sin \alpha - \frac{uw}{r}}{1 + \sin \lambda} + D_{u}, \]  
\[ \frac{Dw}{Dt} = -\frac{1}{\rho} \frac{\partial p'}{\partial z} - \frac{\rho'}{\rho} + e(u \cos \alpha - v \sin \alpha) + \frac{u^2 + v^2}{r} + D_{w}, \]

where \( m \) is the mapscale factor given by

\[ m = \frac{1 + \sin \lambda}{1 + \sin \lambda} \]
senting the velocities in the $x$, $y$, and $z$ directions, respectively. The $e$ and $f$ terms represent the full Coriolis force, where $e = 2\Omega \cos \alpha$ and $f = 2\Omega \sin \alpha$, $\Omega$ is the earth’s angular rotation rate, and $g$ is the gravitational acceleration. The angle $\alpha(x, y)$ is that between the $y$ axis and the local meridian that is required to represent the Coriolis terms with $e$.

Although $x$, $y$, and $z$ are locally orthogonal and Cartesian, on a large scale they are curved, and so apparent forces are needed due to curvature. The terms with $r$ represent the vertical curvature force due to the earth’s finite radius, and the definition of consequently curved $z$ surfaces parallel to the earth’s surface. The terms dependent on the gradient of $m$ represent a fictitious force due to the horizontal curvature of the coordinate. Note that, since the gradient of $m$ vanishes at the pole, and maximizes at the equator, these terms contribute most at the equator. They are necessary to represent the lateral acceleration seen in the ($x$, $y$) coordinate system for an air parcel following a geodesic (great circle), which it would in the absence of any real lateral forces.

In vector form these equations can be written more concisely as

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho} \nabla p - 2\Omega \times \mathbf{v} - \frac{1}{m} \nabla m \times \mathbf{v}_h \times \mathbf{v}$$

$$- \frac{\rho'}{\rho} \mathbf{k} + D_\lambda,$$

where $\mathbf{v} = (u, v, w)$, $\mathbf{v}_h = (u, v, 0)$, and the vertical gradient of $m$ becomes $\partial m / \partial z = -m/r$ using a more general three-dimensional definition of the mapscale factor,

$$m_{2d}(x, y, z) = m_{2d}(x, y) \times \frac{a}{a + z},$$

where $a$ is the earth’s radius at sea level, to also account for the vertical curvature terms. The second term on the right side of (5) is due to the rotation of the coordinate, and the third term is due to its large-scale curvature, illustrating how the apparently diverse curvature terms in (1)–(3) are all related. The nature of these two terms is such that they cancel completely if a kinetic energy tendency is derived by taking $\mathbf{v} \cdot (5)$, and it is important that the model also has such a cancellation.

3. Method

The regular MM5 code has the option of several conformal map projections: polar stereographic, Lambert, and Mercator. These projections use a mapscale factor that only depends on latitude, the purpose of which is to stretch the grid to allow the curved earth’s surface to be mapped on a flat grid. The conformal projections preserve the shape of features by keeping the grid lengths equal in any two orthogonal horizontal directions. However, such projections cannot be extended to cover a whole sphere, so the approach here is to use two overlapping grids. Each is a polar stereographic grid centered on a pole, and extending slightly beyond the equator. The grid size in the projection is fixed, but because of the mapscale factor’s variation with latitude, the real grid distance on the earth at the poles is double that at the equator. That is, the equator has twice the grid resolution.

The polar stereographic projection distorts even more rapidly beyond the equator, but the method to be described here will effectively not use points beyond the equator that are around the rim of each domain, and this is the key to making the global model work. Viewing Fig. 1, every point within the circle describing the equator is a forecast column for that domain. All the points outside the equatorial circle (evenly shaded regions) are interpolated from the other domain at every time step. The procedure is to first advance the northern domain by one time step, then the southern domain, then exchange boundary information between them. The exchange is done symmetrically in that results do not depend upon which domain gets the boundary values first. Points within the equatorial circle such as $A_1$ and $A_2$ are used to fill information in the other domain’s outer shaded regions such as, respectively, $B_1$ and $B_2$, at the corresponding geographical locations. The interpolation only goes in this direction and interior points are unaffected.

While, in practice, computations are still carried out at the outer shaded points because the model calculation loops cover all the indices, these values are overwritten by the other domain’s interpolated values. This represents a waste of about 25% of the computations in each domain, but this is a small price paid to keep compatibility with the regular MM5 code, and is similar in this respect to the overwriting of coarse-mesh values with fine-mesh ones at every step of a two-way nested simulation. The considerable benefit of this method is that the MM5 physics and dynamics routines are unaltered in the global version of the model. The multiple-domain capability already in MM5 to handle nesting has facilitated the use of a second domain in the global application, where we effectively now have two coarse domains instead of one.

The method of interpolation is a simple bilinear four-point method. A high level of sophistication is not needed here because the values interpolated are really just boundary conditions at the equator, providing values for gradients only. Note also that the resolution of both domains is comparable and is highest at the points near the equator. All the model three-dimensional variables, and the two-dimensional variables that are needed in horizontal gradients, such as terrain elevation, are interpolated this way. The global simulations show no sign of the equatorial interface in features advecting across the equator, as tests shown later will demonstrate, so this method appears adequate.

To execute this method, arrays are precalculated that...
FIG. 1. Northern and Southern Hemispheric domains showing topography with a 120-km grid size. Shaded areas outside the equator show where the model variables are specified by the other domain.

carry the \((x, y)\) coordinates of every point beyond the equator relative to the opposite hemisphere’s grid. This allows easy determination of the array indices of the four points used and their weightings in the procedure. These coordinates are calculated using the point’s latitude \((\lambda)\) and longitude \((\phi)\) and the map factor \((m)\) of the opposite hemisphere:

\[
x = am \cos \phi \cos \lambda, \quad y = am \sin \phi \cos \lambda,
\]

where \(x\) and \(y\) are readily transformed into grid index
space after dividing by the nominal constant grid length, Δx.

In interpolating fields, care is taken to allow for the grid staggering of horizontal velocity points with respect to the others, and also their rotation. The velocities are grid-direction velocities, and in a polar stereographic domain centered on the pole, the x/y wind component, u/v, rotates relative to the westerly/southerly wind component by an angle dependent on the difference of the longitude and the “central” longitude. In the Southern Hemisphere, the rotation is in the opposite sense with increasing longitude from that in the Northern Hemisphere. This means that the relative direction between the u/v wind components in each domain rotates 720° as the longitude varies 360°. This rotation is accounted for in the interpolation procedure, using both u and v from the opposite hemisphere to calculate an interpolated u value, for instance. The B-grid staggering in which u and v are collocated makes this rotation quite straightforward. Note that the mapscale factor differences do not have to be taken into account, because the model wind speeds always represent true earth-relative, not grid-relative, speeds.

In the regular regional MM5’s outermost row and column, tendencies of variables are specified by analyses. In the global version this specification is replaced by tendencies derived from interpolated variables from the other domain. Since two time levels of the variables are interpolated, a tendency can be derived from them at each time step. Thus a boundary input file is no longer needed, as both domains can take specified values and tendencies from each other.

The idea of composite meshes to cover the sphere goes back to Phillips (1957). Browning et al. (1989) have evaluated a similar technique of using two hemispheric polar stereographic grids against other numerical techniques for the shallow water equations on a sphere. Apart from efficiency concerns, the composite mesh method was found to be as good as the spectral and gridpoint ®nite differencing distinguishes it from the others, and also their rotation. The velocities are grid-direction velocities, and in a polar stereographic domain centered on the pole, the x/y wind component, u/v, rotates relative to the westerly/southerly wind component by an angle dependent on the difference of the longitude and the “central” longitude. In the Southern Hemisphere, the rotation is in the opposite sense with increasing longitude from that in the Northern Hemisphere. This means that the relative direction between the u/v wind components in each domain rotates 720° as the longitude varies 360°. This rotation is accounted for in the interpolation procedure, using both u and v from the opposite hemisphere to calculate an interpolated u value, for instance. The B-grid staggering in which u and v are collocated makes this rotation quite straightforward. Note that the mapscale factor differences do not have to be taken into account, because the model wind speeds always represent true earth-relative, not grid-relative, speeds.

In the regular regional MM5’s outermost row and column, tendencies of variables are specified by analyses. In the global version this specification is replaced by tendencies derived from interpolated variables from the other domain. Since two time levels of the variables are interpolated, a tendency can be derived from them at each time step. Thus a boundary input file is no longer needed, as both domains can take specified values and tendencies from each other.

The idea of composite meshes to cover the sphere goes back to Phillips (1957). Browning et al. (1989) have evaluated a similar technique of using two hemispheric polar stereographic grids against other numerical techniques for the shallow water equations on a sphere. Apart from efficiency concerns, the composite mesh method was found to be as good as the spectral and gridpoint ®nite differencing distinguishes it from the others, and also their rotation. The velocities are grid-direction velocities, and in a polar stereographic domain centered on the pole, the x/y wind component, u/v, rotates relative to the westerly/southerly wind component by an angle dependent on the difference of the longitude and the “central” longitude. In the Southern Hemisphere, the rotation is in the opposite sense with increasing longitude from that in the Northern Hemisphere. This means that the relative direction between the u/v wind components in each domain rotates 720° as the longitude varies 360°. This rotation is accounted for in the interpolation procedure, using both u and v from the opposite hemisphere to calculate an interpolated u value, for instance. The B-grid staggering in which u and v are collocated makes this rotation quite straightforward. Note that the mapscale factor differences do not have to be taken into account, because the model wind speeds always represent true earth-relative, not grid-relative, speeds.

In the regular regional MM5’s outermost row and column, tendencies of variables are specified by analyses. In the global version this specification is replaced by tendencies derived from interpolated variables from the other domain. Since two time levels of the variables are interpolated, a tendency can be derived from them at each time step. Thus a boundary input file is no longer needed, as both domains can take specified values and tendencies from each other.

The idea of composite meshes to cover the sphere goes back to Phillips (1957). Browning et al. (1989) have evaluated a similar technique of using two hemispheric polar stereographic grids against other numerical techniques for the shallow water equations on a sphere. Apart from efficiency concerns, the composite mesh method was found to be as good as the spectral and gridpoint ®nite differencing distinguishes it from the others, and also their rotation. The velocities are grid-direction velocities, and in a polar stereographic domain centered on the pole, the x/y wind component, u/v, rotates relative to the westerly/southerly wind component by an angle dependent on the difference of the longitude and the “central” longitude. In the Southern Hemisphere, the rotation is in the opposite sense with increasing longitude from that in the Northern Hemisphere. This means that the relative direction between the u/v wind components in each domain rotates 720° as the longitude varies 360°. This rotation is accounted for in the interpolation procedure, using both u and v from the opposite hemisphere to calculate an interpolated u value, for instance. The B-grid staggering in which u and v are collocated makes this rotation quite straightforward. Note that the mapscale factor differences do not have to be taken into account, because the model wind speeds always represent true earth-relative, not grid-relative, speeds.

4. Comparison with other global models

a. Types of global model

Most current global atmospheric models fall into two categories: general circulation models (GCMs) and numerical weather prediction (NWP) models. The former category, which includes climate models, features models that are run for months to years typically, and need to be highly efficient, usually implying simplified physics and low resolutions both spatially and temporally. Numerical weather prediction models are also designed for efficiency due to operational constraints, but since they are run typically up to 10 days, their resolutions can be higher than climate and general circulation models.

The global version of MM5 does not fall into these categories as it is a weather research model. Being a research tool alleviates efficiency constraints and allows it to use sophisticated physics options called with a shorter time step, the emphasis being on accuracy rather than efficiency. Its primary role is for case study research on multiday timescales. However, with newer computers, it can be run in real-time forecast mode as will be shown later. It shares in common with operational NWP models that the initialization and physics must be of a sufficient standard to optimize the verification of forecasts against real-data analyses, which is not a need in GCMs or climate models that are judged more by their time-mean statistics.

While there are several community climate models and general circulation models, there have been up till now no community global weather research models, so MM5 will help to fill this gap. This model is distinguished from operational models in having several options for each physics parameterization, and in having code that allows modification to test new options, changes in resolution, or sensitivities relatively easily.

b. Nonhydrostatic global models

The fact that this model is an Eulerian model with gridpoint finite differencing distinguishes it from the majority of global climate and numerical weather prediction models. Furthermore, it is nonhydrostatic, using the fully compressible equations that have almost no approximations for a rotating fluid on a sphere, which also makes it distinct from hydrostatic models or those based on anelastic equation sets.

Several nonhydrostatic global models have been presented recently (Semazzi et al. 1995; Cullen et al. 1997; Smolarkiewicz et al. 2001; Yeh et al. 2002). In contrast
to the current model, these use a spherical polar grid and a variety of techniques that have in common the inclusion of semi-Lagrangian advection and semi-implicit methods that involve the solution of Helmholtz or Poisson equations on the global domain. Such semi-implicit techniques would be difficult to adapt to composite meshes because of the implicit dependence of the two domains’ solutions on each other, and their current use is limited to single-domain spherical polar grids.

Smolarkiewicz et al. tested many schemes including anelastic and elastic dynamics and focused on comparing accurate and efficient numerical algorithms for a future global nonhydrostatic cloud model. Their model is based on perturbation equations suitable for idealized dynamical studies. Semazzi et al., Cullen et al., and Yeh et al. have geared their models toward real-data NWP applications on the global scale. In fact several operational centers are developing global nonhydrostatic NWP models including the U.K. Met Office (Cullen et al. 1997), the Canadian Atmospheric Environment Service (Côté et al. 1998; Yeh et al. 2002), and NCEP (J. Purser 2001, personal communications). Operational considerations almost require that these models be semi-Lagrangian to enable long time steps, but this requirement becomes less stringent for research models.

The Meteorological Research Institute of Japan has also recently extended its nonhydrostatic model, NHM, to global scales using a generalized form of the Mercator projection and having a domain that extends 160° in longitude. This model has full physics and uses numerical methods similar to MM5 for Eulerian advection and the split semi-implicit treatment of sound waves (K. Saito 2001, personal communication).

Nonhydrostatic effects are starting to become resolvable by global models. According to the estimate of Daley (1988) a total wavenumber of 400 is sufficient to see the frequency reduction effect in the deepest gravity modes, and such resolutions, corresponding to 50–75-km grids, are just starting to be run routinely at the major operational centers. A benefit of this dynamics that may even appear at low resolution is the inclusion of the full Coriolis force that is not often accounted for in hydrostatic models since it includes a vertical acceleration term. The cosine-latitude component of the Coriolis force may become important in regions of slow large-scale vertical motion, such as the subsidence in the subtropics. A good argument for neglecting this component based on scale analyses is given by White and Bromley (1995).

c. Vertical coordinate and base state

The vertical coordinate in most nonhydrostatic models, both regional and global, is based on height, while hydrostatic models almost always use pressure-based coordinates. However, some recent nonhydrostatic models have followed the approach suggested by Laprise (1992a) of using a hydrostatic pressure as the basis of their terrain-following sigma coordinate, and these include Yeh et al. (2002) who are developing the Canadian global forecast model with this coordinate. The global MM5’s vertical coordinate is a sigma coordinate based upon reference pressure, which is more like terrain-following height coordinates and is therefore similar to the majority of nonhydrostatic models. The vertical staggering in MM5 is a Lorenz-type staggering in which temperature is at the same level as other scalars and horizontal velocities, while several semi-implicit semi-Lagrangian nonhydrostatic models are using the Charney–Phillips staggering with temperature at the same levels as the vertical velocity (e.g., Tanguay et al. 1992; Qian et al. 1998; Cullen et al. 1997).

The use of a base-state temperature and pressure profile in models is beneficial in calculating the horizontal pressure gradient force over sloped terrain because large canceling parts of the pressure gradient that arise from sloped coordinates are excluded from the force unlike in the situation, once common in hydrostatic models, where full pressure/geopotential is used. In other global models where a base state is used it is often isothermal to allow an easy separation of terms for their semi-implicit schemes, while MM5’s reference temperature is a more realistic linear function of log pressure capped by an isothermal stratosphere. Increased accuracy in the base state helps with the cancellation of the horizontal pressure gradient terms (e.g., see Qian et al. 1998). It is important to note that the equations are not linearized about the base state, so that there is no reliance on the perturbations being small for the continuous equations to be accurate. This is vital for a global application in which there are necessarily large deviations from a horizontally uniform base profile.

d. Initialization and acoustic modes

Solving the fully compressible equations and having a rigid upper boundary may also have advantages in the initialization of a global model. For most hydrostatic sigma-coordinate global models, an important necessary component is an initialization technique that removes spurious gravity waves that would otherwise adversely impact the forecast because these modes persist, particularly in a global model where there are no lateral boundary zones to remove them. Normal mode initialization techniques (e.g., see Daley 1979) have been developed that are successful in preventing noisy solutions.

Experience with the nonhydrostatic model shows that unbalanced convergence and mass distributions in the initial conditions manifest themselves more as acoustic modes than gravity modes probably because these modes have the highest-frequency response to such imbalances, and because this model’s rigid upper boundary does not permit external gravity modes. As seen from the linearized equations (e.g., see Daley 1988; Kasahara
and Qian 2000), fully compressible nonhydrostatic models permit acoustic modes as well as gravity modes, and the former have distinctly higher frequencies at all wavelengths, while hydrostatic models with a constant-pressure upper boundary are effectively incompressible and do not have acoustic modes. The benefit of this separation of modes is that the MM5 model’s split-explicit scheme damps acoustic modes quite selectively, quickly removing the high-frequency noise without affecting meteorologically important modes. This is achieved within the finite-difference technique through time off-centering in the vertically implicit short-step dynamics for the vertically propagating acoustic modes, and divergence damping for the horizontal modes (see Dudhia 1993 for more details), and moreover, the shortness of the acoustic time step aids the speed of this adjustment. It appears that special initialization techniques to remove acoustic or gravity modes are not needed, but the MM5 preprocessing system still employs a simple column net divergence removal to help the adjustment.

Semi-implicit nonhydrostatic models also use a time off-centering technique (e.g., Semazzi et al. 1995) to reduce numerical noise. This damps acoustic modes but also damps gravity modes as shown by Tanguay et al. (1992) and so is less selective than MM5’s method of damping. Furthermore the semi-Lagrangian technique can reduce gravity wave phase speeds if long time steps are used.

e. Map projection and grid

Figure 2 shows a comparison of the grids with a spherical polar (latitude–longitude) grid (Fig. 2a) and overlapping polar stereographic grids (Fig. 2b) that have the same number of total grid points (420 × 210 in this case). The polar stereographic grids have properties that distinguish the horizontal coordinate from the commonly used spherical polar coordinates. Primary in this respect is the distribution and strength of the horizontal curvature force, which maximizes, and in fact becomes infinite on the pole of a spherical polar grid, as can be inferred from the curvature of the grid lines seen in Fig. 2a. This is important because one reason for problems in Eulerian global models using spherical polar coordinates is that the behavior, and definition, of the velocities is highly distorted by curvature effects at the poles, while they retain a Cartesian behavior there in this projection (Fig. 2b). Within a few gridlengths of the pole, in the case shown in Fig. 2a, the curvature error becomes significant because the radius of curvature becomes comparable with the grid length, making it difficult to calculate flow trajectories accurately. In semi-Lagrangian models the vector momentum technique of Bates et al. (1990) can overcome this problem. On the other hand, a polar stereographic hemisphere is well suited to Eulerian models as the minimum radius of curvature is about the earth’s radius, and that value is at the equator where the resolution is highest, minimizing the error.

Figure 3 shows the grid distance versus latitude for this case of a 120-km grid size at 60°N (solid) together with the latitudinal (dashed) and longitudinal (dotted) grid distances for a spherical polar grid. It is well known that a uniform spherical polar grid tends toward zero grid size at the poles leading to strong restrictions on the time step in Eulerian models. This problem can be overcome by semi-Lagrangian techniques or thinning or smoothing the grid values nearer the poles. However a
polar stereographic projection naturally varies grid distances in a smooth manner between pole and equator. Furthermore, it could be argued that, given a choice of higher resolution in the Tropics or in polar regions, it is more valuable to have the higher resolution in the Tropics because of the relatively smaller scale of the dominant weather systems there.

It should be noted here that the icosahedral–hexagonal grid presented by Ringler et al. (2000) for a general circulation model, and by Majewski et al. (2002) for a new version of the German Weather Service’s global model has a very uniform grid size, which optimizes the efficiency for a given minimum resolution.

f. Equatorial interface
The added complexity of the equatorial interface may be viewed as a trade-off for the complexity of dealing with poles, but it turns out to be a much simpler problem to solve. Mesoscale models including MM5 have had such interfaces for many years, in which all the information beyond a certain boundary is specified from a parent domain or from a time-interpolated analysis. In the regular regional MM5 at a nest boundary, values and their tendencies are specified from a coarse mesh with three times the grid size and three times the time step. This can be done with little need of filtering, provided the spatial interpolation to the fine grid is done with sufficient monotone interpolation methods (Smolarkiewicz and Grell 1992). The two-way nest option additionally requires feeding information back to the coarse mesh in the nest interior, and a smoothing operation is generally needed because of the resolution mismatch.

The global version’s equatorial interface is greatly simplified by the fact that the domains are of equal resolution both in space and time at the juncture, and no feedback is required in domain interiors. This means that points beyond the equator are updated every time step, and are interpolated from a grid of similar resolution. In practice this interface is therefore even better behaved than the commonly used nest interfaces and lateral boundaries in mesoscale models, and a simple four-point bilinear interpolation suffices instead of higher-order interpolation methods. We will demonstrate some tests in the next section to verify the cleanliness of this interface zone.

g. Computational efficiency
Using an Eulerian model restricts the time step due to the Courant–Friedrichs–Lewy criterion. A typical robust value is 216 s for a 120-km grid (which is actually 64 km at the equator) and 23 levels. This is a much shorter time step than semi-Lagrangian models would require with comparable resolution. However, this enforced short time step also helps improve the accuracy in the treatment of gravity waves and of “dynamic equilibrium” processes, such as saturated vertical advection and boundary layer development, in which a balance exists between terms in a time-developing state. Much of the physics in MM5, including microphysics and boundary layer parameterization, is run on the same step as advection. While the global MM5 is consequently slow compared to global operational weather forecast models and global climate models, it is no longer prohibitively slow for scientific studies and experimental multiday forecasts given the current cost per performance of computers. We have been able to run routinely at resolutions close to that used by operational NWP global models on a modest computer. The computing cost versus resolution is further discussed in the appendix.

An issue with current-day large computers is distributed-memory performance. This model is particularly well suited to such architectures because of the lack of global pressure solvers or transforms and transposes that would otherwise hinder its performance. The use of a prognostic equation for the pressure localizes the grid-column dependencies to only nearest neighbors, except for the interdomain boundary exchange, greatly simplifying the application of the model across distributed nodes by mitigating communications requirements. This could also lead to good scaling properties as the number of nodes is increased. The distributed-memory performance may be improved in the future because both domains run alternately on the same nodes, and the boundary swapping communication can be minimized by assigning the nodes to index-space areas such that a given node maximizes the overlap of the corresponding geo-
at these grid scales, using a rigid-lid (model without the upper radiative boundary condition speeds. improve long-term predictions of tropospheric wind mountainous regions. This should be included as it may drag formulation that many global models have to rep-

siderations that are not normally needed for mesoscale not easily changed, and the resolution is not fine-tun-
es it from most other global models where the grids are vertical levels to match the needs and computing re-

model is easily configurable in terms of grid size and fields, and running an analysis straightforward. The
MM5's preprocessing system can be used as is for the global version of the model, which makes setting
up terrain elevation and land use, ingesting gridded fields, and running an analysis straightforward. The model is easily configurable in terms of grid size and vertical levels to match the needs and computing resources of potential users. This feature also distinguishes it from most other global models where the grids are not easily changed, and the resolution is not fine-tun-
able.

For 100-km grid lengths there are some other consider-
ations that are not normally needed for mesoscale grids (<50 km). MM5 does not have a gravity wave drag formulation that many global models have to represent the effects of subgrid momentum transport in mountainous regions. This should be included as it may improve long-term predictions of tropospheric wind speeds.

We have also found that it is preferable to run the model without the upper radiative boundary condition at these grid scales, using a rigid-lid (w = 0) boundary condition instead. This is because the dominant resolved modes have a significant Coriolis influence that is not accounted for by the radiative boundary conditions, which are designed to transmit hydrostatic gravity waves. In practice the rigid lid causes none of the problems seen at mesoscale grid scales, possibly because the inertial influence on the horizontal group velocity dis-

perses upward-propagating gravity wave energy down-
stream of source regions, such as mountains, removing the possibility of setting up resonances between the mountain and lid that can occur with purely vertically propagating hydrostatic gravity waves.

Effects of fractional cloud coverage, such as in MM5's older radiation scheme, should be included in the newer schemes, which currently consider the grid box uniform. This adds the need for assumptions about how clouds at various levels overlap. Microphysics could also take account of subgrid variability and allow partially cloudy grid boxes.

Version 3.4 of the regular MM5 model now also has sea temperature and sea ice variation enabled via spec-
ification of lower boundary fields that can be updated at intervals. We also recently added a specified monthly variation in the vegetation fraction. This will allow the global model to be used for seasonal timescale forecasts. Running the global model with the NCEP-OSU LSM would enable snow-cover prediction, as well as a soil moisture prediction and sea ice effects that would benefit both medium-range and seasonal forecasts. In section 5 we will present some tests of the model, followed by showing some real-time forecast results in section 6.

5. Tests of the global model

New aspects of this global model are the equatorial interface and the capability for nesting within it. In this section four tests will be presented to demonstrate that these new aspects function as intended. First, the model will simulate radiating acoustic and gravity waves in an idealized setting, then the horizontal advection of an ideal local disturbance across the equator will be shown. The third test will demonstrate a two-way interactive nested domain in a 3-day forecast, and finally we will present the rainfall results of a 100-day trial run that was carried out to test the model’s long-term simulation capabilities.

a. Acoustic and gravity wave propagation

The global model was initialized with a uniform sounding, taken from the tropical Pacific, with no topo-
graphy, no Coriolis force, no wind, and no physics including no surface fluxes or friction. This made it a purely dynamical atmospheric model without any sur-
face interaction, and no motion existed unless a per-
turbation was added because the perturbation pressure was hydrostatically balanced. The nominal grid length was 120 km, and there were 23 levels up to a reference pressure of 50 hPa.

A cylindrical column with a radius of five grid points in the Caribbean region of the Northern Hemisphere was subjected at the initial time to a large pressure perturbation by uniformly adding 10 hPa in the whole cy-

linder. The pressure evolution in the model is shown in Fig. 4. Figure 4a shows the pressure perturbation at a middle level 6 h into the simulation. The basic features are fairly independent of height, and consist of an ad-
vancing wave front that has nearly reached the North Pole at the northern extreme and is also propagating across the equator in the Pacific and Atlantic, and a slower propagating more dispersive circular feature centered on the original perturbation. Note that the map distortion makes these physically circular features appear more elliptical.

The faster feature primarily appears in the pressure field, but not in the potential temperature or vertical velocity fields, and is clearly an acoustic mode as would be expected from an initial mass imbalance. The acoustic wave disperses very little because its speed is governed only by the temperature, and the vertical variation in sound speed is very small in comparison to its absolute speed. The slower feature appears additionally in the potential temperature and vertical velocity fields, and represents gravity waves that disperse and separate into waves of differing vertical wavenumbers with the deepest internal mode propagating fastest. There is no external mode because of the model’s upper boundary.
condition on \( w \). Gravity waves are forced because the initial pressure perturbation is also a weak potential temperature perturbation, since the temperature was kept constant as the pressure perturbation was applied.

Of interest in this test is the equator (the largest complete latitude line depicted) where, as may be recalled from Fig. 2b, grid directions abruptly vary. Note that, even though the area outside the equatorial circle is made up of interpolated values from the other hemisphere, the pressure contour lines are continuous, indicating no noise associated with the interface, and this applies also to other contoured fields not shown.

Figure 4b shows the progression of the sound wave and dispersive gravity waves at 12 h in the Northern Hemisphere, and Fig. 4c shows the Southern Hemisphere 6 h later when the sound wave has reconverged on the antipodal point of the initial perturbation. It can be seen that the wave front has retained its circular shape despite having passed through widely varying grid sizes and orientations, depending upon which great-circle route the various parts of the front have taken, and this indicates that the map factors are representing the physical grid sizes accurately. Note also in this figure that the deepest gravity waves are separating from the rest and are crossing the equator unperturbed by the interface. Figure 4d shows the Southern Hemisphere at 24 h when the sound waves are rediverging from the antipodal point, and are about to meet the deepest gravity modes moving in the opposite direction.

b. Advection across the equator

The setup for this test was very similar to the previous test, except that a vertically uniform large-scale wind with a cross-equatorial component at 90°W was accelerated from rest to 30 m s\(^{-1}\) during the first hour, after which the model was allowed to evolve without further forcing. The perturbation introduced this time was a horizontally parabolically varying water vapor depletion with a minimum value of half the initial value in the sounding throughout the column, together with a slight warming to maintain the same virtual temperature, which minimizes buoyancy changes that would lead to gravity waves. The region of the perturbation was the same as in the previous test (Fig. 5a).

Because there was no shear introduced, all levels show the same features, and Fig. 5 shows the water vapor field at the initial time, 12 h, and 24 h at the lowest model level. It can be seen that between 12 and 24 hours the feature crosses the equator into the southern hemisphere. With the second-order numerics and the sharpness and speed of the feature there is evidence of Gibbs waves behind the perturbation, but Fig. 5c shows that even this subtle feature is preserved as it crosses the equator.

The lack of equatorial effects is also borne out by animations of these fields, especially vertical velocity where there is no spurious equatorial motion after the disturbance caused by velocity initialization method has quickly decayed.

c. Nesting in the global model

One of the major new features brought to global modeling by MM5 is its multiple nesting capability in which nested domains are forced by the parent domain at their boundaries, and feed back to the parent domain in their interiors. This is known as two-way nesting, and MM5 allows multiple nest levels as well as multiple nests on each level. The nested grid size is fixed at one-third that of its parent with the same reduction in time step. A nest can start and stop any time in the simulation, and can make use of higher-resolution topography and analyses than the parent domain. A restriction with the global version is that the nest cannot straddle the equator.

For a nesting test, we arbitrarily chose a 0000 UTC 1 January 2001 initial condition, and a North American nested domain that ran for 3 days in two-way nested mode. The grid sizes were 120 km for the hemispheric domains, and 40 km for the North American domain, which is nested in the Northern Hemisphere domain. The topography in the nest was also enhanced to be compatible with its higher grid resolution. It was found that the upper radiative condition was needed in the nest to prevent excessive noisiness in the solution. The full model physics was used, as described later in section 6a.

Comparison runs were performed with and without the nest, and some results are displayed in Fig. 6. Figures 6a and 6b show the 24-h rainfall and sea level pressure at 72 h into the simulation without the nest, where the plots zoom in on just North America. Figures 6c and 6d show the same fields for the nested domain in the nested run. Comparing the rainfall patterns in Figs. 6a and 6c, additional detail is seen in the interaction of a Pacific cold front with the Canadian Rockies where the topography is better represented by the nest. Since the whole nested domain is plotted, it can be seen from the sea level pressure in Fig. 6d that the boundaries are well behaved.

d. A 100-day global run

The 1 January 2001 case was run on a 120-km grid for 100 days to test the robustness of the full-physics model and whether it could maintain realism when run this long without any controlling forcing. The model was run in perpetual January mode, whereby the sea surface temperature and solar declination were fixed at their 1 January 2001 values, thus allowing the model to develop a January climate without seasonal-scale changes in the forcing.

Figures 7a and 7b show, respectively, the Northern and Southern Hemispheric total rainfalls for the 100 days. The plots show the intertropical convergence zone.
Fig. 5. (a) Water vapor at sigma = 0.995 for the advection test run. Northern Hemisphere shown at the initial time with a contour interval of 1 g kg⁻¹. Positive deviations from initial value are dashed; negative solid. (b) As in (a) but at 12 h. (c) As in (a) but for the Southern Hemisphere at 24 h.

(ITCZ) north of the equator in the Pacific, and farther south in the eastern Atlantic, as is commonly seen in the climatology. The ITCZ rainfall averages 20–30 mm day⁻¹ along much of its length. The southern Pacific also has a climatologically correct rainfall band extending southeastward from the western tropical Pacific. In the Northern Hemisphere the relatively weaker Pacific and Atlantic storm tracks are seen in midlatitudes.

The equatorial region again shows no indication of problems when viewing these rainfall totals there. Closer examination of mean behavior in the model has shown that there is a cooling trend in the polar stratosphere, and there appeared to be an abrupt tropospheric warming event after day 70, which was possibly related to the degraded high-level meridional temperature gradient. Such effects point to a possible need for improved stratospheric physics, and a higher model top than the current 50 hPa. Further study of these issues is needed before this model can be used for seasonal or annual simulations of the general circulation, but the trends are show enough that they are unlikely to impact the 5–10-day forecasts that are the primary purpose of this model.
6. Real-time global forecasts

a. Setup and physics considerations

For the global forecasts, we use many of the regular MM5 physics options without any modification (e.g., see Grell et al. 1994). The Grell convective parameterization is a single-cloud version of the Arakawa–Schubert scheme based on the quasi-equilibrium closure assumption. It includes downdrafts and recalculates clouds every time step. The resolved-scale microphysics has a simple ice parameterization (Dudhia 1989) that includes snow and ice clouds at temperatures below 0°C and interacts with the radiation scheme. The radiation scheme uses the shortwave method of Dudhia (1989) and the Rapid Radiative Transfer Model (RRTM) longwave scheme (Mlawer et al. 1997).

Horizontal diffusion uses a Smagorinsky-type deformation term as part of the mixing coefficient, multiplied by a fourth derivative of the field being diffused. The planetary boundary scheme and vertical diffusion are based on the Medium-Range Forecast (MRF) scheme (following Hong and Pan 1996), with several thinner
layers in the lowest kilometer, and employ both an enhanced eddy mixing and a nonlocal transfer term within the unstable boundary layer, the depth of which is estimated from a bulk Richardson number criterion. Surface exchange coefficients are found from standard Monin–Obukhov similarity theory, with a viscous sub-layer for moisture fluxes (e.g., see Oncley and Dudhia 1995). The land surface has a five-layer soil thermal diffusion model, and is represented by 24 categories of land use based on satellite data and data provided by the United States Geological Survey (USGS). Albedo, moisture availability, emissivity, roughness length, and thermal inertia depend on the land use category and season. For water a Charnock relation makes the roughness length a function of wind speed.

Since this model is to be used on medium-range forecast timescales of 5–10 days, with grid lengths on the order of 100 km, and it is to be initialized with global analyses, several additions have been made to this version of the model, and more are being considered for the future.

We are not yet running the NCEP–OSU LSM but snow cover prediction has been added by using a heat and moisture budget equation to predict water-equivalent snow depth. This can be initialized from existing global analyses that carry such a variable, as is the case with the MRF analyses.

Sea ice cover is initialized based on the sea surface temperature. Currently a threshold of 273 K is used to discriminate between sea ice and water. This would also depend on the incoming dataset, and some of those may already contain sea ice information. As with the regular model, sea ice is treated like permanent ice.

The forecast setup consists of two hemispheric domains, each with $210 \times 210$ points and 23 levels extending to about 100 hPa or, more recently, 50 hPa. The sigma levels from top to bottom are $0.025, 0.075, 0.125, \ldots, 0.825, 0.870, 0.910, 0.945, 0.970, 0.985, 0.995$, and the last five are typically in the lowest kilometer. The grid size is defined to be 120 km at 60° latitude, varying from 128 km at the poles to 64 km at the equator (Fig. 3). We have found that a time step of 216 s is robust, corresponding to 100 time steps per 6-h forecast. The acoustic steps are 108 s, resulting in four per leapfrog step.

The topography (Fig. 1) is interpolated from an elevation dataset of comparable resolution, and has had the two-grid-length waves selectively filtered out.

The forecasts are now initialized twice daily from NCEP Aviation Model (AVN) global analyses utilizing all available observations in a Cressman reanalysis on each domain. The forecasts are regularly run for 5 days, and are sometimes extended to 10 days. Outputs are saved for plotting every 6 h, and the plots are available online (http://rain.mmm.ucar.edu/mm5). Recently these global forecasts have been made part of an Antarctic Mesoscale Prediction System (AMPS), giving medium-range guidance to Antarctic forecasters.

The forecasts were initially run on a four-processor shared-memory Compaq workstation, but have more recently been ported to a 32-processor, 8-node, distributed-shared-memory workstation, and then a 16-pro-
We have run the global model almost every day since October 1999, now numbering hundreds of overlapping 5-day simulations, and this has helped us understand its behavior and predictive capabilities. This may be the first global nonhydrostatic model to be run on a regular real-time basis.

Global model output files are saved routinely starting from January 2001. There are 1.7 Gb of output for each 5-day forecast, but an extensive statistical evaluation has not yet been done, and will be left for a future study. However six earlier 5-day forecasts (initialized 0000 UTC 1–6 March 2000) have been studied by examining the Northern Hemisphere 500-hPa height field’s correlations between pairs of forecasts verifying at the same time. Note that we have used full height, not anomalies, so the correlations are always very high because of the dominance of the mean latitudinal variation.

As seen in Table 1, forecasts verifying at the same time have a higher correlation with each other than with the analyses at the verifying time. The best correlation was between the 3-day forecasts and 2-day forecasts where the five cases had an average correlation of 0.993, compared to, for example, five 1-day forecasts only having a 0.980 correlation with the analysis. While 0.980 shows considerable skill compared to the 0.954 average correlation between all pairs that did not have the same verifying time, it is at first surprising that the 3-day forecast looks more like the 2-day forecast, than the 1-day forecast looks like the analysis. However this is possibly explained by the fact the objective analyses represent nonequilibrium states for the model because they are unbalanced due to the analysis procedure. Once the transients introduced by these imbalances decay, forecasts look more similar to each other, despite starting with different analyses. The high correlation between successive forecasts verifying at the same time is an indicator of good continuity between forecasts in the 2–3-day range. There is also a good correlation between 5- and 1-day forecasts (0.974) indicating medium-range skill for this small sample.

Figure 8 shows an initial analysis for 0000 UTC 1 March 2000, and the 5- and 3-day forecasts, and analysis valid at 0000 UTC 6 March 2000. This period was not chosen for any particular reason, other than being the beginning of a month, and so it represents a random sample from our forecasts. The wavenumber-5 pattern seen in Fig. 8d can be compared with that in Figs. 8b and 8c. There is skill in even the 5-day forecast in capturing all of the large-scale troughs in the 500-hPa height field. Despite the relatively low (0.947) correlation with the analysis, this would probably be regarded as a useful forecast of the major troughs located at the east and west U.S. coasts, the central Pacific, east Asia, and Russia.

Figure 9 shows that at the surface two Pacific cyclones and an Atlantic cyclone are captured well by a 3-day forecast. The predicted depths were 962, 969, and 968 hPa for the cyclones, respectively, near the Kamchatka peninsula, the Aleutians, and Iceland, versus 964, 967, and 958 hPa in the analysis. Also note that the midlatitude and subtropical high pressure regions were well captured in the central and east Pacific and the east Atlantic.

These and other results give us confidence in the model’s medium-range forecasts, and viewing the output on a daily basis confirms that generally long-wave patterns are forecast well to 5 days, while mid- and high-latitude surface patterns are forecast well to 3 days. These patterns fully develop on those timescales from small perturbations, while others existing at the initial time decay, and so the model captures their whole life cycles accurately. The Southern Hemisphere midlatitudes show slightly less predictability from subjective analyses. There is sufficient resolution in the Tropics to show rotation in tropical storms and hurricanes. The global model captures the tracks of developing and existing tropical circulations well, possibly with a tendency toward overprediction of development in some cases.

Some simulations have been extended to 10 days, and these too have shown realistic behavior throughout the period with no obvious biases developing over time. A next step would be a more thorough examination of model biases in these forecasts, because that would point to areas where the physics may be improved. These time and space scales are fairly new for MM5, and there are also regions of the world where MM5 has not yet been evaluated extensively. Global verification statistics might be a valuable resource for future regional applications in new geographical areas.

### Table 1. Correlations between forecasts verifying at same time.

<table>
<thead>
<tr>
<th></th>
<th>0 day</th>
<th>1 day</th>
<th>2 day</th>
<th>3 day</th>
<th>4 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>0.980</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 day</td>
<td>0.967</td>
<td>0.987</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 day</td>
<td>0.960</td>
<td>0.983</td>
<td>0.993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 day</td>
<td>0.957</td>
<td>0.977</td>
<td>0.987</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>5 day</td>
<td>0.947</td>
<td>0.974</td>
<td>0.985</td>
<td>0.981</td>
<td>0.987</td>
</tr>
</tbody>
</table>

7. Summary and conclusions

A global version of the PSU–NCAR Mesoscale Model (MM5) has been presented. This is a gridpoint Eulerian global model utilizing the fully compressible nonhydrostatic equations for a rotating thin spherical atmosphere.

The method employs two interacting domains with polar stereographical projections centered on, respectively, the North and South Poles. The domains interact through an equatorial interface. Interpolation fills in-
Fig. 8. (a) The 500-hPa height analysis at 0000 UTC 1 Mar 2000 (contour interval is 60 m). (b) As in (a) but the 120-h forecast verifying at 0000 UTC 6 Mar 2000. (c) As in (a) but for the 72-h forecast verifying at 0000 UTC 6 Mar 2000. (d) As in (a) but for the analysis at 0000 UTC 6 Mar 2000.

formation beyond the equator from the other domain at each model time step.

The model is fully compatible with the existing regional model code and can therefore share all of the basic subroutines handling physics and dynamics. Furthermore, its compatibility with MM5’s preprocessing system makes the domains easily reconfigurable to different resolutions and various gridded and observational data inputs. The postprocessing programs and graphics for MM5 will also work with the global output, and nesting capabilities allow the global model to provide physically consistent high temporal resolution boundary conditions to a regional domain in a focus area of interest. This makes it potentially a valuable extension to the regional model that opens several new areas of research and model validation. These areas include medium-range prediction, global data assimilation, long-term physics and dynamics evaluations, and global dynamics studies.

Tests have shown that the equatorial interface zone
behaves transparently and that while 100-day simulations are possible, further work is needed to make this model drift free for such long integrations.

The model has been demonstrated as part of a real-time medium-range forecasting system for over a year, and has shown robustness and verifiable usefulness in the multiday forecast range using a 64–128-km grid. This model is positioned well for future advances in computer technology by having a full suite of physics that has already been developed for resolutions better than 100 km. The calculation localization is such that it also should be capable of utilizing massively parallel architectures efficiently.

If computing trends continue, within a few years global NWP models will be able to run routinely with 30-km grid sizes, and within another 10 years it will be 10 km. Regional models are already able to run real-time predictions at these resolutions, and a large research community is actively engaged in improving the MM5 model for numerical weather prediction at this scale. It is clear that past and current advances made in regional model physics will apply to global models in the future. These improvements extend beyond physics to data assimilation, and model initialization techniques, as well as coupling to land surface, atmospheric chemistry, hydrology, and ocean models. Offering a single model for both global and regional application will allow us to directly link the current regional and future global model research within a single framework, which has obvious benefits for the transfer of ideas between the regional and global modeling applications.

Acknowledgments. We would like to acknowledge the support of the Air Force Weather Agency, which provided funding for this work. Computing resources have been provided by iMSC, Compaq, and ARA through a multi-year agreement with the Mesoscale and Microscale Meteorology Division at NCAR, and by the Scientific Computing Division at NCAR, funded by the National Science Foundation. Thanks also go to Al Bourgeois and John Michalakes of NCAR/MMM for parallelizing the global version of the model for the Compaq and IBM platforms used in this work. Two anonymous reviewers also made suggestions that helped us to improve the paper.

APPENDIX

Computer Requirements

For a grid length $\Delta x$ (km) at the true latitude of 60°N/ S the number of points on a side of the square hemispheric domain, $n$, should satisfy

$$n \leq \frac{a}{a + \sin \lambda} \Delta x \approx 23773 \text{ km},$$

where $a$ is the earth’s radius, to overlap the equator by a minimal $2\Delta x$ margin. This dictates the memory required for any given resolution. Table A1 shows three example grid sizes and the floating-point operations requirements to do a 24-h global forecast. Note that the cost in floating point operations goes approximately as the inverse cube of the grid size, because the time step is proportional to grid size.

To interpret the cost, a 1 Gflop s$^{-1}$ performance machine could do a 4 Tflop calculation in \((4 \times 10^{12}/10^9 = 4) \times 10^3\) s, and this is verified by timing the process on a machine that can run the global MM5 at nearly 1 Gflop s$^{-2}$ (a four-processor shared-memory Compaq ES40 computer with 660-MHz chips). This corresponds to just over an hour per forecast day. The 120-km case requires 400 Mb of internal memory, and about 100 Mb of ext-
ternal memory (disk space) for input and for each output time, and 200 Mb for each restart time.

It is difficult to compare the resolution of gridpoint models with spectral models, but one method given by Laprise (1992b) is to equate the number of grid columns, \( N_G \), with \((n_s + 1)^2\), the number of spectral coefficients (Laprise’s \( L_1 \) method), as this is an objective measure of the information content in the global fields. If we exclude the shaded regions beyond the equator in Fig. 1, the number of active grid columns is approximately given by

\[
N_G \approx 2\pi(1 + \sin\theta)\sigma/\Delta x^2
\]

and for a 120-km grid with a true latitude at 60°, \( N_G = 61,706 \) (Table A1). Equating \((n_s + 1)^2 = N_G\) gives \( n_s \approx 247 \), so this equates to a T247 truncation spectral model, which is comparable to current operational global NWP models. This may be regarded as an optimistic estimate because gridpoint models diffuse their smallest features more than spectral models, but on the other hand they can resolve the phases of long waves to the accuracy of a grid length, and can differentiate grid-length displacements of small features such as mountains, coastlines, and convection.

Alternatively, taking the mean grid size of 91 km, and comparing that with a Gaussian grid at the equator (Laprise’s \( L_1 \) method) yields an equivalent spectral resolution of about T146, which may be regarded as a pessimistic estimate of the gridpoint model’s resolution from Laprise’s arguments. The 64-km equatorial grid length may be equated to a T208 truncation by this method.

### REFERENCES


