A Case Study of Upper Boundary Condition in MM5 over Antarctica

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1. Introduction

Recently the upper boundary condition has been addressed more and more frequently because nonhydrostatic models become widely available for numerical weather prediction. Ideally, the boundary conditions should be imposed in such way that makes the flow behave as if the boundaries were not there.

In the past rigid lid upper boundary condition was utilized since it purportedly eliminated rapidly moving external gravity waves from the solutions thereby permitting longer time steps. The effectiveness of this approach has been demonstrated when the model top is set far above from the region of interest or the advective effects are dominant in comparison to the vertical propogation of internal gravity wave energy. Otherwise this condition has the undesirable effect of reflecting vertically propagating waves. Reflection does not allow the wave energy to exit the model domain; reflection traps the waves in the domain where they can erroneously interact with other waves. To overcome this flaw, another kind of upper boundary condition has been developed to avoid wave reflection at the upper boundary. Among them the radiation boundary condition proposed by Klemp and Durran (1983) has been applied to a number of climate models and mesoscale models. This condition permits internal gravity waves to exit the domain. It is more physically based. However there are some constraints when it is applied. First, it must be applied spectrally. It is difficult to employ in more generally applied numerical models because the vertical wavenumber and frequency of the radiated waves must be specified. Second, it also requires a relatively deep model domain so that the vertical radiation of gravity wave energy is of secondary importance at the model top, otherwise the spurious momentum flux is not negligible (Klemp and Durran, 1983). Absorbing upper boundary condition is another prominent scheme in this category. It tries to damp out the vertically propogating waves within an upper boundary buffer zone before they reach the top boundary by using smoothing, filtering or some other approaches such as adding frictional terms to model momentum equations.

Previous studies show that the radiation and absorbing upper boundary conditions reduce the wave reflection to a large extent, however little work has been done to investigate how they perform over those areas with steep slopes. The Antarctic continent has high and steep terrain. Internal gravity waves induced by topography are stronger than over relatively flat regions. Therefore the model top should be set higher and the absorbing factor should be stronger in order to damp out the strong internal gravity waves. The radiation and absorbing upper boundary conditions are anticipated to have less effect on reducing wave reflection when they are appied to Antarctica without any modification.

For radiation upper boundary condition, Klemp and Durran (1983) suggested truncation of the radiation condition at the small-wavenumber end. The cutoff wavenumber is determined using a reasonable estimate for ω. However, because this radiation condition is derived for pure hydrostatic gravity waves (ignoring the Coriolis forcing), the assumption used in this upper boundary condition may be no longer valid over Antarctica where the internal gravity-inertia waves propagated upwards are very strong due to steep topography and a strong Coriolis forcing. Therefore the approach to reduce the cutoff wavenumber cannot fully solve the problems caused by the radiation upper boundary condition.

Further raising the model top must be limited as a result of constraints in computer resources. Moreover when the model top is set within the stratosphere, the interaction between troposphere and stratosphere has to be considered in the model physics. This interaction may be important for climate simulation but will bring extra complexity for weather prediction. Therefore increasing absorbing factor should be

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a promising approach to solve upper boundary condition problem in the Antarctica. However as implied by the results of Morse (1973) the increasing filtering cannot be applied abruptly at some selected distance from the boundary because erroneous reflection back into the internal model will result. As Pielke (1984) pointed out, both insufficient damping and excessive damping in the absorbing layer will cause reflection. In addition, an absorbing layer whose depth is greater than the vertical wavelength of the mesoscale disturbance is required.

In this study, a new nudging upper boundary is designed. The large-scale forcing is nudged to model simulation with exponential function within absorbing upper boundary layers. In this way the smoothing and filtering increase more gradually from the bottom absorbing layer to the model top. Considering its baroclinic feature in the tropopause and the lower stratosphere, only temperature field is applied to this condition, and winds can be adjusted freely according the model physics. Polar MM5 is applied to simulate the synoptic and mesoscale evolution of the atmospheric state over Marie Byrd Land and Siple Coast, West Antarctica, for 9-14 October 1995 with different upper boundary conditions. Global Positioning System / Meteorology (GPS/Met) soundings are adopted to validate model results.

2. Model description and experimental design

The model used in this study is Polar MM5 V2. It is a version of Pennsylvania State University/ National Center for Atmospheric Research (PSU/NCAR) MM5 specifically adopted for polar regions (Bromwich et al, 2001). The main modifications get a better representation of the cloud cover and radiative fields over extensive ice sheets. The ice nuclei concentration equation (Meyers et al., 1992) is implemented in the explicit microphysics parameterization of the Polar MM5. The cloud ice and water content predicted by the explicit microphysics parameterization is now used to determine the radiative properties of clouds in the CCM2 radiation parameterization. Two additional substrate levels [which increases the substrate depth to 1.91 m (Compared to 0.47 m in the unmodified version)] are added to the multi-layer soil model proposed by Dudhia (1996). A final modification to MM5 is the addition of variable fraction sea ice surface type. This surface type allows a fractional sea ice cover to be specified for each oceanic grid point in the model domain. The surface fluxes for sea ice grid points are calculated separately for the open water and sea ice portions of the grid points and averaged before interacting with the overlying atmosphere.

For the simulations discussed in this extended abstract, the Polar MM5 is used with the nonhydrostatic option. 9-14 October 1995 is chosen as the simulation period. During this period a number of synoptic scale low pressure systems crossed the Marie Byrd Land coast and moved inland over West Antarctica. The initial and boundary conditions are generated by ECMWF TOGA data [European Centre for Medium-Range Weather Forecasts (ECMWF) Tropical Ocean-Global Atmosphere (TOGA)].

Figure 1 shows the model domain and topography. It includes 121x121 grid points at the horizontal resolution of 60km. There are 28 full vertical sigma levels.

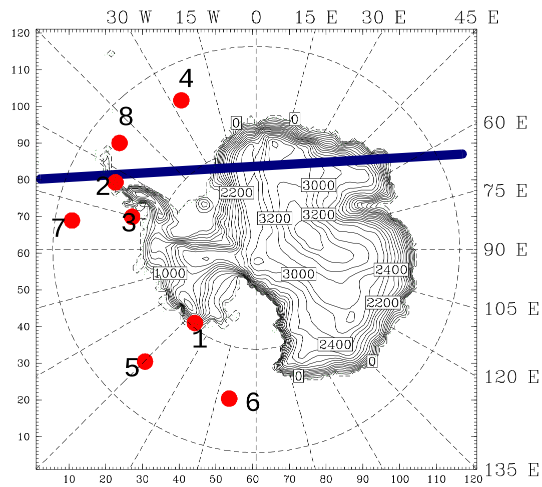

Fig.1 Model domain and topography (Red Dots are GPS/Met points and the blue line is for cross-section discussed later)

8 experiments with different upper boundary schemes have been designed in this study (Table 1). The model top is set to 100 hPa for the first three experiments and 10 hPa for the other five. In standard MM5, the truncated wavenumber for the radiation condition is 6. As mentioned in the first section, in order to eliminate the spurious momentum flux generated at the model top, the wavenumber should be truncated at the small end over the Antarctic. So in Exp.Wave3 the truncated wavenumber for the radiation boundary condition is 3. The procedure that is used in Exp. Asm is a simple (Shapiro) filtering with gradually decreasing strength from complete four-point smoothing at the top to no additional smoothing at level six. The damping is applied to temperature, wind and specific humidity fields. Rayleigh frictional term is added to the momentum equations in the up 5 model layers. The frictional coefficient increases with the height. In Exp. Nudge, the relaxation lateral

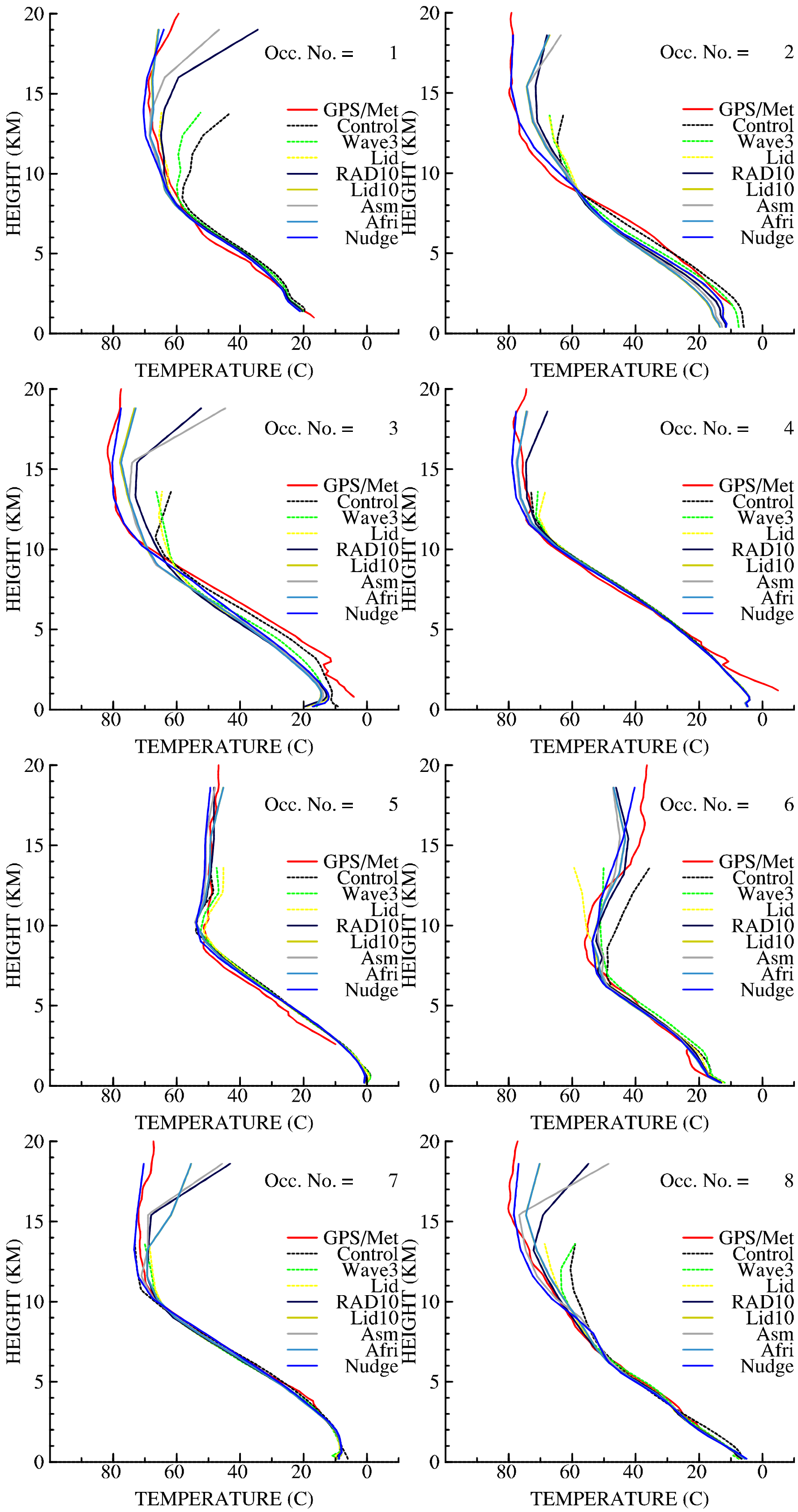

Fig.2 Temperature Sounding

boundary condition proposed by Davies and Turner (1977) is revised as a upper boundary condition. The temperature tendency in up 8 model layers is given as follows:

$$(\frac{\partial \alpha}{\partial t})_n = F(n)F_1(\alpha_{LS} - \alpha_{MC}) - F(n)F_2\Delta_2(\alpha_{LS} - \alpha_{MC}) \quad n=1,2,\ldots,8 \qquad (1)$$

α_{LS} is a large-scale value, and α_{MC} is a model solution value. N=1 is the model top level. We have changed F from a linear function to an exponential function so the nudging decreases more gradually from the top boundary to the bottom of the buffer zone.

$$F(n) = e^{-\frac{n+3}{9-n}} \qquad n=1,2,\ldots,8 \qquad (2)$$

Where F_1 and F_2 are given by

$$F_1 = \frac{1}{10\Delta t} \qquad (3)$$

$$F_2 = \frac{\Delta s^2}{50\Delta t} \qquad (4)$$

Δt is time step and Δs is model horizontal resolution.

Experi-ment	Upper Boundary Condition	Model Top (hPa)	Description
Control	radiation	100	truncated WN=6
Wave3	radiation	100	truncated WN=3
Lid	rigid lid	100	
Rad10	radiation	10	truncated WN=6
Lid10	rigid lid	10	
Asm	absorbing	10	smoothing u,v,t,q at up 5 layers
Afri	absorbing	10	Adding rayleigh friction at up 5 layers
Nudge	nudging	10	exponential function for top 8 layers

Table 1 Experiments

3. Results

(1) Temperature Sounding and sea level pressure

Figure 1 shows eight GPS/Met points whose observed time is just within one hour from our model simulation output times. The first three points are located in continent and the other points are over the ocean. And point 8 is close to the coast. Figure 2 depicts the vertical temperature soundings for GPS/Met and 8 simulation experiments. The values of the model simulation are interpolated to GPS/Met height coordinate. In general the model simulation has a good agreement with GPS/Met in the lower and the middle troposphere. Over those areas where the internal gravity waves are almost impossibly generated by terrain such as points 4, 5 and 6, there is less difference among different experiments, and even in the model top the model simulates temperature pretty well compared with GPS/Met. However the large difference is found among different simulations at the top of those soundings over the continental Antarctic or the ocean close to the coast where the strong internal gravity waves are generated over these areas due to the topography. Exps. Control and Wave3 produce the worst results though the latter makes some improvements as a result of the reduced cutoff wavenumber.

When the model top is raised from 100 hPa to 10 hPa, the model generates more reasonable temperature profile. There is not too much difference between Exp.Lid10 and Exp. Afri, which indicates that the frictional coefficient used in Exp. Afri maybe too small. From the profiles over points 3, 7 and 8, the temperature linearly increases with the height for Exp. Asm. It implies that there are some wave reflections from the upper boundary in this case. One of the possible reasons is that the smoothing coefficient is not used properly in this experiment. It is clear to see that Exp. Nudge produces the best temperature profile over anywhere.

Some relatively large biases of sea level pressure are also found among the simulations. Raising the model top from 100 hPa to 10 hPa has reduced the biases significantly. Only slight further improvement is found in Exp. Nudge compared with Exp.Top10.

(2) Upper level jet and 500 hPa geopotential height

6-day mean wind velocity at 200 hPa (not shown) implies that control run underestimates the magnitude of the upper level jet as large as 10 m/s. From the vertical cross sections along the line (shown in Fig.1) of wind velocity at 00UTC, October 9 1995 (not shown), the location of the upper level jet is near 250 hPa. while it is simulated 50 hPa lower in the control run and the magnitude is 5 to 10 m/s lower than ECMWF/TOGA data. Both Exp.Top10 and Exp.

Nudge get the correct location of the jet, but the magnitude in Exp. Nudge is closer to analysis data.

(3) Wave reflection

Maddox's (1980b) band-pass filter, based on Barnes's scheme, is applied to the vertical velocity. It is found that that with the radiation boundary condition the large scale waves can pass the boundary unreflected, however for the scale of internal gravity-inertia waves (< 1000 km), there are some reflections when they reach the upper boundary. The same reflections are also found for rigid lid and absorbing upper boundary condition even for longer scale waves. However less wave reflection has been found in Exp. Nudge when nudging upper boundary condition with exponential function is applied.

4. Conclusion

In this study the effects of upper boundary conditions on mesoscale modeling over the Antarctic have been investigated. It is found that:

(1) Because the Antarctic has high and steep terrain which easily generates internal gravity waves, the model top should be set relatively high so that the model has enough space to damp these waves before they propagate to the upper boundary. Otherwise there are some wave reflections near the upper boundary which can lead to large biases in temperature, wind and sea level pressure.

(2) Further raising the model top is at the expense of computational resource. The alternative approach to solve the wave reflection at the upper boundary is to find some smoothing and filtering to damp out the internal gravity waves. And the strength of damping should be dependent on the strength of the propagating waves. The reflection will be generated no matter whether the damping is too strong or too weak. The nudging upper boundary with proper damping scheme has been demonstrated to be promising to solve the wave reflection in the model top over those areas with complex and steep terrain such as Antarctica.

(3) The current radiation upper boundary in MM5 is derived for pure hydrostatic gravity waves without considering Coriolis forcing. The assumption used in this upper boundary condition may be no longer valid over Antarctica where the internal gravity-inertia waves propagated upwards are very strong due to steep topography and a strong Coriolis forcing.

5. Acknowledge

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