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HIGH-RESOLUTION WINTER-SEASON NWP: PRELIMINARY EVALUATION OF THE WRF ARW AND NMM MODELS IN THE DWFE FORECAST EXPERIMENT

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The Weather Research and Forecast (WRF) Developmental Test Center (DTC) conducted a winter NWP forecast experiment from 10 January to 31 March 2005 - the DTC Winter Forecast Experiment (DWFE). The experiment consisted of running daily 48h forecasts using the Advanced Research WRF (ARW) model (Skamarock et al, 2005), developed at NCAR, and the Nonhydrostatic Mesoscale Model (NMM, Janjic, 2003; Janjic et al, 2001) developed at NCEP. The two models were run at high resolution (Δx = 5 km) for the continental US, and the full model fields at 3 hour intervals during the forecast are available to the community on the NCAR mass storage system. More information about the forecast experiment can be found on the DTC website at *http://www.dtcenter.org/projects/dwfe*.

From a large-scale perspective, the forecasts are very similar. This is perhaps to be expected because the initial conditions and boundary conditions for both models are interpolated from the 40 km Eta analyses and forecasts (derived from the 12 km Eta). Hence, the high-resolution DWFE forecasts largely represent a downscaling of the larger-scale forecasts.

An important question to address pertains to the accuracy of the downscaling: are the dynamics, kinematics, and statistics of the smallest resolvable structures correct, and do they verify against observations? Verification of the smallest resolvable structures is difficult, so, to complement and augment the traditional verification computed for the DWFE forecasts, we have been examining (1) the smallest-scale structures produced by the models, and (2) the mesoscale portion of kinetic energy spectra of the model forecasts. We have found that the ARW's and NMM's DWFE forecasts often evince different structures on the smallest resolvable scales and different spectra in the mesoscale. To summarize briefly:

(1) At low atmospheric levels on the smallest scales representable on the grid (2-4 Δx), the NMM's DWFE forecasts contain more kinetic energy than the ARW's forecasts. In addition, compared to the ARW forecast fields, the NMM forecast fields at low levels and smallest scales often evince more structure, and these 2-4 Δx structures sometimes appear unphysical.

(2) At upper atmospheric levels through most of the mesoscale, the NMM forecasts appear smoother and possess less kinetic energy than the ARW forecasts.

With regard to item (2), we note that, from large scales most of the way down through the mesoscale, and at all atmospheric levels, the ARW forecasts exhibited kinetic energy spectra that closely resemble climatologically observed spectra. The NMM model's spectra resembled the climatological observations at large scales, but on mesoscales at upper atmospheric levels they exhibited significantly less energy than the climatological observations.

With regard to item (1), we note that the models cannot resolve the smallest representable scales (2-4 Δx) accurately, and we point out that these are the scales where the ARW forecasts contained less energy than the NMM forecasts at all atmospheric levels.

We hypothesize that the two major forecast differences noted above are due largely to differences in numerical dissipation and filtering configurations in the models. Secondarily, because the NMM used unsmoothed terrain for its DWFE forecasts whereas the ARW used smoothed terrain, we hypothesize that unsmoothed terrain might also contributed to NMM's greater kinetic energy at the smallest representable scales.

Model filters should remove structures on the smallest scales representable that are not accurately resolvable, or such structures should be forced as little as possible in the first place. We also believe that the forecast kinetic energy spectra should resemble climatologically observed spectra in most contexts (such as DWFE's). Modifying the dissipation and filtering in NMM, and using smoothed terrain, should improve the NMM's performance in both areas.

In the remainder of this preprint, we show examples of DWFE forecasts and present kinetic energy spectra, and we outline results of ongoing tests of dissipation, filtering configurations, and terrain smoothing in the NMM that are more like configurations used in other mesoscale models. With these trial configurations, the NMM produces kinetic energy spectra that more closely

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resemble climatological observations down through most of the mesoscale and less strongly forces the smallest-scale structures, as does the ARW model. We are currently formulating and testing higher-order horizontal filters for the NMM that should more-strongly filter the smallest-scale structures.

1. ARW AND NMM FORECAST DIFFERENCES

An example of the differences between NMM and ARW forecasts appears in Figure 1, which shows contours of potential temperature in a vertical cross section extending from northwest of Washington state to central Texas for a 12 hour forecast valid at 12 UTC January 13, 2005. At upper atmospheric levels, the NMM forecast appears noticeably smoother and the topographically-forced gravity waves smaller in amplitude than in the ARW forecast, consistent with observation (2) summarized in the introduction.

Which forecast better predicts the atmospheric state in the mesoscale, including the smallest scales representable in the models? We have few observations at these scales (especially aloft), and features on these scales are predictable, in a deterministic sense, only for a much shorter time than the DWFE forecast time scale, so a more appropriate question might be: Are the structures on mesoscales down to the smallest representable scales correct in a statistical sense?

One statistical measure that can help us address this question is the atmospheric kinetic energy (KE) spectrum. For example, Skamarock (2004) examined the ARW model's atmospheric KE spectra for high-resolution forecasts, mostly for warm-season convection over the central US[*]. Following Skamarock (2004), we have computed KE spectra for the DWFE forecasts. Figure 2 shows 24-48 hour averaged ARW and NMM DWFE forecast KE spectra, averaged over the period from January 7-25, 2005. (We show 24-48 hour forecast KE spectra because the spectra typically "spin up" fully by 24 hours). Although similar at large scales, the model KE spectra differ substantially in the mesoscale. The ARW forecast spectra exhibit the climatologically observed transition from a wavenumber (k) dependence of k^{-3} at large scales to $k^{-5/3}$ in the mesoscale at all levels in the free troposphere and lower stratosphere. (See Nastrom and Gage (1985) and Lindborg (1999) for details about the climatological observations). In contrast, the NMM spectra in the lower and middle troposphere exhibit at best a subtle transition, while in the upper troposphere it exhibits a KE dependence of k^{-3} throughout the mesoscale (i.e., the spectrum exhibits no transition).

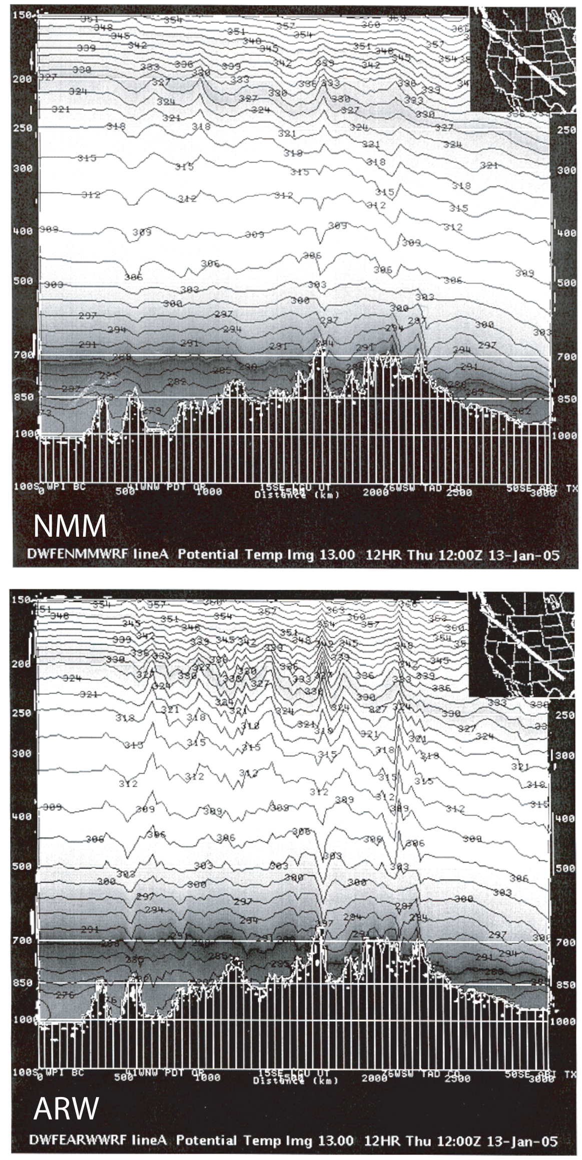

Figure 1. Vertical Cross sections of potential temperature (c.i. = 3 K) from the ARW and NMM 12 hour forecasts valid 12 UTC 13 January 2005.

These spectra are consistent with the potential temperature fields shown in Figure 1; that is, at upper atmospheric levels (e.g., 300-200 mb) in the mesoscale, the NMM forecasts contain less energy than do the ARW forecasts (Figure 2), and NMM's fields aloft are smoother and structures are smaller in amplitude (Figure 1).

Figure 2 also shows that at lower atmospheric levels, the NMM forecasts contain more KE at the smallest wavelengths than ARW's forecasts. This difference is not obvious in Figure 1, but further examination of the NMM forecast fields reveals significant structures at the smallest representable scales. For example,

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[*] Skamarock and Baldwin (2003) and Janjic and Black (2003) discussed spectra computed from forecasts by earlier configurations of NMM and ARW. These papers and further discussion can be found at *http://www.mmm.ucar.edu/individual/skamarock/spectra_discussion.html*

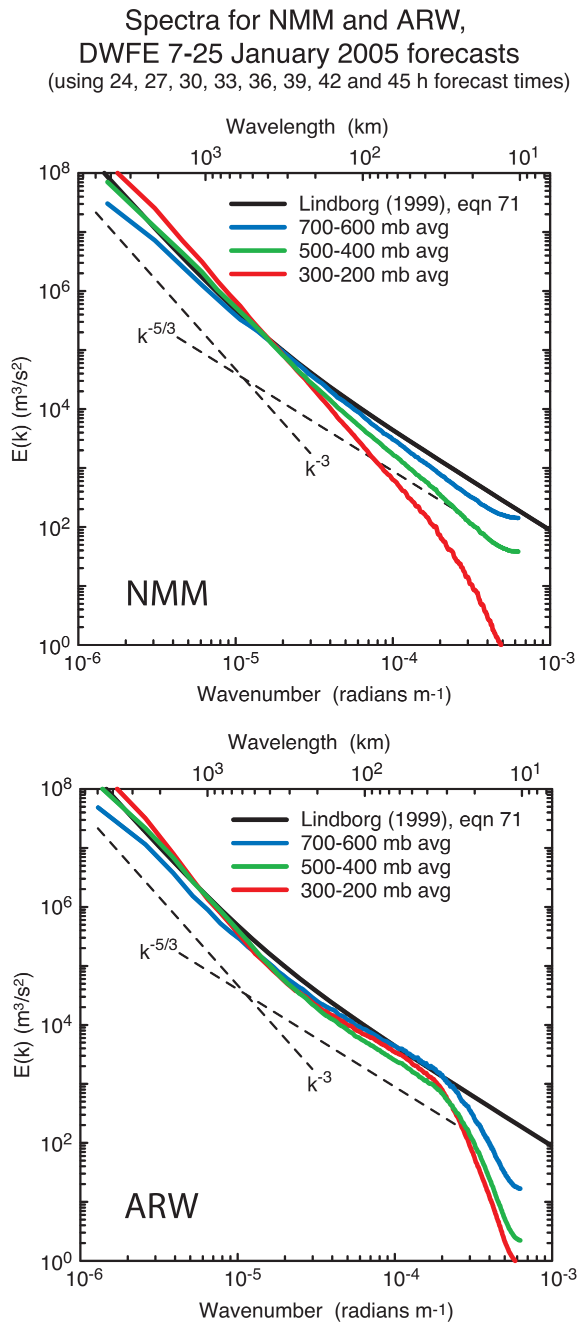

Figure 2. Spectra from the 5 km DWFE forecasts from 7-25 January 2005. The black curve is a function fit to spectra derived from the MOZAIC aircraft observations by Lindborg 1999.

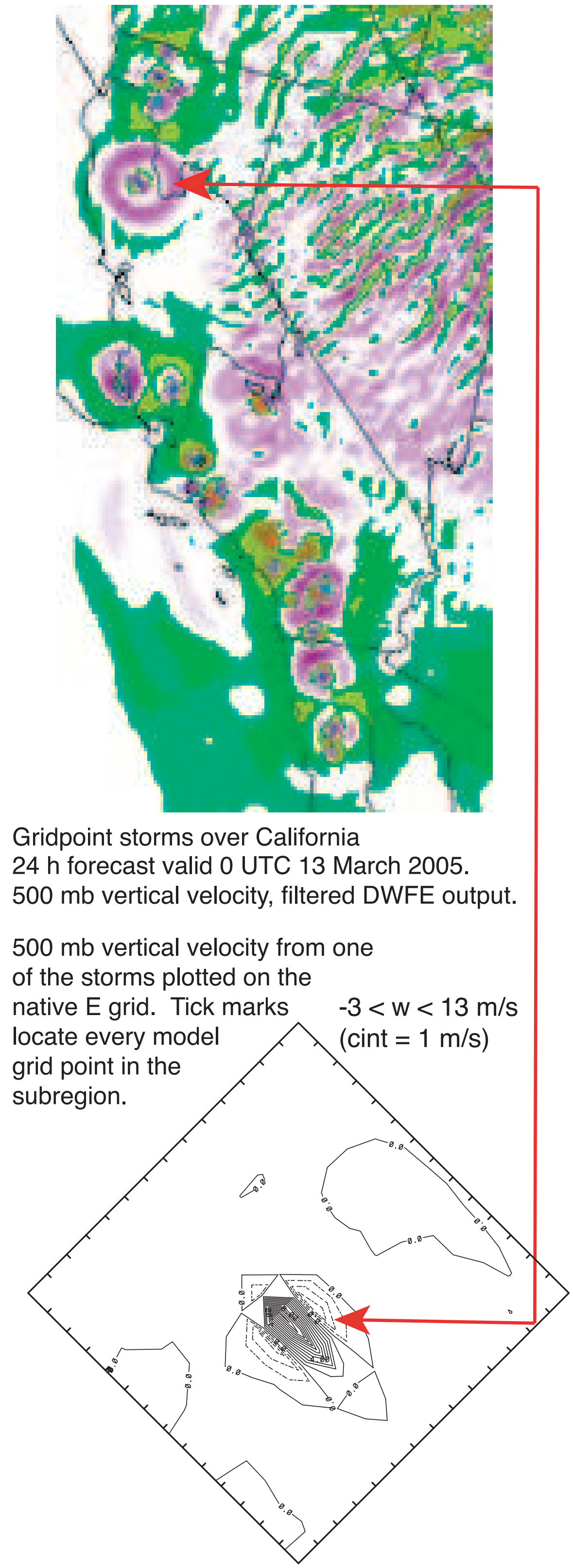

Figure 3. 500 mb vertical velocity over California from the NMM 24 hour forecast valid at 0 UTC 13 March 2005.

Figure 3 shows the vertical velocity at 500 mb in a 24 hour NMM DWFE forecast valid 00 UTC March 12, 2005. The gridpoint storms visible over the coastal mountains of California (which were not supported by observations and did not appear in the ARW forecasts) have large-amplitude updraft/downdraft structures with $2\Delta x$ wavelengths. A convective parameterization might have controlled such features, but by intent the ARW and NMM models treated convection explicitly in DWFE (i.e., convective parameterizations were not used). Finite difference models do not accurately integrate the equations of motion on scales of 2-4 Δx (see Durran, 1991), so in lieu of adequate treatment of transport and other effects on these scales by model physical parameterizations, filters and dissipation mechanisms should suppress the smallest-scale features.

It is not obvious whether or not structures such as the gridpoint storms shown in Figure 3 account for the NMM's higher levels of kinetic energy at the smallest representable wavelengths at lower atmospheric levels (compared to the ARW spectra). However, both higher KE levels at the smallest scales and the appearance of small-scale structures of questionable physical relevance suggest that the NMM's DWFE forecasts should benefit from adjustments to its dissipation and filtering configurations.

2. MODEL FILTERS

We believe that it is primarily the model dissipation and filter configurations that account for the bulk of the mesoscale KE energy differences between the NMM's and ARW's DWFE forecasts.

First consider the upper atmospheric levels. We postulate that the NMM's DWFE forecasts contain less kinetic energy than both the climatological observations and the ARW forecasts because the NMM applies horizontal-divergence damping to the velocity field, which filters horizontally divergent motions. However, in the mesoscale, divergent motions begin to dominate the atmospheric kinetic energy. While large-scale models do not accurately resolve such motions and hence filter them, mesoscale models should resolve many divergent motions well. Among the divergent phenomena suppressed by horizontal-divergence damping in the NMM's DWFE forecasts are vertically-propagating, topographically forced gravity waves. Horizontal-divergence damping should progressively reduce the amplitude of these waves with increasing altitude, consistent with Figures 1 and 2.

Why is it important to produce the correct velocity variance at upper atmospheric levels? Large-scale models parameterize gravity wave drag, which is associated with breaking gravity waves in the upper troposphere and lower stratosphere, but high resolution mesoscale models should resolve breaking gravity waves explicitly. Gravity wave drag cannot be modeled explicitly if gravity waves are not allowed to propagate into upper levels. In addition, forecasts of clear air turbulence require correct velocity variances.

The horizontal-divergence damping filters not only gravity waves but all horizontally divergent motions, including, for example, convection, convective systems, and fronts, all of which are strongly divergent. Additionally, in ensemble forecasts, under-prediction of the velocity variance could lead to an underestimate of ensemble spread and hence forecast uncertainty. Similarly, in data assimilation applications, models that lack velocity variance will likely underestimate error covariances.

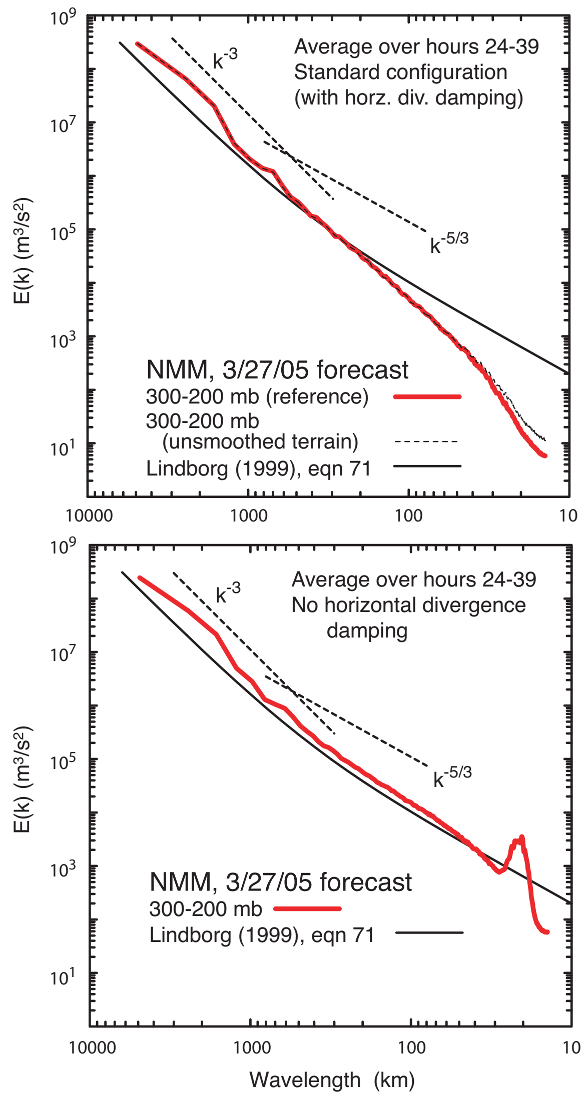

Figure 4. Kinetic energy spectra at upper levels from the NMM forecast for the 27 March 2005 forecast initialized at 0 UTC. The upper panel is spectra from the control (with horizontal divergence damping) showing results with and without terrain smoothing. Note that the forecast labeled reference uses filtered terrain. The bottom panel shows spectra for the reference configuration except without horizontal divergence damping.

2.1 *An External Mode Filter*

To test our hypotheses that (1) NMM's horizontal-divergence damping is responsible for the depressed mesoscale KE at upper atmospheric levels, and (2)

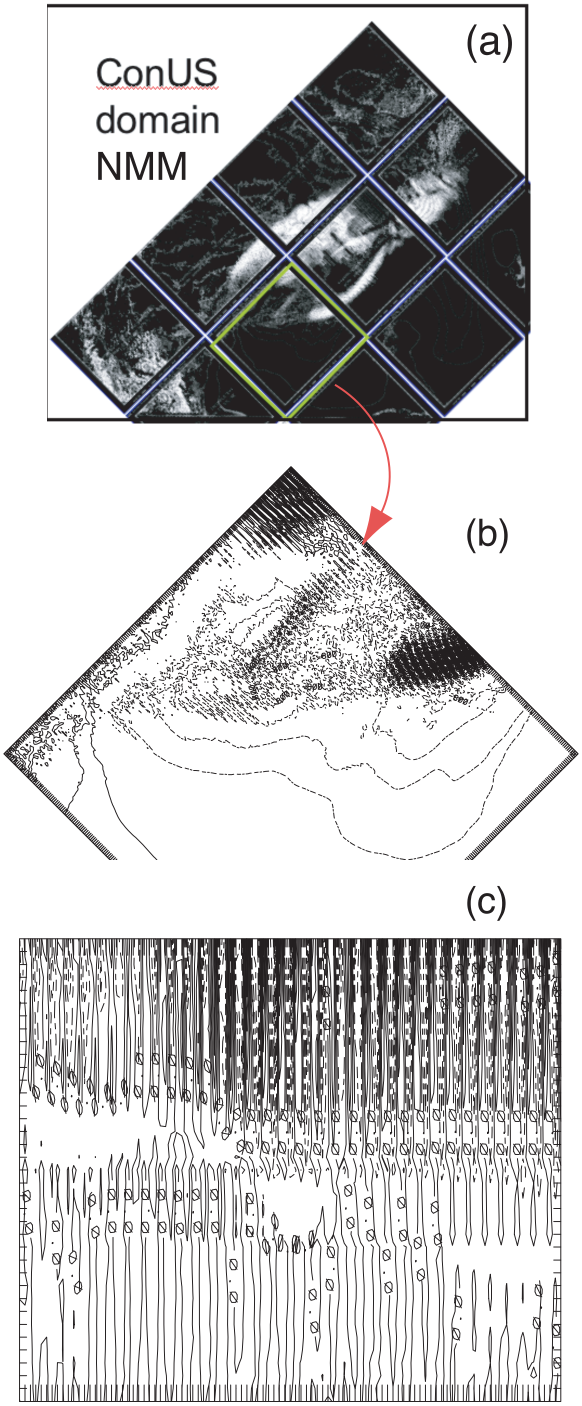

Figure 5. (a) Horizontal plot of $0 \longrightarrow 3$ hour pressure change plotted on the native E-grid, and (b) a close-up of a subregion. The contour interval is 2/3 mb/h. (c) A vertical cross section of vertical velocity at 3 h, through one of the subregions, showing the structure of the external mode. The contour interval is 0.5 m/s, and $-10 < w < 9.5$ m/s.

unsmoothed terrain contributes to higher KE in the smallest-wavelength portion of the spectrum, we have

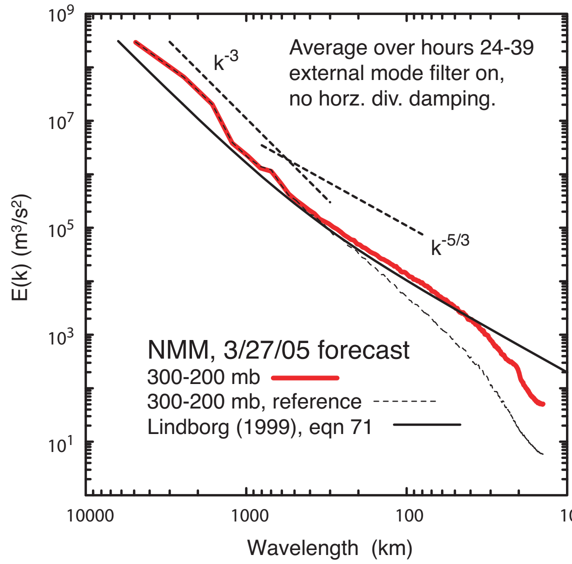

Figure 6. Spectra from the NMM forecast using an external mode filter and without horizontal divergence damping. The results for the reference simulation (with horizontal divergence damping) is also shown for comparison.

re-run the NMM in several configurations for a representative DWFE case (initialized at 00 UTC March 27, 2005).

First, we smoothed the NMM's terrain by applying a Cressman filter (with radius of influence 1.8 times the model grid spacing) to $30'$ lat/lon terrain data. This produced a terrain energy spectrum closely approximating the ARW model's during DWFE (though the ARW used a different smoothing method). We then re-ran the NMM using the smoothed terrain. As expected, the KE at the smaller-wavelength end of the spectrum decreased modestly at all atmospheric levels, by as much as a factor of two (see the top panel in Figure 4). For subsequent NMM reruns (described below) we continued to use the smoothed terrain.

Figure 4 shows the 24-39 hour (averaged) forecast KE spectra for a reference run of the NMM and for a rerun with the horizontal-divergence damping turned off. With the damping removed, the mesoscale kinetic energy in the upper atmosphere (300-200 mb) increases to climatologically observed levels, and the slope of the spectrum exhibits the climatologically observed transition from k^{-3} to $k^{-5/3}$ dependence. Unfortunately, a large anomaly also develops in the KE spectrum near the gridscale. Examination of the forecast reveals that this anomaly is associated with large amplitude external modes in the solution, with energy that peaks at wavelengths of about $3\Delta x$ at all atmospheric levels. The external modes, which had previously been suppressed by the horizontal-divergence damping, are depicted in Figure 5.

To address this new problem we have implemented an external-mode filter in the NMM, borrowing its formulation from a similar filter in the ARW (Skamarock et al, 2005). Figure 6 shows NMM's KE spectrum for the test where we remove the horizontal-divergence damping (as before) but add the external-mode filter. The external-mode filter effectively removes the anomalous energy near the gridscale while retaining the energy at longer wavelengths.

In experiments with the ARW model several years ago, we encountered evidence of high-frequency external modes produced by imbalances in the initial fields. These modes led us to develop the external-mode filter currently used in the ARW model. To see if the ARW would produce external modes for the 27 March 2005 DWFE case, we reran the ARW DWFE forecast without the external mode filter. However, we were unable to reproduce the anomalous, near-gridscale kinetic energy produced by NMM. The ARW has no horizontal-divergence damping, which raises the question: why didn't the ARW produce the same anomalous external-mode energy as NMM in our test forecasts? There are several possible explanations. First, although both models were configured with weak, 2nd-order, explicit horizontal diffusion, the NMM's advection scheme has no implicit diffusion whereas ARW's higher-order advection scheme has high-order implicit diffusion. As a consequence, removing horizontal-divergence damping from NMM leaves it with less dissipation than the ARW (as evidenced by the KE spectra at the smallest scales). It is possible that the ARW model's implicit diffusion helps it control external modes even without an explicit external mode filter. However, in one test rerun, increasing the strength of NMM's 2nd-order horizontal diffusion did little to control the external modes in our test case. Second, the NMM is using a time-splitting scheme that is only first-order accurate and has been known to produce gridscale noise on occasions (Purser and Leslie, 1991; Skamarock and Klemp, 1992). Also, the NMM uses a second-order Adams Bashforth time integration scheme (Janjic, 2003) that is unconditionally unstable without filtering (see Durran, 1991). It may be that the level of filtering, without the horizontal divergence damping, is insufficient in some cases to stabilize the Adams Bashforth Scheme for these high frequency external modes.

2.2 *Model Dissipation*

Replacing the NMM's horizontal-divergence damping with an external mode filter produces KE spectra that much more closely resemble the climatologically observed spectra, including the transition to $k^{-5/3}$ dependence in the mesoscale. However, aside from removing external modes, the external mode filter does not otherwise reduce the NMM's forecast kinetic energy in poorly resolved structures near the gridscale. In

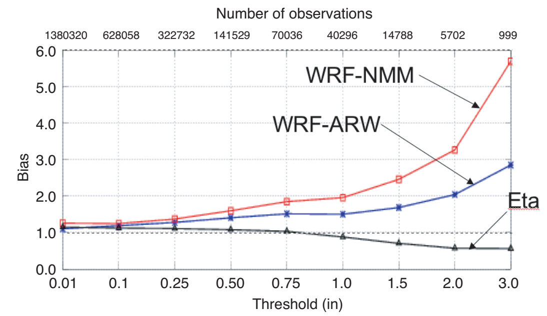

Figure 7. Precipitation biases for the NMM, ARW and Eta forecasts for 15 January - 31 March DWFE forecasts.

gridpoint models, significant energy at these scales can reflect unphysically to the larger scales, which can produce a spurious $k^{-5/3}$ spectral slope dependence. This problem, discussed in more detail in Smith (2004) and in Skamarock (2004), can be alleviated by tuning model filters to remove energy at the gridscale such that KE drops sharply at the smallest wavelengths ($< 4\Delta x$).

Greater gridscale filtering in NMM might help control the unphysical small-scale structures of the sort shown in Figure 3 and discussed in Section 2.0. Perhaps not coincidentally, the NMM DWFE forecasts exhibited a very high precipitation bias at the higher precipitation thresholds (see Figure 7), higher than the ARW's bias (possibly significant statistically) and much higher then the eta model's (negative) bias for the same forecast period. (Precipitation biases were computed as part of the standard verifications of the DWFE forecasts.) Both the appearance of unphysical gridscale structures and high precipitation biases at high precipitation thresholds also point to the need to improve the model physics, but in lieu of such improvements, grid-scale features should be filtered.

All three of these measures of model behavior (KE spectra, the appearance of grid-scale 'storms' and other gridscale structures, and precipitation biases) suggest that the NMM could benefit from more gridscale filtering. We have experimented with the 2nd-order horizontal diffusion in the NMM, but our experience shows that this filter is not very scale selective. Increasing this filter's damping rate, while filtering the gridscale noise, also significantly damps the well-resolved mesoscale modes (that is, features with wavelengths $> 10\Delta x$). This is not unexpected (see Skamarock 2004), and almost all cloudscale, mesoscale and large-scale models use higher-order filters. We are currently testing 4th-order horizontal diffusion for the NMM, and we expect the results to be consistent with the results in Skamarock (2004). That is, the higher-order filter should be more scale-selective and will remove energy at the gridscale while retaining more of the velocity variance at the larger scales. We hope to report on the 4th-order diffusion results at the conference.

3. ACKNOWLEDGEMENTS

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