Effects of Horizontal Model Resolution on Convection

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Abstract

Model resolution has continued to increase across the years as technology and computation power advance forward, resulting in high resolution forecasts. The purpose of this study is to determine whether there is increased forecast skill by switching from a 3-km grid spacing model to a 1-km grid spacing model. An analysis is performed on the case day of July 14th, 2010, utilizing data collected during the Polarimetric Cloud Analysis and Seeding Test 3 (POLCAST3). 3-km and 1-km resolution model forecasts are generated and skill is assessed to the forecasts subjectively and objectively using the Method for Object-Based Diagnostic Evaluation (MODE) Tool to compare the forecasts to observations. It is determined that for the case day, the 1-km model did not increase forecast skill, and the 3-km and 1-km models looked significantly more like each other than that which was actually observed.

1. Introduction

As technological advances move our world forward, computer resources and computational power continue to increase, leading to more high-resolution numerical weather models. Progress of constant gain in computer resources can be seen in the Eta model. The Eta model was originally run at a horizontal resolution of 80 km in 1993 (Black et al. 1993; Rogers et al. 1995) and after regular updates, since 2001, it is currently running at a 12 km resolution. In 2005 it was renamed to the North American Mesoscale (NAM) model, acquiring Weather and Research Forecasting (WRF) physics a year later. Currently there are nested 4-km high-resolution runs of the NAM model available (Rogers et al. 1998).

It is clear that with increasing computer resources, Numerical Weather Prediction (NWP) model resolutions have increased significantly, leading to what are considered more accurate and more realistic representations of mesoscale phenomena. Resolutions of 4 km and finer allow for convection to be explicitly resolved as convective parameterizations are turned off, a practice that is considered erroneous and unrealistic with 5-km to 10-km grid resolution (Weisman et al. 1997). As resolution continues to increase, numerous questions arise of whether the benefit of increased resolution is worth the computational cost associated with it and whether there actually is a significant enough improvement in forecast skill to need finer resolution models.

2. Background

During the summer of 2010 (June 22nd – July 23), the Polarimetric Cloud Analysis and Seeding Test 3 (POLCAST3) field campaign was conducted with the purpose of researching the effects of hygroscopic seeding flares in North Dakota's weather modification program. During the campaign, a locally run WRF model was used to forecast convection in the target region. The purpose of these forecasts was for flight planning and to create a timetable for when the seeding aircraft and research Citation would fly to areas of convection and convective initiation. The University of North Dakota's (UND) C-band dual polarimetric radar was also scanning the region during times when convection was present.

The WRF model used to forecast for the POLCAST3 field campaign had 3-km horizontal grid spacing with explicitly resolved convection. The model was initialized daily at 00 UTC, and forecasts were made hourly out to 36 hours. Initial conditions were taken from the 40-km NAM forecast and interpolated to a 27-km domain, which contains a nested 9-km grid, and the nested 3-km grid used for the campaign forecasts. The dimensions of the 3-km model grid were 126 by 114, and contained 44 vertical levels, with more levels concentrated near the boundary layer.

The microphysical scheme is the WRF Single-Moment 6-class scheme, which accounts for ice, snow, and graupel processes, and is a good representation of actual atmospheric processes for high-resolution simulations according to the WRF-ARW User's Guide (UCAR ARW User's Guide 2011). Longwave radiation is parameterized with the Rapid Radiative Transfer Model (RRTM) scheme and shortwave radiation with the Dudhia scheme. The surface layer is simulated using the MM5 similarity parameterization, which is based on Monin-Obukhov with Carlson-Boland sub-layer. Land surface processes are represented by the Noah Land Surface Model. The planetary boundary layer (PBL) scheme is the Yonsei University Scheme. Simple diffusion is used as well as 2D deformation K option, with the PBL scheme handling vertical diffusion. Cumulus parameterization is utilized for the 27-km domain as well as the 9-km nested grid but not for the 3-km nested grid.

Since there was an option to switch to a 1-km model to forecast for the POLCAST4 field campaign, which occurred in the summer of 2012, the idea arose of whether a 1-km resolution model would provide significant benefit and higher forecast accuracy over a 3-km grid spacing model. The 1-km resolution is hypothesized to be able to replicate the formation, structure, and evolution of convection better, thereby improving explicitly resolved convection (e.g. Weisman et al. 1997; Petch et al. 2002; Bryan et al. 2003; Petch 2006). This hypothesis is especially true of organized linear features such as squall lines (e.g. Shamarock et al. 1994; Weisman et al. 1997; Bryan et al. 2003; Bryan & Morrison 2012), and supercells (e.g. Droegemeier et al. 1994; Alderman & Droegemeier 2002; Fiori et al. 2011). However, in a study done by Kain et al. (2008), in which a comparison of 4-km and 2-km simulated reflectivity fields was done, they state that although 2-km forecasts provide more detailed depictions of convection, there is little to no added forecast skill, and if there was, it was not worth the computational costs of increased resolution. The study stated that model simulated reflectivity in both the 4-km and 2-km simulations tended to look more like each other than observed base reflectivity.

The purpose of this to study is to determine if an increase in resolution is beneficial for forecasting summer convection in eastern North Dakota, by comparing 3-km and 1-km forecast skill. To achieve this purpose, the 3-km POLCAST3 forecasts will be rerun at a 1-km model resolution, and both the 3-km and 1-km forecasts will be compared to observations and to see if there is an improvement in forecast skill. Forecast skill will be determined by specifically comparing simulated reflectivity directly with observed reflectivity.

3. Methodology

(a) Simulations

To be able to compare only the effects of horizontal changes in resolution, the 1-km model setup matched the 3-km WRF model setup used during POLCAST3 campaign, including the microphysics. Unfortunately due to unavailability and formatting of the 40-km NAM data that was used to initialize the 3-km POLCAST3 runs, it could not be used to initialize the WRF model. Therefore, the WRF model had to be initialized using North American Regional Reanalysis (NARR) data. NARR data has a resolution of 32-km and since it is reanalyzed data, it has observations reintegrated every three hours (Mesinger et al. 2006), which does not allow for as much error to accumulate as would with a regular forecast. Due to the differences in NAM and NARR resolution and NARR observation reintegration, it would not be suitable to compare the 3-km initialized with the NAM and 1-km initialized with the NARR. Therefore, the 3-km model would also be rerun using NARR data so that the 3-km and 1-km are comparable. For the 1-km grid setup, the 3-km grid was extended so the new 1-km grid could be nested within it. The 3-km grid is still nested within the 9-km grid and the parent 27-km grid as seen in Figure 1.

All the data collected across the POLCAST3 field campaign could not possibly be objectively analyzed due to computer resources and time constraints. Therefore, a case was subjectively selected from the 3-km (NAM initialized) WRF runs based on differences in areal coverage of observed versus simulated reflectivity. The case selected occurred on July 14th, 2010. The case was selected since the forecast contained several convective events across the day, including varying modes of convection, and targets that may have been suitable for POLCAST3 seeding efforts. The case day also identifies some of the difficulties associated with spatial forecast verification.

(b) Procedure

Verification of the 3-km WRF model runs was done by comparing the forecasted simulated radar reflectivity at 1 km to the observed radar reflectivity collected by UND radar at a constant altitude plan position indicator (CAPPI) at 1 km. The simulated reflectivity was calculated using the mixing ratios of rain, snow, ice, and graupel. The comparison was done by comparing each forecast valid time to the closest matching observation time, within 30 minutes, if one existed. If radar observations within 30 minutes did not exist, that data was discarded.

The Developmental Testbed Center's (DTC) Model Evaluation Tools (MET), namely the Method for Object-Based Diagnostic Evaluation (MODE) tool was used to compare the matching times. The MODE tool is an object-based verification for gridded forecasts and observations and has a high amount of user configuration. Object-based verification is essentially the only way to verify convection since traditional skill scores are incapable of accounting for spatial anomalies between the forecasts and observations. It is well known the exact location of convection is nearly impossible to predict due to the chaotic nature of the boundary layer, hence traditional gridded point-to-point verifications cannot be applied. For example, if convection is shifted over slightly on the model grid, a subjectively 'good' forecast would be deemed objectively 'bad'. The verification instead should be more focused on the intensity, mode, and temporal distribution of convection and less on the exact location. The MODE tool verification works on the principles as described in Davis et. al. (2005).

The input required by the MODE tool is outputted by another DTC tool, the PCP-Combine tool, however the PCP-Combine tool deals with aggregating Quantitative Precipitation Forecasts (QPF). Model output data and the raw radar data had to be converted into a format that matched PCP-Combine tool output, in order to be able to use the MODE Tool, except in this case simulated reflectivity values from the model and actual radar reflectivity values would replace QPF. Simulated reflectivity values were calculated by reading in model output and applying the equation and assumptions determined by Koch et. al. (2005) to each element and interpolating the results to a grid at a 1 km height. The radar data consisted of latitude and longitude coordinates with their corresponding reflectivity values at a 1 km CAPPI, as well as azimuth data since the radar ran sector scans at certain points. The radar data was re-gridded to match the model grid, while keeping track of the beginning and ending azimuths in order to display only the data that was collected.

Figure 2 details precisely how the MODE tool analyzes the data. The MODE tool first displays the raw data field and creates 'objects', which are defined as groups of data values spatially adjacent to each other. Relating this to reflectivity, objects are classified as discrete cells created after applying certain area and intensity thresholds. MODE then generates clusters by merging different objects together. Clustering is first achieved by applying a circular convolution to the raw reflectivity field with a radius defined by the user, creating a smoothing gradient. If the gradient generated crosses or meets the gradient of other objects, all of those objects are merged into a cluster. The clustering step is done in both the forecast and observation fields. The final step MODE takes is matching objects from the forecast field to the observation field. MODE calculates 'interest' between how clustered and discrete objects in the forecast field compare to those in the observed field. Comparisons that are considered to be of high interest by MODE are deemed matches and a statistical analysis is done on that match including the calculation of traditional skill scores.

The merging (clustering) and matching process by MODE however, is not ideal for reflectivity. The way MODE merges and matches objects is many times counter-intuitive and the merging/matching processes aren't generally representative of what a forecaster would subjectively analyze. An example of this is shown in Figure 3. Objects that are clustered have the same color and are 'rubber-banded', which is denoted by a black line circling all the objects in a cluster in each field. In this case, MODE merges objects in the forecast field across other objects, which it doesn't include in the cluster. The matching process is similar in many cases. Therefore, MODE's automated matching analysis cannot be used. The traditional skill scores computed, as stated before, also cannot be used. Figure 4 shows a forecast (left), observations (center), and skill scores for that forecast (right). The different skill scores are mostly between .05 and .15, with a 1 being a perfect forecast. One skill score gives the greatest amount of skill in the forecast with a value just below 0.3. Subjectively however, this forecast would be deemed very successful as location, morphology, structure, and intensity are all very similar to what actually was occurring.

Although MODE's analysis of forecast skill is not directly useful for this analysis, some of MODE's output can be used to objectively analyze the data and give an assessment of forecast skill. Since the merging and matching processes are not useful, they are disabled within the tool and convolution is not used. MODE then essentially creates objects using the raw reflectivity field only, and outputs statistics for each of those discrete objects.

For this study, MODE is run with a threshold of greater than 5 dBZ. MODE counts the number of objects and calculates their areas in grid squares for both the forecast and the observed fields for every valid forecast (hourly). The number of objects in both domains and their respective areas can be summed together and binned in order to give an overall summary of forecast skill and if the mode of convection was represented correctly. By taking the summation of area covered by each object and dividing it by the total domain area, an areal coverage ratio can be determined for each hour. Taking the difference between forecast and observed areal coverages gives a good estimate of forecast accuracy. If convection was not present (i.e. 0% areal coverage), the difference in coverage would not be calculated but counted as a missed forecast instead. The hourly objective analyses described above, along with additional subjective analysis, will determine if increased horizontal resolution increased forecast skill and provided a more accurate representation of convection. Forecast objectives will then be assessed to determine if the additional forecast skill is worth the significant additional computational costs.

4. Case Analysis

(a) Observational Overview

For the July 14th, 2010, case day, the primary convection-driving forces can be attributed to synoptic features. Figure 5 shows the progression of the jet stream at 300 mb. A strong low pressure system is seen in southeastern Saskatchewan with jet streak at around 100 knots over the forecast area (FA) of northeastern North Dakota and northwestern Minnesota. Figure 6 displays 500 mb heights and absolute vorticity, depicting an increase in cyclonic vorticity advection moving in towards the FA. 850 mb heights and temperatures (Figure 7) show strong warm air advection bringing in warm air from the southwest toward the northeast as the low propagates eastward. Packing of the isotherms along the trough of the low pressure system also suggests frontogenesis and a front actively making its way through the region. By comparing 500 mb vorticity field, 850 mb temperature field, and following the assumptions in the Trenberth quasi-geostrophic approximation (Trenberth 1978), vorticity advection by the thermal wind suggested that the cyclonic vorticity maximum was being advected into the southern FA. Low levels (Figure 7) also depict a second low pressure system located near the South Dakota-Wyoming border aligned with the front and trough near the surface levels. A contoured surface analysis (Figure 8), shows an occluding front moving towards the FA associated with the low pressure system in Canada.

Cyclonic vorticity advection, strong warm air advection across multiple levels, and frontal convergence all created and aided rising motions. Dew points in the mid 60s and moderately high temperatures in the FA created an environment favorable for convection. It is difficult to find a pre-convective sounding due to the lack of spatial and temporal coverage for upper air readings, even more so that the FA is located in a gap between stations, however Figure 9 displays a 12Z sounding from Aberdeen, SD, which was experiencing a frontal passage. Strong unidirectional shear with height can be seen which, one would expect to lead to development of more organized convection.

Radar observations taken that day are visible in Figure 10. The figure shows base reflectivity from the National Weather Service (NWS) KMVX (Mayville, ND) WSR-88D radar image taken every two hours from left to right. The red box indicates the edge of the model domain. Convection can be seen lined up along the Red River at 02 UTC with some isolated cells in the northwestern region of the domain. These storms cells had some damage reported with them, including a brief tornado touchdown (SPC, 2012b). Two hours later at 04 UTC, the storms that were along the Red River propagate further into Minnesota while new cell initiation is seen to the northwest. At 06 UTC, a cluster of storms is moving into the region from the southwest, propagating east-northeast. By 10 UTC, the storm system is located over the FA and a large bow echo is observed in the southern part of the domain. There are many embedded convective cells in the stratiform rain region and more convective growth is seen to the northwest and far south. The mesoscale convective system (MCS) begins to moves out of the domain by 12 UTC and is followed by several convective and stratiform rain clusters. There is active convection occurring to the south and east outside the domain, however convective mode and intensities cannot be determined as the radar beam over those regions is over 20,000 ft above ground level, and only the upper levels of storms are being sampled. At 20 UTC, stronger convection begins to initiate outside the domain, from the northeast stretching down to the southeast.

(b) Initialization Analysis

An initialization analysis was done on the 27-km parent grid to determine if the same features discussed in the observational analysis were translated into the model grid. As visible in Figure 11, the vorticity maximum is located in the correct location compared with the observed vorticity (Figure 6) with cyclonic vorticity advecting similarly through the FA as observed that day. Strong warm air advection can be seen in Figure 12 across the entire region, however the main frontogenesis occurs to the south of the FA, as visible in the surface temperatures in Figure 13. The model predicted moderate values of CAPE in the FA, with higher values in the southern portions (Figure 14). Simulated reflectivity in the 27-km grid (with CP) favored a linear feature, or a more organized complex of storms to develop and moved through the FA as depicted in Figure 15, which provides a good idea of what mode the convection is predicted to be according to the model.

5. Results

(a) MODE Analysis

Figure 16 shows the summation of all forecasted and observed objects (cells) and their corresponding areas across the entire POLCAST3 field campaign when radar observational data existed. The area of each object was obtained by converting the number of grid squares covered to square kilometers. One grid square at 3-km spacing is equivalent to 9 km^2. MODE analysis on the POLCAST3 data suggest that the model did fairly well in forecasting larger scale features, but tended to over-forecast medium scale features and significantly under-forecast smaller, more cell-scale features such as that on the order of 45 km^2 or less as shown in Figure 16. Therefore, the under-forecasting of objects 45 km^2 or less by the simulated forecasts is equivalent to under-forecasting of objects sized five grid squares or less. These results are hypothesized to be due to the inability of the 3-km model to fully resolve convective initiation processes on finer scales. Therefore, convection doesn't initialize when it normally would and any convection that should be on a finer scale is in fact initialized later, allowing for a build up of energy. The build up of energy is hypothesized to lead to an over-intensification of the system.

Figure 17 shows basic forecast skill for all times that radar data existed within 30 minutes of valid forecast, specifically the amount of times forecasts were verified, misses, or false alarms across the entire POLCAST3 campaign. Approximately 175 of 275 forecasts were verified, and the model had about 20 false alarms. However around 80 cases, or approximately 30% of the total matching times, were misses. A subjective analysis of 20 out of the 80 'miss' cases suggested that most misses occurred when observed convection was small scale, which matches the conclusion from Figure 16, where the 3-km resolution model seems to have trouble correctly forecasting small-scale convection.

The accuracy of each individual forecast when both the observation and forecast fields contained convection (corresponding to first column in Figure 17) was then computed. The accuracy was determined by taking the difference between forecasted and observed area ratios. The area ratios were determined by comparing the amount of area covered by convection to total area of the model domain or radar range. The results can be seen in Figure 18, which shows that around 90 cases have less than 5% difference in area coverage, around 30 cases between 5 and 10%, and around 20 cases each between the 10 to 20% and 20 to 50% difference range. These results suggest that the model did well in forecasting the amount of convective coverage in cases where both forecasted and observed domains included convection. The misses in Figure 17 likely correspond with the under-forecasting of the 9 to 45 km^2 area bin seen in Figure 16, meaning the misses are likely small-scale convection.

In summary, the results obtained from the analysis seems to suggest that the 3-km model cannot correctly resolve smaller-scale convection, which reinforces the hypothesis that the 1-km model forecasts should theoretically better resolve such features.

(b) 3-km and 1-km Model Runs

Both the 3-km and 1-km model runs (Figures 19 and 20, respectively) immediately begin initializing convection, and by 04 UTC, both models show similar features lining up along the Red River. The 1-km model has significantly more detail than the 3-km model, however, convective mode and intensity are rather similar. These forecasted cells most likely correspond to the convective cells observed at 02 UTC (Figure 10(a)) around the southeastern part of the domain, in which the morphology agrees. The time delay may be representative of the fact that the observed cells were occurring in the domain at 00 UTC, when the model was being initialized. 06 UTC is arguably when the greatest difference between the 3-km and 1-km models is seen. The 1-km resolves a strong gust front/bowing feature right over Fargo, ND while the 3-km does not. Although this feature was not present or observed at this time, the observed Aberdeen sounding would be very supportive of such features. In this case an objective increase of forecast skill is not seen, however when a forecaster looks at the simulated reflectivity and see a feature like this, they can clearly see that favorable conditions exist for wind damage.

A linear feature is seen moving through in both forecasts at 10 UTC. A cross-section performed on the southern edge of the linear feature is shown in Figure 21, with the 3-km on the left and the 1-km on the right. There is very little change between the 3-km and 1-km forecasts, however, the 1-km forecast appears to resolve some additional turbulence and mixing as seen in the equivalent potential temperature field. By looking at the area where the over-shooting top is found, the 1-km forecast resolves vortices associated with rising and sinking air. The 3-km forecast smooths out and blends over this turbulence.

Both model runs resolve a bow echo feature at 11 and 12 UTC. This feature matches the observed bow echo at 10 UTC very well, however, the forecasts simulate the bow echo too far to the north compared with observations. The intensity and magnitude is accurately depicted. As the forecasted bow echo moves off, both models display some numerical noise in association with a poor resolution of stratiform region. Closer to the end of the forecast period at 18 and 20 UTC, both models begin to initiate some small cells in the north central part of the domain. The new convective initiation corresponds to the initiation in the observed domain, with only a slight shift in location.

There seems to be no increase in forecast skill in the 1-km forecasts as compared to the 3-km forecast. Initially, the model solutions look similar to each other and do not match up with the observations. Later in the forecast period, skill in both forecasts increases as they subjectively match up with observations better. However, this means there is no improvement when switching from the 3-km to the 1-km.

5. Discussion and Conclusions

The results show that there is no increase in forecast skill by switching from a 3-km resolution model to a 1-km resolution model for the case surveyed, which seem to agree with Kain's findings (2008). Both model runs look more similar to each other than to the observations. The 1-km forecast does add significantly more detail in the horizontal, however this does not aid in objective forecast skill. The extra detail and features presented by the 1-km forecast may subjectively help a forecaster determine what hazardous weather conditions to expect. It is important to note however that only one case was surveyed. More cases need to be studied, involving different initiation processes, in order to get a more accurate answer of whether forecast skill is increased with increasing resolution on an already high resolution scale such as going from 3-km to 1-km grid spacing.

1-km resolution has been used as a golden standard for high resolution model runs, however new studies are suggesting it is not enough. Petch (2002; 2006) argued that resolutions below 1-km are needed to accurately resolve convection due to differential surface heating, as boundary layer turbulence and eddies need to be resolved to be able to accurately illustrate convective initiation. Droegemeier (1994) also stated that to marginally resolve smaller cell-scale features that occur, you would need resolutions of 500 m or smaller. Many clouds and updrafts are around 1 km^2, therefore finer resolutions are needed to resolve those features.

Increasing horizontal resolution may be just one step towards developing more realistic forecasts and increasing forecast skill. Changes in vertical resolution may have to be examined, as convective processes, especially convective initiation and convective modes, are dependent on vertical motions in the boundary layer. More vertical detail near the surface would theoretically allow the model to capture the transfer of heat and moisture into the boundary layer more accurately, and more detail near the tropopause, near the jet, to help better predict jet motions and interactions (UCAR COMET 2002). Using more nested grids can influence forecasts and cause additional boundary issues as features are translated between grids. Using coarse parent grids with cumulus parameterizations and high resolution nested grids without cumulus parameterizations may also introduce undesirable noise and have adverse effects on the high resolution grid, especially in terms of intensity and timing (Warner 2000).

An important fact not to neglect is that observational data also has flaws. Observation stations can never spatially cover enough area to allow for 'ideal' model initialization, and many regions (like the domain of this study) have poor coverage compared to other locations. The model is forced to then interpolate and determine a 'best guess' of what conditions really exist. Radar data is not without fault as well, as shown in this study. Advanced algorithms are used to remove ground clutter and false echoes, however certain objects still slip through. Second-trip echoes and unwanted objects will always affect data, although many of these artifacts can be carefully removed. Issues such as attenuation (although this relates more to intensity differences) are more difficult to address, especially as radar wavelength decreases in an attempt to increase accuracy and observational resolution.

6. Future Work

The first major step that needs to be taken is to perform an analysis on a larger sample of data to get a better statistical representation of results. During the summer of 2012, the POLCAST4 field campaign issued both 3-km and 1-km model forecasts, with an almost identical setup to this study, producing forecasts for the same region. Model forecast data from both models has been archived. Once the observational data is processed, a direct analysis can be done following the same procedure on how well both the 3-km and 1-km models did, respective to the observational data. The POLCAST4 data set will allow for a quantitative comparison between the 3-km and 1-km forecasts. The quantitative results from the 1-km can then be analyzed by MODE, and can be compared against the 3-km MODE analysis. Both 3-km and 1-km forecasts are also being made in western North Dakota for a long-term weather modification project. Data collected from the project can also be possibly utilized to help determine the added statistical effect of increased resolution and forecast skill.

Unwanted artifacts still exist in radar observations, which have unwanted effects on the analyzed data. Instances of ground clutter that are not filtered by radar algorithms and second-trip echoes add to the smallest observed area bin counts, which may bias the results. Additional methods must be formulated and developed to deal with such issues to assure the findings are accurate and data quality is not undermined.

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