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THE EFFECT OF TOPOGRAPHY ON THE INITIAL CONDITION SENSITIVITY OF A MESOSCALE MODEL

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1. INTRODUCTION*

Errors in NWP model forecasts are typically due to deficiencies in the model formulation, inaccuracies associated with the numerical integration techniques, and errors in the specification of initial conditions. This study investigates the latter of these three issues and, in particular, elucidates the errors in the initial conditions due to inadequate data resolution. In a basic sense, for the atmosphere to be adequately sampled at a given length scale, it is not always necessary to increase the number of samples throughout the entire domain. Increased sampling resolution has the greatest benefit in the regions where gradients in the atmospheric conditions exist. Targeted observation techniques attempt to take advantage of this fact by using additional observations to improve the initial analysis in the regions that will have the most impact on forecast accuracy (Emanuel *et al*. 1995). The result is an economical means to reduce initial condition error and improve forecast accuracy.

It is well known that terrain can serve as a localized forcing mechanism in high-resolution models. In addition to acting as a forcing mechanism, variations in terrain can also create strong gradients in the atmospheric fields of models using terrain following vertical coordinates. It is reasonable to assume that if these gradients were better represented in the initial conditions, forecasts accuracies could improve. The present study examines the relationship between terrain variability and the sensitivity of a high-resolution wind forecast to errors in the initial conditions in these areas.

The background behind this study and a brief description of the terrain and atmospheric characteristics of the cases used in the experiments are presented in section 2. Initial condition sensitivity analysis results from the fifth generation Pennsylvania State University (PSU), National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) adjoint and forward models are contained in sections 3 and 4. A summary of the results and conclusions are found in section 5.

2. BACKGROUND

The objective of this study is to improve the accuracy of short-term high-resolution model forecasts in the presence of terrain through the reduction of initial condition error. Since not all initial condition errors contribute significantly to model forecast error, knowledge of terrain induced NWP model forecast sensitivity may be important when developing and deploying a weather sensor network to support a regional scale NWP model. The terrain induced model sensitivity can provide an indication of which variables in the initial conditions have a significant influence on the forecast and where initial conditions need to be most accurate to minimize model forecast error. A sensor network could then be designed to minimize these errors by deploying critical sensors in sensitive locations, thereby reducing relevant initial condition error without the costly deployment of a high-density sensor network. This is similar to the targeted observation technique first suggested by Emanuel *et al.* (1995), except that in this example, the targeted observations would be designed to reduce initial condition error associated with poorly resolved atmospheric features associated with the terrain.

To isolate initial condition error, this study makes the “prefect model” assumption. While it is not realistic to make this assumption when examining total model forecast error, it is essential in an analysis seeking to understand the contribution and/or reduction of initial condition error. This assumption has been used in a number of similar studies (eg. Bergot *et al.* 1999).

2.1 TERRAIN SPECIFICATION

The first step towards reducing initial condition errors associated with elevated terrain is to develop a basic understanding of and to what extent the observational errors in complex terrain influence the model forecast. Initial condition data sets for both the adjoint and forward model sensitivity components of the study were created with the MM5 V3 data preprocessing software (Dudhia *et al.* 2000). Terrain is derived from the 30-arc-second digital elevation map (DEM) data set and interpolated to the 1 km horizontal resolution model grid by the MM5 TERRAIN preprocessing program. The 30-arc-second data are equivalent to an x-y resolution of approximately 680 by 925 meters at this latitude. Figure 1 illustrates the terrain environment in the Hudson River

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valley region of eastern upstate New York, western Massachusetts, and southern Vermont. The existing terrain is further modified to create an idealized terrain environment. An "idealized mountain" is made by cutting real terrain from the model domain shown in Fig. 1. The region cut from the real terrain for use as the idealized mountain is enclosed in the region inside the white rectangle in Fig. 1. The remainder of the domain the terrain is modified to make it more flat. The new domain design creates an idealized terrain environment that combines a single realistic looking mountain surrounded on all sides by a flat plain. The idealized terrain is produced by taking the unmodified terrain, previously interpolated to the model grid by the MM5 TERRAIN preprocessor, and multiplying it by an exponent. The exponents used to create the idealized terrain are as follows:

Mtn Domain: $elevation = elevation$ **(1)**

Mtn Domain + 1-3 grid points: $elevation = (elevation)^{0.92}$ **(2)**

Mtn Domain + 4-6 grid points: $elevation = (elevation)^{0.8}$ **(3)**

All remaining grid points: $elevation = (elevation)^{0.1}$ **(4)**

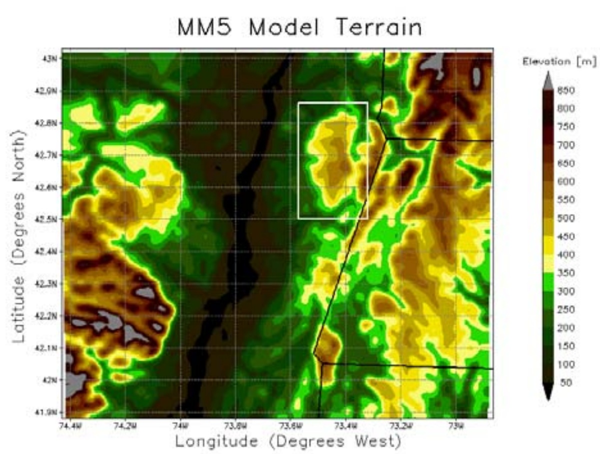

Fig. 1. The unmodified terrain for the MM5 1 km model domain for the adjoint and forward model simulations. The rectangle highlights the area cut from the unmodified terrain to create the "idealized mountain" domain.

The "mountain domain" represents the x-y grid coordinates where the normal terrain is retained. The terrain transitions from real values at the mountain to an elevation near sea level over the six grid points surrounding the mountain. The flat portion of the domain is created by using Eqn. 4. at the remaining grid points. This creates a relatively homogenous terrain environment at about 1 m above sea level that varies by less than 1 m over the domain. The result, shown in Fig. 2 demonstrate that this technique creates a realistic looking mountain surrounded on all sides by a flat plain located slightly above sea level.

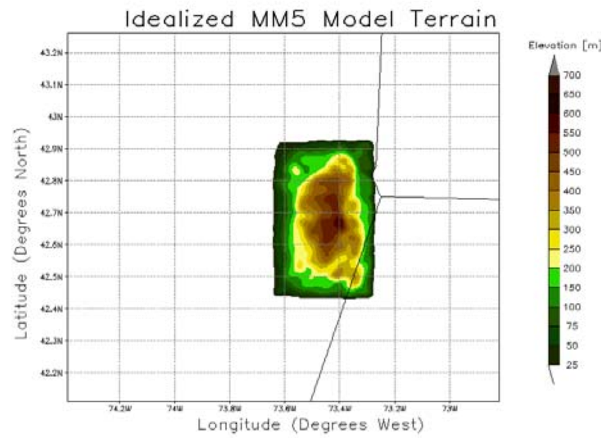

Fig. 2. A depiction of the model domain and idealized terrain used in the MM5 adjoint and forward model simulations. The horizontal resolution is 1 kilometer.

2.2 ATMOSPHERIC CHARACTERISTICS

A case with weak synoptic scale forcing is used in order to minimize larger scale influences such that the results primarily reflect the impact of small-scale variations in terrain elevation. The initial atmospheric conditions for the sensitivity study are based on the initial fields from the 20 km resolution RUC model. The data used in this case were from 16:00 – 19:00 universal coordinated time (UTC) on October 4th, 2001. This was a case with negligible synoptic scale forcing and relatively uniform environmental flow. On this day, skies were mostly clear, winds were primarily out of the west-southwest at 10-15 knots, and there was no significant precipitation in the region. The vertical profile of horizontal winds were backing with height and varied from southerly at 5 knots at the surface, to westerly at 20 knots at the top of the mountain (Fig. 3). The initial condition fields are held constant for all of the sensitivity simulations in an effort to minimize variations in the outcome of the sensitivity study due to factors other than terrain.

In a study involving wind flow over or around terrain it is important to know the characteristics of the flow. The Froude number (Fr), (Eqn. 5) is typically used to characterize these types of conditions.

$$Fr = \frac{U}{NH} \quad \textbf{(5)}$$

In Eqn. 5, U is the environmental wind speed, N is the Brunt Vaisala frequency, and H is the mountain height. The square of the Froude number is proportional to the ratio of kinetic energy in the environmental wind to potential energy required for the air to flow up and over the terrain barrier (Bluestein, 1993). In this case the $Fr^2 \cong 2.0$, implying supercritical or cross barrier flow. An examination of the low-level wind forecasts around the idealized mountain confirms that this is a situation in which the wind flows over the terrain.

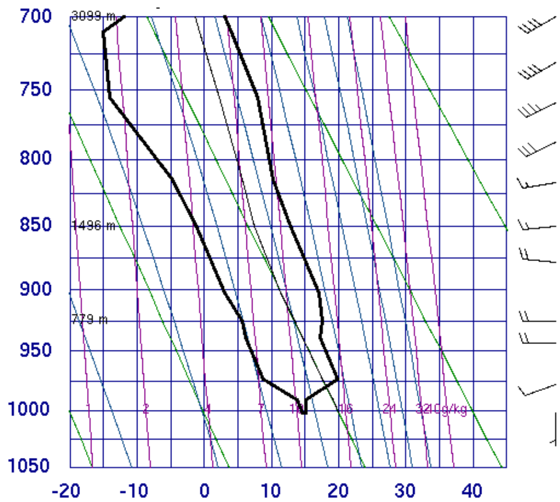

Fig. 3. A stüve diagram illustrating the vertical structure of temperature, dew point temperature, and winds from the surface to 700 mb on October 4th, 2001. The sounding, taken at Albany, NY indicates that the winds are backing with height and increase in speed from approximately 5 knots at the surface to 20 knots at the top of the idealized terrain.

The type of case used in this study removes much of the forecast sensitivity that would typically be associated with the larger scale atmospheric phenomena and provides a situation in which local terrain can have a strong influence on the model forecast. The RUC analysis is interpolated to a 19 vertical (sigma) level, 1 km horizontal resolution MM5 model domain by the MM5 Version 3 REGRID and INTERPF data preprocessing programs. No additional observations are included in the MM5 initial conditions beyond those already present in the 20 km resolution RUC analysis. The initial conditions created by the MM5 data preprocessing software are then converted to the MM5 Version 2 format to be ingested by the adjoint modeling system.

3. ADJOINT MODEL SENSITIVITY ANALYSIS

3.1 EXPERIMENTAL DESIGN

Adjoint models are tools used to perform reverse modeling. They can be used in situations where models of physical systems are used and the relationship between the model outcome and the state of the physical system at some earlier time is desired. Data assimilation, model tuning, and initial condition sensitivity analyses are among the more common applications in meteorology (Errico 1997; Giering and Kaminski, 1998).

This study uses the adjoint of the MM5 model to investigate the initial condition sensitivity of a model to terrain variability (Zou *et al.* 1997,1998). The impact of small errors in the initial analysis associated with elevated terrain on the downstream forecast is the principle interest of this study. The adjoint model is used to analyze the origin of forecast anomalies associated with variations in the initial conditions. An example of a simple application of an adjoint model in a sensitivity study is shown in Figs. 4 and 5. This case illustrates a situation where moisture from one point is linearly transported by the wind to a downstream location. Any change in the amount of moisture in the air is transported downstream and broadened by diffusion (Fig. 4). An adjoint model can be used to study the inverse of this process, which would be to determine the origin of an upstream anomaly from a downstream point. Figure 5 graphically illustrates how the adjoint model determines that a change in the conditions (or forecast) at one location can be caused by the propagation of an anomaly or error from an upstream location. This makes it possible to identify regions where the model is preferentially sensitive to perturbations in the initial conditions. The present study uses this tool and technique to identify the upstream location that influenced the surface wind forecast.

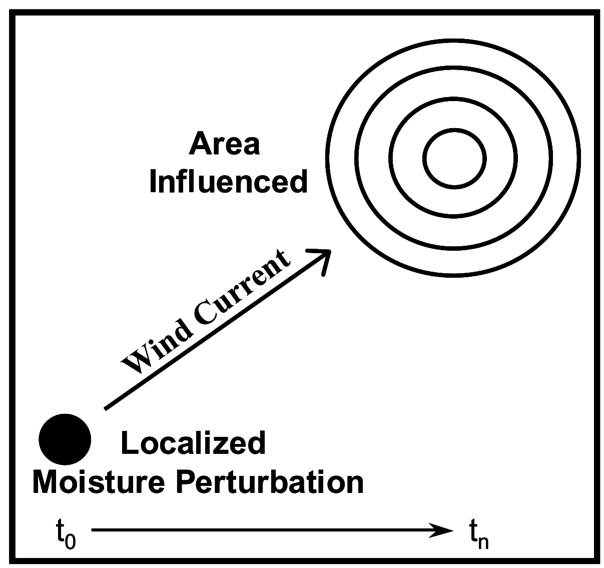

Fig. 4. Forward model example illustrating a perturbation and the downstream diffusion of the perturbation by the winds.

The adjoint sensitivity analysis can be used to characterize not only the locations of sensitivity, but also the variables, and magnitudes of initial condition sensitivity that will have the most significant impact on the surface wind forecast. This study uses relative sensitivity to evaluate the adjoint sensitivity results. Relative sensitivity is a non-dimensional representation of the gradient output from the adjoint model and can be used to contrast the sensitivities of the different variables (Zou *et al.* 1993; dePondeca *et al.* 1998). Here relative sensitivity is used to identify the locations of initial condition sensitivity for a series of simulations containing the ideal terrain that ranging from 10 to 180 minutes in length. Terrain induced initial condition sensitivity is diagnosed by prescribing vorticity and divergence as the response functions in a 3 by 3 point grid box at the lowest model level. Vorticity and divergence were used since it is a combination of both the *u* and *v* wind components.

A corresponding set of adjoint simulations, based on the same initial conditions with terrain removed, are also made. Relative sensitivity results from simulation without terrain, (which will be referred to as “flat”) and the simulation using the idealized mountain terrain (which will be referred to as “mountain”) provide a measure of adjoint initial condition sensitivity versus simulation length. The centers of the adjoint sensitivity regions are visually identified for each simulation. Then the terrain heights below the center points of the adjoint sensitivity regions are determined. Forecast impact from the idealized mountain cases are compared to the flat cases and contrasted with the terrain elevation below the center of the adjoint initial condition sensitivity region. The results illustrate the relationship between initial condition sensitivity and the presence or lack of terrain for a given length of the simulation.

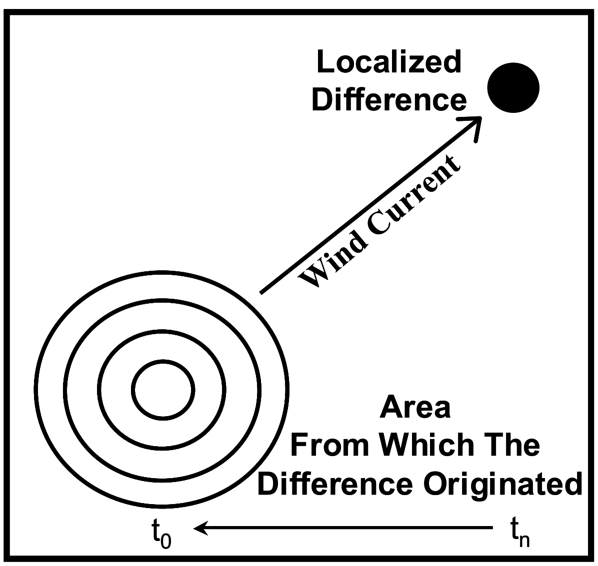

Fig. 5. Adjoint model example illustrating advection and the diffusion of influence.

The influence of terrain on forecast sensitivity to initial conditions are determined by comparing the maximum and minimum relative sensitivity values from the each of the mountain simulations to comparable adjoint simulations without terrain. The maximum and minimum values are pulled from the entire domain and are not necessarily from the lowest model level; however, the adjoint sensitivity in this study is typically confined to the lower model levels. Figure 6 illustrates a typical horizontal adjoint sensitivity cross-section, where the center of the sensitive region is denoted by the ⊗. The center point of the sensitivity region serves as the location of initial condition sensitivity in this study. This is a reasonable assumption for short simulations (i.e. 3 hours or less) where the gradient results are typically localized. If these center points are plotted on the map they illustrate a backward trajectory of initial condition sensitivity of the variable being examined. Depending on the environmental conditions this is a different quantity than a simple backward wind trajectory. This occurs because the adjoint sensitivity is based on the wind conditions at all model levels while a wind trajectory only provides a measure of parcel motion based on an average wind value or the winds at a single level (Fig 7).

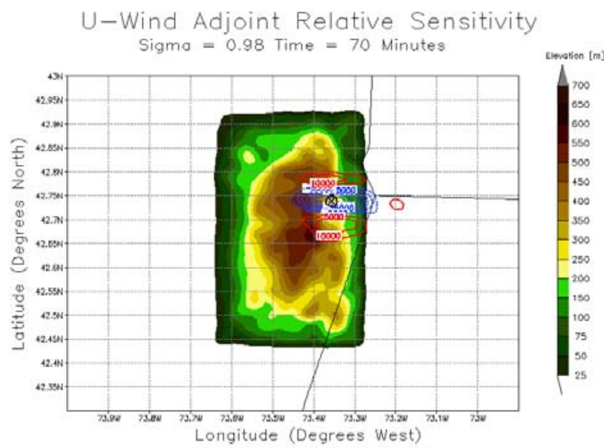

Fig. 6. A horizontal cross-section of adjoint relative sensitivity from the 70-minute simulation. The cross-section represents the sensitivity in the initial *u*-wind fields at the lowest model level. The ⊗ symbol marks the location visually identified as the approximate location of the center of the adjoint sensitivity.

3.2 RESULTS

Although most of the variables show some indication that the terrain influences the adjoint initial condition sensitivity, the *u* and *w* winds exhibit the most prominent signatures. Maximum and minimum *u*-wind relative sensitivity values are combined with corresponding terrain elevations to illustrate the relationship of adjoint sensitivity to terrain (Fig. 8). Here, the relative sensitivity clearly increases in the mountain simulations when the initial condition sensitivity region occurs over elevated terrain versus flat terrain. In contrast to the strong signal exhibited by the *u*-wind sensitivity, the *v*-wind sensitivities show no appreciable response to the presence of the mountain (Fig. 9). Although other variables show some indication that initial condition sensitivity may be influenced by terrain, this study focuses on the horizontal winds. This is done because horizontal winds provided a clear indication of terrain induced sensitivity and wind measurements were available to examine this relationship further in a subsequent study that used real observations.

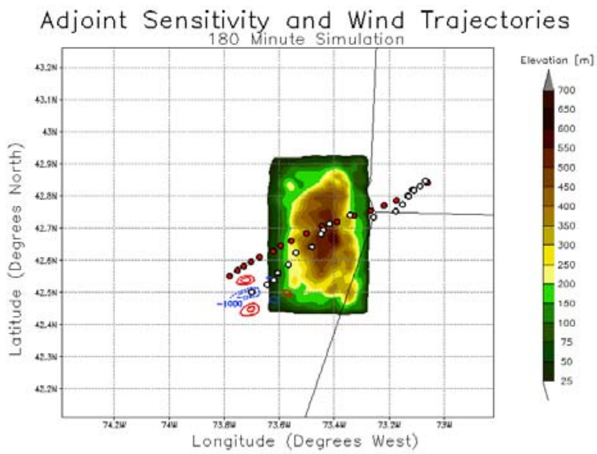

Fig. 7. Adjoint sensitivity and wind trajectories for a series of simulations ranging in length from 10 to 180 minutes. The wind trajectory is based in the winds at the lowest model level and denoted by the red dots. The adjoint sensitivity trajectory illustrates the locations of the centers of sensitivity for the series of simulations and are denoted by the white dots. This example illustrates how the two trajectories will often not match each other.

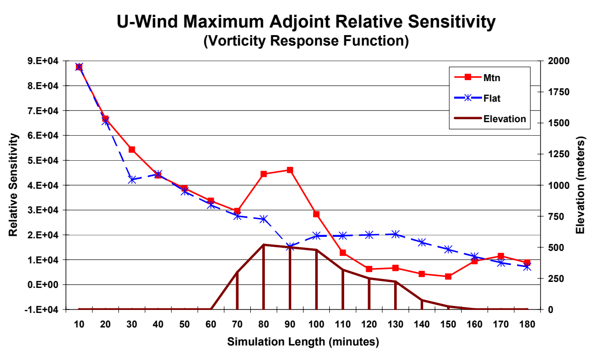

Fig. 8. Maximum and minimum values of adjoint relative sensitivity of the *u*-winds vs. simulation length. The approximate terrain heights below the center point of the relative sensitivity regions are illustrated at the base of the plot. Significant increases in adjoint sensitivity occur in the mountain simulations over the idealized mountain when compared to comparable flat simulations.

The adjoint sensitivity analysis clearly indicates that the *u*-wind initial condition sensitivity increases when terrain is present (Fig. 8). Although not shown, the adjoint sensitivity results from simulations using a divergence response function also indicates a similar relationship between initial condition sensitivity and elevated terrain. The strong sensitivity signal in the *u*-wind and the lack of signal in the *v*-wind results are most likely due to the terrain orientation and the westerly environmental flow. In the absence of other forcing mechanisms, upstream low altitude winds are the most obvious element influencing the downstream wind forecast in a short duration model simulation like the one used in this study. These results suggest that for this case, perturbations made to the initial *u*-wind fields over the elevated terrain will have a larger impact on the surface wind forecast than perturbations made over the flat terrain.

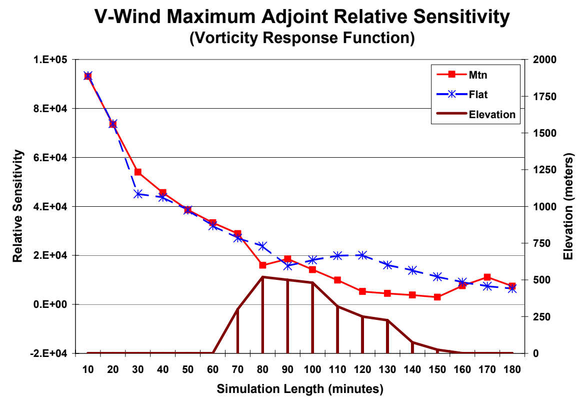

Fig. 9. Maximum and minimum values of adjoint relative sensitivity of the *v*-wind vs. simulation length. The approximate terrain heights below the center point of the relative sensitivity regions are illustrated at the base of the plot. No significant increases in adjoint sensitivity occur in the mountain simulations when compared to the flat simulations.

4. FORWARD MODEL SENSITIVITY ANALYSIS

4.1 EXPERIMENTAL DESIGN

The adjoint sensitivity analysis described above indicates that the surface wind forecast downwind of elevated terrain is more sensitive to the initial horizontal winds over elevated terrain than over flat terrain. A second analysis using forward model simulations is used to confirm this finding and characterize initial condition sensitivity over elevated terrain relative to flat terrain. This analysis consists of a series of three forward simulations, one perturbs the initial conditions in the mountain simulations, one perturbs the initial analysis used by the flat simulation, and the final set leaves the initial conditions unperturbed and serves as the control simulation. The impact on the surface wind forecasts is determined by subtracting the surface wind forecast based on the perturbed initial condition simulation from the control simulation surface wind forecast. The forecast impact results from both the mountain and flat cases are contrasted with the terrain below the centers of adjoint sensitivity. This makes it possible to measure the relative forecast impact of an initial wind perturbation directly in the region considered to be the most sensitive to an adjustment. Because the initial perturbations are made throughout the whole of the sensitive region, the forecast impact can be considered to be a measure of the maximum forecast impact for a given perturbation magnitude, simulation length, and underlying terrain. Consequently, it is reasonable to compare the magnitudes of forecast impact between the mountain and flat cases to determine the relative impact that the terrain variability has on initial condition sensitivity.

Separate perturbed initial condition sets are created, and range from 10 to 180 minutes in 10-minute intervals. The adjoint relative sensitivity results dictate the locations where the initial conditions are perturbed. This is justifiable because it is reasonable to assume that the adjoint model identifies areas where analysis error directly influences the forecast (Errico 1997; Xu *et al.* 2001). The wind adjustment is made in the MM5 initial analysis prior to the preprocessing step where the data are interpolated to the sigma coordinates by the MM5 INTERPF software. This minimizes the introduction of gravity wave oscillations that may occur due to vertical accelerations being induced in the model when the initial wind pressure fields are not in balance.

The initial conditions used in the mountain and flat terrain simulations are perturbed by 3 m/s in all regions where the absolute value of the horizontal wind (*u* or *v*) adjoint relative sensitivity is greater than 1000. The 3 m/s wind perturbation is well within the bounds considered reasonable for an analysis error in the horizontal winds (Hoecker 1963; Xu *et al.* 2001). Furthermore, the magnitude of this perturbation is consistent with the measured differences between the radar wind observations and the model initial analysis, both valid at 16:00 UTC on October 4th, 2001. Because of the limited size of the wind perturbations (typically less than 10 km in diameter) when averaged within the entire wind flow the perturbations modify the overall wind flow by less than 3%. Therefore the perturbations (in particular the -3m/s perturbations) will not significantly alter the barrier wind flow characteristics of the problem. By holding the perturbation magnitude constant in both the mountain and flat simulations it is possible to diagnose the locations where the initial condition perturbation will have the greatest impact on the forecast. Figure 10 illustrates a horizontal cross-section of a typical perturbed initial condition field.

Forecast impact is calculated for several variables: the individual *u* and *v* wind magnitudes, total wind magnitude, divergence, and vorticity. Since surface wind is frequently a model forecast requirement, this study evaluates model forecast impact at the lowest model level. An example of a typical *u*-wind impact field from the forward model simulations is shown in Fig. 11. Overlaid in red on this image is the location where the vorticity response function was defined in the adjoint sensitivity component of this study (Fig. 11). As anticipated, the surface wind forecast impact from all of the simulations are found in the area in and around the region where the response function was defined in the adjoint sensitivity simulations. Forecast impact in both the mountain and flat terrain simulations are computed in a forecast verification region. The use of a verification region is effective in eliminating corruption of the impact computations that can occur at the domain boundary. The verification region encompasses the area within 73.0° to 72.8° W longitude and 42.7° to 43.0° N latitude (Fig. 11).

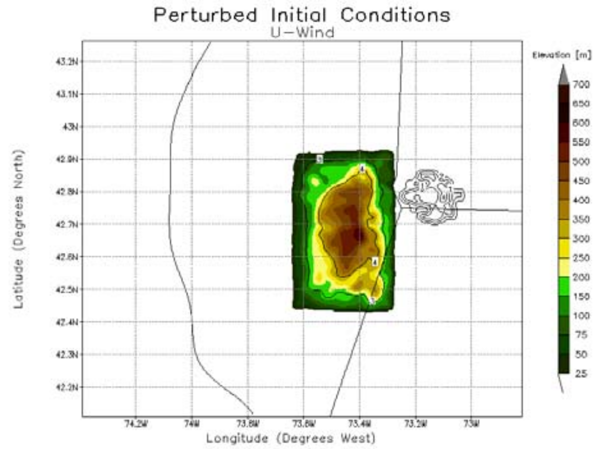

Fig. 10. A horizontal cross-section of the *u*-wind from the perturbed initial condition field for the 50-minute, mountain terrain simulation. The cross-section is taken at the lowest model level. The area of perturbed winds is located in southeastern Vermont.

Maximum forecast impact values are one of the measures used to assess the impact of the perturbed initial conditions on the surface wind forecast. This simple measure effectively captures variations in the magnitude of forecast impact. In addition to the maximum value computations, RMS impact in the surface wind forecast is also calculated. Since RMS impact is calculated over the entire verification domain, it effectively captures the spatial variability of the impact fields that the maximum value metric does not describe. The maximum value and RMS impact results compliment each other and provide a robust description of the forecast impact.

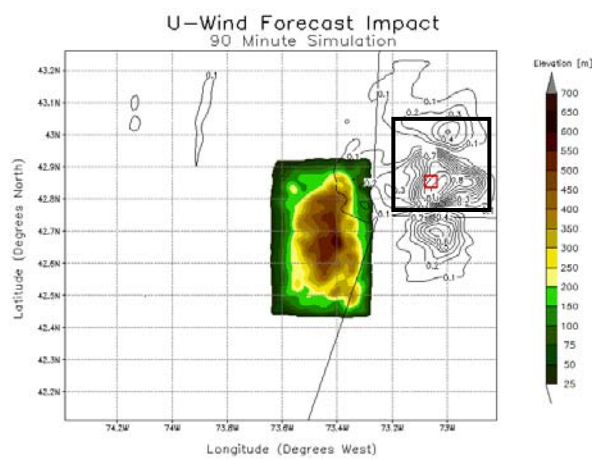

Fig. 11. A horizontal cross-section of the absolute value of the *u*-wind forecast impact from the 90-minute, mountain, forward model simulations. The red square represents the location where the response function was defined in the adjoint sensitivity analysis, and the approximate location where forecast impacts are anticipated. The larger black square denotes the location of the forecast verification region used in the analysis. The maximum *u*-wind forecast impact in this simulation is 1.35 m/s.

4.2 RESULTS

The maximum forecast impact computations confirm findings suggested earlier by the adjoint sensitivity analysis that there is a correlation between forecast sensitivity to initial conditions and the presence of terrain. First, the results from an experiment where a +3 m/s perturbation was made to the initial *u*-wind fields will be discussed. Overall, forecast impact values generally tend to decrease as the simulation length increases (Fig. 12). This is expected, and is an indication of the initial condition perturbation's diminishing impact as the initial condition perturbation becomes more removed from the forecast verification region. Maximum *u*-wind forecast impact values and although not shown, vorticity and divergence, are markedly higher when the initial condition perturbation was specified over the idealized mountain than in the comparable flat terrain (Fig. 12). When the difference in the maximum forecast impact values between the mountain and flat terrain cases are examined, the influence of terrain is even clearer (Fig. 13). An equivalent experiment using a -3 m/s perturbation yields similar results.

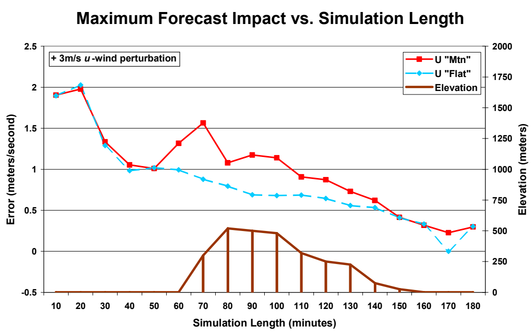

Fig. 12. Absolute forecast impact values for the surface *u* wind forecasts versus the length of the forward model simulation. The approximate terrain elevation below the center of the initial condition perturbation is provided. Forecast impact values in the *u*-wind clearly increase in the simulations when the initial +3ms *u*-wind perturbation was made over elevated terrain.

The RMS impact results also show a strong indication that terrain influences the sensitivity of the surface wind forecasts to initial condition perturbations. There is a distinct increase in the mountain simulation, absolute *u* and *v* wind RMS impact values when the initial condition perturbation was made over elevated terrain (Fig. 14). This is in contrast to the relatively monotonic variations exhibited by the *u* and *v* wind RMS forecast impact values in the flat terrain simulations (Fig. 14). The *u* and *v* wind, RMS forecast impact differences between the mountain and flat cases clearly show a strong indication of increased sensitivity coinciding with the terrain (Fig. 15). Comparable results were found in the experiment that used a -3 m/s perturbation to the initial u-wind field.

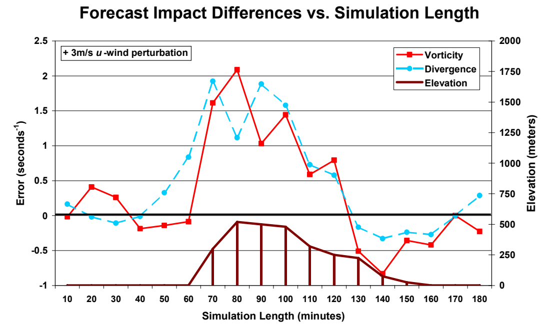

Fig. 13. Maximum forecast impact differences in the surface divergence and vorticity forecasts between the idealized and flat terrain simulations versus simulation length. The approximate terrain elevation below the center of the initial condition perturbation is also provided. Maximum forecast impact difference values in the vorticity forecast clearly increase when the initial *u*-wind perturbation was made over elevated terrain.

Some variables, (i.e. *v*-winds) showed little or no sign of initial condition sensitivity in adjoint simulations. To verify that some variables do not show a correlation between initial condition sensitivity and terrain, a separate analysis investigating of the impact of perturbations from the "no-sensitivity" or null case was conducted. Perturbations of +3 m/s were made to the initial *v*-wind fields for this analysis. All thresholds and procedures from the *u*-wind experiments described earlier were retained. Other than a slight decrease in sensitivity on the upwind side of the mountain, there were no distinct differences between either the maximum impact or RMS impact values in the mountain and the flat terrain cases (Fig. 16). These results confirm the adjoint sensitivity analysis and suggest that the *v*-winds in this case do not show an increased sensitivity to initial conditions over terrain.

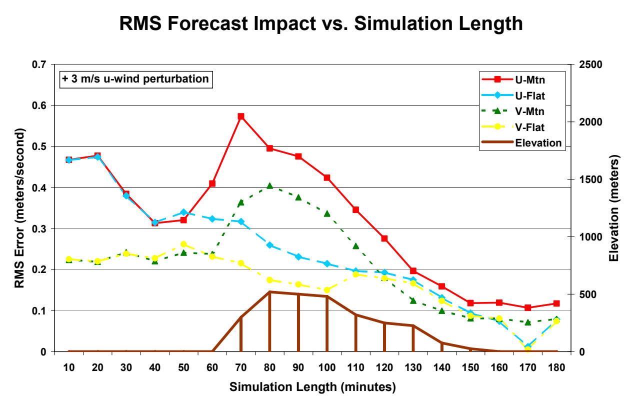

Fig. 14. Absolute RMS forecast impact in the surface *u* and *v* wind forecasts versus the length of the forward model simulation. The approximate terrain elevation below the center of the initial condition perturbation is provided. Forecast impact values in the u-wind clearly increase in the simulations when a +3 m/s perturbation is made to the initial *u*-wind fields over the elevated terrain.

5. SUMMARY

The results of two initial condition sensitivity experiments are presented in this paper. An idealized terrain environment in which a lone mountain surrounded by homogeneous flat terrain was used to characterize the impact that terrain has on initial condition sensitivity. The sensitivity analyses were conducted using simulations from a mesoscale model and its adjoint. The adjoint sensitivity results were used to make a preliminary assessment of sensitivity and provide information regarding the locations where the surface wind forecast may be sensitive to perturbations in the initial conditions. The forward model sensitivity analysis examined the sensitivity of the surface wind forecast to perturbations in the *u* and *v* wind initial conditions fields.

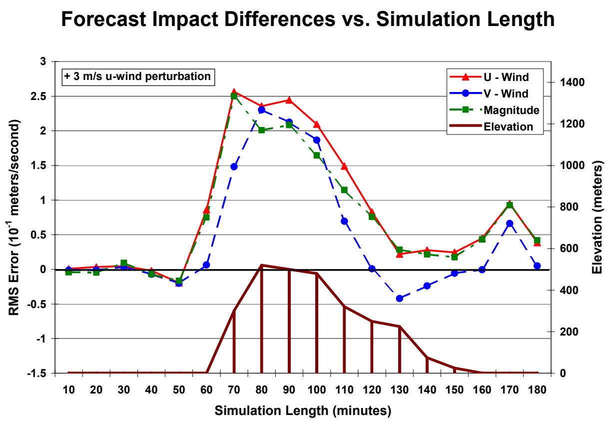

Fig. 15. RMS surface wind forecast impact differences between the mountain and flat terrain simulations versus the length of the forward model simulation. The approximate terrain elevation below the center of the initial condition perturbation is provided. RMS surface wind forecast impact difference values clearly increase when the +3 m/s *u*-wind perturbations were made to the initial conditions over elevated terrain.

The results of the adjoint sensitivity analysis indicate that there was an increase in adjoint initial condition sensitivity in the *u*-winds over the terrain. Many of the other variables showed some sensitivity to the presence of terrain; however, none were as pronounced as the *u*-wind. For this reason, and because wind observations were available to examine this issue in a subsequent analysis with real data, this study focused on the model sensitivity to the initial horizontal winds. Furthermore, the analysis also indicated that most of the initial condition sensitivity in all of the variables was located in the lowest model levels (i.e. near the surface). Overall, the results of the adjoint sensitivity analysis indicate a distinct relationship between the *u*-wind initial condition sensitivity and elevated terrain and little or no indication of a similar relationship for the *v*-wind component.

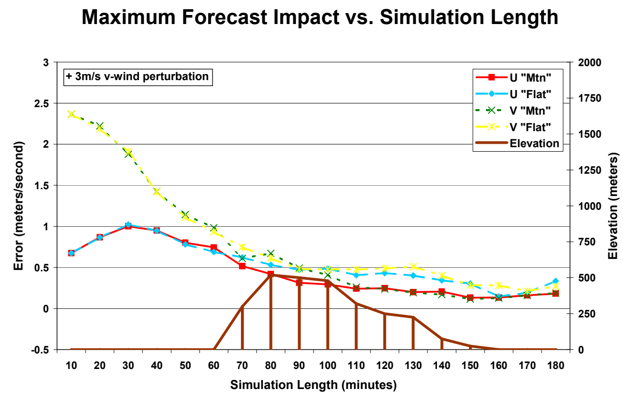

Fig. 16. This plot illustrates maximum forecast impact in the surface wind forecasts versus the length of the forward model simulations when a +3 m/s perturbation was made to the initial *v*-wind field. The approximate terrain elevation below the center of the initial condition perturbation is also provided. RMS forecast impact values in the surface winds show no significant variability in any of the simulations.

In the forward model sensitivity analysis, the initial *u* and *v* wind fields are perturbed by a constant factor in the regions diagnosed as sensitive by the adjoint model. The surface wind forecasts from these simulations are used to determine the impact of the initial condition perturbations. The results confirm that a larger forecast impact occurs when the *u*-wind field is perturbed over elevated terrain than when a comparable perturbation was made when the terrain was removed. Although they varied in magnitude, both maximum impact magnitudes, and RMS impact computations show that a perturbation to the *u*-wind initial conditions over terrain will result in a greater impact on the forecast. Conversely, the null case (i.e. where the *v*-wind initial conditions were perturbed) showed no significant indication of enhanced initial condition sensitivity associated with terrain.

When observations are used to adjust initial conditions in the real world they often do not improve the initial analysis in the dynamically sensitive regions. In other cases the addition of observations can actually degrade the analysis. Since it is not possible to control all of the conditions in an experiment using real observations, it is often essential to conduct controlled studies that do not use real world data. Here, the use of a controlled setting made it possible to make the best possible estimate of relative forecast improvement that could occur as a result of improvements made to the initial analysis over elevated terrain versus flat terrain. This experiment measures the impact of an initial analysis perturbation made in what is the best estimate of where the model is sensitive to initial conditions. Because the initial perturbations are made throughout the whole of the sensitive region, the forecast impact can be considered to be a measure of the maximum forecast impact for a given perturbation magnitude, simulation length, and underlying terrain. Consequently, it is reasonable to compare the magnitudes of forecast impact between the mountain and flat cases to determine the relative impact that the terrain variability has on initial condition sensitivity. Overall, this analysis suggests that when elevated terrain exists in the model domain, an improvement in the initial specification of *u*-winds over the elevated terrain should provide more of an improvement to the forecast than if the initial conditions were improved in areas with more homogeneous terrain. This finding is also being examined with real world observations to further evaluate the benefits that can be derived from using local terrain to determine where to deploy additional observational platforms.

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