The Effect of Topographic Variability on Initial Condition Sensitivity of Low-Level Wind Forecasts. Part I: Experiments Using Idealized Terrain

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(Manuscript received 4 March 2011, in final form 4 November 2012)

ABSTRACT

The concept of improving the accuracy of numerical weather forecasts by targeting additional meteorological observations in areas where the initial condition error is suspected to grow rapidly has been the topic of numerous studies and field programs. The challenge faced by this approach is that it typically requires a costly observation system that can be quickly adapted to place instrumentation where needed. The present study examines whether the underlying terrain in a mesoscale model influences model initial condition sensitivity and if knowledge of the terrain and corresponding predominant flow patterns for a region can be used to direct the placement of instrumentation. This follows the same concept on which earlier targeted observation approaches were based, but eliminates the need for an observation system that needs to be continually reconfigured. Simulations from the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) and its adjoint are used to characterize the locations, variables, and magnitudes of initial condition perturbations that have the most significant impact on the surface wind forecast. This study examines a relatively simple case where an idealized mountain surrounded by a flat plain is located upwind of the forecast verification region. The results suggest that, when elevated terrain is present upstream of the target forecast area, the largest forecast impact (defined as the difference between the simulation with perturbed initial conditions and a control simulation where the initial condition was not perturbed) occurs when the initial analysis perturbations are made in regions with complex terrain.

1. Introduction

Errors in numerical weather prediction (NWP) model forecasts are typically attributed to deficiencies in the model parameterizations, 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, contrasts the forecast impact of initial condition errors that occur in variable terrain versus the impact due to comparable errors over flat terrain. Forecast impact is defined as the forecast field from the simulation with perturbed initial conditions minus the forecast field from a control simulation where the initial condition was not perturbed.

It is well known that numerical forecasts are sensitive to uncertainties in the initial conditions. Research by Thompson (1957) on the growth of NWP model forecast errors from flawed initial conditions began shortly after the initial, pioneering NWP experiments. Although it was known that a strong connection existed between forecasts and initial condition errors, the degree of this sensitivity was not appreciated until 1963. Lorenz (1963) was the first to demonstrate that nonlinear dynamical systems, like those used to represent the atmosphere, are in fact very sensitive to small variations in initial conditions. More recently, improvements in our understanding of the impact of initial condition error on model forecasts have
resulted from examining localized regions of initial error and the associated model error growth properties. Studies by Rabier et al. (1996), Pu et al. (1997a,b), Gelaro et al. (1998), and Bergot (1999) all demonstrated that forecast errors can be explained by localized defects in the initial analysis, particularly when they occur in regions subject to large error growth. The results of these studies indicate that a substantial portion of the short-term forecast error can be mitigated by reducing localized defects in the initial conditions.

Emanuel et al. (1995) was one of the first to suggest that it might be possible to define these localized defects in the initial analysis by using adjoint or ensemble techniques, and then target additional observational resources in those areas. As a result, the targeted observation concept became a component in several field programs: the California Landfalling Jets Experiment (CALJET; Emanuel et al. 1995), the Fronts and Atlantic Storm Track Experiment (FASTEX; Joly et al. 1997), the North Pacific Experiment (NORPEx; Langland et al. 1999), and the 1999 and 2000 Winter Storm Reconnaissance (WSR) programs (Szunyogh et al. 2000, 2002). Aberson and Franklin (1999) evaluated this concept in an effort to better use dropwindsonde observations to improve hurricane track forecasts made by the Tropical Prediction Center. In all of these experiments, targeted observations are taken in regions where the initial condition error is expected to grow rapidly into significant forecast errors in the defined impact region.

The early results from these studies indicate that this concept shows promise as a practical technique for reducing forecast errors in global, synoptic, and hurricane forecast models (Emanuel and Langland 1998; Aberson and Franklin 1999). In the WSR 2000, 2001, and 2002 missions, both the quasi-inverse linear method (Pu et al. 1997b) and the ensemble transform Kalman filter (Bishop et al. 2001) targeting techniques were used operationally to direct observational resources. Forecast error reductions of 2%–15%, resulting from the addition of the targeted observations, were measured (Montani et al. 1999; Cardinali and Buzzi 2003). Hello et al. (2000) also showed that gradient sensitivity results from adjoint-model simulations can improve atmospheric model forecasts when used in combination with observations.

Much of the research on predictability and NWP model forecast sensitivity to localized initial condition error has been conducted using synoptic-scale forecast models. This was a result of the wide operational use of these lower-resolution models and the demanding computational requirements associated with high-resolution modeling. In the early 1990s, Vukičević and Errico (1990) Vukičević (1991), Errico and Vukičević (1992), and Errico et al. (1993) compared the relative influence of localized initial and lateral boundary condition error on limited-area hydrostatic mesoscale model forecasts. Vukičević and Errico illustrated that the primary difference between studies of forecast error due to initial condition deficiencies in global or synoptic-scale and limited-area models is in the contributions of the lateral boundary conditions to model forecast error. More recently, Xu et al. (2001) examined the feasibility of using the adjoint of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) in conjunction with ensemble modeling techniques to improve forecasts of mesoscale convective systems.

One study that represents the most relevant example of the use of an adjoint model to characterize initial condition sensitivity in areas of elevated terrain is a study by Doyle et al. (2007). In this work, the authors also examine a problem involving flow over terrain obstacles and the sensitivity in a leeside wind simulation associated with upstream initial conditions. Their work examined the variability that occurs in the initial condition sensitivity structures for varying terrain obstacle heights. They found that the sensitivities tilt vertically against the shear for smaller terrain features, and that complicated sensitivity patterns develop when the terrain height is increased to the point where gravity waves are present. Doyle et al. (2007) also demonstrated that perturbations introduced into the flow where the adjoint model suggested initial condition sensitivities resulted in structures that evolved into “vertically decaying evanescent waves.”

The motivation behind this study is to test the hypothesis that targeting techniques similar to those described above can be applied to mesoscale models in situations where a terrain feature is present in the modeling system (e.g., terrain obstacle, land–sea interface, etc.) that induces a localized enhanced sensitivity in the model to initial condition adjustments. It uses a study design similar in a number of respects to Doyle et al. (2007) and utilizes an adjoint model to study initial condition sensitivities in atmospheric flows over terrain obstacles of varying height. In contrast to Doyle et al. (2007), which focused directly on initial condition sensitivity over terrain obstacles, this study examines initial condition sensitivity over both areas of elevated and flat terrain to contrast how initial condition sensitivity varies between elevated and flat terrain and the corresponding implications for targeting observational assets. Assuming that differences are present between the elevated and flat terrain, then as was the case in the targeted observation studies discussed above, improvements made to the initial conditions in one area will have a larger positive impact on a mesoscale model forecast than comparable initial analysis improvements made in another.
The work described here is the first in a two-part series of papers. In Part I we examine this question in a more controlled environment where we introduce initial condition perturbations for terrain obstacles of varying heights surrounded by a flat plane. In the second paper of the series, Bieringer et al. (2013, hereafter Part II), we examine the same question using real-world terrain, Doppler radar velocity observations for adjusting initial conditions, and measurements from a small network of surface wind sensors for validation. Together the two papers allow us to answer some basic questions in a more complex operationally relevant situation, and demonstrate that it can be used to improve the forecast.

We start by examining the physical mechanism that suggests that enhanced initial condition sensitivity will be found over elevated terrain. To support this conjecture we will make use of the shallow-water equations. Let us consider a shallow-water fluid in one dimension:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -g \frac{\partial [h(x) + d]}{\partial x}, \quad (1a)
\]
\[
\frac{\partial d}{\partial t} + u \frac{\partial d}{\partial x} = 0, \quad (1b)
\]

where \( u \) represents the fluid velocity in the spatial dimension \( x \), \( t \) denotes time, \( g \) is the gravitational constant, \( d \) denotes the fluid depth, and \( h(x) \) denotes the spatially varying topography. The dependent variables, \( u \) and \( d \), are assumed to comprise a steady, base state, and a perturbation state denoted by \( u = U(x) + u' \) and \( d = D(x) + d' \), respectively. First, let us suppose that the fluid is at rest \([U(x) = 0]\), the bottom surface is flat and the fluid depth is constant [i.e., \( H(x) = H \)]. The perturbations are nonzero, and represent perturbations added to the initial step. Substituting the expressions for \( u \) and \( d \) into (1a) and (1b), and linearizing we obtain the following:

\[
\frac{\partial u'}{\partial t} = -g \frac{\partial d'}{\partial x}, \quad (2a)
\]
\[
\frac{\partial d'}{\partial t} = -H \frac{\partial u'}{\partial x}. \quad (2b)
\]

For hyperbolic partial differential equations, we can assume waveline solutions of the following form:

\[
u' = \tilde{u} e^{ik(x - ct)}, \quad (3a)
\]
\[
d' = \tilde{d} e^{ik(x - ct)}, \quad (3b)
\]

where \( \tilde{u} \) and \( \tilde{d} \) represent the wave amplitude, \( k \) is the wavenumber, \( c \) is the phase speed, and \( i \) is the imaginary unit. Substituting (3a) and (3b) into (2a) and (2b), we obtain that the phase speed of the wave is proportional to the square root of product of the fluid depth and the gravitational constant \( (c = \pm \sqrt{gD}) \). Because there is no imaginary component associated with the phase speed, the waves and hence the perturbations, do not grow.

Now, let us investigate the effect of adding perturbations to a shallow-water fluid when an obstacle is present at the lower boundary. First, and foremost, the addition of an obstacle to the shallow-water model will introduce fluid depth and velocity gradients into the base state of the fluid if the far field fluid velocity is nonzero. We will show that it is the presence of these depth and velocity gradients that enhance the impact of initial condition perturbations. The shallow-water equations that govern the steady-state flow field in one direction are given by

\[
U(x) \frac{\partial U(x)}{\partial x} + g \frac{\partial D(x)}{\partial x} + g \frac{\partial H(x)}{\partial x} = 0, \quad (4a)
\]
\[
\frac{\partial}{\partial x} [D(x) U(x)] = 0. \quad (4b)
\]

Again, we introduce the relations \( u = U(x) + u' \) and \( d = D(x) + d' \) into (1a) and (1b), linearize and subtract the base state equations (4a) and (4b) to obtain the following:

\[
\frac{\partial d'}{\partial t} + u \frac{\partial U(x)}{\partial x} + U(x) \frac{\partial d'}{\partial x} + g \frac{\partial d'}{\partial x} = 0, \quad (5a)
\]
\[
\frac{\partial d'}{\partial t} + u \frac{\partial D(x)}{\partial x} + U(x) \frac{\partial d'}{\partial x} + D(x) \frac{\partial u'}{\partial x} = 0. \quad (5b)
\]

Again, assuming waveline solutions of the forms in (3a) and (3b), and substituting these solutions into (5a) and (5b), one can derive the following relation for the wave phase speed:

\[
U(x) = k^{-1} i \frac{\partial U(x)}{\partial x} \pm \sqrt{k^{-1} i g \frac{\partial D(x)}{\partial x} + g D(x)}. \quad (6)
\]

Here the phase speed includes an imaginary component denoting that the wave amplitude will exhibit growth depending on the sign of the velocity gradient. The square root term is more difficult to interpret because an imaginary term is also present. Further investigation of this term provides the interpretation that the positive root adds to perturbation growth when the height gradient is positive, thus maximum perturbation growth is achieved when the velocity gradient is negative and the height gradient is positive, as expected. What is important to note, is that the instability is not tied to the presence of an obstacle at the
lower boundary, but to the base-state fluid depth gradient, and more importantly the base-state fluid velocity gradients created from the presence of the obstacle. In the shallow-water system, the negative velocity gradient in the base-state flow field causes convergence near the wave amplitude, causing the amplitude to grow.

While the above analysis does not include all of the dynamics present in mesoscale flows involving terrain, it provides insight on where we should expect increased initial condition sensitivity. The location of the initial condition sensitivity is linked to the Froude number in the shallow-water system:

$$\text{Fr}_{\text{SW}} = \frac{U}{\sqrt{gD}}.$$  \hspace{1cm} (7)

The sign of these gradients will be a function of the Froude number, as this number determines whether the flow field is supercritical or subcritical as it passes over the terrain obstacle. When the Froude number is greater than unity, the flow is supercritical, and the fluid flow velocity decreases as it ascends the mountain (Durran 1990). As a result, we should expect the initial condition sensitivity to be greatest on the windward side of the mountain during supercritical flow. On the contrary, when the Froude number is less than 1, the flow velocity increases during ascension and decreases as the fluid flows down the mountain. Therefore, we expect our initial condition sensitivity to be greatest on the lee side of the mountain during subcritical flow. The above analysis does not account for nonlinear effects such as flow splitting, flow blocking, and vortex generation on the lee side during subcritical flow. However, such phenomena create velocity gradients, and thus increased initial condition sensitivity is expected with these phenomena. Further, because the dynamics are highly idealized in the shallow-water system, we do not expect this exact behavior with a numerical model that approximates the atmosphere; however, we expect similar behavior qualitatively among the different equation sets.

In recent years the grid increments of operational weather forecast models have decreased to the point that they now are resolving mesoscale processes. This trend and the likelihood that it will continue, emphasizes the need for predictability research at this scale. Characterizing this behavior is also of practical relevance to the data assimilation community and for operational applications where high-resolution NWP is used to produce short-range forecasts. For example, short-range convective weather forecasts produced by the Variational Doppler Radar Assimilation System (VDRAS; Sun et al. 2010), and the wind and transport and dispersion simulations produced by the Pentagon Shield modeling system (Warner et al. 2007) are examples of applications where this hypothesis is relevant. The performance of systems like VDRAS and Pentagon Shield can likely be improved by deploying the limited sensing resource to locations, which provide the most forecast improvement on a per-sensor basis. The targeted observation strategies discussed above can accomplish this goal, however, they typically require that the sensing platforms be redeployed in real time to the locations where the model is most sensitive to errors in initial conditions. For many applications this is not logistically or economically feasible. This work explores the possibility of realizing some of the benefits of targeted observations without the logistical/economic expense of continually redeploying sensors. Here we examine if knowledge of the underlying terrain in the model can be used to dictate the most efficient way to improve forecast accuracy through the optimal siting of fixed sensing systems.

We address this question by examining the impact of terrain-elevation variability on initial condition sensitivity using both adjoint sensitivity experiments and forward-model forecast impact experiments. Sets of 18 simulations using the adjoint of the MM5 were created for forecasts ranging from 10 to 180 min in length, at an interval of 10 min. These forecasts all end at the same time, but correspond to differences in lead time. These simulations provided initial condition sensitivity results for both flat and irregular terrain. To identify the impact of the terrain on the adjoint sensitivity, the results of the set of 18 adjoint simulations with irregular terrain are then contrasted with a set of comparable simulations where the terrain was flat. Because the adjoint model is a linear approximation of a nonlinear system of equations, and subject to error in situations where the solutions are highly nonlinear, a second forecast impact experiment using the forward version of the MM5 was conducted. Here the locations of adjoint sensitivity from the set of 18 simulations described above were used to define the locations for perturbation of the initial winds. The impact of these perturbations on the downstream forecast is then quantified by contrasting the forecasts with a comparable set of simulations where the terrain was flat. This study was conducted using environmental conditions, which were synoptically and convectively inactive in an effort to isolate the impact of the terrain variability. This work is similar in some respects to the study published by Doyle et al. (2007) where they examined the sensitivity of gravity waves forced by a two-dimensional ridge using an adjoint model. The similarities are that both studies examine the forecast sensitivity to upstream terrain obstacles of varying heights using an adjoint model. The focus of the Doyle et al.
(2007) study was on downslope wind storms and the corresponding impact of gravity waves, while this study is considerably more general and examines a range of conditions that extend from cross-barrier to blocked flow conditions. Furthermore, this study does not focus on the downslope area of the terrain, but instead looks at the sensitivity of the forecast farther downstream with the overall goal of addressing the following questions:

1) Does the presence of irregular terrain upstream of a target forecast region increase the sensitivity of the target region forecast to wind perturbations in upstream observations?

2) If the answer to the above question is yes, is there a relationship between the forecast error (difference between the forecast and the control run) and the height of the upstream irregular terrain?

The analysis using the shallow-water system tells us that the answer of the first question is yes, and the answer to the second question is that the forecast error is related to the flow field gradients, which is a function of terrain height as well as the upstream properties of the flow field. However, because the shallow-water equations are highly idealized, they do not fully capture the solutions to a more realistic and complex flow field. For this reason we investigate the solutions to the more realistic flow field within the framework of a numerical model that more accurately describes the atmosphere. The experimental design used to answer these questions is described in section 2. Section 3 contains the results of the adjoint sensitivity and forward-model forecast impact analyses. Section 4 contains a summary of the results and a brief discussion of their implications.

2. Experimental design

a. Terrain and environmental conditions

Except for the cases with no terrain variability, all of the experimental simulations used a Gaussian-shaped mountain ridge, 15 km wide (east–west) and 40 km long (north–south), which varied in elevation (from experiment to experiment) from 375 to 1300 m. Figure 1 is a rendering of the model domain and Gaussian-shaped terrain feature used in the simulations. To capture small-scale gradients associated with the terrain, this study used a 1-km horizontal grid spacing. The lateral boundary conditions and unperturbed initial conditions for the sensitivity study are based on the analysis from the 20-km Rapid Update Cycle (RUC) model (Benjamin et al. 2004a,b), for a region centered over Albany, New York. The time period studied was 1600–1900 UTC 4 October 2001. The case selected involved negligible synoptic-scale forcing and a relatively uniform environmental flow at low levels (Fig. 2a). On this day, skies were mostly clear, low-level winds were primarily from the west-southwest at 5–8 m s\(^{-1}\), and there was no significant precipitation in the region. The horizontal winds backed with height, and speeds varied from southerly at 2.5 m s\(^{-1}\) at the surface, to westerly at 10 m s\(^{-1}\) at heights between 700 and 1300 m. (Fig. 2b). The choice of a case that was not synoptically or convectively active simplifies the interpretation of the results, such that they primarily reflect the impact of the local variations in the terrain elevation. Perhaps the underlying terrain will similarly influence initial condition sensitivity during situations that are less benign; however, the goal of this study is to first identify if a relationship exists between terrain variability and the growth of initial errors for a relatively barotropic flow. The location, date, and time used in this study were selected to coincide with Part II of this study, which focused on using real-world observations and terrain.

The 20-km RUC analysis is interpolated to a 19 vertical (sigma) level, 1-km horizontal grid using the MM5, version 3, REGRID and INTERPF data preprocessing programs. No additional observations are included in the MM5 initial conditions beyond those already represented in the 20 km 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. The same large-scale initial condition fields are used for all of the sensitivity simulations and the lateral boundary conditions remain unchanged between all of the simulations.
Inserting a terrain obstacle into the model without bringing the flow into balance can result in a significant shock to the model; however, the design of the adjoint experiment required that the model be run without a spinup period. To minimize this effect, the initialization process used follows the standard methods typically used to set up the mesoscale model by bringing the flow into balance with the underlying terrain prior to the start of the simulation. This study also examined forecast impact for a simulation where the model was spun up (e.g., run for 60 min) prior to incorporating perturbations to the upstream winds. By examining the initial condition sensitivity for both a cold-start and a spunup case we have confirmed that the results are not influenced by transients associated with model shock during the spinup period.

b. Modeling tools

The forward model used in this study is the MM5, version 3. The MM5, version 3, is a nonhydrostatic limited-area primitive equation model that is suitable for both atmospheric research and operational weather forecast applications. It is a flexible tool providing numerous options for physical parameterizations and initializations, and can be used for a wide range of model grid spacings. Detailed descriptions of the MM5 can be found in Grell et al. (1994).

The MM5 adjoint-modeling system is used in conjunction with the forward version of the MM5, version 3, to examine initial condition sensitivity and forecast accuracy in this study. The adjoint model is based on a linearized version of the MM5, version 2, nonhydrostatic, limited-area model and can be used to calculate the gradient of a response function with respect to the forecast variables at an initial time. The MM5 adjoint model is available from NCAR and was used with minimal modification in this study. For additional information regarding the MM5 adjoint-modeling system, the reader should consult the detailed discussion provided in Zou et al. (1997) and Zou et al. (1998).

Adjoint models may be used to evaluate the relationship between the model outcome and the state of the physical system at some earlier time. Data assimilation, model tuning, and initial condition sensitivity analyses are among the more common applications for adjoint models in meteorology (Errico 1997; Giering and Kaminski 1998). Adjoint models can provide an effective means to characterize initial condition sensitivity in an atmospheric simulation; however, one limitation is that they only provide a piecewise linear representation of a nonlinear atmospheric model. Because of this limitation, their results can be inaccurate when the atmospheric situation being simulated is highly nonlinear. Because topographically forced flows, like the ones evaluated in this study, can be highly nonlinear, the tangent linear assumption used by the adjoint model may not be appropriate at all times.

The adjoint and forward simulations are designed to be as simple as possible and incorporate only the necessary
physics required to produce a reasonable simulation of surface winds during conditions that were dominated on this day by a large high pressure system. Because this case did not involve precipitation, a cumulus parameterization is not used in the simulations. Although clouds were not anticipated in the simulation, the large-scale precipitation and explicit precipitation microphysics were used in the event that they might occur. Because of the short duration of the simulations, the radiation physics is also turned off. Where possible, the adjoint and forward models are configured such that they used the same physics options. One exception is in the parameterization of planetary boundary layer (PBL) processes where the “bulk” parameterization option is used in the adjoint model while the forward-model simulations uses a more sophisticated Blackadar PBL parameterization scheme (Blackadar 1976, 1979; Grell et al. 1994).

c. Adjoint sensitivity experiment design

The present study first uses the adjoint-modeling technique to identify the upstream location that influenced the near-surface wind forecast in the target area. While this a powerful approach, it is difficult to use the adjoint model to provide physical interpretations for the behaviors of the sensitivity gradients. As discussed in Kleist and Morgan (2005), few studies exist that provide physical interpretations of the sensitivity fields. This study addresses this challenge by isolating an element of the model state (presence or lack of an upwind terrain feature) to demonstrate the relationship between initial condition sensitivities when irregular terrain is or is not present.

For a series of simulations of different forecast lengths, the locations where initial condition sensitivity occur follows a backward trajectory. This makes it possible to identify regions where the model is preferentially sensitive to perturbations in the initial conditions. Figure 3 shows an example of an adjoint sensitivity field, and illustrates the backward trajectory formed by the adjoint sensitivity regions as the simulation initial time moves backward in time. In their limited-area modeling studies, Vukičević and Errico (1990) found that model forecasts are sensitive to initial condition errors until the region of initial condition sensitivity coincides with the lateral boundaries. At this point, model forecast errors can be attributed primarily to the lateral boundary conditions.
This has obvious implications for the experimental design of this study and any other study evaluating model sensitivity to initial condition errors using a limited-area model. A more detailed description of the meteorological applications of an adjoint model, including a discussion of its use in initial condition sensitivity studies like this one, can be found in Errico (1997), Giering and Kaminski (1998), Zou et al. (1993), and Kleist and Morgan (2005).

To characterize forecast sensitivities in the wind forecasts, a vorticity response function is used in the adjoint model. Vorticity is chosen as the cost function because its formulation contains the gradient of the wind components, which is of fundamental interest in this study. For all of the adjoint simulations, the response function is specified in a 3 by 3 point grid box on the lowest model level, located downstream from the terrain. The small square in Fig. 1 denotes the location where the vorticity response function is defined. This location is chosen so that the trajectory of initial condition sensitivity would cross over the center of the idealized terrain feature. For each terrain scenario (flat or variable), 18 adjoint simulations, ranging in length from 10 to 180 min, are run, where all simulations have the same final time.

This study uses the center points of the adjoint sensitivity regions to provide a geographic reference for the initial condition sensitivity. Because the locations of initial condition sensitivity typically move upwind with increasing simulation length, the set of adjoint sensitivity centers form what can be considered to be a backward trajectory of initial condition sensitivity. As this trajectory moves upstream, it becomes collocated with the terrain, making it possible to relate adjoint initial condition sensitivity to the underlying terrain. To determine the effect of the terrain, the results of the simulations containing terrain are then contrasted with a comparable set of simulations where the terrain was flat. This is discussed in more detail in section 4.

d. Forward-model forecast impact experiment design

A second analysis based on forward-model simulations is then used to evaluate the findings of the adjoint sensitivity analysis and better characterize the growth of initial errors over irregular terrain relative to flat terrain. This analysis consists of a series of four forward simulations: one where the initial conditions in simulations containing irregular terrain are perturbed, one where the initial conditions in simulations with flat terrain are perturbed, and two control simulations for the flat and irregular terrain configurations where the initial conditions are unperturbed. Separate perturbed initial conditions are created for each simulation ranging from 10 to 180 min (in 10-min intervals) before the final time. The previously described adjoint sensitivity results dictate the region where the initial conditions are perturbed. The wind adjustments are made in the MM5 initial analysis prior to the preprocessing step where the data are interpolated to the sigma coordinates by the MM5 INTERPF preprocessing software.

The initial conditions used in the irregular and flat terrain simulations were perturbed in all regions where the absolute value of the horizontal wind ($u$ or $v$) adjoint sensitivity is greater than 1000. Perturbations of $+3 \text{ m s}^{-1}$ were separately made to both the $u$- and $v$-wind components. The $3 \text{ m s}^{-1}$ 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 Doppler radar wind observations and the model initial analysis, both valid at 1600 UTC 4 October 2001, which are discussed in Part II. Because of the limited area of the wind perturbations, typically less than 10 km in horizontal extent, the perturbations modify the winds over less than 3% of the domain area. Therefore, the perturbations do not significantly alter the overall mountain flow response. By using perturbations of the same magnitude (e.g., $3 \text{ m s}^{-1}$) in both the mountain and flat simulations, it is possible to compare the forecast impacts between the simulations and characterize if the perturbations made over the terrain have a different impact on the forecast than those made over the flat terrain. For reference, see Fig. 4, which illustrates a horizontal plan view of a typical perturbed initial condition field over the elevated terrain.

The impact on the surface wind forecasts is determined by subtracting the surface wind forecast that is based on the perturbed initial conditions from the control simulation’s surface wind forecast. The forecast impact from both the irregular and flat terrain cases are related to the terrain below the diagnosed centers of adjoint sensitivity where the perturbation is imposed. This makes it possible to measure the forecast impact, with and without terrain variability, of an initial wind perturbation imposed in the region diagnosed to be the most sensitive to an adjustment.

The process described above is used to illustrate the influence that a 650-m high terrain feature has on the impact of initial condition perturbations. This mountain height is comparable to the terrain features that make up the Berkshire Mountains of western Massachusetts where the background environmental data were taken. The final analysis conducted in this study considers whether the magnitude of the terrain anomaly influences the model wind forecast sensitivity to initial conditions. This component of the study uses the procedures described above to characterize the impact of perturbations made to the initial analysis over terrain features.
of varying heights. In addition to the 650-m mountain ridge, terrain features of 325, 925, and 1300 m are examined. The results from each analysis are contrasted with each other to determine if the amplitude of the terrain anomaly has an impact on forecast sensitivity to initial conditions.

3. Results

a. Adjoint sensitivity analysis

The gradient results provide a measure of the sensitivity of the near surface model variables at a given forecast length to the upstream initial conditions. Of particular interest in this study is the improvement of near-surface wind forecasts, consequently for simplicity the sensitivity analysis focuses on the upstream wind components.

The gradient results are a three-dimensional representation of forecast sensitivity to the initial conditions. Since the sensitivity shows up in one or more levels, it is insufficient to look at only a single level. For this reason, this study uses a vertically integrated, absolute value of gradient sensitivity to characterize the locations of model sensitivity. The absolute value of the sensitivity is used in order to avoid the situation where positive adjoint sensitivity at one level is offset by negative adjoint sensitivity at another level, and provides an effective means to relate the total forecast sensitivity for a grid column to the underlying terrain. This technique is similar to that used by Gelaro et al. (2002) to vertically integrate the values of the average energy function associated with the most significant singular vectors. All of the adjoint sensitivity results presented in this paper are vertically integrated.

Figure 3 illustrates a plot of the vertically integrated adjoint sensitivity of the vorticity forecast to the $u$ winds, where the subjectively identified center of the sensitive region is denoted by $\otimes$. The center point of the sensitivity region serves as a surrogate for the entire pattern in this study. This is a reasonable assumption for short simulations (i.e., 3 h or less) during which the sensitivity results remain relatively localized. The vertically integrated adjoint sensitivity values are combined with corresponding terrain elevations to demonstrate the relationship of adjoint sensitivity to terrain (Figs. 5a,b).

For the $u$-wind component, the sensitivity is clearly greatest when the center of the sensitive region is located over the elevated terrain. This strong signal exhibited by the $u$-wind sensitivity is not present in the $v$-wind sensitivities that show no appreciable response to
the presence of the mountain. Although not shown, a similar relationship between initial condition sensitivity and terrain elevation was present in simulations that use divergence as the response function. The strong sensitivity signal in the $u$ wind and the lack of a signal in the $v$-wind are the result of the magnitude of the $u$-wind component relative to the $v$-wind component. As illustrated in Fig. 4 the only thing that differed between the control and experimental simulations is the terrain elevation and the corresponding gradients in the atmospheric variables that were associated with the terrain. As discussed earlier, it is not possible to specifically identify from the adjoint model what causes the increased gradient sensitivity (the presence of the terrain obstacle or the associated gradients). Regardless of the source, the results suggest that the gradient sensitivity is higher over the terrain obstacle. 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 downstream vorticity forecast than perturbations made over flat terrain.

**b. Forward-model forecast impact results**

The question of the relative forecast impact of comparable initial perturbations made over flat and irregular terrain is also examined in this study through a forecast impact analysis. The model forecast impact analysis is performed for several variables at the lowest model level: the individual $u$- and $v$-wind magnitudes, total wind magnitude, divergence, and vorticity. The initial conditions used in both the irregular- and flat-terrain simulations were perturbed in all regions where the vertically integrated absolute value of the horizontal wind ($u$ or $v$) adjoint sensitivity is greater than 1000. A perturbation of $\pm 3 \text{ m s}^{-1}$ is separately applied to both the $u$- and $v$-wind components. An example of the $u$-wind forecast impact field from the 70-min forward-model simulation with the elevated terrain feature is shown in Fig. 6. Although not shown, the forecast impact field from the flat terrain simulation exhibits a similar pattern, but it has a different magnitude. Overlaid on this image, as a small square, is the location where the vorticity response function was defined in the adjoint sensitivity component of this study. As anticipated, the surface wind forecast impact from all of the forward simulations (not shown) is found in the area where the response function was defined in the adjoint sensitivity simulations. Forecast impacts in both the mountain and flat-terrain simulations are computed only within the forecast verification region. The verification region encompassed an area within $73.0^\circ W$–$72.8^\circ W$ longitude and $42.7^\circ N$–$43.0^\circ N$ latitude indicated by the larger square in Fig. 6. It is believed that because this area did not include grid points directly influenced by the lateral boundary conditions, and the results of the sensitivity analysis will be dominated by the perturbations made to the initial conditions, the effects of the downwind lateral boundary conditions are negligible in the forecast impact analysis.

Figures 7 and 8 indicate that forecast impact values [in terms of maximum value and root-mean-square (RMS) within the verification domain] generally tend to decrease as the simulation length increases. This is expected, and is an indication of the initial condition perturbation’s diminishing impact as the initial condition perturbation becomes more spatially removed from the forecast verification region. However, the maximum
forecast impact computations further illustrate the findings suggested earlier by the adjoint sensitivity analysis that the forecast sensitivity to initial conditions increases in the presence of elevated terrain. A comparable experiment that used a $-3 \text{ m s}^{-1}$ perturbation yielded similar results (not shown).

Maximum perturbation-impact values are just one of the measures that can be used to assess the impact of the perturbed initial conditions on the surface wind forecast. In addition to the maximum value computations, the RMS value of the surface wind forecast impact is also calculated. This study uses the standard definition of RMS shown below:

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{N}}. \tag{8}$$

Here $x$ represents the forecast impact which is defined as

$$x = u_{\exp} - u_{\text{con}} \quad \text{for the } u \text{ wind} \quad \text{and} \quad x = v_{\exp} - v_{\text{con}} \quad \text{for the } v \text{ winds}. \tag{9}$$

Here $u_{\exp}$ and $v_{\exp}$ represent the $u$ and $v$ winds from the experimental simulations where the initial conditions are perturbed. The $u_{\text{con}}$ and $v_{\text{con}}$ represent the $u$ and $v$ winds from the control simulations where the initial conditions are not perturbed. Because the RMS impact is calculated over the entire verification domain (large solid-line box in Fig. 6), it captures the overall impact of the initial condition perturbations.

The RMS impact results in Fig. 8 also show that irregular terrain influences the sensitivity of the surface wind forecasts to initial condition perturbations. There is a distinct increase in the $u$- and $v$-wind RMS impact values when the initial condition perturbation was made over elevated terrain. This is in contrast to the monotonic decrease with time exhibited by the $u$- and $v$-wind RMS forecast impact values in the flat terrain simulations. Comparable results are found in the experiment that uses a $-3 \text{ m s}^{-1}$ perturbation to the initial $u$-wind field (not shown). There is minimal impact of the terrain for simulations that use perturbations to the initial $v$-wind component (not shown), consistent with the previously described adjoint sensitivity analysis.
While the results from the adjoint and forward sensitivity studies both show an enhanced sensitivity to initial condition adjustments made over elevated terrain, it is possible that this enhanced sensitivity is not due to the gradients present over the terrain, but is instead associated with transient features present over the terrain at the start of the simulation that propagated downwind from the mountain. One example of such a transient phenomenon are gravity waves that move downwind from the mountain after the model “cold start” initialization. Another form of transients are the changes in model fields associated with forcing of the lateral boundary conditions. Throughout the simulation, the model wind fields were examined for the presence of other transients to confirm that the enhanced initial condition sensitivity is not due to the presence of a transient feature. Two steps were taken to ensure that transient features did not influence the results. First, the perturbations were made at a time and location where an analysis of the wind fields confirmed that no transients were present. Second, the model was run for a 60-min period prior to making perturbations to the winds. The 60-min “model spinup time” was based on an analysis of the domain-mean perturbation pressure during the simulation (Fig. 9). This analysis indicates that there were significant perturbation pressure oscillations.

**Fig. 7.** Maximum forecast impact values (m s\(^{-1}\)) for the (a) \(u\)-wind forecasts and (b) \(v\)-wind forecasts in the lowest model level vs the length of the forward-model simulation for simulations where a \(+3\) m s\(^{-1}\) \(u\)-wind perturbation was made to the initial conditions. The approximate terrain elevation below the center of the initial condition perturbation is shown at the bottom.

**Fig. 8.** The RMS values of forecast impact (m s\(^{-1}\)) for the (a) \(u\)-wind and (b) \(v\)-wind forecasts vs the length of the forward-model simulation for simulations where a \(+3\) m s\(^{-1}\) \(u\)-wind perturbation was made to the initial conditions. The approximate terrain elevation below the center of the initial condition perturbation is provided.
during only the first 40 min. To avoid any issues associated with these fluctuations associated with model spin up a +3 m s\(^{-1}\) perturbation, similar to those described above, were made to the winds after 60 min. This was done in the same manner as was done in the cold-start simulations described above. The results again show that a perturbation to the upstream winds made over the elevated terrain had a larger impact on the downstream forecast than a comparable perturbation made over flat terrain (Fig. 10). These results also show an increased forecast impact at forecast times longer than 140 min. This difference from earlier results is due to an interaction of the perturbed area with a transient wind feature induced by the lateral boundary conditions. This wind feature was not present in the cold-start simulation, which started 60 min earlier.

c. Sensitivity of the initial condition perturbation’s impact to the magnitude of the terrain elevation

The results presented in the previous section indicate that perturbations made to model initial conditions in the presence of irregular terrain can have a more significant impact on the downwind forecast of near-surface winds than comparable perturbations made over flat terrain. The next question to be examined is whether the elevation of the terrain can also be used as a predictor of the relative impact that perturbations made to the initial conditions will have on the model forecast. In this analysis, terrain features of 325, 650, 975, and 1300 m in height are used. The procedures used here to determine the relative impact of terrain elevation are the same as those used in the analyses described above that used a 650-m Gaussian-shaped terrain feature.

The Froude number described in (7) is a commonly used parameter to characterize fluid flow over terrain.
obstacles in a shallow-water framework. Unfortunately it is difficult to apply this analog to the atmosphere because of the differences between the defined fluid depth in (7) and the vertically unbounded flow in the atmosphere. An alternative (not without deficiencies) that is often used for the atmosphere is

$$Fr = \frac{U}{NH}.$$  \hspace{1cm} (11)

In (11), $U$ is the environmental wind speed, $N$ is the Brunt–Väisälä frequency, and $H$ is the height of the terrain obstacle (Durran 1990). 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 and has been used to infer cross-barrier versus blocked flow conditions. Using this formulation, in high Froude number flows where $Fr > 1$, the air has adequate kinetic energy to flow up and over the terrain obstacle. When $Fr < 1$, the air does not have sufficient kinetic energy to fully overcome the potential energy required to flow up and over the terrain obstacle. High Froude number scenarios are often referred to as cross-barrier flow and low Froude number scenarios are referred to as being blocked or partially blocked flows (Bluestein 1993). Low Froude number flows typically become more complex than the high Froude number flows and can result in flow stagnation associated with the terrain feature and in low Froude number cross-barrier flow conditions are more likely to contain gravity waves and flow separation (Smolarkiewicz and Rotunno 1990). Similar to the Smolarkiewicz and Rotunno (1990) study this work examines the properties of fluid flow over terrain of varying heights and corresponding Froude numbers. Here the $Fr \cong 2.8, 2.0, 1.0,$ and $0.7$ for terrain obstacles with heights of $325, 650, 975,$ and $1300$ m, respectively. These cases span conditions ranging from cross-barrier flow for the lower elevation terrain obstacles, to flow that is partially blocked near the surface for the $1300$-m terrain obstacle. An examination of the low-level wind forecasts around the idealized mountain confirms that this is the case in these simulations.

The results shown in Fig. 11 from the adjoint analysis indicate that an increase in the terrain elevation results in an increase in the sensitivity of the model’s vorticity forecast to the $u$-wind initial condition perturbations over the elevated terrain. Shown is the adjoint sensitivity for the experiments with terrain amplitudes ranging from flat to $975$ m. For reference purposes, the terrain elevations from the simulations using the $650$-m terrain feature are plotted at the base of the plot. These values do not exactly correspond to the $325$- and $975$-m simulations.

The impacts of the perturbations on the forward simulations are shown in Fig. 12. As suggested by the adjoint sensitivity results, a larger forecast impact is realized from a perturbation made over the $975$-m terrain feature than the impact realized from a comparable perturbation.
made over a 325-m terrain feature. The forecast impact that occurs when perturbations are made to the initial conditions of a 1300-m terrain-amplitude simulation is larger than in any of the other simulations. This is reflected in Fig. 13, which shows results from the 975- and 1300-m terrain simulations. As described above, the 1300-m simulation represents a situation in which the flow regime has transitioned from a cross-barrier flow to a partially blocked flow (Fig. 14b). This was confirmed through examinations of the near-surface flow fields for

FIG. 12. Maximum values of forecast impact in the $u$-wind forecasts vs simulation length for simulations with terrain heights ranging from flat to 975 m. For reference, the approximate terrain elevation below the center of the initial condition perturbation from the 650-m terrain simulation is provided at the bottom of the plot.

FIG. 13. Maximum values of forecast impact vs the length of the forward-model simulation for simulations with flat, 975-, and 1300-m terrain. For reference, the approximate terrain elevation below the center of the initial condition perturbation from the 650-m terrain simulation is provided as a reference to previous plots.
Simulations with terrain of 975 m and lower that resembled the image for the 650-m terrain in Fig. 14a. For the partially blocked flow case (e.g., 1300-m terrain) the main region of adjoint sensitivity to remain fixed over the terrain feature for all simulations longer than 70 min. The presence of breaking lee waves was also observed in a vertical cross section of potential temperature from the 1300-m simulation. The extended period of elevated forecast impact in the 1300-m simulation, for all forecasts greater than 70-min duration, is a consequence of this area of forecast impact remaining over the elevated terrain (Fig. 15). The location of the adjoint sensitivity in this figure is representative of all of the simulations greater than 70 min.

The increased sensitivity and forecast impact from adjustments made to the initial conditions over elevated terrain can be explained in the context of the stability analysis of solutions to the shallow-water system described in section 1. For cross-barrier flow in the shallow-water system, the fluid flow velocity decreases as it ascends the terrain obstacle, thus initial conditions sensitivity is expected to be greatest on the windward side of the mountain. In this situation this effect is offset by the fact that the wind speeds are greater at higher altitudes resulting in a higher wind speed at the peak of the mountain. As a result, instead of an increase in fluid flow velocity on the leeward side as predicted by the simpler shallow-water representation of the fluid flow, there is a decrease in the fluid flow velocity on the leeward side of the terrain obstacle (left side of Figs. 12 and 13). This results in a corresponding increased initial condition sensitivity on the leeward side of the obstacle versus the windward side as predicted by the shallow-water equations. This notion is supported by Figs. 12 and 13, where the maximum forecast impact is associated with initial condition perturbations on the leeward side of the terrain obstacle. As the mountain height increases, the integrated forecast impact increases linearly for the cross-barrier flow scenarios as shown in Fig. 16. This is due to a sharper velocity gradient induced by a steeper terrain feature. The linear growth in forecast impact is not predicted by the shallow-water system stability analysis; however, we do not expect the results of the shallow-water model to replicate that of the numerical model because the former is an idealized description of flow over obstacles while the latter provides a more accurate description of atmospheric processes. When the flow transitions from cross barrier to partially blocked, the initial condition sensitivity stays on the leeward side of the terrain, which coincides with the negative velocity gradient on the leeward side of the mountain during partially blocked flow. The transition from cross-barrier flow to partially blocked flow increases the line slope when plotting the forecast impact versus mountain height shown in Fig. 16. This slope increase is likely caused by the addition of nonlinear flow effects such as stagnation points, flow blocking, and vortex generation. The analysis suggests that there is a relation between terrain height...
and initial condition sensitivity, namely, due to the effect the terrain feature has on the ambient wind and pressure fields. These flow field effects are a function of terrain height as well as the properties of the fluid flow upwind of the terrain feature such as flow velocity and static stability.

4. Conclusions

The results of initial condition sensitivity experiments for irregular and flat terrain are presented in this paper using a quasi-idealized numerical framework. These experiments utilize an idealized terrain environment in which a single mountain ridge surrounded by homogeneous flat terrain is used to characterize the impact that irregular terrain has on the sensitivity of forecasts to initial condition perturbations. The sensitivity analyses are conducted using simulations from a mesoscale model and its adjoint. The adjoint sensitivity results are used to make a preliminary assessment of sensitivity and provide information regarding the locations where the surface wind forecast may be sensitive to errors in the initial conditions. The subsequent forward-model sensitivity analysis examines the sensitivity of the surface wind forecast to perturbations in the $u$- and $v$-wind initial conditions fields. By coupling the adjoint sensitivity analysis with a forward-model forecast sensitivity analysis.
analysis, it is possible to infer the downwind forecast impact that perturbations made over an elevated terrain feature have relative to comparable perturbations made over flat terrain.

Since the wind was largely zonal, the greatest sensitivity in the adjoint and the forecast impact results are seen in u-wind component results. When the forward-model sensitivity is examined for various terrain heights, the impact of a comparable adjustment to the initial conditions increases as the height of the terrain feature is increased. The increased sensitivity and forecast impact from adjustments made to the initial conditions over elevated terrain can be explained in the context of the shallow-water model stability analysis described in section 1. The increased impact of adjustments to initial conditions corresponds to the impact the terrain feature has on the flow field and pressure field (and for the shallow-water theory, fluid depth) gradients. In this situation the impact of the initial condition adjustments increase linearly as the height of the terrain obstacle increases when the flow is cross barrier, and initial condition perturbations have a more dramatic effect when the flow field switches from cross barrier to partially blocked. Assuming that the inclusion of additional observations results in a positive adjustment to the initial analysis, the findings of this study suggest that targeted observations deployed over elevated terrain will result in a larger forecast improvement than comparable observations deployed in regions of homogenous terrain. Such findings are not only relevant for mesoscale flows over topography, but also in regions where topographic features influence the synoptic flow field, such as in coastal regions and regions with mountain chains. This work, which is the first of a two-part series of papers, allowed us to characterize these effects in a more controlled environment where the relative impact of varying the terrain obstacle height can be determined. An outstanding question that arose from this work is whether or not this effect can be used to improve mesoscale weather wind forecasts in a more complex real-world setting. The second paper in this series, Part II, specifically addresses this question by examining the relative impact of Doppler radar velocity observations over real-world elevated and flat terrain from western Massachusetts and eastern New York on the accuracy of surface winds downwind from the terrain on the New York–Massachusetts border. Comparable relationships between the relative location of the initial condition adjustment and downstream forecast impact were found in both Part I and Part II of this study suggesting that forecast accuracy can be improved by deploying observations to take advantage of enhanced initial condition sensitivity associated with elevated terrain.

Acknowledgments. The authors would like to acknowledge the MIT Lincoln Laboratory, the Lincoln Scholars program, the National Center for Atmospheric Research’s Research Applications Laboratory for supporting this work, and the late Dr. Tom Warner for his comments and suggestions that have greatly improved this work. The authors also wish to express their appreciation to the insightful and constructive comments of the anonymous reviewers.

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