# Improving Representation of Low-Level Meteorological Fields in Forecasts and Analyses

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## 1. INTRODUCTION

Predictability of low-level meteorological fields is a key requirement for organizations operating under a risk from weather impacts. Increasing computational capability and affordability permits forecasts and analysis of higher spatio-temporal resolution, and use of more complex data assimilation. Choosing the most effective means to create forecasts is a key task which becomes even more essential when extra challenges exist in the simulated problem domain.

Forecasting in areas of complex terrain is such a challenge. The best practice approach to resolve key meteorological features, such as winds and boundary layer characteristics, may be determined by a cost benefit analysis for each individual case. In doing so, it is important to consider the accuracy of the objective analysis and first-guess fields determining the initial model state, and accompanying error. Accurately representing terrain in the analysis step clearly will allow much better forecast guidance to be produced by the model.

One way to do this is to use previous model output as the first guess field for the new analysis, or "cycling" a forecast. The outermost domain's boundary conditions, as well as updated surface parameters for all domains, will still enter from a global model. However, using a previous local forecast as the first guess field will mean the terrain induced flow will already be represented. This creates a more favorable environment in which to place observations through data analysis.

In addition to direct cycling from previous forecasts, variational data assimilation methods such as 3DVAR (Barker et al. 2004) and 4DVAR (Huang et al. 2009) are becoming operationally feasible. In the Advanced Research Weather Research and Forecasting model (WRF-ARW, Skamarock et al. 2008), 3DVAR includes framework for cycling forecasts. This method adds value to the forecast process, especially in the boundary layer, by eliminating errors due to terrain spin-up. The level of improvement in a forecast using 3DVAR data assimilation and cycling is examined here in terms of the improvement found in the forecasted wind field.

## 2. BACKGROUND

One example of data assimilation and cycling of forecasts is the system described by Liu et al. (2008) in consistent development at Army Test and Evaluation Command (ATEC) ranges throughout the U.S. These sites are often impacted by complex boundary layer processes which need to be forecast in order to minimize expense associated with tests. The assimilation system utilizes station nudging described by Stauffer and Seaman (1994) and further adjusted to fit their needs. For their requirements, variational methods were too computationally expensive and their approach produces a similar result. Their model is run to assimilate observations as they come in, and in doing so to create forecast output for the next model initialization. This cycling is primarily a method of including available observations for an immediate forecast start, while including all later observations for archiving purposes, retrospective study, and an initialization point for the next forecast cycle. There is no discussion, however, of the improvement cycling the forecast has on terrain spin-up.

WRF 3DVAR has the ability to incorporate a wide variety of data sources and to be employed around the globe for forecasting mesoscale weather in terrain, as Powers (2007) demonstrated for McMurdo base Antarctica. Here, a severe wind event in which a synoptic low combined with terrain-induced flow was shown to have improved forecast guidance. The ability of WRF 3DVAR to improve forecasts in a range of operational settings provides motivation for an evaluation of the most effective ways in which to employ it. As an example, the importance of fine resolution to forecasting flow in complex terrain has been demonstrated by Carroll et al. (2009). This work is based on 3DVAR as a good choice for data assimilation which will be applicable as 4DVAR becomes more cost effective with increased computational power Huang et al. 2009), and focuses on establishing the value added by the combination of cycling with data analysis in complex terrain.

## 3. METHODOLOGY

The two areas of focus are Southeast Asia and the Black Hills of South Dakota. The former represents an area of strong terrain forcing with large topographic relief, while the Black Hills provide moderate forcing from a more subdued topographic profile. Three domains were employed in each area. In Southeast Asia the outermost domain is centered over 33.7°N 67.8°W and has grid spacing of 9 km covering 2250 km X 2250 km of area (Fig. 1a). The inner domains have 3-km and 1-km grids, spanning areas of 509 km X 480 km and 187 km X 187 km. The three domains covering the Black Hills are centered at 44.2°N - 103.8°W and have grid spacings of 9 km, 3 km, and 1 km, covering areas of 1350 km X 1350 km, 570 km X 144 km, and 169 km X 190 km, respectively (Fig. 1b). The Black Hills forecast environment is a real time modeling system used operationally by SDSMT and the local NWS office, while the Southeast Asia domain is used for research mode only.

Boundary conditions and first guess fields for cold start runs are obtained from the GFS half degree data for Southeast Asia, while the Black Hills domains utilize the NAM WMO 212 and 218 grids with 40-km 3-D fields and 12-km grid surface fields (including 2-m and 10-m meteorological fields), respectively. Cycling forecasts first-guess fields were extracted from the exterior domain of the previous forecast, supported by the GFS or NAM fields supplying the outermost domain's boundary conditions. This method also provides updated SST and other valuable land surface values, as well as preventing error growth by continually providing input from a global model on the outer boundaries. Data assimilated includes available sounding, metar, ship, and buoy data.

For both the North American and Southeast Asian domains, WRF is run using the WRF Single-Moment 6-Class (WSM6) microphysics scheme (Hong and Lim 2006), the NOAA land surface model (Chen and Dudia 2001a,b), the YSU planetary boundary layer scheme (Hong et al. 2005), the Kain-Fritsch 2 cumulus scheme (Kain and Fritsch 1990, 1993), rapid radiative transfer model for longwave radiation (RRTM, Mlawer et al. 1997), the Dudhia shortwave radiation scheme (Dudhia 1989), and the MM5 similar Monin-Obukhov scheme for surface layer physics.

An effort is made to study periods without synoptic forcing so the terrain spin-up signature is isolated. When this is not possible in the case of some cross correlation studies, several months are averaged in order to smooth any synoptic signature.

The qualitative evaluation method of comparing streamline fields at specific heights above ground is performed on days with as little forecast divergence as possible. The forecast initialized twenty-four hours previously should be very similar to an analysis at free-air levels. The terrain spin-up from a cold start with high resolution terrain can then be visually discerned in the flow field.

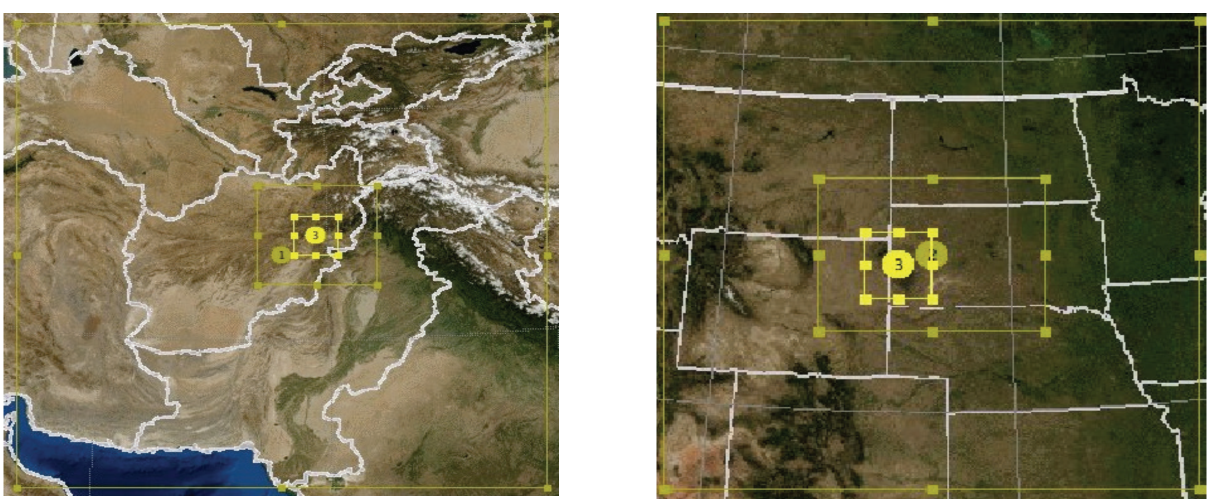

*Figure 1: Projections showing the three domains over each area.*

## 4. RESULTS AND DISSCUSION

In order to display terrain spin-up, a portion of the outermost domain is shown in Fig. 2 displaying streamline flow over terrain for the SE Asia scenario for 1800 UTC 26 September 2010 at 250 m above ground level (AGL). Forecasts did not diverge and were for weak synoptic forcing under slightly zonal flow. The comparison is between cold start forecasts, initialized six hours previously, and the current forecast's analysis. Both forecasts' initializations included data assimilation through 3DVAR which adjusts the entire forecast solution over the outermost domain closer to observations using minimization of a cost function. These low-level differences show that after six hours terrain has induced flow and circulation features which are not incorporated into the analysis. This terrain spin-up introduces error into the first hours of a forecast

The forecast for 1800 UTC, initialized 6 hours previously, is a representation of what the analysis could look like if it included the effects of the high resolution terrain by incorporating model spin-up. Comparing the previous forecast's 8-hr winds to that of the current forecast's 2-hr winds at 250 m and 1900 UTC in Fig. 3, we can see that the model rapidly starts to adjust toward the environment represented in the forecast which had 8 hours to spin up the terrain flow features. In other words, the current forecast's environment 250-m winds have started to converge towards a reasonable terrain-following state after two hours of simulations. To what degree errors still exist in the 2-hour forecast, due to terrain spin-up, may be difficult to determine in an operational forecast setting. At 750 m AGL in Fig. 4, for the same time as Fig. 3, higher above terrain, the flow is slower to adjust to forcing from terrain beneath. Two hours out, the flow is only responding to the more noticeable terrain patterns, while at 250m AGL there were many adjustments to the flow pattern. Forecast hour 8 demonstrates that given enough time, significant impact from the terrain is noticeable at this height. Moving ahead three more hours, in Fig. 5 the development of very similar flow pattern starts to emerge due to terrain spin-up. Yet there are noticeable differences in the forecast initialized 11 hours previously which suggest that errors due to terrain spin-up still exist. Due to these errors, the value of guidance at this level has been lessened for at least five hours. Depending on the forecast situation these errors could have significant impact on the remainder of the forecast.

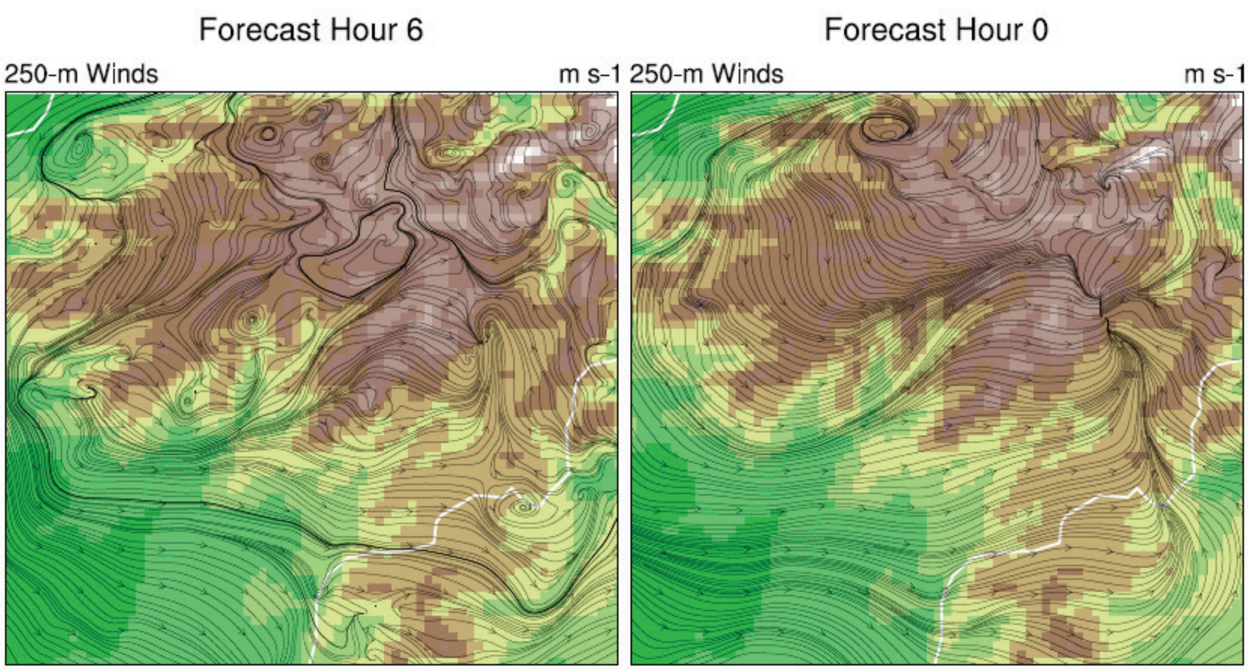


*Figure 2: Cold start forecasts initialized six hours apart from GFS data 1800 UTC 26 September 2010 over SE Asia outer domain (9-km grid spacing). 3DVAR used for both runs with sounding, surface, ship, and buoy data. .*

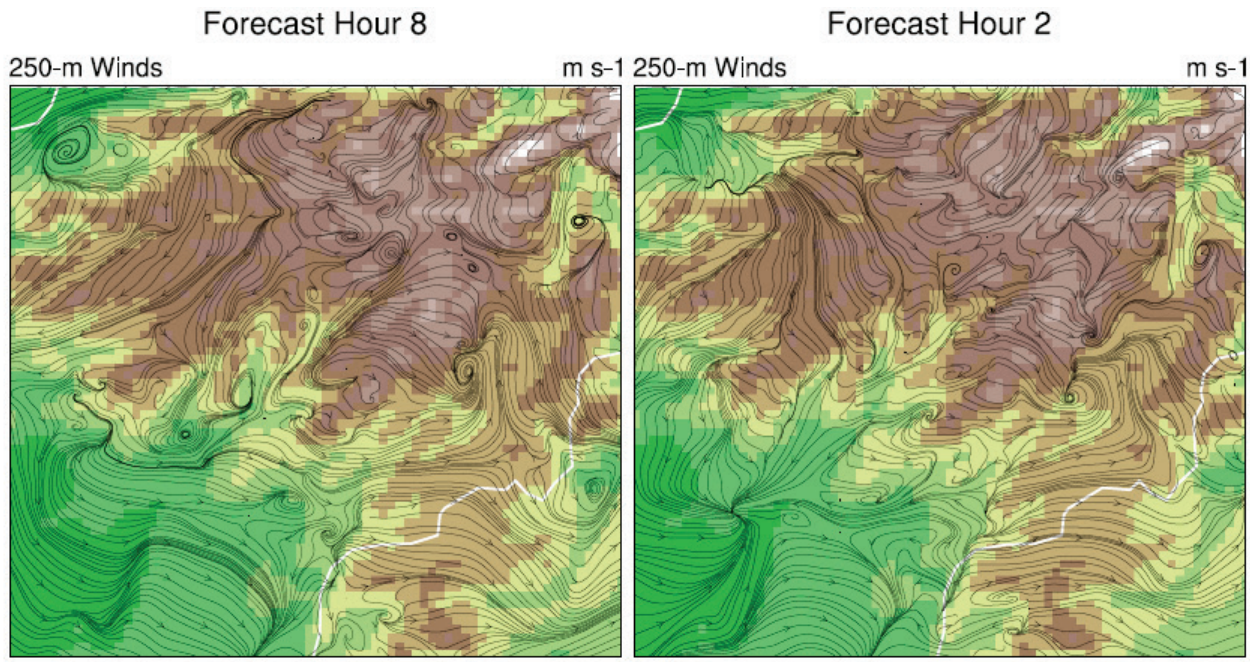


*Figure 3: The same forecast initializations of Fig. 2, but two hours advanced. Flow has begun to divide over ridges, showing drainage flows and circulations in valleys.*

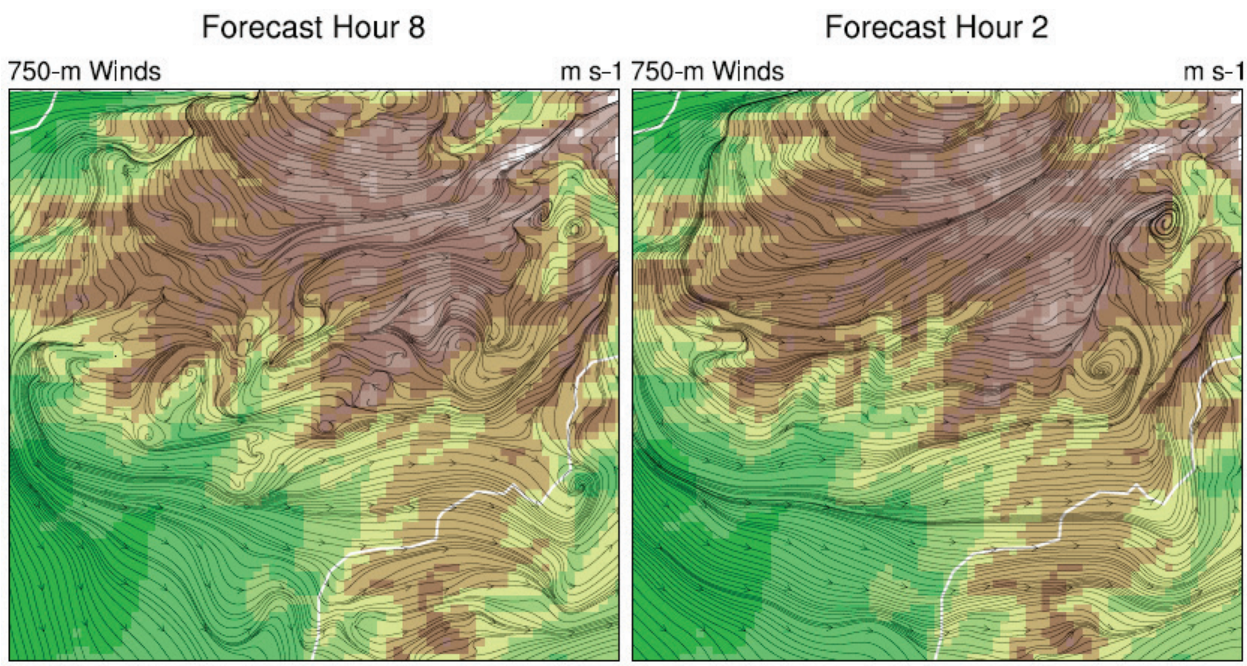


*Figure 4: The same date and forecast hours as Fig. 3 but for 750 m AGL.*

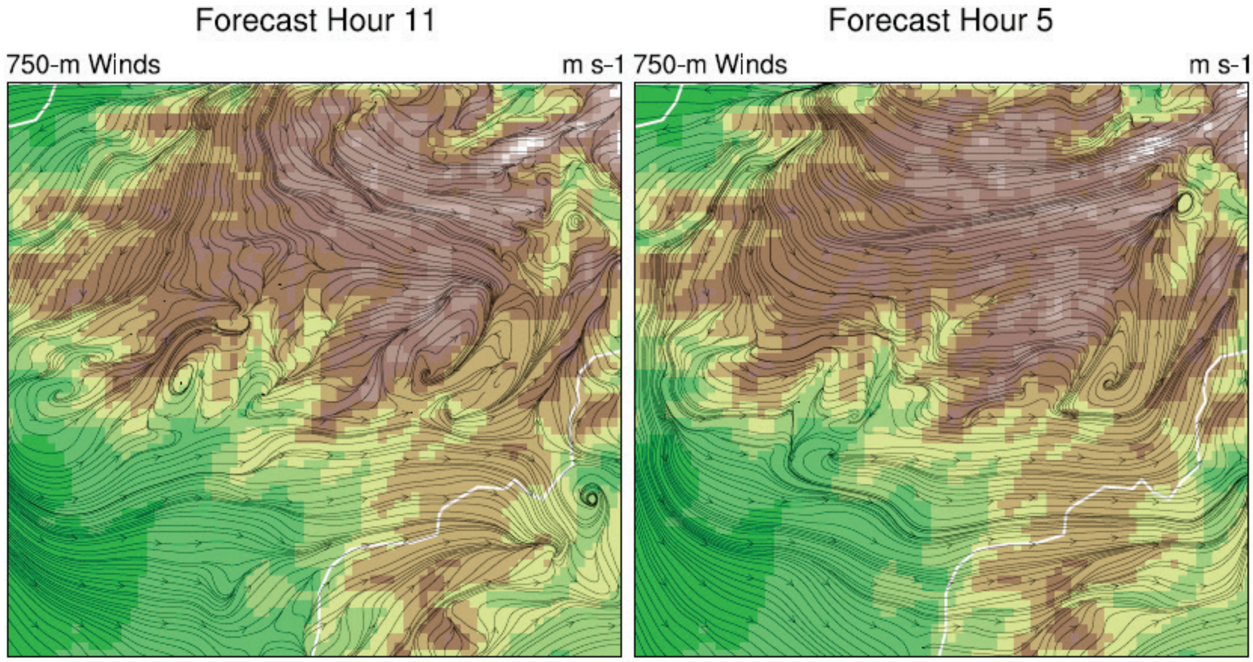


*Figure 5: Advancing three hours from Fig. 4 at the same height.*

It is important to note high spatial observation density would allow 3DVAR to produce an analysis closer to the flow pattern driven by terrain. Perfect observations would still lead to a bad analysis if the first guess field used possesses significant error. Creating a local first guess field which includes the dynamical effects of terrain forcing should eliminate much of the terrain spin-up and add value to the vital first hours of a forecast.

This added value is quantified by plotting the cross correlation of wind over the third, innermost domain in the Southeast Asia scenarios for a synoptically mild period of 10 days for both cold start and cycled forecast initializations set apart by 6 hours. The cross correlations are averaged over the domain, and over the 10 days of forecasts from 0000 UTC 01 September 2010 to 0000 UTC 10 September 2010, to produce Fig. 6 showing the time development of cross correlation with height above ground. The upper levels are generally similar; however, the terrain spin-up generated difference is noticed at the lower levels. The first few hours in the cold start exhibit low cross-correlations which actually get better with time. It would be expected that due to model uncertainty, forecast times closest to the previous initialization would be most similar. However, for the cold starts, this is not the case due to terrain spin-up. Using the past forecast as a first guess through 3DVAR run on the outermost grid, as well as updating the surface fields and outer domain boundary conditions, produces the expected pattern of forecast divergence over time

The Black Hills of South Dakota is seen in Fig. 7 for 1800 UTC on the 14 October 2010 showing that the same condition exists as in SE Asia (Fig. 2). Analyzed dates do not correspond for cycling and cold start cross correlation graphs because forecasts were generated for an initial period of time using 3DVAR data assimilation in cold start. Beginning in March 2011, the Black Hills forecast framework was changed to the cycled method, but forecasts were not retrospectively generated. As such, the data for the cold-start scenarios are for 10 October 2010 to 31 December 2010, while the recycled scenarios are for 01 March 2011 to 07 June 2011.

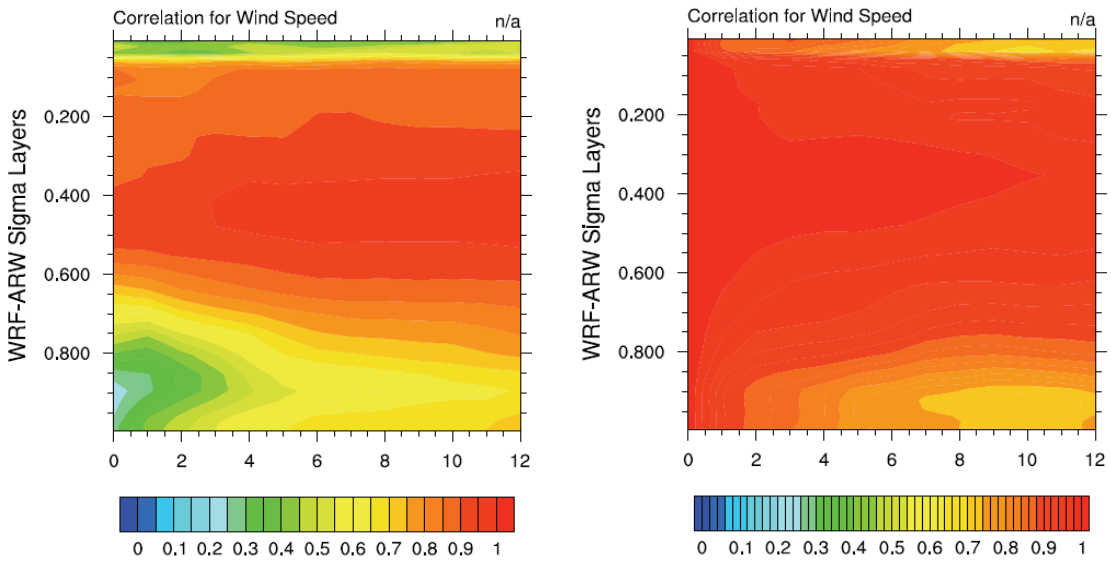


*Figure 6: SE Asia innermost domain, 0000 UTC 01 September 2010 to 0000 UTC 10 September 2010 for cross correlation values of wind speed as contours plotted with increasing forecast hour and height. The forecast hour on the x axis is for the more recent forecast which is being compared to a previous initialization forecast hour 6. Cold start forecasts are represented on the left and cycled forecasts are displayed on the right.*

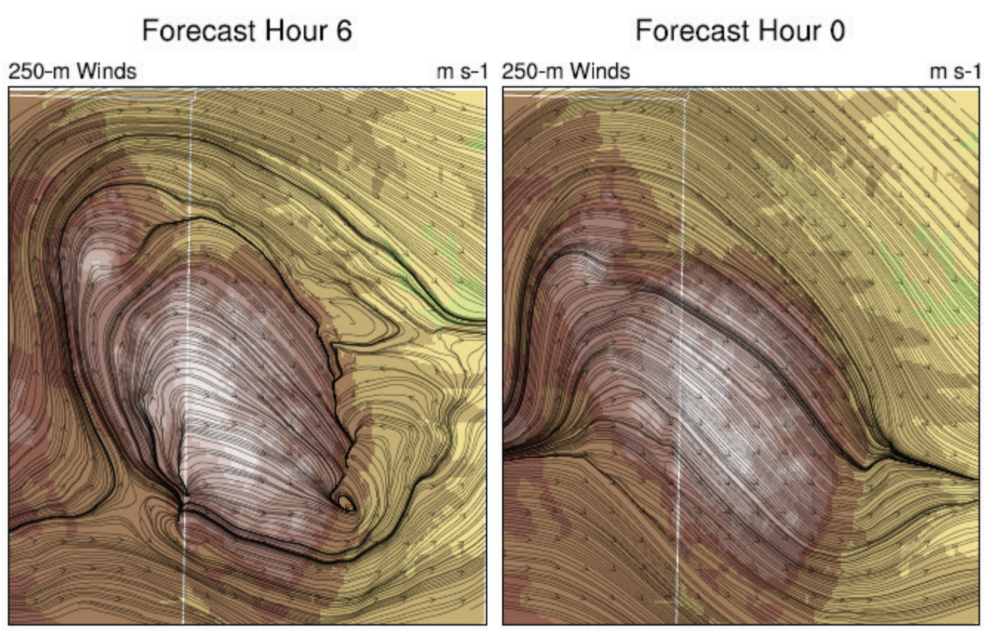


*Figure 7: Inner domain over the Black Hills for 1800 UTC 14 October 2010 demonstrating flow differences between cold start forecasts as in Fig. 2 but at 1-km grid spacing.*

As seen in Fig. 8, there is less improvement in the pattern for the Black Hills than seen in the SE Asia scenarios when using cycling through 3DVAR. In spite of the subdued topography, and not seeing as strong a signature from terrain spin-up to begin with, some limited value is added to the boundary layer forecast especially over the first 4 hours. The cold start plot shows low-level cross correlations up to 0.7 until 4 hours while the value is over 0.7 until 4 hours for cycled starts. These long periods were chosen because there was not a sufficient break from synoptic forcing to clearly show any terrain spin-up signature. Further study is needed to fully understand the improvements of model spin-up exhibited at higher levels than impacted by the Black Hills topography. One possible explanation is simply that the Black Hills are preceded upwind by terrain with larger topographic relief in southern Montana, Wyoming, and northern Colorado. Another likely reason is because the Black Hills are an isolated uplift in the topography without the large-scale complex relief realized in the SE Asia environment. As such, flow often goes around the Black Hills (as shown in Fig. 7) with flow downwind from the uplift frequently producing von Karman vortex streets, especially in cold season forecasts. Because 3DVAR is being cycled on the outermost domain, some of this improvement, especially around sigma levels of 0.7, may be due to improved terrain spin-up in those areas of topography as seen in Fig. 1b.

Another important consideration is Background Error (BE), which is the error typical between a previous forecast and the current analysis. This error is typically generated over a period of time for the area being forecast for and is an important part of the 3DVAR process. Changes in the BE can be expected to have a measureable effect on the analysis and subsequent forecast. The existence of error in the analysis due to terrain spin-up during cold start means that the background error will be affected. This is an important consideration to take into account when using variational methods of data assimilation in areas of terrain.

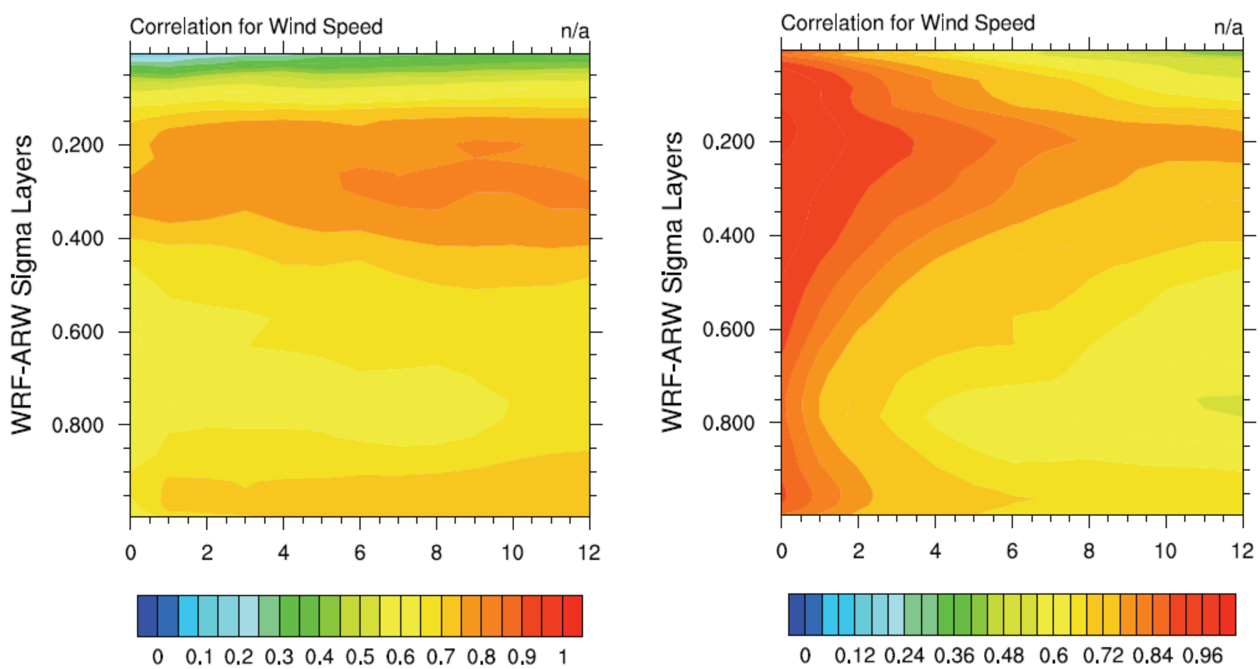


*Figure 8: Cross correlation plots for the Black Hills innermost domain in SD using the same plotting conventions as in Figure 6. Cold start cross correlation pattern is on the left, generated by averaging cross correlations of a series of forecasts from 10 October 2010 to 31 December 2010. The cycled pattern is on the right, averaging over a series of forecasts from 01 March 2011 to 07 June 2011.*

## 5. CONCLUSIONS

There is a significant level of improvement achieved in the analysis and forecast when utilizing 3DVAR in cycling mode. This is especially true for the first few hours of boundary layer forecast which are most affected by terrain spin-up. Observations can only move the model solution so far without creating spurious gradients and producing un-representative atmospheric features. Therefore, models will benefit from a first guess field that is as close to reality as possible. Creating a first guess field local to the area of study, which utilizes high resolution terrain, measurably decreases error in the analysis especially in the boundary layer due to terrain spin-up. Running 3DVAR on a cycle not only includes the value added by up to date observations, but also adds in local meteorological features which can be resolved in the model but may not be depicted by observations, or the first guess provided by a global model. Evaluating the most effective application of data analysis methods adds value to the guidance provided decision makers in the first hours of a short term high resolution forecast.

The benefit of this work will continue to be valid for future work in 4DVAR. One disadvantage of 3DVAR is that it is not able to assimilate high-frequency data. This work provides valuable understanding for effective application of 4DVAR's more costly advantages. Additional work may also involve improvements in forecast relevant BE selection in order to create an efficient use of available observations and resources.

## 6. ACKNOWLEDGEMENTS

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