Project Summary for 2016 DTC Task RE8

Hybrid Vertical Coordinate Testing and Evaluation in the RAP and HRRR

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1. Introduction

The terrain-following sigma coordinate (Phillips, *J. Meteor.*, 1957) has been implemented in many NWP systems including the Weather Research and Forecasting (WRF) model, and has been used with success for many years. However, a number of drawbacks are known to exist with this particular vertical coordinate. Due to the way that the horizontal component of the pressure gradient force is expressed in sigma coordinates, numerical truncation errors can occur over areas of steep terrain where coordinate surfaces depart significantly from a horizontal orientation. These errors then manifest as spurious horizontal and vertical accelerations in the model equations, often resulting in vertical columns of numerical noise in the model wind field (and other variables) over mountainous regions.

Given the impact these related errors can have on model variable accuracy and resulting forecasts (e.g., Park et al., *Geophys. Res. Lett.*, 2016), a number of methods have been developed to mediate these problems. One such effort was undertaken by Joe Klemp of NCAR (2011, *Mon. Wea. Rev.*), with an eventual goal of adding this vertical coordinate option to WRF. In order to reduce some of the spurious horizontal and vertical accelerations associated with a pure terrain-following sigma coordinate, a smoothed, hybrid-coordinate was developed, in which the sigma coordinate is transitioned to a purely isobaric vertical coordinate at a specified level. Initial tests showed promising results for idealized cases with a considerable reduction in small-scale spurious accelerations. Based on these preliminary findings, the DTC was tasked with committing this new smoothed, hybrid coordinate option to the WRF repository, as well as testing and evaluation within both the RAP and HRRR in order to assess impacts on both retrospective cold-start and real-time forecasts.

2. Project Deliverables

- Incorporate the hybrid vertical coordinate into WRF and submit it to the official repository (conducted by the NCAR node of DTC)
- Report on the performance of the new coordinate in both the RAP and HRRR
  - The NCAR node of DTC was in charge of evaluating the new hybrid coordinate on a suite of cold-start, retrospective cases from all seasons for both the RAP and HRRR

   - The GSD node of DTC was tasked with testing the new hybrid coordinate for a number of cold-start, retrospective simulations within the RAP, as well as fully-cycled, multiple-day simulations for both the RAP and HRRR
- Publish results in a refereed journal (to be spearheaded by the GSD node of DTC)

3. Methods

The NCAR node of DTC completed the initial WRF code changes necessary to implement the new hybrid vertical coordinate in late 2016. Once the code was committed to the RAP/HRRR repository, the GSD node of DTC began immediate testing in the RAP to analyze the impacts on forecast accuracy. Two controlled simulations of the new vertical coordinate were conducted in the RAP, using GFS data for initialization. A cold start simulation was conducted for 17 November 2016 at 1200 UTC and run for 39 hours, while a fully-cycled case was run from 4-9 September 2016, also with 39-hr forecasts. For each controlled simulation, two runs were conducted, one with the hybrid vertical coordinate, and one with the original sigma, terrain-following coordinate. However, during the execution of these simulations, it quickly became clear that a problem existed, as numerous model crashes ensued and spurious/excessive jet-level wind characteristics were found upon analysis of model results. These findings were shared with WRF developers at NCAR, and after thorough inspection of the code, a bug related to the map scale factor was found and corrected in early 2017.

Following a new version of the code being committed to the GSD repository, testing began again in March 2017. This time, a cold-start RAP simulation from 7 March 2017 at 0000 UTC was conducted, along with fully-cycled RAP and HRRR retrospective runs from 7-13 March 2017 and 3-10 September 2016, respectively. The RAP simulations contained forecasts out to 39 hours, while the HRRR ran to 15 hours for each cycle. Verification was undertaken by analyzing both time series and vertical profiles of temperature, relative humidity, and wind speed. Comparisons were then made between results from the hybrid coordinate simulation versus the sigma, terrain-following coordinate retrospective run. In addition, plots of 250 hPa wind speed differences between the vertical coordinate runs were created as a function of forecast lead time to assess how jet-level winds evolved based on the vertical coordinate used. Finally, vertical cross-sections through the Rocky Mountains were generated to assess the impact of the vertical coordinate over steep terrain.

4. Results

After the latest version of the WRF code was checked out and compiled, initial results from the RAP retrospective simulations produced stable results. With the completion of the 7 March 2017 0000 UTC cold-start experiment, analyses of the results commenced by comparing differences between hybrid and non-hybrid coordinate upper-level winds. Differences were found to be negligible at initialization time, but by six hours into the forecast, 250-hPa wind speed values within the core of the upper-level jet for the hybrid coordinate were found to exceed values in forecasts using the original, terrain-following vertical coordinate (Fig. 1). As discussed previously, the terrain-following coordinate is known to produce spurious accelerations, resulting in enhanced vertical mixing of horizontal momentum. This enhanced mixing typically reduces horizontal wind speeds, so it is not surprising to see stronger wind speeds aloft with the new hybrid vertical coordinate.

Outside of the major upper-level jet, a few areas were found where wind speeds were slower for the hybrid coordinate. Most wind speed differences between experiments were found to occur over or downwind of major mountain ranges, specifically in the western areas of North America. In addition, no differences were found to occur well away from land, such as over the Pacific Ocean, or in areas that were not downwind of major terrain, indicating the hybrid vertical coordinate was not producing unintended consequences and working as intended.

Differences in upper-level winds between the two vertical coordinates were also evident in vertical profile verification of the extended, fully-cycled 7-13 March 2017 RAP experiment (Fig. 2). While it can be seen that for the full continental United States (CONUS), bias and RMSE are reduced for upper-level winds, bias is slightly increased in the western CONUS. Therefore, wind speed forecast improvements are found with the hybrid coordinate for upper-level winds in the eastern United States only during this experiment. Given that the 7-13 March 2017 retrospective period was chosen based on the existence of strong upper-level winds, it is hypothesized that the hybrid vertical coordinate may result in winds that are slightly too strong over mountainous terrain during synoptically active periods. Other results from these fully-cycled retrospective runs showed statistically-significant reductions in RMSE and bias for temperature and relative humidity for the CONUS as a whole. Finally, it should be noted that verification below about 500 hPa showed no statistically significant differences between the two retrospective simulations, highlighting the impact of the hybrid vertical coordinate on jet-level winds, particularly in mountainous regions.

It was also important to assess whether the hybrid vertical coordinate was able to correct noisy vertical motion artifacts generated by the terrain-following coordinate over steep terrain. To investigate changes to upper-level vertical motion, cross-section plots of absolute vertical velocity at 35,000 feet AMSL were generated over western North America, comparing results from the GSD RAP (using the hybrid coordinate) and the NCEP RAP (sigma, terrain-following vertical coordinate). One such example is shown in Figure 3 from a 6-hr forecast, valid at 18 UTC on 25 May 2017. When comparing the two cross-section plots, it is clear that the hybrid vertical coordinate has drastically reduced the amount of upper-level, vertical motion noise that is present in the sigma, terrain-following coordinate (NCEP RAP). Instead of the artificial vertical velocities indicating the location of the steep terrain due to the sigma vertical coordinate (as shown in the NCEP RAP), the GSD RAP cross-section highlights areas of true vertical motion associated with the jet-like features found over the Desert Southwest and Alaska. Pilot reports of turbulence (green dots) are also found in the vicinity of the vertical motion shown from the GSD RAP cross-section.

In addition to the RAP retrospective cases, the GSD node of the DTC also ran a week-long simulation of the HRRR from 3-10 September 2016 to assess the impact of the hybrid coordinate at convective-resolving resolution. Results from this simulation showed a vastly reduced impact of the hybrid coordinate. No statistically significant differences were found between the two vertical coordinates out to the full 12 hours of each forecast, and only minor, non-statistically significant differences were found at 12 hours, limited to regions above 200 hPa. One possible explanation for these findings is that the upper-level winds were fairly weak from 3-10 September 2016 and that differences were minimized for such a scenario. Given stronger winds aloft, such as those seen in the RAP retrospective runs, larger differences between hybrid and non-hybrid simulations in the HRRR would be expected. Another possibility is that the lack of atmospheric cycling in the HRRR minimizes the retention of hybrid coordinate benefits from run to run. It is possible that by either fully cycling the HRRR or by using a winter HRRR retro period with stronger upper-level winds, more differences would be seen between non-hybrid and hybrid simulations.

The NCAR node of DTC also conducted testing of the new hybrid coordinate, including two cold-start MMET cases for both the RAP and HRRR. One set of simulations, with initializations at both 0000 and 1200 UTC on 9 May 2016, highlighted a severe weather event over the Central Plains (summer case). A second set of simulations featured a strong Nor'easter, with three initializations between 0000 UTC on 25 January 2015 and 26 January 2015 at 0000 UTC (winter case). For both the RAP and HRRR, control experiments were run with the sigma, terrain-following vertical coordinate, followed by a comparison configuration where the new hybrid coordinate was used (the vertical coordinate was the only difference between simulations).

Similar to what was found by testing conducted by the GSD node of the DTC, only very minor differences were seen between the terrain-following and hybrid coordinates in both the RAP and HRRR surface verification of temperature, dew point, and relative humidity. Time series of these variables showed a slight increase in differences with later lead times, especially in the western United States; statistical significance could not be computed given the limited amount of data. These findings held true for both the summer and winter cold start simulations. However, spatial difference plots of surface variables for both the RAP and HRRR did show some differences between the vertical coordinates, particularly for the summer case. Upper-level winds over the western United States were stronger aloft during this summer case than for the winter case, likely leading to larger surface variable differences between the two vertical coordinates.

Trends in the vertical profile plots for both models and for both cases are difficult to establish given the limited number of initializations; however, for the most part, more differences are seen for the summer case, and for dew point and wind speed vertical profiles. Many of these differences fail to show a clear preference for a particular vertical coordinate, but there is a qualitative indication of a slight advantage with the hybrid vertical coordinate for dew point profiles in both the RAP and the HRRR (Fig. 4). However, without statistical significance testing, it is difficult to assess whether this advantage is meaningful. Finally, differences between the vertical coordinates in the vertical profiles increased with forecast lead time, similar to findings from the GSD node when looking at the week-long RAP retrospective simulations.

Upper-level spatial difference plots showed much greater discrepancy between the simulations. These plots indicated that areas where the vertical coordinates differed were confined to regions downwind of major mountainous terrain, such as the Rockies, and that areas over the ocean were unaffected. This finding, again, confirms the correct implementation of the hybrid vertical coordinate. Figure 5 illustrates differences for 500 hPa relative humidity and 250 hPa wind speed between the vertical coordinates for 12-hour forecasts issued from 9 May 2016 at 1200 UTC. It is likely that differences seen in the 250 hPa wind speed plot are due to discrepancies in the placement of convection, especially downwind of the Rockies, as strong updrafts interact with upper-level flow.

5. Conclusions

Overall, the hybrid vertical coordinate produces the largest impact at upper levels, where the differences in coordinate surfaces are most pronounced due to the reflection of terrain over mountainous regions. As a result, wind speeds are generally increased near jet axes aloft, owing to the decrease in vertical and horizontal mixing of momentum that occurs within the terrain-following coordinate. In addition, the depiction of vertical velocity at upper levels is greatly improved with reduced spurious noise, and better correlation of vertical motion to forecast jet-like features.

A number of cold start cases and longer retrospective runs for both the RAP and HRRR indicated a modest improvement in upper-level temperature, relative humidity, and wind speed verification when using the hybrid vertical coordinate. Select MMET cases also showed that the majority of the differences between the vertical coordinate were located downstream of mountainous terrain and focused in the upper-levels. Finally, MMET simulations of the HRRR indicated differences in vertical profile verification for all variables tested, in sharp contrast to the week-long HRRR retrospective simulations. Therefore, the MMET runs indicate that differences between the vertical coordinates in the HRRR are possible without full atmospheric cycling, and suggest that upper-level winds in the 3-10 September 2016 HRRR retrospective run were insufficient to generate differences between the simulations.

A summary of these findings will be compiled and submitted for publication in an AMS journal prior to the end of 2017. In addition, the journal article will contain a detailed description of the hybrid vertical coordinate and will highlight the interaction of NOAA and NCAR through the DTC in order to complete this work.

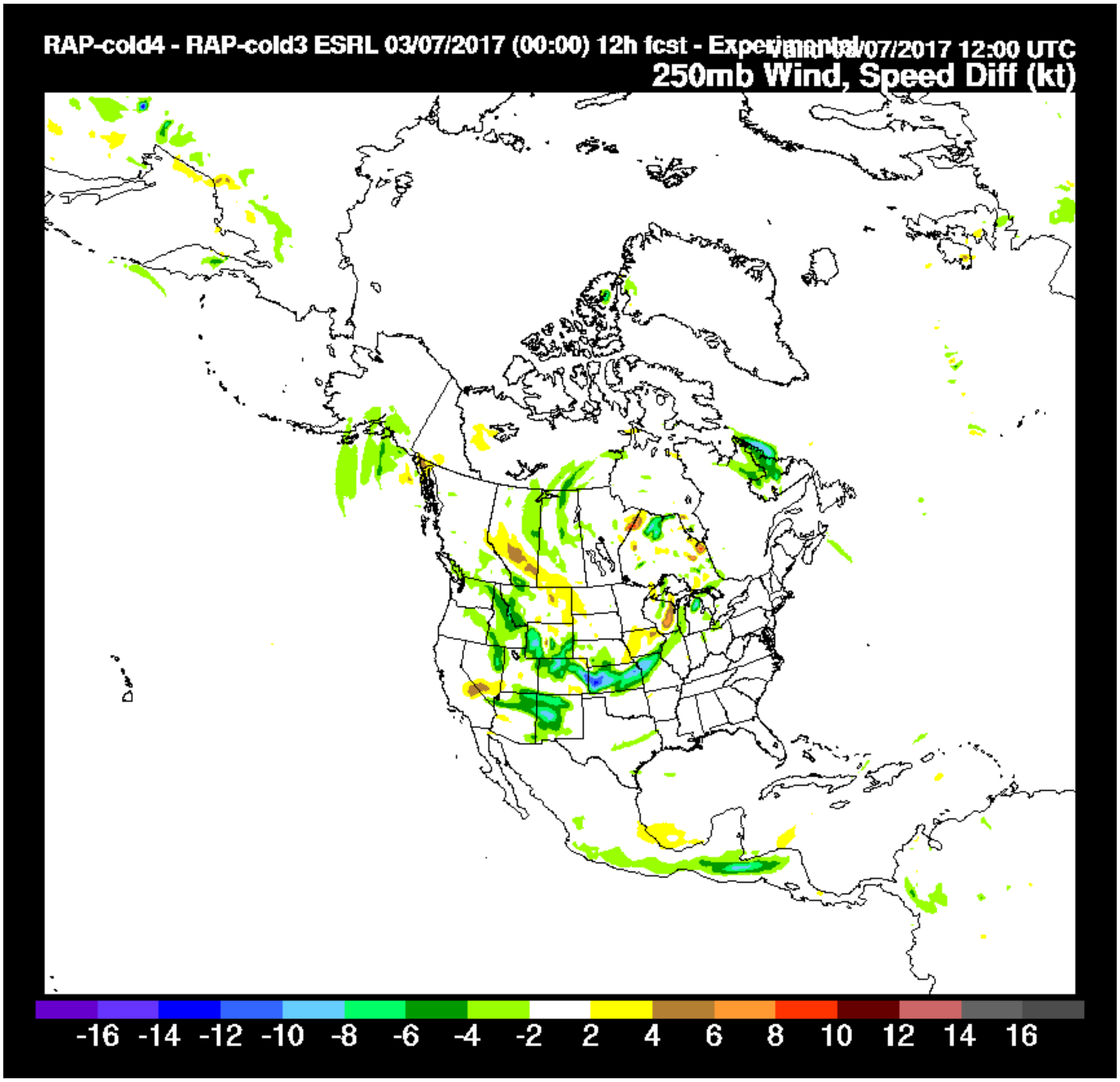

Figure 1. Twelve-hour 250 hPa wind speed forecast differences for two cold start RAP simulations (hybrid vs. non-hybrid) from 7 March 2017 at 1200 UTC. Cool colors indicate areas where the hybrid coordinate forecasts showed faster winds, while warm colors show regions where winds were slower for the hybrid coordinate.

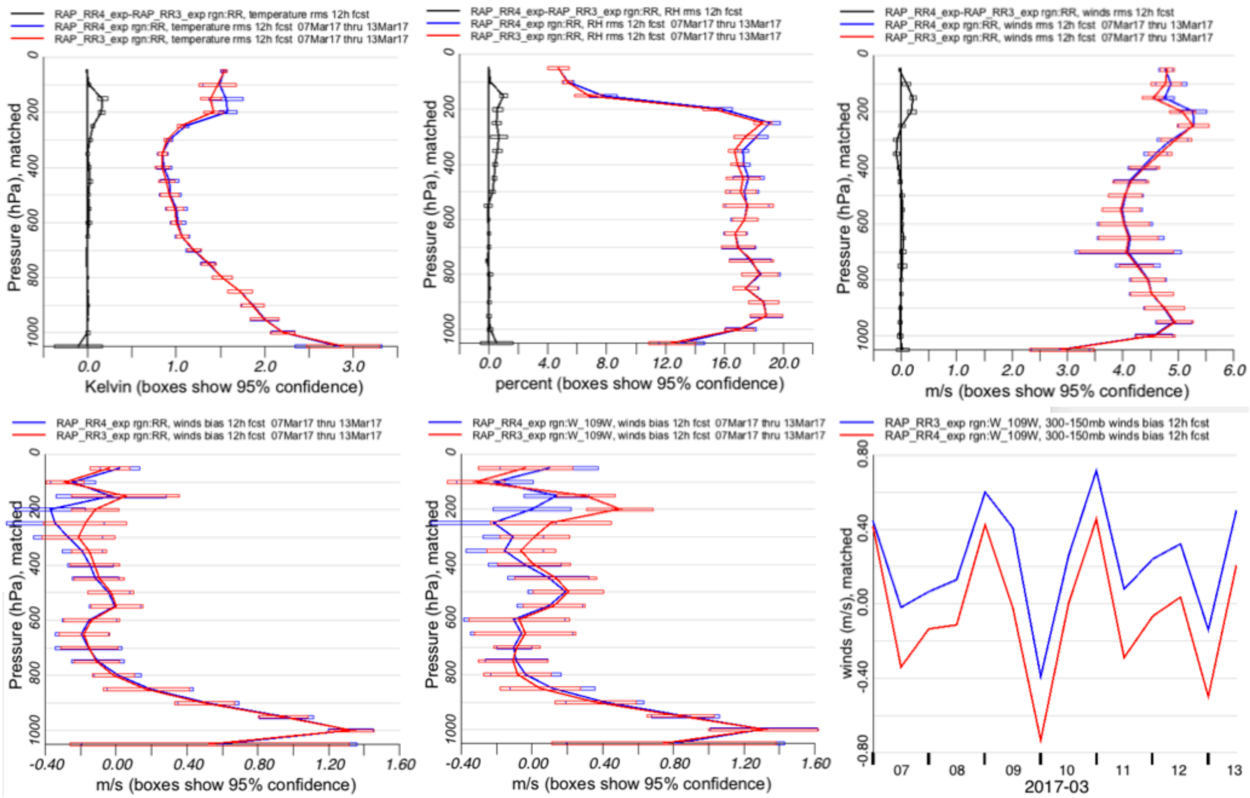

Figure 2. Hybrid coordinate (red) and terrain-following coordinate (blue) results from the RAP retrospective forecasts for 7-13 March 2017. CONUS RMSE is shown for temperature (upper left), relative humidity (upper center), and wind speed (upper right), and bias for wind speed (lower left). Wind speed bias for the western CONUS is shown in the lower center plot, and a time series of averaged wind speed bias for the western CONUS from 300-150 hPa is shown in the lower right.

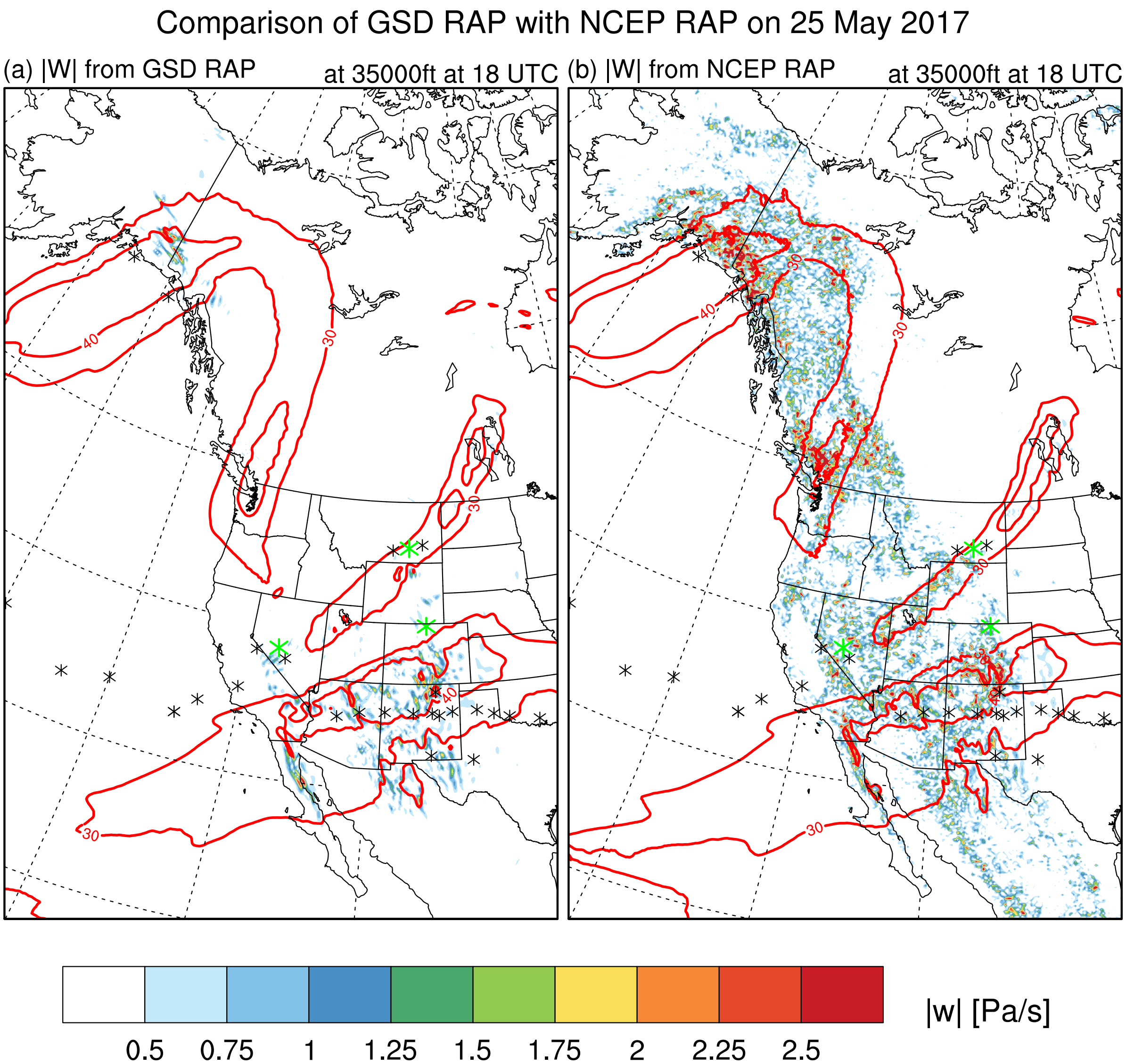

Figure 3. RAP forecast plots of absolute vertical motion (|w|, in color) with horizontal wind speed (contoured at 30 and 40 ms^{-1}) for 35,000 ft AMSL over western North America for a 6-hr forecast valid at 18 UTC on 25 May 2017. The hybrid vertical coordinate (from the GSD RAP) is shown on the left, while the sigma, terrain-following coordinate (from the NCEP RAP) is shown on the right. Pilot reports for smooth (turbulence intensity of zero) a bumpy (turbulence intensity >= 2) conditions are shown in black and green stars, respectively. Reports were made within a ± 2 hr window of 18 UTC, and ± 1000 feet of 35,000 AMSL.

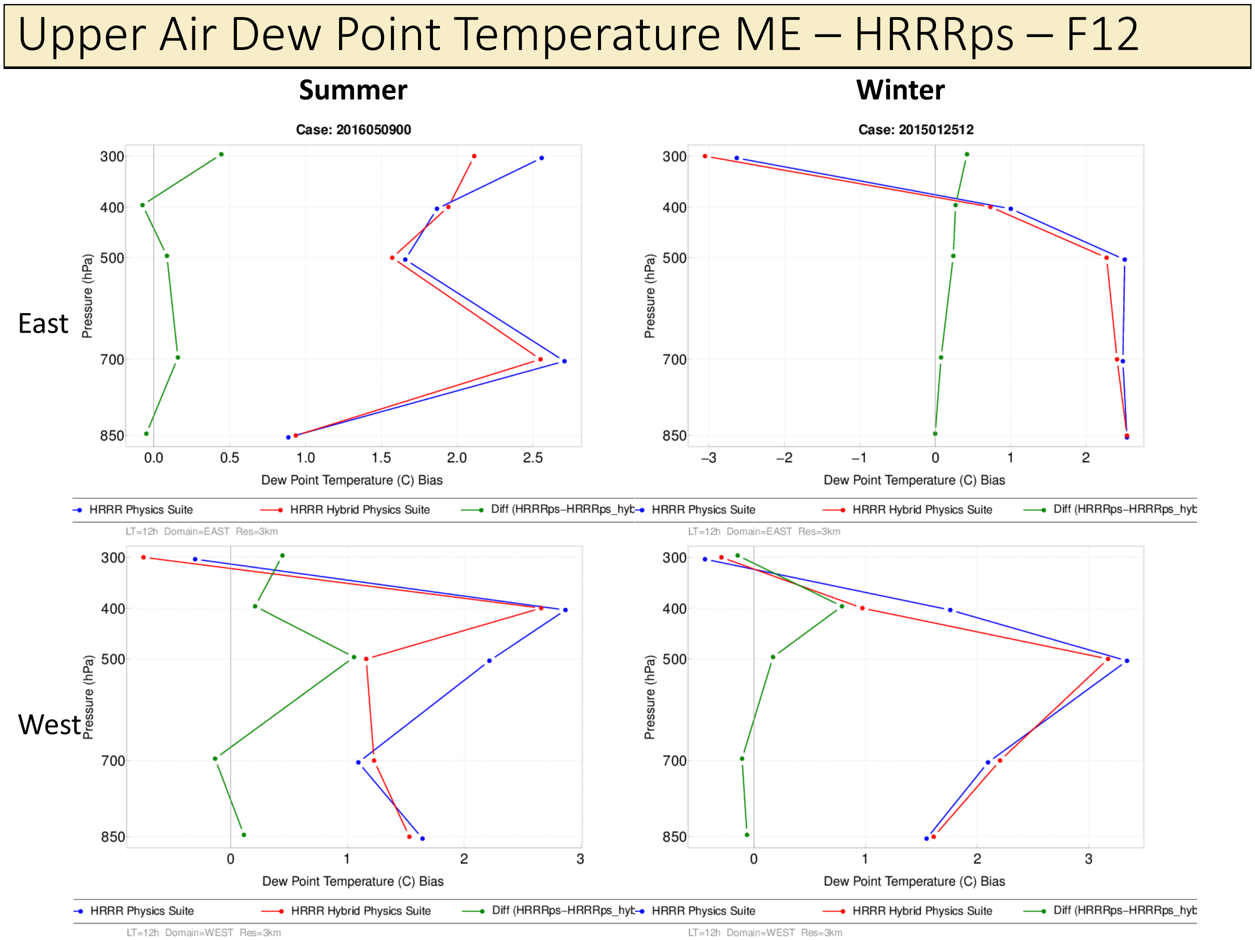

Figure 4. Vertical profile verification of dew point temperature for the HRRR for both the summer and winter cold start MMET cases for the western and eastern United States. The red line indicates the hybrid vertical coordinate, while the blue line is for the terrain-following coordinate. The green line is the difference between the two vertical coordinates.

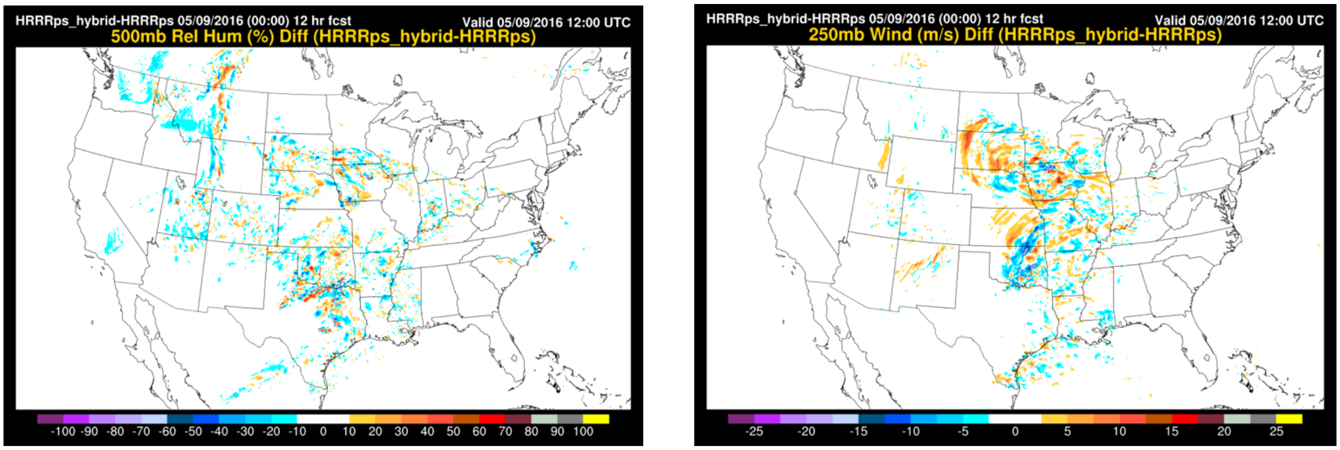

Figure 5. HRRR difference plots for 500 hPa relative humidity (left) and 250 hPa wind speed (right) for 12-hour forecasts from 9 May 2016 at 1200 UTC between the hybrid and non-hybrid vertical coordinates. Cool colors indicate drier relative humidity (left) and weaker wind speed (right) values for the hybrid coordinate.