VERIFICATION OF WRF OVER COMPLEX TERRAIN AND COASTAL REGIONS USING FIELD DATA AND ENSEMBLES

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1. INTRODUCTION

The Weather Research and Forecasting (WRF) model has been shown to realistically simulate organized deep convection and hurricane evolution, but there have been few detailed verification studies of WRF in areas of steep topography. There is a broad spectrum of mesoscale phenomena over complex terrain, such as barrier jets, mountain waves, gap flows, and orographic precipitation. Recently, a growing number of field studies have collected in situ and radar data near steep topography, such as IMPROVE-2 over the central Oregon Cascades and the Southeast Alaska Regional Jet Experiment (SARJET) (Winstead et al. 2006). These field datasets serve as useful verification datasets for WRF.

Meanwhile, WRF is now run at high resolution or in an ensemble configuration at many locations, such as at NCEP-EMC and Stony Brook University. The long-term verification datasets collected by these ensemble efforts are also important in evaluating WRF simulations in the coastal zone of sea breezes, coastal fronts, and organized convection approaching the coast.

This paper highlights some WRF verification results for a few different coastal environments. The orographic flows in WRF at 1.33-km grid spacing are compared with in situ flight-level data for a barrier jet event along the Southeast Alaskan coast on 26 September 2004 and NOAA P-3 observations on 4-5 December 2001 of IMPROVE-2. During the warm season the sea breeze WRF simulations around Long Island, NY have been evaluated using mesonet surface observations and ACARS data. The physical parameterization performance has also been evaluated using a 13-member WRF/MM5 ensemble over the Northeast U.S. at 12-km grid spacing using mixed physics (convective and PBL) and initial conditions (GFS, NAM, CMC, and NOGAPS).

2. DATA AND METHODS

The IMPROVE-2 field experiment occurred over the central Oregon Cascades in December 2001 (Stoelinga et al. 2003). Several ground-based and aircraft platforms were utilized to better understand orographic precipitation and the associated terrain-forced flows. This paper highlights some kinematic WRF comparisons with the in situ and Doppler observations from the NOAA P-3 during the 4-5 December 2001 event. In a companion workshop paper, Lin et al. (2006) evaluates the WRF precipitation and microphysics from this IMPROVE-2 event.

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The WRF-ARW (version 2.1.1) was run at 36-, 12- and 4-, and 1.33-km grid spacing in a one-way nest configuration with 33 vertical levels. The 36-km domain covers much of the central and eastern Pacific (not shown), while the 1.33-km domain includes the region shown in Fig. 1. The GFS forecast at 1200 UTC 4 December was used for WRF initial and boundary conditions. The Eta (Mellor-Yamda-Janic) PBL, Thompson bulk microphysics, and Grell convective parameterization (36 s 12-km only) were also applied.

The SARJET field campaign was conducted between 24 September and 21 October 2004 over the Alaskan coastal waters near Juneau, AK. The objective of this field study was to obtain *in situ* observations of the boundary layer flow using flight measurements obtained from the University of Wyoming's King Air research aircraft. SARJET was very successful. There were a total of 11 IOP's, four of which included double flights by the King Air. The WRF-ARW (version 2.1.2) was used to simulate the 26 September 2004 IOP at 36, 12, and 4-km grid spacing using a one-way nest interface and 33 vertical levels. The 6-h GFS analyses were used to initialize the WRF at 0000 UTC 26 September and supply boundary conditions. The control WRF run used the YSU PBL, WSM-3 microphysics, and Grell convection parameterization on the 36- and 12- km grids. A separate simulation tested the Eta PBL.

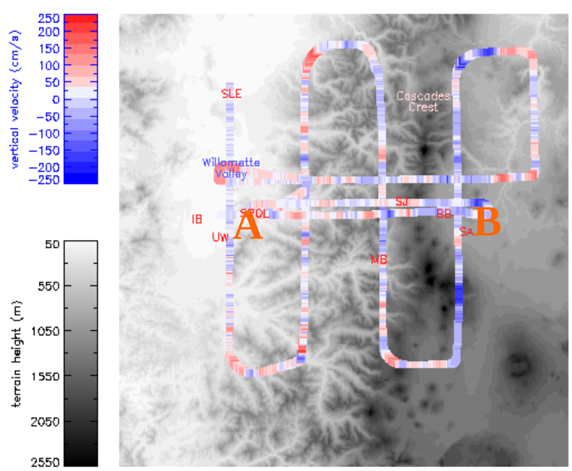

Figure. 1. NOAA P-3 flight-track and in situ vertical motion (color shaded in cm s^{-1}) from 2300 UTC 4 December to 0200 UTC 5 December 2001. Terrain is shaded for reference. Location of the cross section and time series for Figs. 4 and 5 is shown by segment AB.

3. RESULTS

3.1 4-5 December of IMPROVE-2

This IOP featured a landfalling baroclinic wave over the Pacific Northwest (not shown). Shortly before the aircraft reached the IOP region at 0100 UTC 5 December there was moist west-southwesterly flow at 15-20 m s^{-1} near crest level (800 mb) at the UW sounding site (UW on Fig. 1). The WRF was within 5 m s^{-1} of observed below 600 mb, and the model and observed stratification was slightly more stable than moist neutral in this layer. The WRF did not simulate the shallow sub-saturated layer near the surface as well as the nearly calm winds at the lowest level.

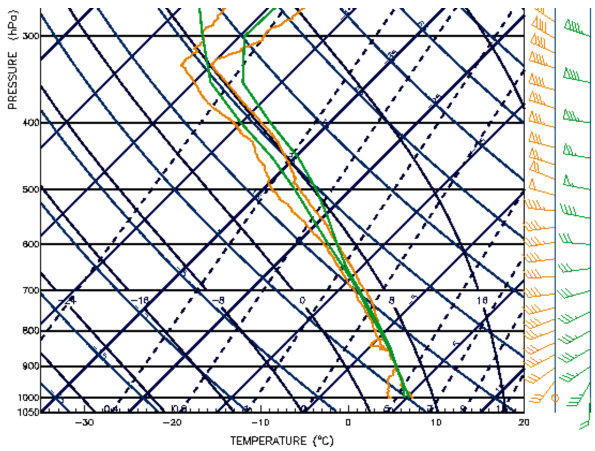

Figure 2. Observed (orange) and 1.33-km WRF (green) sounding at the UW sounding site at 0100 UTC 5 December 2001. See Fig. 1 for UW location.

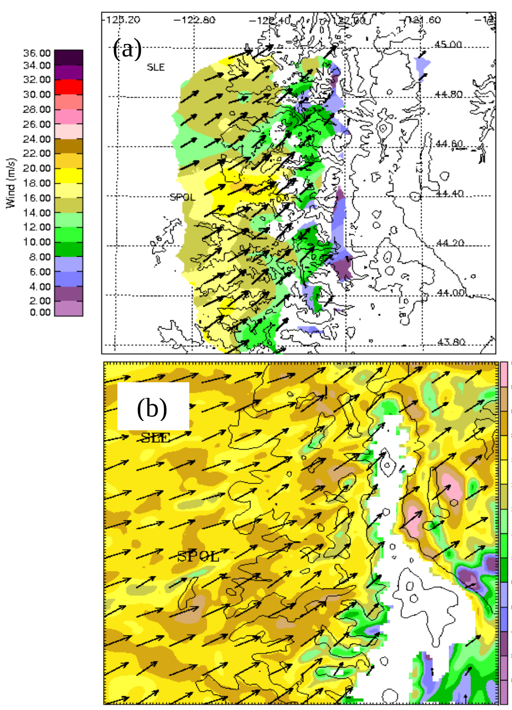

Figure 3. (a) NOAA P-3 tail-radar derived Doppler winds (m s^{-1}) at 1.5 km ASL between 2300 UTC and 0045 UTC 5 Dec 2001. (b) Same as (a) except for the 1.33-km WRF at 00 UTC.

The simulated winds over the Cascades were compared with the Doppler winds derived from the NOAA P3 tail radar between 2300 and 0030 UTC 5 December (Fig. 3). The observed winds at 1500 m ASL decelerated from 15-20 m s^{-1} to less than 5 m s^{-1} and became more southerly towards the crest (Fig. 3a). The 1.33-km WRF winds at this level were 2-5 m s^{-1} too strong upstream of the Cascades. A cross section (AB) showed that WRF's shear in the boundary layer was too shallow as compared to the P3 at 0200 UTC 5 December (Fig. 4). This shear layer was also not properly simulated using other WRF PBL schemes, such as the YSU and MRF (not shown), and the same problem has been noted over the Cascades using the MM5 (Garvert et al. 2006). The WRF was able to simulate the wind speed increase towards the crest associated with the mountain gravity wave.

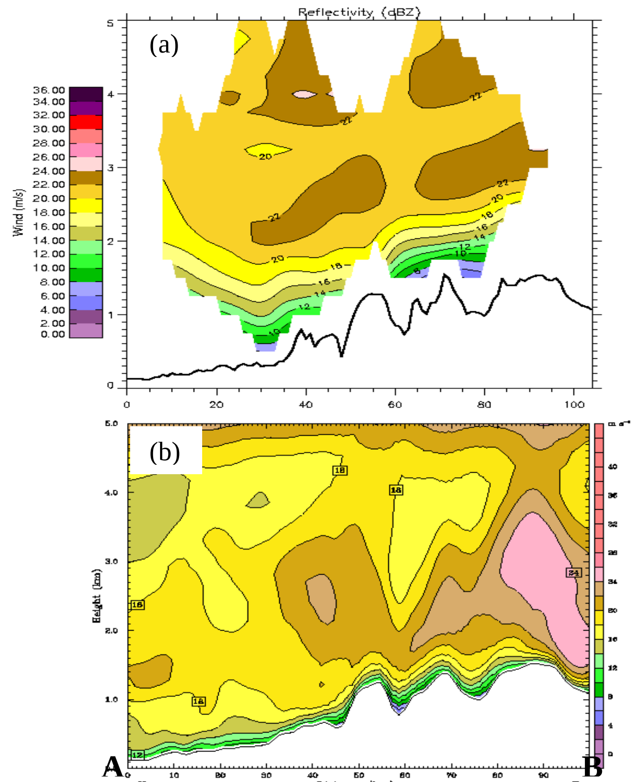

Figure 4. (a) NOAA P3 tail-radar derived Doppler wind speeds (shaded every 2 m s^{-1}) at 0200-0217 UTC 5 December along section AB in Fig. 1. (b) Same as (a) except for the 1.33-km WRF at 0200 UTC 5 December (14 h). The same color scale is used for (a) and (b).

Similar to other IMPROVE-2 IOPs (Garvert et al. 2006), the southwesterly cross barrier flow produced numerous mountain (gravity) waves over the Cascade ridges, as apparent in the NOAA P3 in situ vertical motion observations of +/- 1 m s^{-1} along the north-south and west-east flight legs over the Cascades (Fig. 1). Figure 5 shows data from segment AB on Fig. 1 to compare the P3 with the 4- and 1.33-km WRF. The 1.33-km WRF was able to generate the vertical velocity perturbations over the ridges as well as the wind speed profile over the Cascades at 3.1 km ASL from point B (east) to A (west). The 4-km WRF could not resolve as well the magnitude of these vertical motion fluctuations given its smoother topography. Both the 4- and 1.33-km WRF wind directions were 5-10^{o} too southwesterly at flight-level.

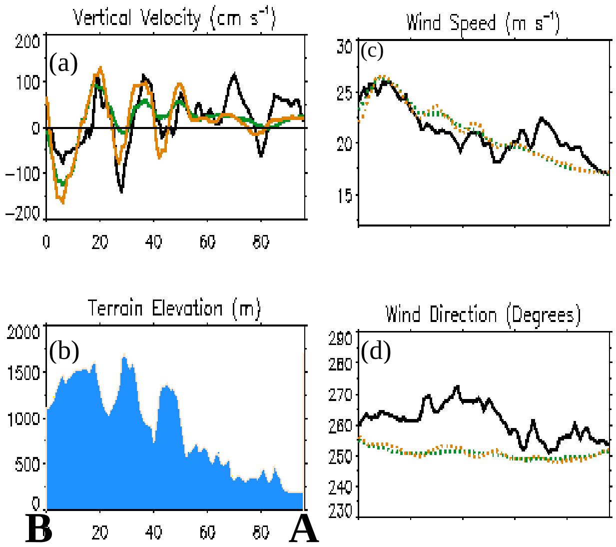

Figure 5. (a) Vertical velocity (cm s^{-1}) from the NOAA P-3 (black), 1.33-km WRF (orange), and 4-km WRF (green) between points AB in Fig. 1 at 3.1 km ASL. (b) Observed terrain profile (in m) below the flight track. (c) Same as (a) except for wind speed (m s^{-1}). (d) Same as (a) except for wind direction (in degrees).

3.2 26 September 2004 of SARJET

The 26 September 2004 SARJET IOP provides an opportunity to verify WRF for a coastal barrier jet event. Figure 5 shows an IR satellite image, sea-level pressure GFS analysis, and surface observations at 1200 UTC 26 September 2004. There was a 986 mb cyclone near the Gulf of Alaska, with a strong pressure gradient and southeasterly flow to the southeast of the cyclone in the IOP area. The WRF predicted the cyclone within a few mb at this time (not shown).

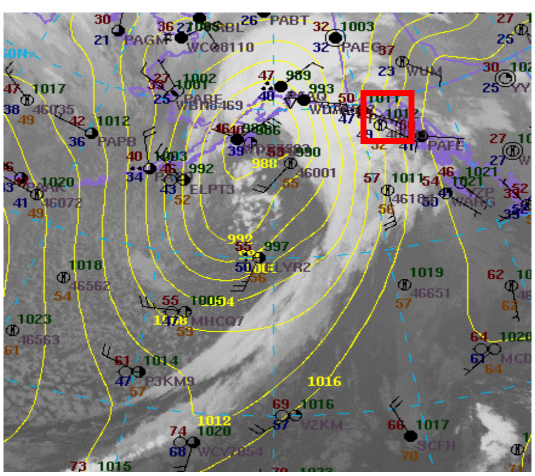

Figure 6. IR satellite, surface observations, and the GFS sea-level pressure analysis from 1200 UTC 26 September 2004. The red box indicates the SARJET study area for Fig. 7.

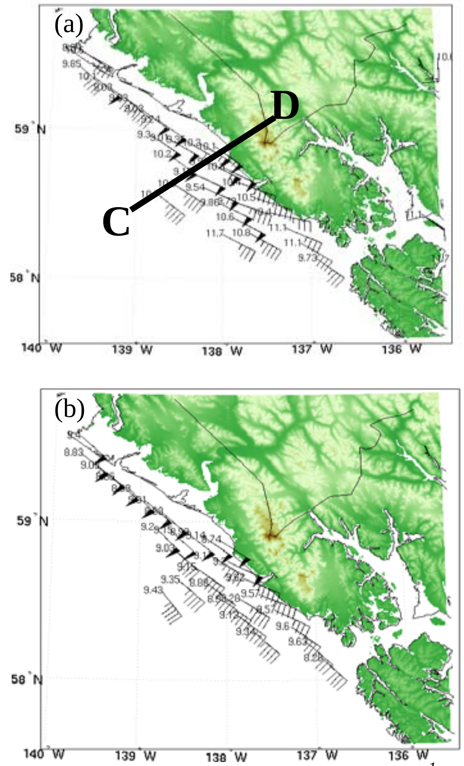

Figure 7. Flight level winds (1 full barb = 5 m s^{-1}) at 150 m ASL from 1500-1600 UTC 26 September 2004 for the red box in Fig. 6. (b) Same as (a) except for the 4-km WRF (forecast hours 15-16).

Figure 6 shows the flight-level winds and temperatures at 150 m ASL between 1500 and 1600 UTC 26 September as well as the corresponding 4-km WRF winds along the same track. The observed flow is generally southeasterly at ~20 m s^{-1}, with a 3-5 m s^{-1} enhancement near and downwind of the steepest coastal terrain. The observed temperatures were around 10 ^{o}C, with little variation away from the coast at this level. The 4-km WRF realistically simulated both the temperatures and winds at this level for this IOP; however, the WRF temperatures were ~1 ^{o}C too cool at this level.

Cross section CD around 2200 UTC reveals an observed wind speed maximum of ~32 m s^{-1} at ~1 km ASL 20-30 km upwind of the coast (Fig. 8a). The downward-sloping isentropes extending west of the coast are typical of a cold anomaly near the terrain associated with a classical barrier jet. The 1.33-km WRF using the YSU-PBL was able to realistically simulate this temperature pattern (Fig. 8b), but the YSU-PBL winds were 3-5 m s^{-1} weaker than observed, with no well-defined barrier jet. Meanwhile, the Eta-PBL resulted in stronger low-level winds and a better-defined barrier jet. These differences are also highlighted in a time series for a stack of flight legs between CD (Fig. 9). Only the Eta-PBL simulated the gradual decreasing wind speed away from the coast at 1.0 km; however, the Eta-PBL winds were too strong at < 0.5 km. Both PBLs were ~1 ^{o}C too cold. There was mechanical turbulence during the flight as revealed by the +- 1 m s^{-1} vertical velocities (Fig. 9d). The Eta-PBL TKEs were within 20-30% at many times, but missed some of the larger TKE variations (Fig. 9e).

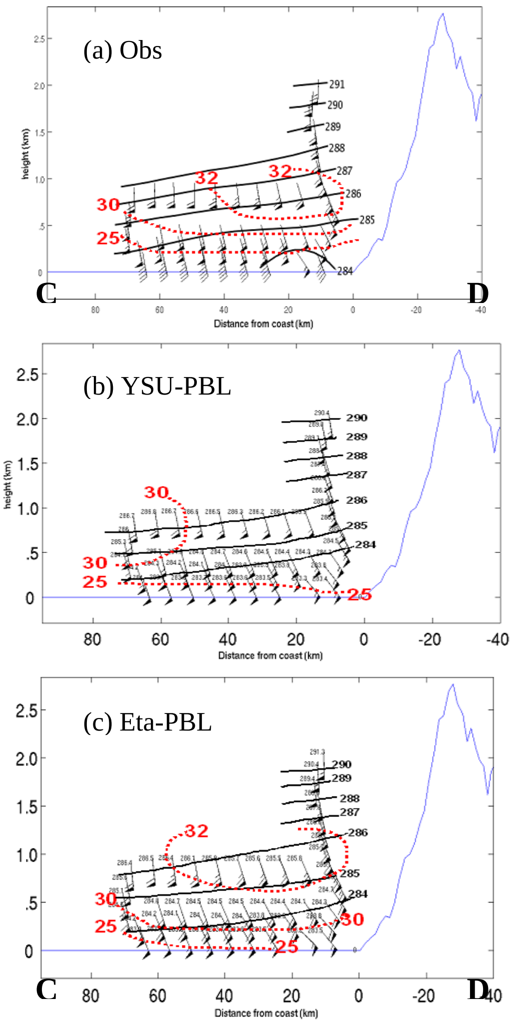

Figure 8. Cross section CD showing potential temperature (solid every 1 K) and wind speed (red dashed in m s^{-1}) for the (a) observed, (b) WRF YSU-PBL, and (c) WRF Eta-PBL runs between 2150-2253 UTC. See Fig. 7a for section location.

3.3 Real-time 4-km WRF and 12-km ensembles

A few years ago Stony Brook University setup an 18-member MM5 ensemble down to 12-km grid spacing over the Northeast U.S. using different physics and initial conditions (Jones et al. 2006). This ensemble has recently been modified to include 7 MM5 members and 6 WRF-ARW members, using a mix of initial conditions (GFS, NAM, CMC, and NOGAPS) as well as convective and PBL parameterizations (http://chaos.msrc.sunysb.edu/NEUS/nwp_graphics.html). The 4-km WRF using the YSU PBL has been evaluated for coastal circulations around LI, such as the sea breeze. For example, Fig. 10 shows the observed and simulated (18-h) Long Island sea breeze at 1800 UTC 28 May 2006. The WRF-YSU is able to realistically predict these island sea breezes, and preliminary results suggest that the WRF-YSU no longer has the 1-2 h early bias in sea breeze movement as noted for the MM5-MRF (Colle et al. 2003). However, the WRF is 1-3 ^{o}C too cool over coastal land areas during the day on average (not shown), which has resulted in somewhat weaker sea breezes moving inland slower than observed.

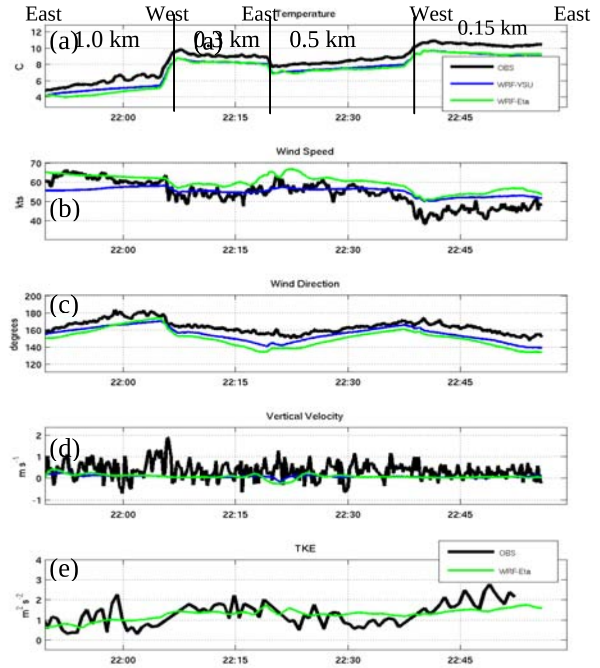

Figure 9. Time series of observed (black), WRF YSU-PBL (blue), and WRF Eta-PBL(green) along four east-west King Air legs across CD at 1.0, 0.3, 0.5, and 0.15 km showing (a) temperature (^{o}C), (b) wind speed (kts), (c) wind direction, (d) vertical velocity (m s^{-1}), and (e) TKE (m^{2} s^{-2}).

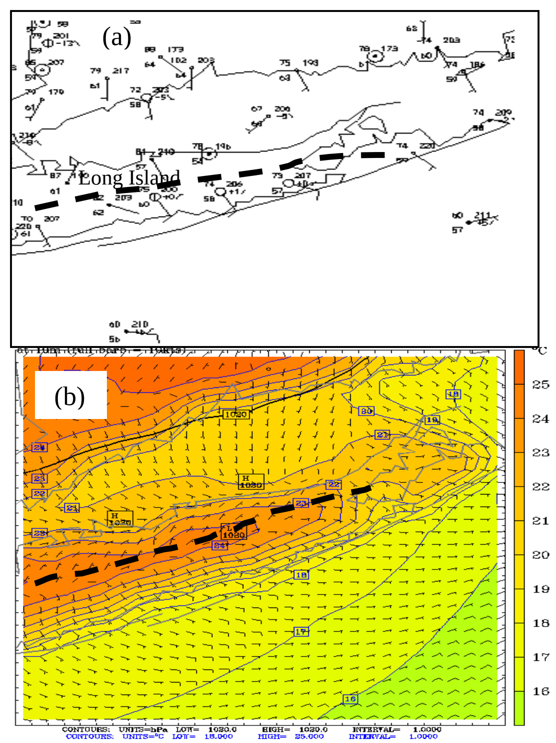

Figure 10. (a) Surface observations around Long Island at 1800 UTC 28 May 2006 showing temperature and dewpoint (^{o}F), and winds (full barb = 5 m s^{-1}) (b) Same as (a) except for 4-km WRF surface winds and temperature (shaded in ^{o}C). The sea breeze front is denoted by the dashed line.

Figure 11 shows a forecast time series from the Stony Brook WRF-ARW ensemble member predictions and ensemble mean (black dot) for the New York City surface winds during the 28 May 2006 sea breeze event. The sea breeze transition is evident around 1800 UTC as the winds become more southerly and increase, with some member spread in timing and magnitude. This wind uncertainty for the sea breeze increases the following day (29 May) at 1800 UTC 29 May (hour 42).

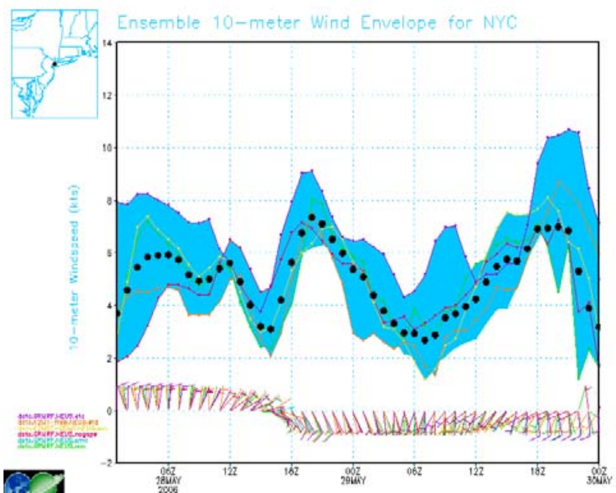

Figure 11. Time series of wind direction and wind speed for each member of the 6-member WRF ensemble run at Stony Brook using different initial conditions and physics

4. SUMMARY

This paper has evaluated WRF in areas of steep terrain using field data as well as real-time ensemble predictions over the Northeast U.S. These preliminary results are encouraging for WRF, but many challenges remain given the broad spectrum of solutions produced by the model physical parameterizations. In general, it has been found that the Eta PBL produces stronger low-level orographic flows than YSU and MRF, with the Eta PBL winds often verifying better in these regions. This agrees with the fact that the Eta PBL has been used in other recent IMPROVE modeling studies near steep terrain (Garvert et al. 2005, 2006). However, the Eta-PBL has a low-level cool bias during the day, especially during the warm season (Jones et al. 2006), which was also evident in this WRF study. The Eta PBL (and YSU) also produces a low-level shear layer over topography that is too shallow and weak. Meanwhile, the mountain waves generated by flow over the narrow (10-15 km) windward ridges were well predicted by the 1.33 km WRF, but somewhat more damped at 4-km grid spacing. This agrees with the Garvert et al. (2005) using MM5, which suggested that ~1 km grid spacing is needed to resolve mountain waves over these narrow ridges in areas of complex terrain.

Future work will evaluate the ensemble WRF results more closely over the Northeast U.S. as well as complete more feature-based verification of WRF for sea breezes, convective mode near the coast, and orographic precipitation structure.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Colle, B.A., J. B. Olson, and J. S. Tongue, 2003: Multi-season verification of the MM5: Part I, Comparison with the Eta over the Central and Eastern U.S. and impact of MM5 resolution. *Wea. Forecasting*, **18**, 431-457.

Garvert, M., B. A. Colle, and C. F. Mass, 2005: The 13-14 December IMPROVE event: Part I, Synoptic and mesoscale comparison of the observed structures with a mesoscale model simulation. *J. Atmos. Sci.*, **62**, 3474-3492.

Garvert, M.F., B. F. Smull, and C.F. Mass, 2006: Mountain wave structure occurring within an orographic precipitation event. Submitted to *J. Atmos. Sci.*.

Jones, M. S., B. A. Colle, and J. S. Tongue, 2006: Evaluation of a mesoscale short-range ensemble system over the northeast United States. *Wea. Forecasting*. Accepted.

Stoelinga, M., P.V. Hobbs, C.F. Mass, J.D. Locatelli, B. A. Colle, and co-authors, 2003: Improvement of microphysical parameterizations through observational verification experiments (IMPROVE). *Bull. Amer. Meteor. Soc.*, **84**, 1807-1826.

Winstead, N. S., B. A. Colle, N. Bond, G. Young, J. Olson, K. Loescher, F. Monaldo, D. Thompson, and W. Pichel, 2006: Barrier Jets: Combining SAR Remote Sensing, Field Observations and Models to Better Understand Coastal Flows in the Gulf of Alaska. In press to the *Bull. Amer. Meteor. Soc.*