MESOSCALE COMPARISON OF SIMULATED AND OBSERVED WINDS DURING SANDY'S LANDFALL ON NEW JERSEY

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1. INTRODUCTION

Hurricane Sandy was exceptional in many ways – its rare track, its extratropical transition (ET) just prior to landfall and associated late secondary intensification, and the extensive damage it caused to a major coastal metropolitan area from both storm surge and wind. Fortuitously, understanding the fine structure of this storm during its landfall on New Jersey is aided considerably by two key resources: (1) the pair of resilient mesonets, the New Jersey Weather and Climate Network and the Delaware Environmental Observing System, that continued to log surface observations throughout the storm and (2) a 500 meter resolution, 4 billion grid point, Weather Research and Forecasting (WRF) simulation that was run on the Cray XE6 "Blue Waters" at the National Center for Supercomputing Applications (NCSA).

The original goal of this work was to leverage the high resolution mesonet and WRF simulation data to understand mechanisms that caused the patchy nature of tree-fall experienced throughout Sandy's landfall region. However, as work progressed, this goal evolved to also include (1) understanding storm features that caused fine structure in surface wind fields observed during landfall, (2) characterizing Sandy's late-stage of extratropical transition and associated air streams and their evolution and (3) evaluating the performance of the 500-meter resolution WRF simulation during the landfall period.

2. DATA

During 36 hours spanning landfall time of 00Z on October 30, WRF winds representing 10 meter elevations were compared with surface winds observed every 5 minutes by New Jersey (NJWxNet) and Delaware (DEOS) mesonets and on nearby NOAA Automated Surface Observing Systems (ASOS) stations and National Data Buoy Center (NDBC) marine platforms. Other data, such as WSR-88D radar, rawinsonde soundings, satellite imagery and reconnaissance flight observations, were studied along with prior Sandy WRFsimulations (e.g., Galarneau et al., 2013) to gain insights regarding the low-level 3-D wind field structure.

The 96 hour simulation (Johnsen et al., 2013) using Advanced Research WRF version 3.3.1 was initialized at 12Z on October 26, 2012 and 224 Gigabytes of output were archived every half-hour for a total of 43 Terabytes. NOAA/NCEP GFS global model output was used for initialization and boundary conditions. The grid size was 5320x5000 with 150 layers and execution required 58 hours using 140,000 cores (CPUs).

Surface observation intervals are 5 minutes except for NDBC, which varies from 5-60 minutes by site. Wind speed sampling and averaging differs among the surface observation networks. For wind speed, NJWxNet records a single instantaneous sample every 5 minutes, DEOS records an average of 15 equally-spaced instantaneous samples every 5 minutes, and ASOS records 2-minute averages every 5 minutes.

By comparison, WRF 10 meter wind speeds represent averages over 1 to 4 minutes, depending on wind speed. As found by Skamarock et al. (2004) using kinetic energy spectra analyses, WRF's effective horizontal resolution is 7 times the grid spacing. Thus, WRF's effective averaging time for 35 m/s wind speeds, for example, is about 7x500/35 = 100 seconds.

Mesonet and NDBC anemometer heights that are not 10 meters are adjusted to 10 meters by fitting a logarithmic wind profile to wind speed averages for stations having anemometers at the 2 most common heights, 10 and 3 meters, as described below. Although this attempts to account for anemometer height variation among sites, it does not account for surface roughness variation, which is a much greater challenge.

First we discern the time window for which most stations have valid wind speed observations, which yields a 24-hour window of 28 Oct 18Z through 29 Oct 18Z. We discard stations that have missing observations in this window (14 of 121 sites) and calculate the mean wind speed for each station during this 24-hour window.

For the two heights (3 and 10 meters) where there are many stations, we calculate the mean speed to average the impact of roughness length (z0) variability among stations. There are 31 stations having 10 meter heights and 60 stations having 3 meters. We fit the wind profile algorithm to the two "height means" by varying z0 and friction velocity (u*) using the wind speed profile algorithm $U = u^*/k \ln(z/z0)$, where U is wind speed and z is its measurement height. The fit yields realistic values of z0 (0.5 m) and u* (2.1 m/s) and yields our wind speed adjustment algorithm of:

$$U_{10} = U_Z \ln(10/z0) / \ln(z/z0) = 3U_Z / \ln(z/0.5)$$

In the above, U_Z is the wind speed measured at height z. It might be argued that the z0 value of 0.5 meters used in the above wind speed profile algorithm might be significantly lower than 0.5 meters over open water. However, the ocean is very rough during the period of this analysis and a z0 value of 0.5 meters for its surface roughness may not be unreasonable.

Understanding the 3-D structure and evolution of the WRF output variable fields, as well as 2-D fields of WRF surface variables and mesonet observations, was aided significantly by using NCAR's VAPOR interactive 3-D visualization environment (Clyne et al., 2007). Visualizations for this work, including animations, are posted on www.seedme.org/node/70880 and also can be viewed via the workshop's presentation link.

3. INVESTIGATIONS

Investigations focused on comparing WRF output with mesonet observations, both quantitatively and qualitatively, and on fusing WRF and mesonet observations for storm features characterization.

3.1. WRF/Mesonet Quantitative Comparisons

In comparisons of mean wind speeds, except for buoys, observed mean wind speeds are generally lower than WRF's. Specifically, over land, observed wind speeds are 35-45% lower than WRF's while over the ocean, observed wind speeds are 2% higher than WRF's. In general, sites with smoothest terrain agree best.

The highest *WRF* surface wind speeds over land occurred mostly between 17Z and 22Z on 29 October within 60-120 km *south* of the storm track from a *westerly* direction, whereas the highest *observed* surface wind speeds over land occurred mostly *later* between 22Z and 02Z within 60-120 km *north* of the storm track from an *easterly* direction.

3.2. WRF/Mesonet Qualitative Comparisons

Overall, the simulation's storm center track and timing are exceptionally accurate until near landfall time, especially in view of its initialization time at 84 hours before landfall. By two hours before landfall the simulation begins to turn the storm center slightly left of the actual track and by an hour after landfall its translation speed slows considerably compared to observations. WRF also maintains a smaller wind speed "eye" after landfall than observed.

WRF 10 meter wind speeds do not exhibit as much variability on a multi-hour time scale compared to those observed on the mesonet. In particular, the speed enhancement observed on the mesonet during the several-hour period of maximum winds spanning landfall time was not manifested as strongly in the WRF output. As expected, WRF 10 meter speeds are much lower everywhere over land compared to over water; however, peculiarly, the highest WRF 10 meter winds over land are constrained to smoothest terrain and highest mountains.

Regarding temperature comparisons, WRF 2-meter temperature fields exhibit a spatial evolution across New Jersey that is very similar to the mesonet's but WRF is 4-5 hours too soon. Similar early WRF behavior is seen in regional average time series of wind speed maxima.

Profile comparisons are desirable to understand and compare the planetary boundary layer (PBL) characteristics. The WRF PBL height variable was not archived but we plan to produce virtual soundings from WRF output to compare WRF and rawinsonde PBL profiles directly. However, in the interim, we compared WRF and observed PBL heights and stability estimated from graphical displays of variables at 3 nearest rawinsonde sites (OKX, WAL, IAD) for 29 October 18Z and 30 October 00Z launches. Results show that both WRF and rawinsonde profiles exhibited similar stability conditions as measured by the lapse rate spanning the lowest 1 km. Also, both WRF and rawinsonde profiles exhibited PBL heights in the 1 to 2 km range, where rawinsonde PBL height was estimated from the height of the lowest lapse rate increase, while the WRF PBL height was estimated from the height of the lowest part of the tightest vertical gradient in potential temperature.

3.3. Storm Features Characterization

WRF exhibits many features in the storm's structure and evolution that were also seen in observations, although often differing in timing and spatial details: Low level jets, warm and cool intrusions, and roll vortices.

Radar exhibits rapid symmetry destruction in Sandy before landfall. A pair of **low level jets** (LLJ) over New Jersey appears to play a role, as supported by WRF and mesonet data. In 3 hours (18Z-21Z) a northeasterly warm, moist, maritime-sourced LLJ transforms circular rain-bands near Sandy's core into a northwestward arc as an intensifying warm front. An easterly cooler, continental-sourced LLJ plunges eastward into the northern NJ coast at 22:30Z, sweeps westward across New Jersey through 00Z, and stretches the remaining convection bands westward even further. Timing of the above is consistent with regional average time series of mesonet wind speeds and temperatures and with the storm center's traversal of cool coastal shelf water.

WRF 3-D wind speed fields show that these LLJs traversed the region from 29 October 18Z through 30 October 00Z. The southern jet's intensity appears to be overdone in WRF during at least 14Z-22Z during which the surface jet spans a buoy. These LLJs appear to be helically spiraling as exhibited by WRF wind fields. In profile, WRF exhibits a wind speed increase from 10 to 1250 meters altitude, which is consistent with the Upton, NY rawinsonde wind profile at 00Z. At 00Z the highest WRF wind speeds are at 1 km over the middle Chesapeake Bay and at or above 3.4 km over the Hudson River. Maximum radar winds above Fort Dix, NJ are 50 m/s between 1.1 and 1.9 km during 17:42 to 20:22Z which is consistent with WRF and the 18Z Upton, NY rawinsonde profile.

The leading edge of a **warm intrusion** is marked by a warm front that strengthens onshore west of the storm center in the late stage of ET, with a weak wind speed zone evident along the warm side of the surface front. The warmth enters New Jersey during 15Z to 22Z on NNE winds as seen in mesonet observations and radar base velocity fields. Temperatures begin to both warm (09Z) and cool (22Z) earlier along the coast compared to inland (14 and 00Z, respectively), indicative of the westward intrusion of both the warm and cool air as seen on regional average temperature time series. Warming of 4-6 degrees C that occurs along and north of the storm track is not experienced south of the track, although cooling accelerates south of the track around 00Z as seen on regional average temperature time series. The warm front does not progress southward beyond about 50 km south of the track.

The **cool intrusion** is exhibited in wind profile observations which suggest that the leading edge of the southern cooler, drier LLJ that encircled the storm center advanced faster aloft over northern New Jersey, destabilizing the boundary layer there. It is hypothesized that this promoted downward momentum transport of easterly LLJ winds that contributed to higher winds over northern and central New Jersey near and after landfall time. Tongue noted (2014) boundary layer destabilization at Upton, NY and its possible role in contributing to higher winds during Sandy and Hewson (2015) discusses similar mechanisms for extratropical cyclones.

There is periodic structure of various wavelengths and longitudinal directions throughout the lowest 3.4 km of the WRF wind field, especially evident at 00Z. We attribute these structures to **roll vortices** which have been observed in other storms, e.g., Zhang et al. (2008). Longer wavelength structures are also seen in radar reflectivity and base velocity and have WRF wavelengths of 11 km versus 12 km observed on radar. Roll vortex signatures are seen in WRF horizontal and vertical wind fields over eastern PA and northern NJ throughout the depth of 10 to at least 1250 meters. Mountain-aligned radar-observed vortex signatures in PA and northern NJ occur during 18Z to 22Z while ones nearly perpendicular to mountains begin to appear over northern NJ at 22:33Z, advance southwestward, and persist through at least 12Z on October 30. Roll vortex signatures become less prominent after the warm front passes their vicinity. Shorter wavelength structures have WRF wavelength of about 7 km but are not observed as radar signatures.

4. SUMMARY

Many aspects of the WRF/observation comparison agree well. The pre-landfall track and timing and wind speed magnitude over water agree exceptionally well. Also exhibiting good agreement are the surface warm and cool air intrusions and their structures, the rapid 3-hour pre-landfall storm symmetry collapse, the low level jets' heights and wind speeds, the roll vortices' wavelengths and longitudinal dimensions and the PBL height and wind profiles.

Others aspects differ, however, such as the post-landfall track, timing and storm core size, the wind speed magnitude over land, and the timing and spatial evolution of maximum winds and warm air intrusion. Glaringly, WRF exhibits less wind speed variability on a multi-hour time scale than mesonet observations.

Overall, the fine-resolution observations and WRF simulation results, studied jointly, enabled the identification and investigation of storm structures that likely contributed to the wind speeds observed across the landfall region. These structures include low level jets, warm and cool surface air intrusions, and roll vortices. This positive experience exemplifies the value of the 500 meter resolution WRF simulation in interpreting and understanding the range of features that are exhibited in the mesonet and other observations.

5. PLANS

Since this study represents work in progress, many questions arose which inspire upcoming investigations:

- Spotty tree-fall across the landfall region: Is it caused by wind bursts? By downward momentum transport from LLJs? Would the effect be reproduced using a WRF large eddy simulation (LES) PBL scheme?
- Hourly-scale wind speed variability: Why is it not seen in WRF time series? Are mesonet LLJ features decoupled from the surface too much by the WRF PBL scheme? Would WRF wind speed time series at the LLJ level exhibit them?
- Land versus ocean WRF wind speeds: Can we account for differences with better wind speed profile scaling?
- 3-hour storm symmetry collapse: What is the key mechanism in the final rapid symmetry change?
- Roll vortices: Are their signatures manifested in mesonet time series?
- Other WRF storm features not discussed herein: Are features such as the oceanic surface wind dart, mesoscale pressure troughs, and hypothesized coastal estuary thermal "shadows" far offshore detectable in observations?

Visualizations for this work are posted on www.seedme.org/node/70880.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Clyne, J., Mininni, P., Norton, A., and Rast, M., 2007: Interactive desktop analysis of high resolution simulations: application to turbulent plume dynamics and current sheet formation. *New Journal of Physics*, **9**, 301.

Galarneau, T. J., C. A. Davis, and M. A. Shapiro, 2013: Intensification of Hurricane Sandy (2012) through extratropical warm core seclusion. *Mon. Wea. Rev*., **141**, 4296–4321, doi:10.1175/MWR-D-13-00181.1.

Hewson, T., 2015: Cyclonic Windstorms – Morphology, Predictability and Model Representation. Fifth Workshop on European Storms, Bern, Switzerland.

Johnsen, P., M. Straka, M. Shapiro, A. Norton, and T. Galarneau, 2013: Petascale WRF Simulation of Hurricane Sandy: Deployment of NCSA's Cray XE6 Blue Waters. SC13, International Conference for High Performance Computing, Networking, Storage and Analysis, Denver, CO, USA — November 17-21, 2013.

Skamarock, W. C., 2004: Evaluating mesoscale NWP models using kinetic energy spectra. *Mon. Wea. Rev.*, **132**, 3019–3032.

Tongue, J., 2014: Hurricane Sandy – Boundary Layer Structure Effects on Winds and Storm Surge. Fifth Tri-State Weather Conference, Danbury, CT, 7.

Zhang, K. B. Katsaros, P. G. Black, S. Lehner, J. R. French, and W. M. Drennan, 2008: The effect of roll vortices on turbulent fluxes in the hurricane boundary layer. *Bound.-Layer Meteor.*, **128**, 173–189.