WEATHERNEWS' OPERATIONAL IMPLEMENTATION OF THE WRF-ARW MODEL FOR GLOBAL OPERATIONS

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1. INTRODUCTION

Weathernews Incorporated (WNI), the world's largest, publicly-traded, full-service weather company, provides weather risk communication services to a wide variety of industries, as well as broadcast and mobile phone weather information, often in an "infotainment" format, directly to subscribers. Currently WNI operates in 15 countries around the world.

WNI forecasters have typically relied on meteorological models produced by government agencies in the US, Japan, and Europe as part of routine operations. Although these models can provide high quality guidance, relying on multiple external sources presents a set of challenges for WNI software engineers, IT staff, and the operational forecasters. Additionally, many countries severely restrict access to their data, requiring WNI to purchase these grids. Therefore, operations emphasize the use of a single global model, such as the Global Forecast System (GFS) provided freely by the US National Weather Service. However, the global models do not provide sufficient resolution to resolve important details in areas of highly-variable topography or near coastlines. Finally, the use of externally-produced forecast grids limits WNI's ability to rapidly integrate new research and development results into operational services.

To address these issues, WNI began an effort in late 2004 to develop an internal environmental modeling system to provide state-of-the-science numerical forecast guidance, globally uniform services, and a mechanism to rapidly infuse new science. The new system, deemed the Original Weather Numerator (OWN), consists of the WRF-ARW model for the forecast module, the Local Analysis and Prediction System (LAPS) developed by the NOAA Environmental Systems Research Laboratory/Global Systems Division (Albers et al. 1996) for data assimilation, an internally developed WRF post-processor (OWN-WRFPOST), and a suite of scripts and utilities to provide a robust operational environment that includes real-time product generation, data transfer, and process monitoring. OWN began real-time operation in April 2005, and has been maintained as a fully operational system since July 2005, even as work continues to refine and improve upon the existing configuration.

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2. SYSTEM DETAILS

2.1. Computing System

OWN currently runs in the WNI Oklahoma operations center on a commodity-based clustered computing system. The cluster was purchased and installed in March 2005, and consists of 50 computational and 2 graphical production servers from Sun Microsystems. All of the servers contain AMD Opteron CPUs running RedHat Enterprise Linux, with all of the computational servers containing two CPUs each. Network traffic on the cluster is divided into two separate networks. For normal TCP/IP traffic, Gigabit Ethernet is used. For MPI inter-process communications, however, the cluster uses a dedicated, low-latency Myrinet interconnect from Myricom. This has proven to be an extremely powerful and reliable but cost-effective computing solution.

2.2. LAPS Data Assimilation

Often, WRF is used to simply "downscale" coarser numerical guidance from other agencies as a means to provide higher-resolution forecast guidance. To rely on this technique globally means that one either has to initialize the model from a pure forecast, or alternatively wait for the global or regional analyses to be made available by external providers, which ties initialization times to the typical synoptic hours. To address this, WNI chose LAPS to apply the vast amount of global observational data already ingested for operations to improve initial conditions for the forecast model. This also provides the ability to use flexible model initialization times, thereby allowing for a better balance of computational load while providing more frequent forecast updates for a given region.

WNI uses LAPS to perform a diabatic initialization of the WRF model, including the initialization of the hydrometeor fields (Shaw et al. 2001). This "hot start" technique has been shown to dramatically improve the forecasts of clouds and precipitation in the early hours of model integration, effectively eliminating the model "spin-up" period required. Data incorporated into the LAPS initialization within OWN include:

- Visible and IR satellite data
- Radar reflectivity data (WSR-88D, Europe KNMI, and JMA data)
- Wind profilers (NOAA and JMA)
- GOES cloud-drift winds

- RAOBs
- METAR, synoptic, maritime, and mesonet surface data
- Polar-orbiting satellite soundings

Work to ingest additional observational data, including QuikSCAT winds, aircraft observations, and WNI-proprietary Micronet observations is ongoing.

2.3. WRF Model Configuration

The OWN implementation of WRF is currently based on the WRF-ARW core, version 2.1.2. Minor modifications have been made to the WRF registry to output additional variables used in post-processing. One advantage of using WRF is the ability to incorporate the latest efforts of the NWP research community very rapidly. In general, the OWN implementation of WRF has been upgraded to the latest version within a month of being made available to the public.

Based on the operational requirements and limitations of the existing computational architecture at WNI, all of the current OWN regions being produced use grid spacing ranging from 9 km to 15 km. Thus, the Kain-Fritsch convective parameterization is employed. Additionally, the WRF code was modified to provide some feedback of parameterized condensation into the resolved microphysical arrays. This option provides additional consistency for algorithms within the WRF post-processing that utilize the microphysical arrays (e.g., radar reflectivity, surface visibility, precipitation type, lightning potential, etc.).

For the land surface, OWN-WRF uses the NOAH Land Surface Model option. Following the method used by the NWS operational RUC model, the OWN implementation recycles the prognosticated soil fields to improve the initial conditions for subsequent forecasts. This change was implemented in all OWN regions in May 2006, after testing showed a significant reduction of surface temperature and dewpoint biases and errors.

Other physics options employed for OWN operations include the WSM6 microphysics, the RRTM long-wave radiation scheme, the Dudhia shortwave scheme, and the YSU PBL scheme.

2.4. WNI WRF Post-processor (OWN-WRFPOST)

OWN-WRFPOST performs typical post-processing tasks, including de-staggering of the momentum fields, conversion of state variables to useful forecast parameters, vertical interpolation to pressure levels and height levels, and derivation of a wide variety of parameters supporting specific forecast needs, including:

- Lightning potential using an algorithm developed at WNI, partially based on the USAF BOLT algorithm (Keller 2004)
- Wind gust potential based on the UKMET NIMROD (Hand 2000) algorithm.
- Clear Air Turbulence guidance based on the Ellrod and Knapp (1992) algorithm.
- Sensible weather, encoded for use with WNI databases supporting mobile and broadcast content
- Cloud forecasts, including total sky cover and ceiling information
- Visibility, based on algorithms developed at the NOAA ESRL/GSD and by Stoelinga and Warner (1999)

Additionally, OWN-WRFPOST provides a variety of formats to support WNI software engineers responsible for integrating the WRF output into various internal operational systems and products. Output formats include:

- WMO GRIB-2 gridded data for input into interactive forecaster tools
- Textual time-series point forecasts
- Binary data and control files for GrADS and IDL visualizations
- WRFSI “gribprep” format, used to feed back soil fields and/or provide lateral boundary conditions to nested regions.

OWN-WRFPOST typically executes on the same server that is handling the WRF I/O processes for a given simulation, and runs concurrently. WRF is configured out output a single forecast time per output file, so as new files appear, the OWN-WRFPOST immediately processes them, thereby providing the most rapid access of new forecast data to the WNI operational forecasters.

3. OPERATIONAL APPLICATIONS

Currently, OWN is primarily used internally by WNI operational forecasters. As of May 2006, it is configured to cover three major continental areas with 15 km grid spacing four times daily. Additional, there is a higher resolution domain (9 km) supporting operations in Japan, and one “floating” 9 km region that can be rapidly relocated to support any area of interest in the world. Figure 1 shows the existing regions.

OWN has especially benefited the WNI forecasts is in areas affected by complex terrain. For example, the OWN model is currently being used in the WNI marine section to forecast strong gap wind events in the Gulf of Tehuantepec. The winds through this gap have been known reach 30 m s^{-1} as far out to sea as 150-450 km, depending upon the duration of the event. Due to the high volume of ship traffic near the Gulf of Tehuantepec and the resultant high waves, forecasting these events correctly is critical to many of WNI’s maritime customers. OWN output helps WNI forecasters to more accurately forecast the onset as well as the decreasing intensity of the Gulf of Tehuantepec wind events.

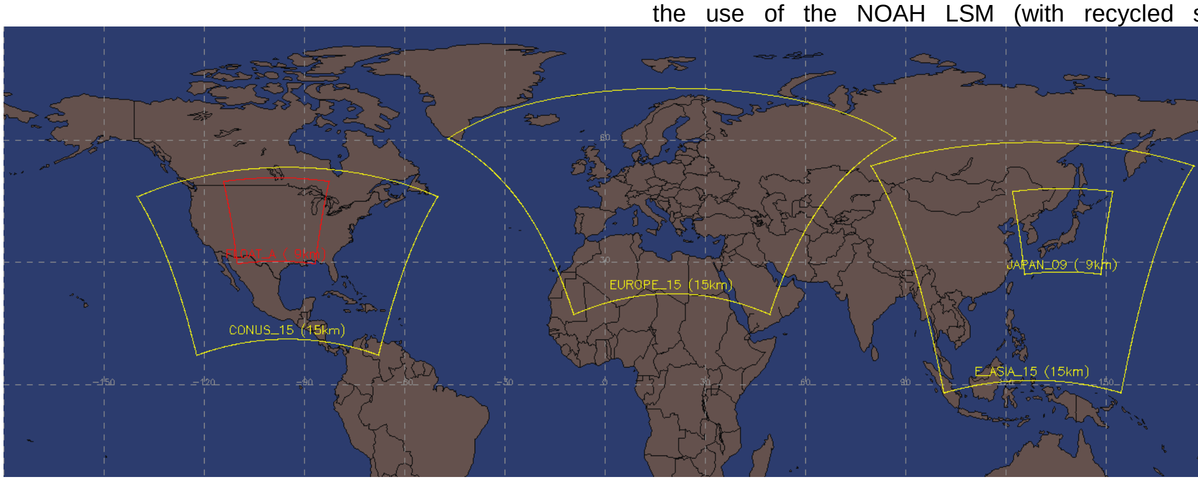

Figure 1. Operational OWN regions as of May 2006.

OWN has also been of great benefit within WNI marine operations during tropical storm season as well as for forecasting off-shore squall lines affecting oil rig operations. Wind intensity and tropical storm track forecasts from OWN have proven to be more realistic than those represented in the coarse global model data normally used at WNI. OWN has helped WNI forecasters more accurately pinpoint the areas of significant tropical storm impacts for offshore oil, port, and shipping operations. Additionally, the floating domain will allow WNI to better analyze and forecast tropical systems in the open ocean as they are developing.

WNI aviation forecasters are using OWN to more accurately forecast when heavy rain, high winds, or wind shifts will impact airports used by its commercial airline customers. Accurately forecasting the timing of these events greatly increases the efficiency and planning of an airline's operations. Additionally, the OWN-WRFPOST system uses the high-resolution (spatially and temporally) gridded fields to derive parameters to help forecast aviation hazards such as turbulence, ceiling, visibility, and convective storms. OWN helps improve WNI's terminal forecasts and flight hazards, and has lead to better weather briefings for clients.

4. VERIFICATION AND EXAMPLES

4.1. Surface Point Verification Results

Preliminary efforts to objectively verify the quality of the WRF forecasts involved the computation of typical error and bias statistics by comparing observed surface temperature, dewpoint, and wind from METAR observations to model grid point values. It was readily apparent that the OWN configuration of WRF had both a significant cool and moist bias. After doing some initial research and testing, it was hypothesized that partitioning of the sensible and latent heat fluxes from the 5-layer model was not realistic, and was favoring a rapid, early moistening of the boundary layer. A new configuration that included improved vertical resolution in the boundary layer and the use of the NOAH LSM (with recycled soil parameters) was run in parallel test mode with the operational configuration using the FLOAT_A domain shown in Figure 1. Two weeks of continuous testing and verification revealed that this new configuration significantly improved the surface dewpoint temperature, decreasing the RMSE by almost 1 K while reducing the magnitude of the moist bias by nearly 3 K. Table 1 shows the results of this test period computed for all valid METARs at all forecast hours.

Table 1. Surface verification for OWN-WRF using 5-Layer versus NOAH LSM for the surface parameterization.

	RMSE		Bias	
	5L	NOAH	5L	NOAH
Temp (K)	3.0	2.8	-1.3	-1.0
Dewpoint (K)	3.9	3.0	2.2	0.3
Wind Speed (m/s)	2.7	2.8	0.4	0.1

4.2. Hurricane Katrina

The very active 2005 Atlantic Basin hurricane season provided WNI forecasters with an opportunity to either gain or lose confidence in the OWN system. WRF performed surprisingly well for several major tropical systems. Hurricane Katrina was one such example. Although some of the early OWN forecasts (while Katrina was still affecting the Florida peninsula) had the forecast track too far to the east, it was always consistent in forecasting a rapid intensification to Category 5 status in the Gulf of Mexico. By two days prior to landfall in Louisiana, the OWN forecasts were already indicating landfall near New Orleans as a Category 5 hurricane. Table 2 shows the verification of storm position forecasts from operational OWN initialized for 1500 UTC on 27

August 2006, approximately 45 hours prior to landfall. For comparison purposes, the verification of the official NHC forecast issued at the same time is also shown. Positions were verified using the four NHC bulletins issued subsequent to the initialization time. Almost extraordinarily, the 45-hour OWN forecast valid very near the time of landfall was within 15 km (within one model grid point) of the observed location. While it is unrealistic to think OWN can routinely predict tropical systems with this accuracy, forecaster confidence in using what was a very new tool at the time increased dramatically.

Table 2. OWN and NHC position forecast errors for Hurricane Katrina from forecasts issued 1500 UTC on 27 August 2006.

Valid Time	Forecast Length (h)	OWN Position Error (km)	NHC Position Error (km)
28/00Z	9	63	35
28/12Z	21	63	46
29/00Z	33	39	56
29/12Z	45	15	104
Average		45	60.4

4.3. Train Derailment Case Study

On 25 December 2005, a Japan East Railway (JRE) passenger train derailed while crossing a bridge near Shonai, Japan, resulting in four fatalities and injuries to more than 30 other passengers. Immediately prior to the accident, a wind gust of 21.6 m s^{-1} was recorded in Sakata, approximately 6 km from the accident location. While this is not normally considered strong enough to derail a train, these winds were associated with a strong convective line, and it is hypothesized that localized stronger gusts may have occurred, either due to proximity of a convective storm or terrain effects. Because JRE is a major customer, a case study using the WRF model is in progress at WNI. The results of this study will be used to aid in understanding conditions that led to this event, as well as new algorithms that can be developed to improve weather risk management for JRE's operations.

To date, several different high-resolution configurations of WRF initialized using GFS forecast data has yielded some interesting results. WRF shows great promise of capturing mesoscale structures that evolved on the day of the accident when compared to radar imagery.

4.4. WxChallenge Collegiate Weather Forecasting Contest

WxChallenge is a national collegiate weather forecasting contest hosted by the University of Oklahoma and sponsored by WNI (http://www.wxchallenge.com). The competition involves forecasting the minimum and maximum observed temperature, total precipitation, and maximum sustained wind speed for a 24-h period. Forecasts are issued for a selected city each day for a two-week period. The forecasts must be entered each day by 0000 UTC and are valid from 0600 UTC through 0600 UTC the next day. Forecasters are then ranked based on cumulative error points.

Because WNI forecasters were participating in the competition during the beta test period (2005-2006 academic year), scripts were written to extract the required forecast parameters each day for the selected city from the OWN-WRF forecast. These forecasts, along with the standard set of graphical products, were available to the forecasters and were also scored using the same verification rules and observational data used by the contest administrator. Because WNI provides specific city forecasts as part of its mobile content, this was a good opportunity to determine how raw OWN-WRF point forecasts compare to both human and objective forecasts.

OWN compared very favorably to other automated objective forecasts and even to human-generated guidance, despite being pure raw output with no statistical or terrain corrections. During the fall 2005 session, the OWN forecasts finished 47th overall out of 223 forecasts verified, 208 of which were human contestants, one was the official NWS forecast, and the remaining were team consensus forecasts or MOS guidance.

Two forecast periods were exceptionally notable. In the fall of 2005, one of the forecast periods covered Wilmington, NC, and coincided with the period that Hurricane Ophelia impacted that area. The raw OWN forecasts finished in 13th place overall. The next closest automated guidance, GFS MOS, finished in 60th place, and the official NWS forecasts finished at 89th. In the spring of 2006, the final tournament challenge focused on Hastings, NE. During this period, OWN accumulated 121 error points for the 12 forecasts, which gave it an 11th place ranking out of 379 forecasts verified. OWN beat all other automated numerical guidance again, as well as the official NWS forecast, for this period. Coincidentally (or perhaps not?), four of the forecasters advancing to the "Sweet 16" during this tournament period were from WNI. Two advanced to the final eight, and one all the way to the final day before finishing in second place.

These results indicate that OWN is already a credible source of information for automated forecast products for some of WNI's basic subscriber services. With the future addition of statistical post-processing of raw OWN forecasts, skill should continue to improve.

5. FUTURE WORK

Over the next year, OWN capabilities will continue to increase. A new high-performance computing system will be acquired and installed at the WNI Global Center in Makuhari, Japan. This will allow significant expansion of the number of global areas covered by OWN regions, as well as provide additional operational robustness, as the Global Center and the Oklahoma sub-center will be able to back each other up during system maintenance periods.

By the winter of 2006, WNI anticipates using OWN to support detailed road weather forecasts in support of winter weather operations in Japan. This will be accomplished via a combination of high-resolution (2-3 km) OWN-WRF grids and a rapid refresh version of WRF. Various configurations of WRF are now being tested specifically for this application.

In addition to system growth, WNI intends to make continuous enhancements to the OWN system for the benefit of our customers as science evolves. WNI scientists are currently engaged in several OWN-related activities, including:

- Comprehensive objective verification of the OWN forecasts
- WRF model "tuning"
- Derived product algorithm development for specialized applications
- Adding new data types to the LAPS assimilation system
- Investigating alternatives to LAPS, including the WRF-VAR and the University of Oklahoma's ARPS Data Assimilation System (ADAS)
- Statistical post-processing development to account for model biases, which will allow for more automated first-guess forecast products
- Coupling WRF output with coastal and estuary wave models
- Investigation of options for global modeling, including ocean coupling
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Because of the limited size of the WNI research and development staff, collaboration with various academic and government research groups will be critical to our success.

6. SUMMARY

The community-focused nature of the WRF model, along with its advanced numerical scheme, has made it an extremely valuable forecasting tool for real-world applications. Even without sophisticated statistical corrections, raw forecasts derived from the OWN implementation of WRF have shown remarkable skill, especially during significant weather events, even when compared to human-generated forecasts. The flexibility of both WRF and LAPS has allowed WNI to develop a robust, global system that provides uniform services upon which our forecasters are becoming increasingly dependent.

With OWN, WNI has entered a new era of applying the latest NWP research and development to very specific problems in a wide variety of industries. One of the over-arching goals of the WRF project was to bridge the "valley of death" between research and operations, and OWN is one example of how this is occurring very rapidly within the private sector. WNI is not only a WRF user, but also remains committed to advancing the science of meteorology for the benefit of society, and will continue to contribute new results, code corrections, and enhancements back to the community as appropriate.

7. REFERENCES

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