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INITIAL VERIFICATION OF THE NOAA-UNH JOINT CENTER FOR OCEAN OBSERVING TECHNOLOGY REAL-TIME MM5/WRF FORECASTS

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1 Introduction

The Coastal Services Center of NOAA's National Ocean Service is intended to build capacity for informed decision making about our coasts. The Joint Center for Ocean Observing Technology (JCOOT), as part of the Coastal Observation Technology System project, forms part of the Integrated Ocean Observing System which is "envisioned as a coordinated national and international network of observations, data management and analyses that systematically acquires and disseminates data and information on past, present and future states of the oceans and the nation's Exclusive Economic Zone" (NOAA 2007). Based at the University of New Hampshire (UNH), the Center is a collaborative effort among NOAA, UNH, the Gulf of Maine Ocean Observing System and Atmospheric and Environmental Research, Inc. (AER).

JCOOT was established to develop and demonstrate new ocean observing technology by focussing on the synergistic use of data from existing land, atmosphere and ocean observing systems. The geographical focus is the Gulf of Maine's 93,000 square kilometres of ocean, 12,500 kilometres of coastline and 180,000 square kilometres of watershed that are shared between three states and two provinces. A focal point is to develop prototype analyses and predictions of the ocean, atmosphere and land spheres to enhance economic productivity and quality of life for both lay and advanced users. Products have been developed through the optimal fusion of advanced data assimilation, in-situ and remotely-sensed observations, and modelling techniques. This paper will focus on the project's atmospheric modeling, including both subjective and objective verification.

2 NWP-Based Project Goals

Initial work implemented the MM5 system (including 3d-VAR) in a triply-nested configuration centered over the southern half of the Gulf of Maine. Operations were updated to a WRF-based system during March 2007. A primary project goal is to improve marine forecasts of the near-shore environment through high-resolution atmospheric modeling that benefits from improved initial conditions provided by optimally assimilating a diverse set of observations. Current real-time users include the US National Weather Service (NWS) Forecast Offices in Gray and Caribou, Maine, and the UNH terrestrial water budget modeling community. Ultimately the Center strives to be a data repository in which a variety of atmospheric and oceanographic environmental datasets will be available.

3 Model Summary

a. MM5 details

The non-hydrostatic, fully compressible, regional Penn State/NCAR Mesoscale Model Version 5 (MM5) atmospheric modelling system is described by Dudhia (1993). We use version 3.7.3, in conjunction with MM5 3d-VAR, configured for 43 vertical sigma levels up to 100 hPa on a Lambert Conformal projection on triply-nested domains of 130x130 (domain 1), 112x100 (domain 2) and 100x124 (domain 3). These domains are centered on the Eastern US, New England and the Gulf of Maine, respectively.

The grid spacing of the domains (27, 9, and 3 km) was chosen to balance the requirements of domain coverage, resolvable spatial scales and data latency to the forecasters. We anticipate increased detail in the atmospheric temperature and wind fields over currently avail-

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able lower-resolution NWP products in the near-shore regions of Massachsuetts, New Hampshire and Maine covered by domains 2 and 3.

The following model parameterizations were used: Kain-Fritsch2 cumulus convection (Kain 2002), Reisner2 explicit microphysics (an update of Reisner et al. 1998), Hong and Pan (1996) PBL scheme and the AER-developed RRTM longwave radiation scheme (Mlawer et al. 1997).

No cumulus parameterization scheme was initially used on the three domains in an attempt to encourage the explicit development of convection. We note that the ability of the innermost domains to develop explicit convection can be heavily influenced by the presence and choice of parameterized convection schemes on the coarser-resolution domains (Warner and Hsu 2000; Colle et al. 2003). Subsequent subjective evaluation of both the MM5 and the WRF precipitation fields from domain 2 compared to domain 3 indicated that explicit convection was insufficient in the innermost nest and the parameterization scheme was activated in WRF domain 3 following the end of the current period of evaluation in May 2007.

Two-way nesting was used for all domains to allow high-resolution features on a domain to contribute to the flow patterns on the parent domain. The anticipation is that while sub 10-km grid spacing may not increase objective skill scores (Mass et al. 2002), forecasters may benefit from the presence of more realistic small-scale features. The goal of producing the "best" forecast via two-way nesting unfortunately precludes meaningful comparison between the 9-km and 3-km fields.

b. WRF details

During March 2007, the MM5 model was replaced by the Weather Research and Forecast Model (WRF). We use version 2.1 of the Eulerian mass-coordinate (EM) dynamical core of WRF, which is part of the Advanced Research WRF (ARW) supported by the National Center for Atmospheric Research (NCAR) and described in detail in Skamarock et al. (2005).

The WRF model domains are very closely matched to that of the MM5 and used the same number of grid points, approximate placement and map projection. The following physics options were used:

- Radiation: RRTM scheme for long-wave radiative transfer (Mlawer et al. 1997), and Goddard scheme for short-wave radiative transfer,
- Planetary Boundary Layer: Yonsei University scheme (Noh et al. 2003), coupled with the NOAH land surface model and a similarity theory-based surface layer scheme,
- Microphysics: WRF Single Moment 6-class graupel scheme (based on Lin et al. 1983),
- Convection: new Eta Kain-Fritsch scheme (based on Kain and Fritsch 1990, 1993).

These selections were chosen to remain as distinct as possible from the other local NWP guidance available at NWS Gray.

c. 3d-VAR and observations

Initially the standard MM5 3d-VAR package (Barker et al. 2003) was implemented to provide domain 1 with improved initial conditions and lateral boundary conditions for each subsequent MM5 simulation. In March 2007, the version 2.1 WRF-VAR package using 3d-VAR was implemented.

The goal in 3d-VAR is to find an analysis representing the minimum variance estimate of the true (unknown) state of the atmosphere given the *a priori* previous forecast and a set of observations. The fit is constrained through the background, observation instrument and observation representative error covariance matrices. Background error statistics appropriate for mesoscale forecasts of 30-40 km were obtained from NCAR (Nehrkorn 2004, personal communcation) for use in MM5 3d-VAR, instead of the large-scale statistics supplied with the MM5 3d-VAR distribution. These statistics were derived from a month-long dataset of mesoscale (30-km grid spacing) forecasts using the NMC method and were provided by Francois Vandenberghe of NCAR (personal communication, 2004). For WRF, NCEP-derived background errors were used following Wu et al. (2002).

Application of 3d-VAR was limited to domain 1 for several reasons. Most importantly, background error statistics were only available for grid scales of approximately 30 km. Resource limitations, plus a lack of timely data, also placed restrictions on the ability to apply 3d-VAR on other domains.

Data assimilation is carried out prior to model integration using, in part, data from the Global Systems Division of NOAA's Earth System Research Laboratory's Meteorological Assimilation Data Ingest System (MADIS) feed. QSCAT observations from NESDIS' Central Environmental Satellite Computer Center (CEMSCS) are also ingested. The data platforms available from these two feeds include, respectively, surface reports, upper air radiosondes, local mesonets and proprietary aircraft reports; and ocean surface winds from the QSCAT scatterometer. Each analysis on domain 1 typically ingests the following number of observations: 16 SYNOP, 4350 METAR, 150 buoys, 27 soundings at 0000 and 1200 UTC, 11000 AIREP aircraft reports (fewer at night), and 500-1500 QSCAT surface wind observations at 1200 UTC.

Table 1: List of coastal observation sites described in the text and other figures. Values in brackets correspond to the height above sea level (in m) of the anemometer at that location.

METAR	KBHB	Bar Harbor, ME
	KBOS	Boston, MA
	KIWI	Wiscasset, ME
	KNHZ	Brunswick, ME
	KPSM	Portsmouth, NH
	KPWM	Portland, ME
	KRKD	Rockland, ME
C-MAN	MISM1	Matinicus Rock, ME (32.7)
(MM5 only)	MDRM	Mt. Desert Rock, ME (31.7)
	IOSN3	Isle of Shoals (32.3)

4 System Configuration and NWS Products

a. System configuration

The NWP modeling is carried out on a dedicated 62-processor linux cluster located at UNH in Durham, NH. Currently, the WRF model and WRF-VAR are executed four times daily at approximately 0230, 0830, 1430 and 2030 UTC, upon receipt of operational NCEP WRF grib files. WRF-VAR is carried out on domain 1 and the WRF integrates to 48 h with output grib files available every 15 min on domains 2 and 3 on both native model surfaces and pressure levels. Postprocessing to the pressure surfaces is done concurrently with model integration as WRF output files become available.

Complete model data are generally available about 3 h following receipt of NCEP input files. A selection of fields from the 15-min GRIB files is generated in NETCDF format for use in delayed real-time by the UNH hydrological modeling group. Products for the NWS are described in the following section. Web posting to http://www.jcoot.unh.edu/aer/pages_wrf occurs slightly later, following generation of web graphics.

b. NWS products

The primary user of the JCOOT NWP data is the NWS, which receives BUFKIT and GRIB files via the Unidata Local Data Manager (LDM) four times daily. Both of the NWS offices in Maine - Gray and Caribou - receive BUFKIT files for dozens of land and sea sites out to 48 h from domains 2 and 3. The hourly data displayed within the BUFKIT software permits easy intepretation of atmospheric profiles. GRIB files of select fields, with a focus on the boundary layer, are available every 3 h out to 48 h for domains 2 and 3.

Table 2: Domain 3 forecast errors for the MM5 averaged over all forecast lengths from 0 through 48 h during period 1 October 2006 to 21 January 2007. "ALL" refers to all observing sites from all platforms in the domain. Individual METAR and C-MAN stations are those identified in Table 1. Units are degrees Celsius.

Location	**Mean**	**RMS**
MM5 Temperature		
ALL	-0.6	2.1
METAR	-0.5	2.7
BUOY	-0.2	1.7
SOUND	0.2	1.6
AIREP	-0.7	1.6
KBHB	0.9	1.2
KBOS	-0.9	1.1
KIWI	0.6	1.5
KNHZ	0.9	1.4
KPSM	0.2	1.5
KPWM	0.5	1.5
KRKD	0.7	1.4
MISM1	-0.3	1.2
MDRM	-0.1	1.1
IOSN3	0.2	1.3

5 Verification

a. Verification period

We present summary statistics for a modest number of MM5 and WRF forecasts from several months during late 2006 and the first half of 2007. Unfortunately, statistics for each model from an overlapping period of time are unavailable. The MM5 period of record covers four daily 48-h forecasts from 1 October 2006 to 21 January 2007 and for the WRF from 1 March to 11 May 2007. There are 262 (210) MM5 forecasts for domain 2 (3) and 193 for each domain for the WRF.

The verification was carried out in 3d-VAR by restricting 3d-VAR to only compute the difference between the forecasts and observations. All available observations were presented to 3d-VAR. Model forecasts were compared to observations at forecast hours 0, 1, 2, .., 48 for domain 2 and then domain 3. Because a meaningful comparison between domain 2 and 3 is not possible, we present results only for domain 3.

Typically there were approximately 170 METAR sites available for comparsion in domain 3, one sounding (at 0000 and 1200 UTC), but no SYNOP reports. There were typically 34 buoys located within domain 3, however, these data were available only for comparison with the MM5. The number of AIREP reports was highly variable over the course of a day, but typically 100-200

Table 3: As in Table 2, but for wind speed in ms^{-1}.

Location	Mean	RMS
MM5 Wind Speed		
ALL	0.2	3.3
METAR	0.5	1.3
BUOY	1.1	2.3
SOUND	-0.6	3.9
AIREP	-0.1	4.3
QSCAT	0.4	1.8
KBHB	2.4	1.6
KBOS	1.9	1.0
KIWI	2.4	1.6
KNHZ	2.0	1.0
KPSM	2.8	2.2
KPWM	2.2	1.4
KRKD	2.8	2.1
MISM1	0.2	1.5
MDRM	-0.1	1.4
IOSN3	0.2	1.5

Table 4: As in Table 2, but for wind direction in degrees.

Location	Mean	RMS
MM5 Wind Direction		
ALL	2	42
METAR	1	29
BUOY	7	53
SOUND	4	59
AIREP	2	48
QSCAT	1	54
KBHB	8	68
KBOS	7	53
KIWI	13	33
KNHZ	7	86
KPSM	9	50
KPWM	7	68
KRKD	11	52
MISM1	8	60
MDRM	9	51
IOSN3	11	63

were available for verification at 1200 UTC. It should be noted that no wind speed or direction comparisons were carried out for wind speeds less than 2 ms^{-1}. A list of the individual METAR and Coastal-Marine Automated Network (C-MAN) sites referenced in the verification tables is provided in Table 1.

b. MM5 verification

The most notable comments are included below. Forecast error statistics for domain 2 are very similar to those from domain and only results from domain 3 are provided in the tables and below in the text.

Temperature (Table 2)

- Overall bias values are small and negative, indicating a cool bias in the forecasts
- Forecasts exhibit little bias when compared to soundings and have largest rms values when verified with METAR observations.
- Forecast errors at the coastal METAR sites tend to exhibit a small warm bias, while those from C-MAN sites have a very small negative bias.
- There is no appreciable change in bias and rms scores when the forecasts are binned by model start time (not shown). This is the situation for both models and all four fields.

Wind Speed (Table 3)

- Overall bias values are very small overall and exhibit no dependency on forecast initial time.
- The largest rms values are seen for comparisons against aircraft reports.
- For individual METAR sites, forecast wind speeds are too high by approximately 2 ms^{-1}, though with small rms values.
- Forecast bias errors for the C-MAN sites are substantially smaller than for the METAR sites. This may be related to the non-standard anenometer exposure for these sites (refer to Table 1).

Wind Direction (Table 4)

- Overall forecast bias values for wind direction are inconsequential, while rms values indicate a typical error of approximately 50 degrees. The highly irregular coastline of Maine may contribute to the occasional occurrence of rather poor forecast wind directions.
- A substantial range of rms values for the METAR stations may indicate the susceptibility of these stations to the vagaries of coastal orography/landforms. The C-MAN stations, however, do have similar rms values, despite being more exposed to uniform flow.

Table 5: As in Table 2, but for mixing ratio. Units are 100 times g kg^{-1}; i.e., 70=0.7 g kg^{-1} .

Location	**Mean**	**RMS**
MM5 Mixing Ratio		
ALL	-9	60
METAR	-22	93
BUOY	-13	50
SOUND	<1	50
KBHB	43	70
KBOS	-12	81
KIWI	-3	77
KNHZ	3	81
KPSM	-9	80
KPWM	-9	83
KRKD	-11	71
MISM1	-68	85
MDRM	-19	68
IOSN3	-31	89

Mixing Ratio (Table 5)

- Overall mean errors appear small with a slightly negative bias and little dependency on the initial time of the forecast.
- The MM5 verified best against soundings when averaged over all levels, with a bias one order of magnitude smaller than for METARs and buoys. The large fraction of forecast evaluations against soundings in the free atmosphere out of the moist boundary layer likely contributes to the smaller bias.
- METAR station KBHB (Bar Harbor) and the three C-MAN sites exhibit larger bias values of opposite signs, however, rms values are comparable to the other individual sites.

c. WRF verification

The most notable comments are included below. The reader is reminded that the WRF period of record is not coincident with that of the MM5.

Temperature (Table 6)

- Forecast bias values overall are small and negative, indicating forecasts are too cool. This is seen uniformly across each model initial time.
- rms values are slightly larger than the MM5.
- As with the MM5, comparisons against METAR reports result in the largest rms errors.
- Forecasts compared to individual METAR reports exhibit very small biases and agreeable rms values.

Wind Speed (Table 7)

- Forecast bias values are slightly larger than the MM5, while rms errors are slightly smaller. Overall, all values are acceptable.
- Similar to the MM5, rms errors for forecasts compared to aircraft reports exhibit the largest rms errors.
- Error statistics of forecasts compared to coastal METAR stations have errors similar to the MM5.

Wind Direction (Table 8)

- Forecast bias values for wind direction are inconsequential and even smaller than the MM5.
- The rather large range of rms errors may be affected by the highly complex nature of the Maine coastline which can be difficult for even a model with 3-km grid spacing to resolve.

Mixing Ratio (Table 9)

- Forecast bias values tend to be of similar magnitude to those from the MM5, though of opposite sign, indicating forecasts that were too moist.
- Bar Harbor again exhibit the largest forecast bias values, similar to comparison with the MM5.

6 Summary

In general in this preliminary analysis, MM5 verification statistics agree well with those of the WRF, with all four fields from this study exhibiting reasonable bias and rms error scores. The expectation is that these fields can provide valuable guidance to NWP forecasters. Bias scores are not highly dependent upon model initialization time. In the current MM5/WRF configuration - due to two-way nesting - an evaluation of the effect of higher resolution on the forecasts was not meaningful.

There does appear to be a diurnal cycle visible in the temperature bias for all 0000 UTC forecasts verified using METARs (Fig. 1). Forecast errors are pronounced for forecasts valid at 1800 UTC. The largest forecast errors occur during the early afternoon for forecasts initialized at other times. No other platform (SYNOP, SONDE, buoy, AIREP or QSCAT) exhibited this characteristic, which suggests that the WRF systematically underforecasts the early afternoon (local time) surface temperatures over land.

Table 6: As in Table 2, but for the WRF model from 1 March to 11 May 2007.

Location	Mean	RMS
WRF Temperature		
ALL	-0.8	2.7
METAR	-1.1	3.0
SOUND	0.4	1.3
AIREP	-0.4	1.6
KBHB	0.3	1.5
KBOS	-1.1	1.2
KIWI	-0.3	1.7
KNHZ	0.1	1.7
KPSM	-0.3	1.6
KPWM	<0.1	1.6
KRKD	-0.1	1.6

Table 7: As in Table 3, but for the WRF model from 1 March to 11 May 2007.

Location	Mean	RMS
WRF Wind Speed		
ALL	0.4	2.5
METAR	0.5	1.4
SOUND	<0.1	3.1
AIREP	0.1	4.0
QSCAT	0.7	1.6
KBHB	2.3	1.5
KBOS	1.3	0.8
KIWI	2.7	1.9
KNHZ	1.6	0.6
KPSM	2.1	1.2
KPWM	1.8	0.8
KRKD	2.6	1.8

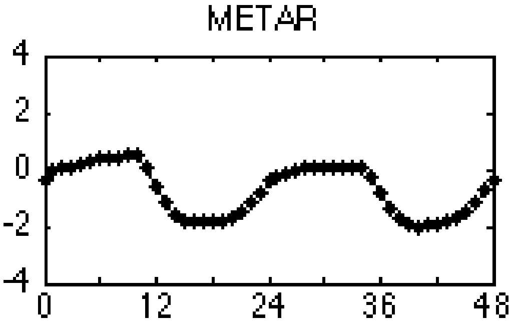
Table 8: As in Table 4, but for the WRF model from 1 March to 11 May 2007.

Location	Mean	RMS
WRF Wind Direction		
ALL	0	46
METAR	<1	38
SOUND	<1	29
AIREP	1	59
QSCAT	<1	50
KBHB	-7	106
KBOS	4	65
KIWI	6	40
KNHZ	6	72
KPSM	4	56
KPWM	-3	74
KRKD	3	66

Table 9: As in Table 5, but for the WRF model from 1 March to 11 May 2007.

Location	Mean	RMS
WRF Mixing Ratio		
ALL	13	81
METAR	19	96
SOUND	11	38
KBHB	79	67
KBOS	24	81
KIWI	43	74
KNHZ	45	75
KPSM	32	79
KPWM	34	78
KRKD	36	67

Figure 1: Bias by forecast length in forecasts of surface temperature from all 0000 UTC WRF runs. Error is in degrees Celsius and is based on comparisons with at least 24,000 METAR observations from approximately 50 WRF runs.



a. Value to NWS operations

Since August 2006, NWS Gray forecasters have been able to ingest JCOOT grib files into AWIPS in time for the operational forecasters to populate the National Digital Forecast Database. (Recently, NWS Caribou has added this capability.) Subjective evaluation of the WRF fields by NWS forecasters identified several cases that were depicted especially well by this implementation of the WRF. These included the post-cold frontal boundary layer marine winds on 30 March 2007, the low-topped post-cold frontal convection on 6 May 2007, as well as the NORLUN trough events (Bosart and Bracken, 1996) on 7 December 2006 and 22 January 2007.

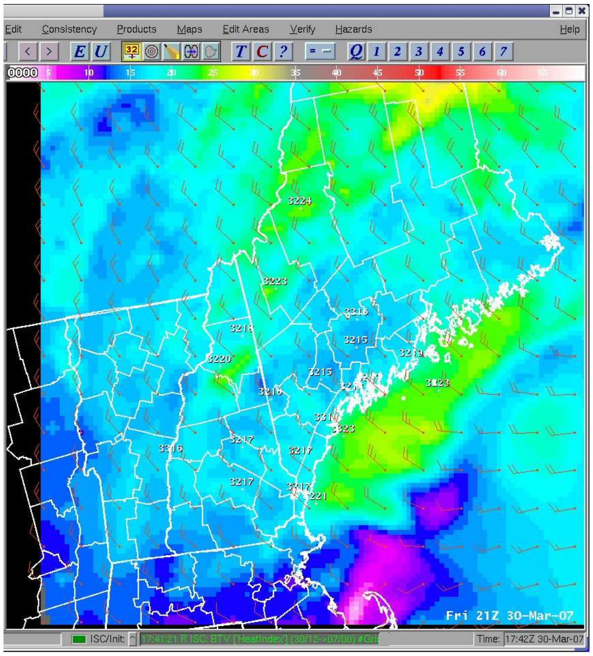
The need for accurate marine wind guidance is especially acute for NWS offices that have marine forecasting responsibility. The value to the operational forecasters, including aiding in the issuance of marine advisories, was demonstrated in a NWS Area Forecast Discussion (AFD) bulletin issued by the Gray, ME, office at 1830

UTC March 30 2007:

> *FOLLOWED AER/UNH WRF MODEL CLOSELY THIS EVENING THROUGH SATURDAY FOR THE SHORT RANGE PORTION OF THE FORECAST. THIS MODEL IS DEPICTING RAPID INCREASE IN WIND GUSTS OVER THE NEXT COUPLE HOURS...FIRST OVER THE MOUNTAINS/FOOTHILLS...BEFORE SPREADING TO THE COASTLINE. COLD AIR ADVECTION OVER THE COASTAL WATERS WILL YIELD WINDS INCREASING INTO SMALL CRAFT ADVISORY SHORTLY AS WELL...WHICH IS DEPICTED WELL BY THE 3 AND 9 KM VERIONS OF THE MODEL. POPULATED WIND GRIDS SHOW THE GUSTY WINDS OVER THE COASTAL WATERS.*

Fig. 2 shows the depiction by the WRF of the wind shift and increase in wind speeds behind the cold front passing into the Gulf of Maine at 2100 UTC 30 March 2007. This AWIPS graphic - on which the above Forecast Discussion was based - depicts domain 3 wind fields ingested into the National Digital Forecast Database for this event from the forecast started at 0600 UTC 30 March 2007.

Figure 2: AWIPS graphic depicting the 10-m wind field in domain 3 of the 0600 30 March 2007 WRF forecast valid at 2100 UTC 30 March. Of note is the wind shift and increase in wind speeds behind a cold front passing into the Gulf of Maine.



17:41:21 R ISC: BTV ['HeatIndex'] (30/12->07/00) #Gri

7 Conclusion

The NOAA-UNH Joint Center for Ocean Observing Technology, funded as part of the Coastal Observation Technology System, aims to develop and demonstrate new ocean observing technology to aid in the enhancement of economic productivity and quality of life for the region's population. The NWP contribution to this center focusses on improving marine weather forecasts by the NWS through generation of timely high-resolution atmospheric fields. Four-times daily NWP runs are available at the NWS Gray and Caribou offices with sufficiently short latency that the fields are utilized by human forecasters in their day-to-day operations. This paper presents the first verification of the NWP fields available to the NWS offices in Gray and Caribou, ME.

Overall, the MM5 and WRF data are of high quality, with bias and rms values reasonable for use in operations at the NWS offices. Of greatest note is the negative bias seen in comparisons with METAR reports valid during the early afternoon local time. This suggests inadequate surface heating is occurring in the WRF model. The more realistic meteorological features simulated by the innermost domain at 3-km grid spacing should provide forecasters with valuable information, in spite of more acute space and time problems associated with these higher-resolution features. NWS forecasters have acknowledged the value of the JCOOT NWP products in text bulletins as part of their daily work. Future work will include a more comprehensive study of ongoing WRF simulations.

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