

# **An Investigation of Terrain-Atmosphere-Ocean Interactions Along the Coastal Regions of North America**

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## **LONG-TERM GOALS**

The long-term goal of this project is to improve our understanding of: (1) the structure, evolution, and dynamics of the interaction of extratropical fronts/cyclones with the coastal orography, (2) air-sea interactions associated with coastal fronts and rapidly deepening cyclones along the East Coast, and (3) the ability of mesoscale models to simulate coastal phenomena at high resolution.

## **OBJECTIVES**

During the past year software has been developed to initialize the three-dimensional structure of a developing baroclinic wave using an idealized modeling setup. These idealized simulations from the Penn State/National Center for Atmospheric Research Mesoscale Model (MM5) will be used to study the interaction of landfalling extratropical cyclones and fronts with coastal orography. There have been a growing number of field case studies investigating this coastal interaction, such as Colle et al. (2002) supported by this project, but there needs to be a more systematic investigation of how terrain affects the structure and dynamical balances of a landfalling front.

This project has begun to investigate air-sea interactions by developing software to run both the NOAA Wavewatch III (WW3) and SWAN (Simulating WAVes Nearshore) wave models in real-time along the East Coast of the U.S. The ultimate goal is to have a two-way interactive modeling system using the MM5 and a wave model in order to investigate how the coupled system changes the surface fluxes and storm development along the East Coast. Before coupling these models, the objective this past year has been to determine which wave modeling system performs best in the coastal environment. Since the Navy runs with WW3, the verification results are important to Naval operations. As a result, this work has involved collaborative efforts with Paul Wittman of Fleet Numerical Meteorology and Oceanography Center, who runs the WW3 for Naval operations.

This study is investigating the landfall of hurricane Floyd on 16 September 1999 along the East Coast of the U.S. using the MM5 down to 1.3-km grid spacing. During this event all the NCEP operational models failed to accurately forecast the cyclone track and heavy precipitation. Our goal has been investigate the reasons for the rapid coastal frontogenesis and extreme precipitation along the mid-Atlantic coast. The simulations are designed to determine the importance of terrain effects, diabatic effects from surface heat and moisture fluxes, and latent heating from precipitation. This research is resulting in the first documented high resolution simulation (< 5-km grid spacing) of the mesoscale features associated with the transition of a tropical storm to a more extra-tropical system.

# Report Documentation Page

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The final goal of this past year has been to continue our comprehensive verification of the MM5 and Eta models along the U.S. East coast. There have been no long-term verification studies of high resolution mesoscale models in this region, a place where air-sea and land-water interactions are important in the evolution of nor-easters, coastal fronts, and sea breezes. This past year we completed a more event-based verification for sea breezes and coastal precipitation. The modeling system is currently being expanded to include ensemble forecasting over the coastal region using different MM5 physical parameterizations and initializations.

## **APPROACH**

This investigation has employed the MM5 in order to investigate the physical processes of frontal and cyclone modification along the coastal zones of North America as well as air-sea interactions. The software developed to initialize a three-dimensional (3-D) baroclinic wave follows the approach of Fritsch et al. (1980) and Nuss and Anthes (1987). This technique combines trigonometric functions and meteorological balances to construct an idealized baroclinic wave with vertical structure of that typically found in the atmosphere. This method initializes a 3-D thermal and pressure wave tilting westward with height, a zonal jet stream near a tropopause, and a low-level moisture maximum in the warm sector of the temperature wave. The MM5 is nested down to 4-km grid spacing near the coast to study the frontal-terrain interaction. This work will quantify the effect of frontal orientation, prefrontal stability influence on flow blocking, and the strength of upper-level dynamics on the structure of the landfalling frontal wave and cyclone motion.

The surface roughness in operational atmospheric models such as the MM5 is parameterized using Charnock's relationship, but this does not take into account wave age and height. Changes in surface roughness by waves can affect the fluxes and the subsequent development of fronts and cyclones near the coast. These processes will be explored by coupling the real-time MM5 at Stony Brook with a wave model. First, it needs to be determined which wave model performs best along the U.S. East Coast; therefore, we are currently running both the WaveWatchIII and SWAN models in real-time and verifying the results at the offshore buoys. Using the coupled model we will explore the impact of waves on the development of a few nor-easter cyclones along the East Coast during the 2002-2003 winter.

A few case studies have been selected to better understand the impact of coastal geometry and terrain on landfalling tropical cyclones and sea breezes along the East Coast. For tropical storm Floyd (16 September 1999), the Appalachians were removed in a MM5 simulation to determine whether the terrain influenced the location and magnitude of the heavy precipitation and coastal front. Surface moisture and heat fluxes were turned off to quantify whether these diabatic processes were important in maintaining the storm as it moved rapidly up the coast. The diabatic precipitation effects were also turned off in the model to determine how much of the storm intensity was driven by dry dynamics later in the event. A few sea breezes around Long Island have been simulated down to 4 -km grid spacing to study the impact of the island geometry on the sea breeze evolution.

A real-time MM5 verification system has been set up in order to determine the benefits/problems of high resolution model forecasts along the East Coast. A 36-km horizontal resolution domain covers the eastern two-thirds of the United States and western Atlantic, a 12-km resolution nested grid extends across the Northeastern U.S., and an inner 4-km resolution grid encompasses Long Island and surrounding areas. For the past three years the MM5 forecasts have been compared with all available observations and the NCEP Eta model in order to assess model skill versus resolution across coastal New England.

## **WORK COMPLETED**

The software for the idealized baroclinic wave has been written and it is currently being tested for different domain configurations and resolutions in the MM5. The simulations so far have used somewhat coarse resolution ( $> 20$ -km grid spacing) in order to determine how the parameters can be changed systematically. For example, the background horizontal shear can influence the tilt of the baroclinic wave and front approaching the coast, and we have developed a parameter to control the prefrontal lapse rate initialized in the model.

The one-hourly wind output from the MM5 is being used to drive a 48-h wave forecast from the WavewatchIII and SWAN models along the East Coast. Software has been written to run these wave models in real-time after the MM5 forecast is finished. Time series plots are being created for the simulated versus observed wave height at the coastal buoys. These comparisons will continue through the winter of 2002-2003, and will also involve comparisons with the NCEP and Navy WavewatchIII modeling systems.

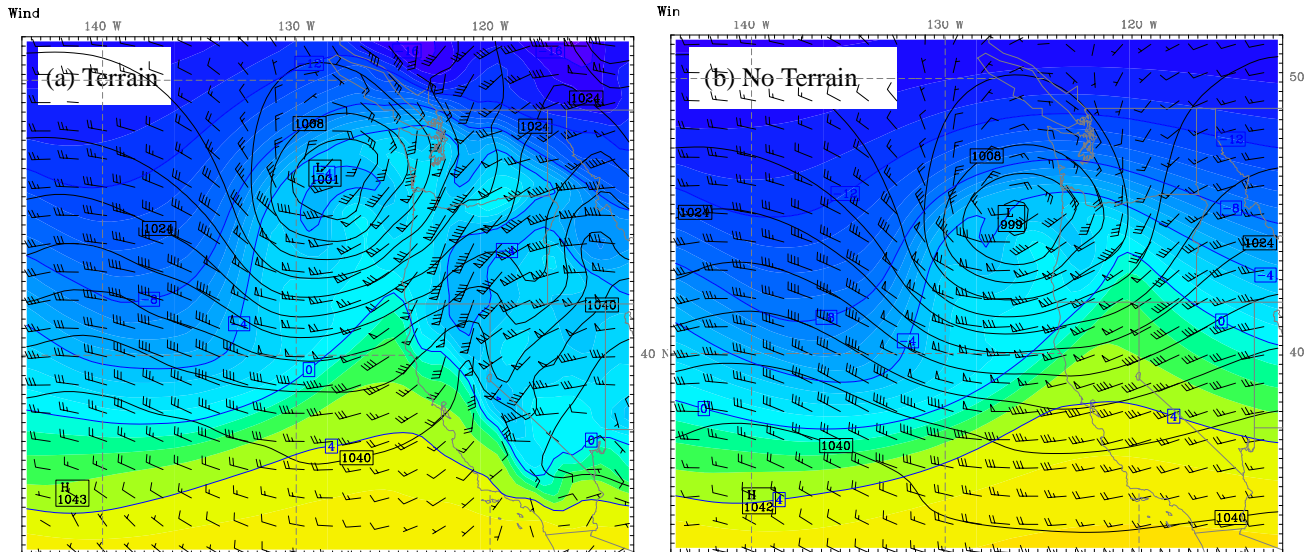
The 4- and 1.3 km MM5 simulations of hurricane Floyd along the East Coast have been objectively verified against all available Cooperative observer and National Weather Service rain gauges across the mid-Atlantic and Northeast regions. Evaluating the physical mechanisms was done by writing software to diagnose the large-scale atmospheric forcings, which includes diabatic heating output from the model. The changes in intensity of the coastal front has been quantified by completing a 3-D frontogenesis budget. The simulations involving no terrain or diabatic effects have been completed. The results are being written up for publication.

The MM5 has been run down to 4-km grid spacing for a sea breeze event across Long Island on 7 June 2001. The MM5 was initialized using the NCEP Eta grids at 30-km grid spacing. The MM5 winds have been verified using all available surface observations, radar, and sounding data. The sensitivity of the sea breeze evolution to the air-sea interactions was completed by varying the sea surface temperatures diurnally. The role of the Coriolis on the local flows was addressed by reducing the planetary rotation in the model by 50%.

The MM5 has been running in real-time twice daily down to 4-km resolution around Long Island using version 3 of the MM5 (<http://atmos.msfc.sunysb.edu/mm5rt>). Upgrading from version 2 to version 3 this past year required a complete rewrite of the automated software to initialize the model. The MM5 and Eta forecasts for the past two years have been verified using all available observations to assess model skill versus resolution across coastal New England. Spatial maps of model biases and errors have been created in the coastal zone. The MM5 has been verified for particular events, such as sea breezes for the past two warm seasons. We have compared the MM5 timing and strength of the sea breeze transitions over Long Island.

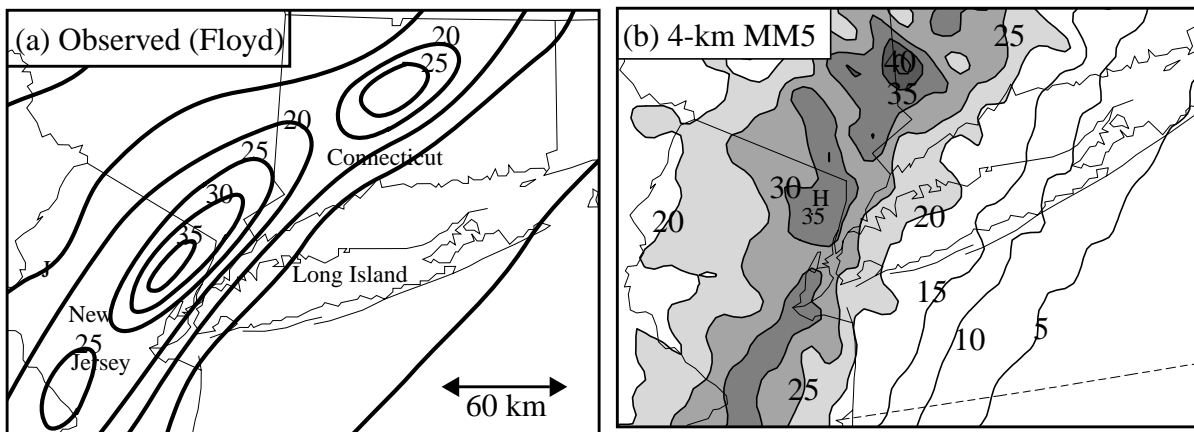
## **RESULTS**

Figure 1 suggests that our idealized baroclinic wave approach yields a stable and realistic solution for a landfalling extratropical cyclone. Even at relatively coarse resolution (54-km grid spacing), there are important differences between a simulation with terrain and another without. The topography results in a poleward deflection of the cyclone, while the low-level thermal wave propagates inland much faster in the simulation without topography. The flow is more southerly along the coast in the control simulation because of the flow deflection by terrain. Overall, these results are encouraging and suggest that the phase space of landfalling cyclones can be completed using our idealized approach at high resolution.



**Figure 1:** (a) Model surface analysis for a portion of the 54-km domain at hour 30 of an idealized simulation with terrain showing sea-level pressure (solid) every 4 mb, winds 30 m above surface (1 full barb = 10 kts), and 925-mb temperatures (blue lines and color filled) every 4 °C. (b) Same as (a) except for the no terrain (NOTER) run. [The terrain over the western U.S. has an important influence on the path and structure of a landfalling extratropical storm.]

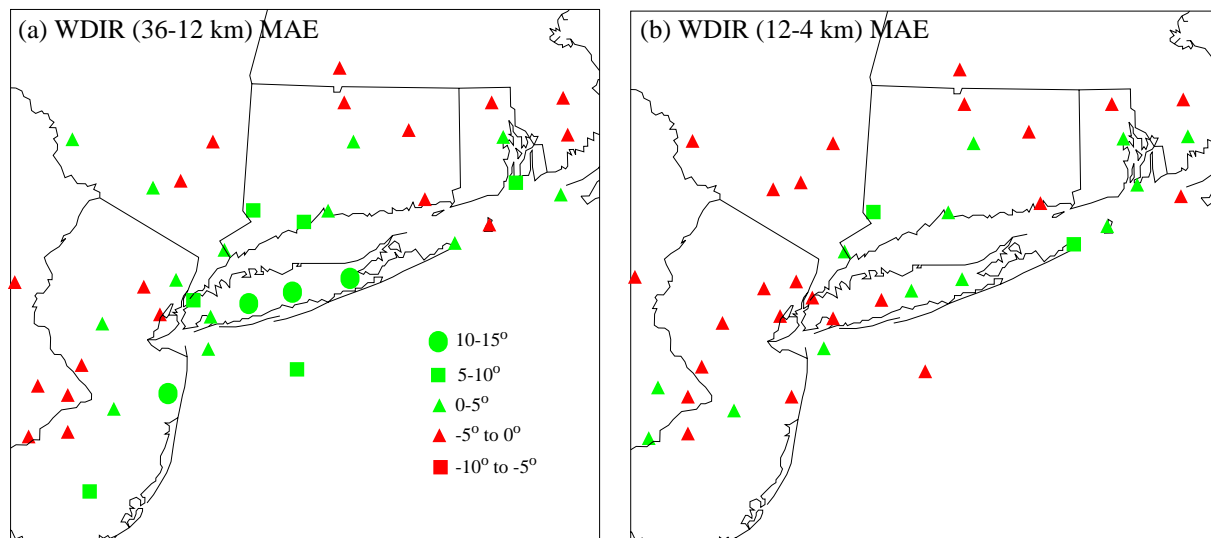
Tropical storm Floyd on 16 September 1999 was successfully simulated using the MM5, both in terms of forecast track and precipitation. Unlike the NCEP operational models, the MM5 maintained a < 985 mb tropical storm as it moved rapidly northward towards southern New England by 0000 UTC 17 September 1999 (not shown). The NCEP models only predicted 50-60% of the observed precipitation (20-35 cm) that fell over New Jersey and Connecticut between 0600 UTC 16 September and 0600 17 September 1999 (Fig. 2a). In contrast, the 4-km MM5 was able to realistically predict the heavy precipitation (Fig. 2b). The MM5 over-predicted precipitation by 20-40% in several locations. Since most of the precipitation involved warm rain processes, there was little sensitivity on the MM5 precipitation using different microphysical schemes (not shown).



**Figure 2.** Observed storm-total precipitation for tropical storm Floyd (contoured every 5 cm) derived using NWS and Cooperative observer rain gauges from 16-17 September 1999. (b) Same as (a) except for the 6-36 h forecast for a portion of the 4-km MM5 domain initialized at 0000 UTC 16 September 1999. The MM5 correctly forecast the heavy precipitation for this event, which allows us to investigate the physical mechanisms for this event.

A simulation was completed with the Appalachians in the MM5 was removed. Without the terrain the coastal front and cyclone maintained its intensity (not shown), and the precipitation was only reduced by 5-10% at 4- and 1.3-km grid spacing. Therefore, even though the precipitation maximum and coastal front was orientated along the 100-200 m Appalachian foothills of New Jersey (Fig. 1), the terrain was only a secondary effect compared to the frontogenesis forcing caused by the storm circulation acting on the larger-scale coastal baroclinic zone. Diabatic effects were also important as the storm transitions to extratropical. For example, with the surface sensible heat and moisture fluxes turned off, the storm was 5-10 mb weaker and shifted 100-200 km further east (not shown). As a result, the 1.3 km precipitation was only one-third the control simulation over the observed flooded areas. When the latent heat from precipitation was turned off, the storm was 10-20 mb weaker and did not propagate up the coast. Overall, not only is the large-scale frontogenesis forcing through deformation important in enhancing and focussing the precipitation in an intense band just inland of the coast, but diabatic effects were important in maintaining the cyclone strength as it transitions to extratropical while moving up the coast.

Since August 2002, the SWAN and WW3 wave models have been run in real-time using the 10-m MM5 winds as forcing. The wave heights are being verified at all buoys over the western Atlantic. With two months of verification from August-September 2002, the WW3 underpredicts wave heights by 0.5 m on average (not shown), with the largest errors at the coastal buoys. This problem is especially apparent during storm events with wave heights greater than 2 m. The SWAN verifies better near the coast, and the underprediction of wave height is much less. The results so far suggest that the SWAN model should be used to couple with the MM5 in order to study coastal problems. The verification dataset between SWAN and WW3 will be expanded into the winter.



**Figure 3. The difference of mean absolute wind direction errors (in degrees) of the 36-km MM5 minus the 12-km MM5 for 30 sea breeze events. The positive (green) labels indicate locations where there is greater skill with increased horizontal resolution. (b) Same as (a) except for the 12-km MM5 minus the 4-km grid spacing.**

Verification of the real-time MM5 forecasts at 36-, 12-, and 4-km resolution around Long Island has revealed some benefits and potential challenges of high resolution NWP near the coastal zone. The verification this past year has focussed on event-based verification. For the 30 sea breeze events objectively identified during the past two warm seasons, there was a significant improvement going from 36- to 12-km grid spacing (Fig. 3), but there was little additional skill going to 4-km because of timing errors and a surface temperature cool bias. Verification of the warm season precipitation events in the MM5 over the last year suggests that there is a significant improvement in the 4-km explicit precipitation using the Grell convective parameterization in the outer domains rather than Kain-Fritsch. The Kain-Fritsch warms and dries mid-levels, resulting in too little 4-km explicit precipitation.

## **IMPACT/APPLICATION**

Landfalling fronts and cyclones along the U.S. West Coast are often associated with strong winds, which are enhanced by the steep coastal topography (“barrier jet”), and heavy precipitation. This study is helping our understanding of landfalling fronts by diagnosing high resolution model simulations.

There have been limited studies using high resolution simulations to document the extratropical transition of a landfalling hurricane along the U.S. East Coast. This study successfully simulated the heavy precipitation and coastal front associated with the landfall of tropical storm Floyd. As a result, the physical mechanisms responsible for the heavy precipitation and frontogenesis are explored.

Verification of the real-time MM5 helps address the question whether increased computer resources should be spent towards running high resolution forecasts (< 10 km grid spacing) or a series of lower resolution ensemble forecasts to produce probabilistic predictions.

## **TRANSITIONS**

The real-time MM5 forecasts and verification are sent to the surrounding National Weather Service forecast offices around New York City for the forecasters to evaluate and use on a daily basis.

## **RELATED PROJECTS**

1 – Our East Coast real-time MM5 verification and ensemble effort is a natural extension of Dr. Cliff Mass’ real-time MM5 work along the West Coast, which is also sponsored by ONR.

## **SUMMARY**

The merger of a landfalling tropical storm with an upper-level short-wave trough approaching U.S. East Coast induces a deep frontogenetical circulation, which results in heavy precipitation along the coastal front. Diabatic effects are important as the storm transitions to extratropical, while the Appalachians only have a minor effect on a storm moving up the coast.

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