Final Report on COMET Partners Project

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Section 1: Summary of Project Objectives

The following is a list of proposed objectives. Description of the findings for the completed objectives is presented in Section 2B. Explanations for omitting some objectives can be found in Section 4C.

A. Objectives Completed

1. To determine the model configuration (e.g., horizontal resolution, number of vertical levels, domain size, ARW core or NMM core) that optimizes the accuracy of lake-effect snow band simulation in the eastern Great Lakes region.
2. To investigate the relationship between cloud-level wind vectors and other environmental conditions over Lake Ontario and Lake Erie and the distribution of snowfall, especially inland extent of significant accumulations.
3. To catalogue the diurnal variability of snow band intensity and structure.

B. Objectives Omitted

1. To quantify the effects of topography on snowfall enhancement downwind of the eastern Great Lakes.
2. To conduct idealized experiments in parameter space to test the sensitivity of lake-induced circulations to environmental factors.

Section 2: Project Accomplishments and Findings

This section will be divided into accomplishments related to student learning followed by accomplishments and findings related to our research objectives.

A. Accomplishments Related to Student Learning

We hired ten meteorology majors for the COMET Research Team (Table 1). Students were expected to attend bi-weekly team meetings and meet with their COMET faculty advisor when asked.

1. Lake-effect Snowstorm Case Studies

A student was assigned to each of the six lake-effect snowstorms (Table 2) chosen for the model evaluation. During the fall semester, these students prepared a synoptic overview for their storm, a mesoscale summary including snowfall distribution and impacts on the public, and an indication of

WRF (Weather Research and Forecasting) model performance. The students presented their findings at a team meeting early in the spring semester. As a result the students increased their understanding of lake-effect snowstorm evolution and behavior and gained confidence in preparing and delivering an oral presentation with graphics.

2. Running the WRF Model

Students learned how to set up the WRF model, provided on DVD by our Partner at NWS Buffalo, on a domain covering the eastern Great Lake (see Fig. 1) for a variety of grid resolutions. They were shown how to prepare initial data and boundary conditions for the WRF from gridded NAM (North American Mesoscale) model data downloaded from the National Climatic Data Center (NCDC). They learned how to run lake-effect snowstorm simulations out to 36 hours for a given set of physical parameterizations. They also learned how to run the post-processing steps to convert WRF output to GEMPAK format so that model results could be displayed using GARP. Since students needed a way to access model output and radar data, Dr. Skubis created individual directories for each case on our server for students to do their analysis of model performance. They had the opportunity to manage very large datasets under the Linux framework.

3. Model Evaluation

In order to determine how horizontal and vertical resolution affects WRF performance in the simulation of our lake-effect snow bands, we developed an Excel 'scoring' spread sheet to compute the model errors in several categories: snow band location, width, intensity, orientation, terminal point, curvature, onset time, offset time, and connection with Lake Huron. Students were instructed on how to enter radar observations and model output in a systematic manner for the purpose of determining model performance for a series of fourteen experiments (Table 3).

One student researcher was assigned to each of our six lake-effect events. The students entered composite reflectivity data simulated by WRF into a 'raw data' spread sheet for at least 10 hours of particular interest during their 36-hour simulations. Composite reflectivity data (from KBUF for the Lake Erie cases and KTYX for the Lake Ontario cases) were entered for comparison at the times closest to the selected WRF hours. WRF simulated reflectivity data were entered in the spread sheet for each of the fourteen experiments. Once all of the experiments were run and results entered in the raw spread sheets, 'scoring' spread sheets were prepared separately for the Lake Erie cases and the Lake Ontario cases. For each of the error categories (e.g., location error, intensity error, etc.), a population mean (error scale) was computed for each lake as the average of the absolute errors for all hours (typically 10 to 12), all experiments (e.g., N10L31, N8L31, etc.) and all cases (3 for each lake). This project enabled students to increase their understanding of numerical modeling as well as the strengths and limitations of mesoscale models in lake-effect snow simulation.

4. Analysis of Radar Data

Since the radar measures reflectivity on conical surfaces, observations at distances farther from the radar represent dBZ values at elevations higher above the ground. Our students had to take this into consideration as lake-effect snow clouds are quite shallow (2-4 km) and the radar beams typically overshoot the core of the storm at ranges greater than about150 km. Hence, it is likely that the radar will underestimate the inland extent of distant snow bands. We decided the best strategy was to use composite reflectivity instead of base reflectivity at 0.5^{o} elevation angle. Although this allows us to better capture band structure and intensity near the radar, it does not address the overshooting problem. Students learned to avoid using single pixels to define regions of maximum reflectivity. Instead, they were asked to use reflectivity "clusters" of pixels which helped to resolve ground clutter issues. Overall, students learned to view radar reflectivity data with caution with respect to radar reflectivity and snowfall distribution.

5. Aphid Rain-to-Snow Study

One of the most spectacular and destructive lake-effect storms in decades occurred 12-13 October 2006 near Buffalo, NY (see www.erh.noaa.gov/buf/storm101206.html for details). One of our COMET student researchers, Nick Camizzi, carried out a study of why rain changed to snow. He concluded that a combination of melting of snow flakes in the lowest kilometer above the ground and the advection of drier air from the southwest into the region of heaviest precipitation contributed to cooling of the lower atmosphere sufficiently to change rain to snow. Nick found that the changeover occurred despite lake temperatures averaging 16°C in part because the heated air over Lake Erie was mixed to unusually high elevations. Therefore, near surface air temperatures remained only a few degrees above freezing. Nick presented his results at the 32nd Northeast Storms Conference (see http://apollo.lsc.vsc.edu/ams/AMS%20VP/Storm%20Conference/NESC%20Presentations/32ndNESC_Presentation/32ndNESCPresentations.html)

6. Snow Survey at Redfield, NY

Faculty and several student researchers from the COMET team traveled to Redfield, NY (35 miles east-northeast of Oswego) shortly after the prolonged 'Locust' storm (3-12 February 2007) dumped over 350 cm of snow in the area. Students measured the mass of the 157 cm (62 in.) snow pack in sampling tubes at several locations and found water equivalents in the range of 23 to 30 cm (9 to 12 in.). Analysis by the students of samples taken at various depths revealed that the snow/water ratio decreased for samples closer to the ground. Students learned correct snow sampling techniques.

B. Accomplishments and Findings Related to Research Objectives

1. Research Objective 1: WRF Performance Versus Grid Resolution and Domain Size

As outlined in our proposal, we evaluated WRF accuracy in simulating lake-effect snow bands for four horizontal grid spacings: 4-km, 6-km, 8-km and 10-km covering the domain in Fig. 1. In eight of the 14 experiments (Table 3), 31 model layers were used. For the 6-km and 8-km simulations, we also ran WRF with 25 and 37 layers for the ARW core and 37 layers with the NMM core to evaluate the effect of vertical resolution. It was not possible to run NMM at 25 or 27 layers with the WRF version provided by NWS Buffalo. Following the suggestion of Koch et al. (2005), errors for each experiment were based on the difference between observed radar *composite* reflectivity and the *composite* reflectivity simulated by WRF. For example, the location error at the fixed longitudes (Fig. 1) was computed as the difference in latitude of the center of the observed band and the center of the simulated band at the same hour multiplied by 111.1 to convert the error to kilometers. A comparison of specifications of the NMM and ARW cores used in this study is given in Table 4.

As planned, we identified the experiment using the NMM core of WRF at 31 layers with 6-km resolution (abbreviated N6L31) as the 'Control' experiment since this is the operational configuration in use at NWS Buffalo. One of our primary objectives was to determine how the accuracy of the Control experiment compares with other configurations in simulating snow band location, width, orientation, intensity, terminal point and curvature. The 'final score' for each experiment is a weighted average of non-dimensional errors (averaged over the selected hours for each run) of the categories above.

The individual categories are evaluated by comparing the simulated composite reflectivity and the NEXRAD composite reflectivity using the following considerations:

Location:	Latitudes where the major band axis crosses each of the three fixed longitudes.
Width:	The 20 dBZ extent perpendicular to the major band axis evaluated at the three fixed longitudes and the location of maximum intensity.
Orientation:	The locations along the major band axis at the two end points of the fixed longitudes.
Intensity:	The maximum intensity (dBZ) along each of the fixed longitudes and the intensity at the location of greatest reflectivity. Students were instructed to ignore small clusters of only a few pixels of greatest reflectivity which tended to occur more often in the NEXRAD imagery.
Terminal point:	The downstream point where the area of coherent main band reflectivities greater than 20 dBZ terminate.
Curvature:	The latitudes of the major band axis at the three fixed longitudes.

We had planned to include onset time, offset time, and connection with Lake Huron in the final error calculation, and students were asked to record this information in the spread sheets for each experiment. Since many of the snow bands (both observed and simulated) persisted beyond the 36-hour limit of the simulations, we decided to eliminate offset time in the 'final' score. Because of uncertainty in identifying onset time with the simulated and observed bands, we also decided to drop onset time in the 'final score'. For connection with a snow band downwind of Lake Huron, we asked students to enter a '0' for hours where there was no indication of a connection, a '1' for a possible connection, and '2' for a definite connection. We found that it was difficult to identify a connection using the Buffalo radar. However, so that our forecast partners can compare the results with onset time, offset time and Huron connection included, we added a 'total' score column on the right side of the Category Error spread sheet (see Table 5 for example). The last column in Table 5 shows the run time for each experiment using a Dell 620 Optiplex computer with two Intel Pentium Four processors and 1 Gbyte of RAM. Each processor has a clock speed of 3.20 GHz and 2.048 MB cache. In the Linux estimated performance system, each processor is rated at 6390 'bogomips'.

a. WRF Performance Versus Horizontal Resolution

i. Absolute Error

The total score (TS) for an experiment such as the control run (N6L31) is defined as

$$TS = \sum_{i=1}^{9} w_i \frac{c_i}{s_i} \quad \text{where} \quad \sum_{i=1}^{9} w_i = 1$$

where c_i is the absolute error, $|r_i - m_i|$, of the ith category averaged over all hours for all cases, i.e., $c_i = \overline{|r_i - m_i|}^{\,n\ \text{times}}$. The quantity r_i is the radar value, m_i is the corresponding model value, and w_i is the weight for each category, as shown in Table 5, Row 4. s_i is the error scale (population mean) for the i^{th} category defined as the average of the absolute errors for all cases, all experiments and all hours. A category score (c_i/s_i) equal to 1 represents a category error equal to the error scale s_i. A score less (greater) than 1 represents a model performance better (worse) than average. See Appendix B for the computation of the 'final' score FS computed by omitting the categories onset time, offset time, and Huron connection for which our confidence in the accuracy of the error values is lower.

In consultation with our NWS Partner, we weighted the category errors according to importance to forecasters in determining a final 'score' for each model experiment (Table 3). Not surprisingly, snow band location is given the highest weight. The error in location of the simulated snow band is computed as the average distance between the center of the simulated band and the center of the band shown by radar at the same time at three fixed longitudes (see Fig. 1). When we considered the lakes separately, we decided to use separate set of error scales for each lake based on all the errors for each category for just that lake. The error scales for Lake Erie are listed in Row 3 of Table 6, while the error scales for Lake Ontario are listed in Row 3 of Table 7. For each lake, the error scale for each category is the average of at least 420 error values (3 events, 14 experiments, and at least 10 hours).

Originally, we planned to include in the calculation of location error the distances between the model and radar bands at the initial point and terminal point (see Fig. 1). However, we found large 'errors' at these locations in the spread sheets. Since we have more confidence in the snow band position at locations closer to the radars (i.e., three fixed longitudes), we decided to compare model performance in band location just at the fixed longitudes. Errors at the western-most fixed longitude for Lake Erie (orange line in Fig. 1) were not included in the average location error to maintain consistency with the Lake Ontario calculation using only three fixed longitudes.

As an example, consider the final score (0.94 in Table 5, Row labeled by N6L31) for the Control Run. This value is the sum of the weighted, normalized category errors in the N6L31 Row. Each category is normalized by the error scale (population mean for all six cases) for that category shown in Row 3. As proposed, the normalized score for the Control Run is used as a standard by which all other experiments are compared.

Comparing the fourteen experiments for all six cases (see Table 5), N8L31 had the smallest (best) location error (15.65 km averaged over all hours, all three fixed longitudes for all cases) followed by the Control Run at 15.67 km. The worst performer A10L31 had an average location error of 24.04 km. Near the bottom of Table 5, we see that the average error for all NMM runs (16.17 km) was significantly better than the average error (23.09 km) for the 31-layer and 37-layer ARW runs. This is an important finding. For our six cases, NMM clearly outperformed ARW in respect to location. Comparing the six experiments in common (31-layer and 37-layer runs), the average location error for all NMM runs (16.17 km) is nearly 6-km better than the average of all comparable ARW runs. It is somewhat surprising that N4L31 was the worst performer for location of the NMM runs. This suggests that going to 4-km horizontal resolution does not result in a more accurate simulation even though the 4-km runs have about a six-fold longer runtime compared to the 8-km runs. With the ARW simulations, there is a slight improvement in going to 4-km resolution, but the runtime (17.1 hours) is excessively large.

With respect to average width error, A6L31 had the lowest value (8.06 km) compared to 13.91 km for the Control Run. The average ARW error for width (9.30 km) is significantly less than the average NMM width error (14.27 km). Apparently, ARW produces a somewhat more realistic snow band than NMM, but the NMM band is, on average, closer to the observed location.

NMM was somewhat better than ARW for average orientation error (8.08 versus 9.92 degrees) and the Control experiment (7.46 degrees) scored best overall. NMM was also a little better with intensity error (6.17 dBZ versus 6.94 dBZ for ARW) with N4L31 best and the Control second best.

It appears that WRF did not perform well in simulating the terminal point (distance inland from the shoreline of the 20 dBZ contour). The average error for all experiments was 61.15 km. Since the radar beam occasionally overshoots the most intense portion of the snow band, there is some uncertainty in establishing the true position of the terminal point. Nevertheless, it is surprising that the simulated terminal point errors are so large.

There was no significant difference in curvature error for ARW versus NMM. NMM was a little better with offset error while ARW was a little better with onset error. ARW was considerably better with Huron connection.

The final score (non-dimensional weighted average of the main category errors) was lowest (0.94) for N6L37 and the Control Run, but N8L31 (0.98) a close second. A6L31, best of the ARW runs, scored 1.01. This suggests that if a forecaster wishes to use the NMM core, there might be more to gain by running with 8-km resolution with its shorter runtime than by increasing the number of levels. All ARW runs had a larger (worse) final score than the corresponding NMM runs. The greatest advantage with NMM was smaller location error.

For the Lake Erie spread sheet (Table 6), the scales for category errors were computed using data only from the three Lake Erie storms. N8L31 again was the best performer in location with an average error of 18.31 km. Location errors were larger for all experiments as compared to errors for all cases combined (Table 5). A10L31 had the largest location error (29.63 km). ARW had much smaller errors in width with A6L31 performing best (6.92 km). NMM width errors were significantly greater for all experiments, but the N8L31 runs had the lowest error among the NMM group. The N8L31 runs also did very well with intensity errors although the N4L31 had the lowest intensity error.

For the Lake Ontario spread sheet (Table 7), the scales for category errors were computed using data only from the three Lake Ontario storms. N6L31 had the lowest average location error (12.59 km) and A6L31 had the lowest average width error of 9.21 km. Location errors were smaller for all the Lake Ontario experiments as compared to errors for all cases combined. This suggests that WRF has less of a problem simulating snow band location for Lake Ontario than it does for Lake Erie. As with the Lake Erie spread sheet, the NMM location errors (average 13.00 km) are smaller than ARW errors (18.67 km for the comparable vertical resolutions). ARW outperformed NMM in width for both lakes, but the width advantage with ARW was greater for the Lake Erie cases. NMM outperformed ARW with location for both lakes, but the location advantage with NMM was greater for the Lake Erie cases.

While NMM had a lower final score than ARW for all comparable experiments, the Control Runs had the lowest final score for all Lake Ontario cases. Results for width errors were similar to the Lake Erie results with ARW (average 9.75 km) outperforming NMM (average 13.87 km). Little difference was found with orientation and intensity errors and, as with the Lake Erie cases, N4L31 had the lowest intensity error.

The main category errors and the final score, averaged separately for all 31-layer NMM and ARW runs, are summarized in a bar graph (Fig. 2a). For the Lake Erie cases, the final score for the NMM runs (0.92) is somewhat lower (better) than the score (1.08) for ARW runs. The normalized location error (judged to be the most important by forecasters at NWS Buffalo) was significantly lower for the NMM runs (0.87 versus 1.13 for ARW). NMM also did much better with snow band orientation and slightly better with intensity and curvature. ARW was significantly better in simulating snow band width and slightly better in distance of terminal point from the shoreline.

For the Lake Ontario cases, we see from Fig. 2b that NMM has a slightly better final score (0.97) versus ARW (1.03) for the 31-layer runs. NMM is much better in snow band location (0.82 versus 1.18 for ARW), but only slightly better in orientation and intensity. As with the Lake Erie cases, ARW scored significantly better with snow band width. Little difference was found in the other categories.

The absolute errors for location, width, orientation and intensity are compared for the 31 and 37 layer ARW and NMM runs against the error scales for all Lake Erie cases in Fig. 3a. A similar comparison is shown in Fig. 3b for the Lake Ontario cases. As before, we see that NMM outperforms ARW in location for both lakes and that the absolute errors in location tend to be larger with the Lake Erie cases (average error 21.8 km) versus 15.8 km for the Lake Ontario cases. ARW outperforms NMM for width for both lakes. NMM has less error in orientation than ARW for Lake Erie, but the difference is negligible for Lake Ontario. NMM is slightly better with intensity for both lakes.

ii. Model Bias

Since WRF will be used to help predict the location, width and intensity of lake-effect snow bands, it is useful to identify any systematic biases of the model. We define a bias as the signed difference between the simulated value and the corresponding value measured from the radar data at the same hour (see Appendix A). A negative (positive) bias represents a smaller (larger) model value compared to the radar value. Biases for specific categories can be interpreted as follows:

location: A negative (positive) bias means that the model band is too far south (north)
width: A negative (positive) bias means that the model band is too narrow (wide)
orientation: A negative (positive) bias means that the model band is rotated counterclockwise (clockwise) relative to the radar band
intensity: A negative (positive) bias means that the model band is less (more) intense than the radar band
curvature: A negative (positive) bias means that the model band is curved more (less) counterclockwise or less (more) clockwise.

From the spread sheet in Table 8, we can compare the average WRF bias for several categories for each experiment. For location, there is a negative bias (model latitude less than radar latitude) at the fixed longitudes on average for all experiments. This means that WRF has a distinct 'south' bias. *This is especially pronounced for the ARW runs where the average bias (-18.66 km) is nearly three times larger than the average bias (-6.33 km) for the NMM runs*. The fact the bias for ARW is nearly as large as the average absolute error (23.09 km) suggests that there is a high probability that an ARW run will produce a simulated band too far south (on average by about 19 km). The average bias for NMM is much smaller than the average absolute error (16.17 km). This indicates that NMM also tends to produce a south bias (for example, see Fig. 4 for lake-effect snow event Bengal), but the trend is less consistent. The N8L31 runs had the smallest average bias (-3.14 km).

For width, it is clear that NMM produces a band that is wider than the band indicated by radar. Not surprisingly the error increases with grid size, but the Control Run (on average) produces bands that are nearly 10 km wider than observed with radar at the fixed longitudes. The width biases for the ARW runs are much smaller, but negative for all experiments. There is a tendency for ARW to produce bands that are slightly too focused even with coarse resolution. Although this might be an advantage, it is offset by the larger location error with ARW bands (Table 5).

With orientation (slope of the snow band axis), ARW had a positive bias for all experiments. A positive bias in this case means that the axis of the model band is rotated clockwise relative to the radar band. With NMM the biases were smaller. The larger positive orientation bias on average with ARW may be responsible for the larger south bias with ARW at the easternmost fixed longitude.

ARW and NMM have a negative bias for intensity for all experiments, but the bias is greater with ARW for all horizontal resolutions. Not surprisingly, the underestimation of intensity increases with grid spacing for both WRF cores. However, with NMM, there is only slight improvement in going from 8-km to 6-km resolution.

The biases for the Lake Erie cases are summarized in Table 9. ARW has large negative (south) bias for all experiments averaging -25.7 km. NMM also has a negative bias for all experiments, but the magnitude is only about half as large. As with the composite for all cases, NMM has a positive width bias averaging about 10.6 km. There is no significant width bias with the ARW runs. Both cores have a negative intensity bias for all experiments, but it is somewhat greater with ARW. The non-dimensional biases for ARW versus NMM for several categories with the Lake Erie cases are compared in a bar graph (Fig. 5a).

The Lake Ontario biases are summarized in Table 10. ARW has a much larger negative (south) bias than NMM for all comparable experiments, but the ARW biases are less than half as large as they are for the Lake Erie cases. For the Lake Ontario cases chosen in this study, NMM does not have a consistent location bias. The NMM width biases for Lake Ontario are similar to those with the Lake Erie cases and about the same magnitude of about 10 km. Intensity negative biases for Lake Ontario are fairly similar to the biases for all cases. However, the Control and N4L31 biases are smaller in magnitude. The non-dimensional biases for ARW versus NMM for several categories with the Lake Ontario cases are compared in a bar graph (Fig. 5b).

The advantage with NMM in simulating snow band location is supported by the time-averaged band locations shown in Fig. 6 for the Lake Erie cases and Fig. 7 for the Lake Ontario cases. On average, the bands simulated using NMM for the Lake Erie cases and for Lake Ontario cases Junebug and Egyptianmau are closer to the time-averaged radar band than are the bands simulated by ARW.

Finally, the effect of horizontal resolution on simulated snow band intensity is shown for all NMM cases versus all ARW cases in Fig. 8. In general, intensity errors increased as grid size was increased from 4 km to 10 km. The effect is more apparent with the Lake Ontario cases ($R^2 = 0.6789$) than with the Lake Erie cases ($R^2 = 0.4783$). However, for the Lake Erie Bengal and Banana NMM runs and the Lake Ontario Junebug ARW run, the intensity errors decreased in going from 6-km to 8-km resolution.

b. WRF Performance Versus Vertical Resolution

Since we were unable to run NMM with fewer than 31 levels, we shall compare runs using 25, 31 and 37 levels for the ARW runs only. As shown in Fig. 9, there is very little improvement in average ARW errors for location, width, orientation, or intensity in going from 25 to 31 levels, or in going from 31 to 37 levels. Similarly, there was very little improvement in NMM performance in going from 31 to 37 levels.

c. WRF Performance Versus Domain Size

To determine if there is an advantage in running WRF on an expanded domain covering the entire Great Lakes region, we made two simulations of the intense snowstorm of 4-5 February 2007 (Locust, Day 2). Locust was a 10-day long event that deposited up to 141" (358 cm) of snow downwind of Lake Ontario. The first experiment N8L31 was run on the 8-km, 31 layer domain of 155 x 121 grid points described in Table 3. The second experiment, we'll call it G8L31, was run on a 253 x 175 grid point NMM domain covering the entire Great Lakes region. We compared the performance of the two simulations during a 30-hour period during which this very intense band moved slowly southward from Jefferson County to Onondaga County. The location error for G8L31, averaged over the 12 hours selected for scoring, was only 4.46 km while the average location error for the N8L31 run was 5.23 km (e.g., see Fig. 10 for simulated radar versus observed at 0600 UTC). Both values are well below the population mean of 16.34 km for our other Lake Ontario cases. N8L31 was slightly better with average width error (7.18 km versus 7.47 km for G8L31). Both of these values are well below the population mean error for width (11.62 km). N8L31 was also slightly better with average intensity error (2.92 dBZ versus 3.08 dBZ for G8L31), while G8L31 was somewhat better for average orientation error (3.88 degrees versus 4.51 degrees for N8L31). Both runs were very good, but the G8L31 simulation was marginally better. A modified final score, taking into account only location, width, orientation and intensity, gave 0.281 for G8L31 versus 0.295 for N8L31. Based on this one case, it is hard to justify expanding the domain currently in use at NWS Buffalo. Further research with additional cases will be conducted to determine if there is an advantage in using the domain covering the entire Great Lakes.

2. Research Objective 2: Factors Controlling Inland Extent of Snow Bands

We looked at six basic influences on how far the 20 dBZ reflectivity contour extends inland from the shoreline – wind speed, wind direction, wind shear, temperature, and temperature difference, and snow band width. Since we wanted to include data from the prolonged Locust event (3-12 February 2007), we used only data from Lake Ontario. Inland extent was estimated separately using the 20 dBZ contour from the observed composite reflectivity and the composite reflectivity simulated by the WRF Control Run at times when the model performed reasonably well. A summary of correlations between inland extent and the factors below is provided in Table 11.

a. Correlation with Wind Speed

i. Inland Extent Estimated from KTYX Composite Reflectivity

Scatter plots relating the inland extent (km) of the 20 dBZ contour to wind speed (m/s) were generated at levels 900, 850, 800, 750 and 700 hPa. Positive correlations were found at all levels, but the greatest correlation ($R^2 = 0.3854$) was found at 750 mb (Fig. 11a). For 750 mb wind speeds near 25 m/s, there is a lot of scatter in the inland extent ranging from 70 to 185 km. This suggests that the correlation with wind speed is rather weak for high wind speed. It is also possible that the 0.5 radar beam overshot the 20 dBZ reflectivity core at large inland distances which would lead to an underestimate of the inland extent.

ii. Inland Extent Estimated from Simulated Composite Reflectivity

When the simulated radar is used to estimate inland extent of the 20 dBZ contour, a positive correlation is found at all levels, but this time the highest correlation (0.491) is at 850 mb (Fig. 11b). However, there is still a lot of scatter in the data indicating a weak relationship. Although the simulated reflectivity (computed from the hydrometeor distribution) is not subject to the overshooting problem, there is a limit because the eastern boundary of the model domain is only about 120 km inland from the easternmost shoreline of Lake Ontario. Therefore, the inland extent is likely to be underestimated for snow bands that form directly east of the lake during periods of strong winds.

b. Correlation with Wind Direction

From the scatter plot in Fig. 12, we see a weak negative correlation between radar-estimated inland extent and meteorological wind direction at 900 hPa. The largest inland extent is found with winds between 260 and 265 degrees corresponding to bands forming parallel to the long axis of Lake Ontario. Smaller inland extent is evident with wind directions in the 290-305 range.

When simulated radar is used, there appears to be no correlation with wind direction. The large scatter may be related to the greater limitation of the domain directly east of the lake as compared to areas northeast and southeast of the lake.

c. Correlation with Speed Shear

We define wind shear as the wind speed at 700 mb minus the wind speed at 900 mb. We found that there does not appear to be any significant correlation between wind shear and inland extent.

d. Correlation with Temperature

i. Inland Extent Estimated from KTYX Composite Reflectivity

We found that there is only a slight positive correlation between lake temperature and inland extent. We would need a larger range of lake temperatures to determine if there is a significant correlation.

There appears to be a weak negative correlation between air temperature and inland extent. This relationship, which is greatest at 700 mb, suggests that the colder the air is over the lake (e.g., at 700 hPa), the farther inland the snow band extends. This may be related to a larger fraction of lighter ice particles with colder temperature and more heavy particles (e.g., graupel) with warmer temperatures that fall out closer to the lakeshore.

ii. Inland Extent Estimated from Simulated Composite Reflectivity

The results are qualitatively similar when simulated radar is used to estimate inland extent except that the correlation coefficients are even smaller.

e. Correlation with Temperature Difference from KTYX Composite Reflectivity

We found a only a slight positive correlation between inland extent and lake-air temperature. The correlation was greatest for the lake minus 700 hPa temperature difference.

There appears to be a small positive correlation between inland extent and vertical temperature gradient averaged over and downwind of Lake Ontario. The correlation ($R^2 = 0.2237$) is greatest for the 900 hPa-to-700 hPa temperature gradient (Fig. 13a). The correlation is smaller but still positive with temperature gradient upwind of Lake Ontario (Fig. 13b)

3. Research Objective 3: Diurnal Variation of Snow Band Structure and Intensity

In order to examine the diurnal cycle of lake-effect snow, students Meredith Mandel and Matt Souders selected 17 cases representing months from October to April. Four cases were rejected, as being too weak or because of missing data, leaving 13 cases (see Table 12).

The students grouped snow bands into the five categories described below:

0: Limited Activity
- **i.** No reflectivity in excess of 20 dBZ at at least four contiguous points, and
- **ii.** No coherent pattern to the precipitation

1: Cellular Convection or Isolated Patches of Precipitation
- **i.** Intense (greater than 20 dBZ) reflectivity in multiple locations
- **ii.** No coherent pattern to the precipitation

2: Heavily Broken Bands or Multiple Bands of Limited Size
- **i.** A coherent "banded" region inside of which patches of precipitation form
- **ii.** The banded region could either be swath containing multiple bands or a single "band" that is heavily broken into a disorganized scatter

3: Regional Precipitation (often seen in marginal environments with orographic forcing or in gapped or ragged single bands or intense multiple bands)
- **i.** The region may take the form of
  - **a.** A patch or blob of continuous (or nearly continuous) high reflectivity values
  - **b.** A ragged or wavy single band with small gaps but a well defined boundary

c. A swatch of intense multiple bands that form an area that is nearly covered with precipitation

ii. The region must be nearly covered with precipitation in excess of 20 DBZ, and small gaps must be narrower than 20 km across and few in number

4: Coherent Single Band

i. Intense, well defined single band with no gaps in the 20 DBZ contour in excess of 5 km

ii. Waves and ripples should be minimal

iii. Band should not be competing with nearby convection since the sinking motion with a well-organized band should inhibit convective activity in the surroundings

KTYX base reflectivity was analyzed every half hour during active periods for all 13 cases. The number of radar samples ranged between 28 and 40 per hour. Using the rules listed above, Matt Souders determined the mode for each sample. The probability of each mode was then determined for each hour. The hourly distribution of the intense modes (3 and 4) and the weak modes (0 and 1) is plotted in Fig. 14. Since the probability of all modes sums to 1.00, the probability of the intense modes at any hour tends to increase as the weak modes decreases.

It is interesting that the probability of an intense mode peaks in the period 0000 UTC to 0400 UTC (7:00 PM to 11:00 PM local time), decreases to a minimum at 1000 UTC (5:00 AM EST), and reaches a secondary maximum between 1200 UTC and 1400 UTC (7:00 AM to 9:00 AM EST) before decreasing again to a secondary minimum at 1700 UTC (noon local time). This is in contrast with the results of Kristovich and Spinar (2005) who found a distinct morning maximum and afternoon/evening minimum in precipitation frequency for the western Great Lakes.

To determine if there is a seasonal influence on the diurnal cycle, the cases were divided into a 'core of winter' group (cases Banana, Date, Junebug, Locust I, Locust II, and Javanese) and an 'edge of winter' group (cases Aphid, Bengal, Caterpillar, Earwig, Egyptianmau, Honeydew, and Nematode). The hourly distribution of mean convective mode for each group is shown in Fig.15. The edge group (dashed line) shows the greatest diurnal variability with higher modes peaking at 3.3 between 0200 UTC and 0300 UTC followed by a rapid drop off to 1.6 at 1000 UTC followed by a secondary maximum at 2100 UTC. Comparison with the all cases plot (solid line) suggests that there is a stronger diurnal signal in the early and late seasons than during the core of winter months.

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

As the WRF model was relatively new in 2006, the National Weather Service Forecast Office in Buffalo, NY (NWS BUF) didn't know how well the WRF would handle mesoscale winter lake-effect snowstorms. In particular, we were curious to see the differences between the NMM and ARW cores. In addition to having a new model with a variety of configurable options, the simulated reflectivity output that is available in the WRF is also a new field available to forecasters. This is a field that we have not used operationally in winter seasons thus far.

As NWS BUF primarily works with the forecasting and eventual short term issues of evolving weather, we do not always have the time to run simulations for past weather events. Therefore, this project was well suited for a nearby university with interests in local modeling. Our Partner, SUNY Oswego, has a faculty and student body well suited to this project. The college ran several simulations on past events to determine the sensitivity of the model during the project.

When comparing WRF cores, we now know that the ARW core may have a more realistic look and feel in terms of width of the snow band, but as for location, we might be better off using the NMM core as a starting point for pin-pointing the areas most likely to be under a heavy snow band.

We also understand that the simulated reflectivity may be slightly underdone in terms of intensity for our horizontal resolution and overdone in terms of width using the NMM. This information, along with the knowledge that the models continue to have a 'south bias' will be helpful for forecasting future lake-effect events.

This project has confirmed that NWS BUF is using a well configured locally run WRF model using the NMM core, 31 layers, and a horizontal grid spacing of 6-km. With the results noted in Section 2, the office will consider decreasing the resolution to 8-km during the winter season in order to improve run-time with only a subtle increase in the potential error of lake band location.

While this project was ongoing, several NWS offices got together and began preparations for creating a local WRF ensemble, with one member of the ensemble being produced at each NWS office. This project is being led by the NWS office in Binghamton, NY. In order for such an ensemble to work, two items had to be identical across all participating NWS offices. First, the offices had to run their respective model using the same relatively large model domain in order to encompass all participating NWS office forecast areas. Second, each office had to use the same model resolution. Due to computer resources and the large domain, we found that we could only use a relatively coarse 12-km resolution, the same resolution as the operational NCEP output.

Initially, we were concerned about the resolution. However, our Partner at SUNY Oswego demonstrated that a local 12-km WRF model using nearly the same configuration as the operational NCEP version could result in different solutions. This is due to the fact that the NCEP version has a significant amount of smoothing applied over several model fields. Our Partner also noted that a 12-km model would take about one eighth as long as a 6-km model to run.

Section 4: Benefits and Lessons Learned: University Partner Perspective

A. Benefits to the University Resulting from the Collaboration

This Partners project was of great benefit to students and faculty at SUNY Oswego. From case studies and discussions during COMET team meetings, the students learned more about lake-effect snowstorm behavior. With the help of Mr. Fred Pierce, Information Technology Officer at NWS Buffalo, faculty and students learned how to set up the Weather Research and Forecasting (WRF) model on any domain, how to acquire initial and boundary data for the model, how to configure the model for a particular simulation, how to run the model, and how to post-process WRF output for display using GEMPAK. The students learned about the strengths and limitations of using a sophisticated mesoscale model to simulate lake-effect snowstorms, and they learned about the limitations of using observed reflectivity data to validate model predictions of snow band location, width and intensity. For example, the radar beam often overshoots the most intense part of the band at large distances from the antenna. As part of this research, students learned how to use Microsoft Excel to evaluate the accuracy of WRF for several different model configurations. They had to plot observed and simulated radar reflectivity using GARP and enter results into formula-driven spread sheets. They learned how to organize a large number of spread sheets and other datasets including some GEMPAK files larger than 2 GBytes in both the Windows and Linux computing environments.

Students benefited from interaction with David Zaff, the Science and Operations Officer at NWS Buffalo. In November 2006, Mr. Zaff made a presentation at SUNY Oswego on a New England winter storm using the Weather Event Simulator (WES). Students learned about the challenges of predicting freezing rain in western New England as well as the advantages of working in the AWIPS environment. Mr. Zaff made himself available by telephone and by e-mail to assist Dr. Scott Steiger, and others in learning how to use WES effectively in the classroom. This enabled Dr. Steiger to use WES during his 'Storm Observation and Forecasting' class in May 2007. Mr. Zaff and other forecasters at NWS Buffalo helped us decide the weights to use for the error categories in evaluation of WRF simulations. During his visits to Oswego in November 2006 and March 2007, Mr. Zaff spoke individually to students about careers in the National Weather Service. In his March visit, he provided insight to several students and professors on the methodology for scoring WRF simulations.

B. Significant Lessons Learned During the Study

We learned the following from this research:

1. There are major limitations in using WRF (and perhaps any mesoscale model) in simulating some aspects of lake-effect snow band behavior. Although the accuracy of WRF in predicting the timing, location and relative intensity of snow bands was fairly good, the model appears to have a persistent 'south' bias in simulating snow band location. This was most apparent when we used the ARW core for our Lake Erie simulations. For both lakes, the model did a poor job in predicting the terminal point (i.e., the inland extent of significant snow).
2. Although the NMM core was generally better in predicting snow band location, it tended to produce a snow band that was considerably wider than the band observed on radar.
3. The NMM simulations using 8-km resolution were on average nearly as accurate as the simulations using 6-km resolution. As compared to the Control (N6L31), the runtime with the 8-km, 31-level configuration (N8L31) is only slightly more than half the runtime of the Control. There may be a benefit in switching from N6L31 to N8L31 for a user who needs to have model output available within a certain time limit, but does not want to sacrifice much model accuracy.
4. There appears to be no significant improvement in accuracy by increasing the number of vertical levels. For a user choosing to run the NMM core, 31 levels are recommended. For the ARW core, simulations using 25 levels produced comparable accuracy as simulations using 31 or 37 levels.
5. The WRF composite reflectivity, derived from the simulated hydrometeor concentrations, was quite useful in analyzing the timing, location, orientation, intensity and curvature of lake-effect snow bands. The simulated composite reflectivity may also be useful in the short-term prediction of the location and intensity of snow bands. Further study will be needed to assess the value of this product for a wide variety of storms.
6. From the set of possible factors affecting inland extent of snowfall, the best linearly correlated factor appears to be the wind speed at cloud level. The low-level vertical temperature gradient also has a similar linear correlation. Other factors such as temperature, wind direction, and vertical wind shear have smaller correlations with inland extent.
7. The most well organized lake-effect snow bands downwind of Lake Ontario tended to peak between 0000 UTC and 0400 UTC with a secondary maximum between 1200 UTC and 1400 UTC. There appears to be a diurnal cycle in snow band organization. This cycle was most pronounced early and late in the lake-effect snow season.

C. Major Problems Encountered and Their Resolution

One of the biggest problems was trying to complete all of the work outlined in our proposal. We underestimated the work involved in identifying the optimal WRF configuration (Objective 1). In our proposal, we stated a goal of determining the optimal configuration by December 1, 2006. We did not even have the scoring spread sheet available until early January 2007. Students were still working on their spread sheets well into March. As a result of the delay in accomplishing our first objective, we had to cut back somewhat on the scope of work. As a group, we decided to abandon Objective 4 - quantifying the role of topography on precipitation enhancement downwind of the lakes because of lack of time and inability to get the REORDER software (Oye and Case, 1995) to read data from the KTYX radar (see next paragraph). We also eliminated Objective 5 on the sensitivity of lake-induced circulations to environmental factors. We would only have been able to start on this time-consuming task once we got the NCAR version of WRF running in late March 2007.

Another problem was converting radar data from polar to Cartesian coordinates. We had planned to use the 'Cartesianized' radar data for Objective 4 (verification of WRF predictions of orographic enhancement of precipitation) by computing vertically integrated reflectivity over a subdomain downwind of Lake Ontario. We found that the REORDER software that we planned to use was not set up to read data from the KTYX radar site. For Objective 2 (identification of factors controlling the inland extent of snowfall), we partially resolved the problem by using the composite reflectivity from KTYX to approximate the inland extent of significant snowfall. Since the radar beam overshot the level of maximum reflectivity at large distances from the antenna, we also computed correlations between meteorological factors and inland extent based on composite reflectivity simulated by WRF.

The most commonly used radar product for lake-effect snow in New York State is the 0.5° base reflectivity at KTYX and KBUF. However, the reflectivity simulated by the WRF is available on constant pressure surfaces. To compare the observed radar with model predictions, we developed a procedure to interpolate the WRF reflectivity on constant pressure surfaces, available every 25 hPa, to a 0.5° conical surface centered on the antenna. Although the simulated 0.5 degree reflectivity agreed reasonably well with the KTYX 0.5° reflectivity over land, it appeared to underestimate the reflectivity over Lake Ontario at several forecast hours for one of our cases. We reluctantly abandoned use of simulated 0.5° reflectivity since further testing would consume valuable time and thus delay the start of the analyses by the students.. Our resolution was to compare observed *composite* reflectivity and simulated *composite* reflectivity (following Koch et al. 2005) to evaluate the accuracy of WRF predictions of band location, width, orientation, intensity and curvature.

For several interesting cases suggested by forecasters at NWS Buffalo, we were unable to obtain both the radar data and the initial and boundary data necessary to run WRF. For example, the initial data for Iron (29-31 January 2004), one of the most intense lake-effect storms in a decade, was not available from either the NCDC archive or the NCAR archive. The resolution of this problem was to add two storms, 'Aphid' and 'Junebug', from the 2006-07 season.

We would like to have run our simulations using consecutive initial analyses (every six hours) to eliminate inaccurate boundary data from the North American Mesoscale (NAM) model as a source of WRF error. Although the initial analyses were available from NCDC for several cases, the version of WRF that we obtained from the National Weather Service was not set up to use consecutive initial analyses. Our resolution was to use the archived NAM *forecast* datasets extending out to 36 hours. An alternative would have been to use the NCAR version of WRF which does support use of consecutive initial analyses, but we did not get the NCAR version of WRF running on our computers until March 2007 – too late to redo the time-consuming model verifications.

Five of the eight students originally hired for the project were seniors in Fall 2006. They worked hard during the fall and first half of the spring semester. However, because of the work required to complete their Capstone research projects, most of the seniors had little time to work on COMET after the middle of March. Our resolution was to hire two new students, Sophomore Ronelle Williams and Junior Eric Wenke, to help with data analysis. Mr. Wenke was available to work during the summer on quality assurance of the spread sheets and preparation of graphics.

Section 5: Publications and Presentations

A. Publications

None yet, but we plan to submit a manuscript early in 2008 to the *Bulletin of the American Meteorological Society* on this research.

B. Presentations

Ballentine, R. J., A. Stamm, S. Skubis and S. Steiger, 2006: COMET *Partners Project 2006-07 with NWS Buffalo*, 1st Lake-effect Conference, October 2006, Oswego, NY.

Camizzi, N. and S. Skubis, 2007: *The 12-13 October Buffalo Snowstorm: The Day the Trees Wept,* 32nd Northeast Storms Conference, March 2007, Springfield, MA.

Sheffield, H.A. and R. Ballentine, 2007: *Lake Effect Snow Case Study "EgyptianMau" December 6-7 2005: Comparing WRF Model Simulations with the Observed RADAR,* 32nd Northeast Storms Conference (Poster Session I), March 2007, Springfield, MA.

Smith, S. and A. Stamm, 2007: *The 23-25 December 2004 Lake Effect Snow Event: Scoring WRF Model Performance as part of COMET Sponsored Undergraduate Research,* 32nd Northeast Storms Conference, March 2007, Springfield, MA.

Thomas, J.T., S. Steiger and J. Wegman, 2007: *Analysis of the WRF model performance for lake-effect event "Javanese"*, 32nd Northeast Storms Conference, March 2007, Springfield, MA.

Section 6: Summary of University/Operational Partner Interactions and Roles

Our operational partners, David Zaff, Fred Pierce, and several forecasters at NWS Buffalo helped us select important lake-effect storms and provided us with the NWS version of WRF and an update. Mr. Pierce was especially helpful in teaching Oswego faculty how to set up and configure the model for our domain. He provided us with initial data for storm 'Aphid' along with his own simulations.

Mr. Zaff provided guidance from the forecaster's point of view on the relative importance of an accurate simulation of lake-effect snow band characteristics such as location, width, etc. He took time to discuss the procedure for creating spread sheets with several students, and talked to them about careers in the National Weather Service. He gave an excellent presentation of a New England winter storm using the Weather Event Simulator during his trip to Oswego in November 2006.

Dr. Ballentine led most of the COMET team meetings, filed the 6-month Report and this report, and supervised the work of Heather Sheffield, Kyle Pieper, and Eric Wenke. He prepared the first version of the scoring spread sheet for Lake Ontario and checked its accuracy by writing a Fortran program that made the same calculations. In response to a question from David Zaff about running WRF with 12-km resolution, Dr. Ballentine sent output from a 12-km WRF run to NWS Buffalo. He developed a procedure for computing WRF reflectivity on a 0.5° conical surface.

Dr. Skubis worked with students Nick Camizzi and Meredith Mandel during the academic year. During the summer of 2007 he worked with Eric Wenke to quality check the data and to do further spreadsheet calculations and graphics. He quality checked the scoring spreadsheets, upgraded them to be more user friendly, and added the curvature calculations. He wrote a C program to compute the root mean square errors between the model runs.

Dr. Steiger helped design the format for scoring the WRF simulations, worked on drafts of this report, and supervised the work of John Thomas and Joe Wegman on the inland extent issue. He supervised the snow survey field trip to Redfield, NY following the long-lasting storm 'Locust' in February 2007. He supervised Meredith Mandel and Matt Souders on the diurnal cycle objective.

Dr. Stamm helped with this report, prepared students to take snow measurements at Redfield, and supervised the work of Shawn Smith and Matt Souders.

Appendix A:
Statistical expressions:

Mean: $$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad \text{or} \quad \overline{x} = \int_{-\infty}^{+\infty} x\, f(x)\, dx$$

where f(x) is the probability density function; $\int_{-\infty}^{+\infty} f(x)\, dx = 1$.

Mean absolute: $$\overline{|x|} = \frac{1}{N}\sum_{i=1}^{N} |x|_i \quad \text{or} \quad \overline{|x|} = \int_{-\infty}^{+\infty} |x|\, f(x)\, dx$$

Variance: $$\sigma_x = \frac{1}{N}\sum_{i=1}^{N} (x_i - \overline{x})^2 \quad \text{or} \quad \sigma_x = \int_{-\infty}^{+\infty} (x - \overline{x})^2\, f(x)\, dx$$

Standard deviation: $$s_x = \sqrt{\sigma_x}$$

Absolute mean error: $$AME = \frac{1}{N}\sum_{i=1}^{N} \left| x_i^{mod} - x_i^{obs} \right|$$

where **mod** stands for model and **obs** for observed

Mean or bias error $$ME = \frac{1}{N}\sum_{i=1}^{N} \left(x_i^{mod} - x_i^{obs} \right)$$

References:

Bhattacharyya, G. K., and R. A. Johnson, **Statistical Concepts and Methods**, 1977, John Wiley and Sons, pp. 639.

Appendix B.

The total score is made up of category scores weighted with a subjective interest. The weights sum to one and are listed as follows.

Locations	Width	Orientation	Intensity	Terminal Pt.	Offset Time	Onset time	Huron Connect	Curvature
0.25	0.17	0.12	0.1	0.1	0.09	0.07	0.07	0.03

A meeting of the COMET group with a NWS representative discussed and decided the weights of interest. Location and width were the top two interests and thus weighted more. The total score can be expressed mathematically as

Total score (TS)

$$TS = \sum_{i=1}^{9} w_i \frac{c_i}{s_i} = \sum_{i=1}^{9} w_i s_{ci} \quad \text{where} \quad \sum_{i=1}^{9} w_i = 1$$

where c_i is the ith category absolute error, s_i is the ith category population absolute error or population scale, s_{ci} is the ith category score defined as $s_{ci} = {c_i}/{s_i}$, and w_i the category weight.

The ith category mean absolute error over a subset of the population is denoted by c_i. The ith categories for the total score are location, width, orientation, terminal point, offset time, onset time, Huron connection, and curvature. The subset of the population can be classified as the NMM run times and the population as all of the NMM and ARW run times combined. Another example, the subset of the population can be classified as the NMM 6km and 31 level run. Hence the subset of the population can be a case, a group of model runs, an individual model run, and so forth. The population can be a case, an individual lake, or combined lakes and depends on the desired relative comparisons of the relevant subsets.

The final score is a similar expression to the total score but with the exclusion of some of the categories. For this study the onset time, offset time, and Huron connection were excluded due to model timing logistics and analysis uncertainties in identifying connections. The final score can be expressed

$$FS = \frac{\sum_{i=1}^{6} w_i \frac{c_i}{s_i}}{\sum_{i=1}^{6} w_i} = \frac{\sum_{i=1}^{6} w_i s_{ci}}{\sum_{i=1}^{6} w_i} \quad \text{where} \quad \sum_{i=1}^{6} w_i = 0.77$$

where c_i is the ith category absolute error, s_i is the ith category population absolute error or population scale, and w_i the category weight.

The final score expression uses the same weights as in the total score but the categories are reduce to location, width, orientation, terminal point, and curvature. The total and final scores basically provide a normalized comparison of model performance which allows for the display of performance using common scaled-axis graphs. The individual category error scores can also be viewed this way and provide valuable insight on model category performance.

Tables

Table 1. Student Research Assistants

Name	Class	Advisor	Principal Tasks
Camizzi, Nick	Senior	Skubis	Analysis of Bengal; study of Aphid cold pool
Mandel, Meredith	Junior	Skubis	Diurnal variability
Pieper, Kyle	Soph.	Ballentine	Analysis of Aphid; scoring of spread sheets
Sheffield, Heather	Senior	Ballentine	Analysis of EgyptianMau; inland extent correlations
Smith, Shawn	Senior	Stamm	Analysis of Banana
Souders, Matt	Senior	Stamm	Modeling of Aphid; diurnal variability
Thomas, John	Senior	Steiger	Analysis of Javanese
Wegman, Joe	Soph.	Steiger	Inland extent correlations; analysis of Javanese
Wenke, Eric	Junior	Ballentine	Check analysis of cases; inland extent; make figures
Williams, Ronelle	Soph.	Skubis	Inland extent analysis of Locust

Table 2. Lake-effect Storms Used for Model Evaluation

Name	Date	Assigned Students	Description
Aphid	12-13 Oct '06	Souders, Pieper	Devastating early season event in Buffalo area
Banana	24-25 Dec '04	Smith	Lake Erie event that closed Buffalo airport
Bengal	24-25 Nov '05	Camizzi	Lake Erie event
EgyptianMau	06-07 Dec '05	Sheffield	Strong Lake Ontario event in Tug Hill region
Javanese	05-08 Feb '06	Thomas, Wegman	Lake Ontario band
Junebug	29 Janury '07	Wenke	Intense, short-lived Lake Ontario event

Table 3. Experiments for the Evaluation of WRF Grid Configuration

Name	Grid Size and x-y points	Layers	Time step and Runtime*
A10L31	10 km, 89 x 64	31	50 seconds, 1.25 hours
A08L31	8 km, 112 x 78	31	40 seconds, 2.36 hours
A06L31	6 km, 135 x 105	31	30 seconds, 5.26 hours
A04L31	4 km, 203 x 158	31	20 seconds, 17.1 hours
A08L37	8 km, 112 x 78	37	48 seconds, 2.37 hours
A06L37	6 km, 135 x 105	37	36 seconds, 5.07 hours
A08L25	8 km, 112 x 78	25	40 seconds, 1.99 hours
A06L25	6 km, 135 x 105	25	30 seconds, 4.35 hours
N10L31	10 km, 121 x 92	31	25 seconds, 0.70 hours
N08L31	8 km, 155 x 121	31	20 seconds, 1.42 hours
N06L31	6 km, 189 x 151	31	15 seconds, 2.76 hours
N04L31	4 km, 285 x 227	31	10 seconds, 8.79 hours
N08L37	8 km, 155 x 121	37	20 seconds, 1.69 hours
N06L37	6 km, 189 x 151	37	15 seconds, 3.28 hours

Table 4. Model Specification Comparison
Parameter differences co-highlighted in red (ARW) and blue (NMM)

ARW 4, 6, 8, 10km @ 31 levels	**NMM** 4, 6, 8, 10km @ 31 levels
From file wrfsi.nl	**From file wrfsi.nl**
&hgridspec	&hgridspec
NUM_DOMAINS = 1	NUM_DOMAINS = 1
XDIM = 203, 135, 112, 89	XDIM = 143, 95, 78, 61
YDIM = 158, 105, 78, 64	YDIM = 227,151,121, 93
PARENT_ID = 1	PARENT_ID = 1
RATIO_TO_PARENT = 1	RATIO_TO_PARENT = 1
DOMAIN_ORIGIN_LLI = 1	DOMAIN_ORIGIN_LLI = 1
DOMAIN_ORIGIN_LLJ = 1	DOMAIN_ORIGIN_LLJ = 1
DOMAIN_ORIGIN_URI = 203, 135, 112, 89	DOMAIN_ORIGIN_URI = 143, 95, 78, 61
DOMAIN_ORIGIN_URJ = 158, 105, 78, 64	DOMAIN_ORIGIN_URJ = 227,151, 121, 93
MAP_PROJ_NAME = 'lambert'	MAP_PROJ_NAME = 'rotlat'
MOAD_KNOWN_LAT = 43.8	MOAD_KNOWN_LAT = 43.8
MOAD_KNOWN_LON = -79.5	MOAD_KNOWN_LON = -79.5
MOAD_STAND_LATS = 43.8, 43.8	MOAD_STAND_LATS = 43.8, 43.8
MOAD_STAND_LONS = -79.5	MOAD_STAND_LONS = -79.5
MOAD_DELTA_X = 4000, 6000, 8000, 10000	MOAD_DELTA_X = 4000, 6000, 8000, 10000
MOAD_DELTA_Y = 4000, 6000, 8000, 10000	MOAD_DELTA_Y = 4000, 6000, 8000, 10000
SILAVWT_PARM_WRF = 0.	SILAVWT_PARM_WRF = 0.
TOPTWVL_PARM_WRF = 2.	TOPTWVL_PARM_WRF = 2.
From file wrf.nl	**From file wrf.nl**
&domains	**&domains**
TIME_STEP = 20, 30, 40, 50	TIME_STEP = 10, 15, 20, 25
TIME_STEP_FRACT_NUM = 0	TIME_STEP_FRACT_NUM = 0
TIME_STEP_FRACT_DEN = 1	TIME_STEP_FRACT_DEN = 1
MAX_DOM = 1	MAX_DOM = 1
S_WE = 1,	S_WE = 1,
E_WE = 89,	E_WE = 62
S_SN = 1,	S_SN = 1,
E_SN = 64,	E_SN = 94
S_VERT = 1,	S_VERT = 1,
E_VERT = 31,	E_VERT = 31,
DX= 4000, 6000, 8000, 10000,	DX= 0.026, 0.039, 0.052, 0.065
DY= 4000, 6000, 8000, 10000,	DY= 0.025616, 0.038424, 0.051232, 0.06404
GRID_ID = 1,	GRID_ID = 1,
PARENT_ID = 1,	PARENT_ID = 1,
I_PARENT_START = 0,	I_PARENT_START = 0,
J_PARENT_START = 0,	J_PARENT_START = 0,
PARENT_GRID_RATIO = 1,	PARENT_GRID_RATIO = 1,
PARENT_TIME_STEP_RATIO = 1,	PARENT_TIME_STEP_RATIO = 1,
FEEDBACK = 1	FEEDBACK = 1
SMOOTH_OPTION = 1	SMOOTH_OPTION = 1
NPROC_X = -1	NPROC_X = -1
NPROC_Y = -1	NPROC_Y = -1

&physics	**&physics**
MP_PHYSICS = 2	MP_PHYSICS = 5
RA_LW_PHYSICS = 01	RA_LW_PHYSICS = 99
RA_SW_PHYSICS = 01	RA_SW_PHYSICS = 99
RADT = 10	RADT = 7
	NRADL = 72
	NRADS = 72
CO2TF = 1	CO2TF = 1
SF_SFCLAY_PHYSICS = 1	SF_SFCLAY_PHYSICS = 2
SF_SURFACE_PHYSICS = 2	SF_SURFACE_PHYSICS = 99
BL_PBL_PHYSICS = 1	BL_PBL_PHYSICS = 2
BLDT = 5	BLDT = 5
	NPHS = 12
CU_PHYSICS = 0	CU_PHYSICS = 0
NTSBD = 72	NTSBD = 144
static CUDT = 5	CUDT = 5
	NCNVC = 12
ISFFLX = 1	ISFFLX = 1
IFSNOW = 1	IFSNOW = 1
ICLOUD = 1	ICLOUD = 1
SURFACE_INPUT_SOURCE = 1	SURFACE_INPUT_SOURCE = 1
NUM_SOIL_LAYERS = 4	NUM_SOIL_LAYERS = 4
MP_ZERO_OUT = 2	MP_ZERO_OUT = 0
MAXIENS = 1	MAXIENS = 1
MAXENS = 3	MAXENS = 3
MAXENS2 = 3	MAXENS2 = 3
MAXENS3 = 16	MAXENS3 = 16
ENSDIM = 144	ENSDIM = 144
&dynamics	**&dynamics**
DYN_OPT = 2	DYN_OPT = 4
RK_ORD = 3	RK_ORD = 3
W_DAMPING = 1	W_DAMPING = 1
DIFF_OPT = 1	DIFF_OPT = 1
KM_OPT = 4	KM_OPT = 4
DAMP_OPT = 0	DAMP_OPT = 0
BASE_TEMP = 290.	BASE_TEMP = 290.
ZDAMP = 5000.	ZDAMP = 5000.
DAMPCOEF = 0.05	DAMPCOEF = 0.05
KHDIF = 0	KHDIF = 0
KVDIF = 0	KVDIF = 0
NON_HYDROSTATIC = .true.	NON_HYDROSTATIC = .true.

MP_PHYSICS (max_dom) microphysics option
= 0, no microphysics
= 1, Kessler scheme
= 2, Lin et al. scheme
= 3, WSM 3-class simple ice scheme
= 4, WSM 5-class scheme
= 5, Ferrier (new Eta) microphysics
= 6, WSM 6-class graupel scheme

RA_LW_PHYSICS (max_dom) longwave radiation option
= 0, no longwave radiation
= 1, rrtm scheme
= 99, GFDL (Eta) longwave (semi-supported)

RA_SW_PHYSICS (max_dom) shortwave radiation option
= 0, no shortwave radiation
= 1, Dudhia scheme
= 2, Goddard short wave
= 99, GFDL (Eta) longwave (semi-supported)

RADT (max_dom) = 10, ; minutes between radiation physics calls
= 7 ; reduce it if grid distance is fine

SF_SFCLAY_PHYSICS (max_dom) surface-layer option (old bl_sfclay_physics option)
= 0, no surface-layer
= 1, Monin-Obukhov scheme
= 2, Monin-Obukhov (Janjic Eta) scheme

SF_SURFACE_PHYSICS (max_dom) land-surface option (old bl_surface_physics option)
= 0, no land-surface
= 1, thermal diffusion scheme
= 2, Noah land-surface model
= 3, RUC land-surface model
= 99 The NMM Land Surface Model (LSM).

The NMM LSM scheme is based on the pre-May 2005 NOAH Land Surface Model in the operational NAM/Eta with soil temperature and moisture in 4 layers, fractional snow cover and frozen soil physics (Ek et al. 2003) and is very similar to Option 2. NMM USERS - Use Option SF_SURFACE_PHYSICS = 99

BL_PBL_PHYSICS (max_dom) boundary-layer option
= 0, no boundary-layer
= 1, YSU scheme
= 2, Mellor-Yamada-Janjic (Eta) TKE scheme

DYN_OPT specifies which dynamical core to use when running the WRF
Current options include:
2 - Advanced Research WRF (ARW) core. Also known as Eulerian Mass (EM)
4 - Advanced Operational WRF (AOW) core. Also known as NMM

Table 5: Overall Lake's categories and experiments. In each category, blue (green) indicates the best (worst) performing experiment.

	Overall Averaged Case Errors By Category											
Category	Loc	Width	Orient	Intensity	Term Pt	Curv.	Offset	Onset	Huron C	Total	Final	Runtime
Units	km	km	deg	dBZ	km	km^-1	hrs	hrs	-	-	-	hrs
Scales/Count	19.39	12.27	8.752	6.5223	55.631	0.00054	0.619	1.429	0.2641	-	-	-
Weights	0.25	0.17	0.12	0.10	0.10	0.03	0.09	0.07	0.07	-	-	-
A10L31	**24.04**	9.08	9.46	**7.77**	**51.86**	4.73E-04	0.67	1.17	**0.14**	1.00	1.04	1.25
A8L31	23.42	8.74	10.03	7.32	63.35	4.94E-04	0.67	**1.00**	0.21	1.02	1.06	2.36
A6L31	22.61	**8.06**	10.42	6.61	58.53	4.98E-04	0.67	**1.00**	0.22	0.98	1.01	5.26
A4L31	22.36	9.97	9.74	5.98	57.48	**7.34E-04**	**0.83**	**1.00**	0.21	1.02	1.03	17.10
A8L37	23.24	9.88	10.20	7.10	63.17	4.93E-04	0.67	1.50	0.19	1.05	1.07	2.37
A6L37	22.86	10.07	9.67	6.85	**71.72**	6.08E-04	0.67	1.83	0.16	1.06	**1.08**	5.07
A8L25	22.85	9.50	**11.08**	7.25	63.83	**4.45E-04**	0.67	1.67	0.16	1.05	**1.08**	1.99
A6L25	23.44	9.80	10.15	6.62	63.42	5.51E-04	**0.33**	1.17	0.21	0.98	1.07	4.35
N10L31	16.35	**15.64**	7.90	6.84	57.82	4.72E-04	0.67	1.67	0.45	**1.07**	1.00	0.70
N8L31	**15.65**	13.98	7.89	6.24	59.73	5.46E-04	0.67	1.83	0.35	1.02	0.96	1.42
N6L31	15.67	13.91	**7.46**	5.98	59.32	4.89E-04	0.67	1.33	0.35	0.98	**0.94**	2.76
N4L31	17.28	13.82	9.97	**5.34**	63.80	5.78E-04	0.67	1.17	0.40	1.04	1.01	8.79
N8L37	15.93	15.40	7.81	6.42	62.62	5.72E-04	0.50	**2.00**	**0.47**	1.06	1.00	1.69
N6L37	16.13	12.87	7.47	6.18	59.46	6.38E-04	**0.33**	1.67	0.39	**0.96**	**0.94**	3.28
Sum	281.83	160.72	129.25	92.51	856.11	7.59E-03	8.67	20.00	3.91	14.29	14.30	58.39
Average	20.13	11.48	9.23	6.61	61.15	5.42E-04	0.62	1.43	0.28	1.02	1.02	4.17
	ARW	ARW	ARW	ARW	ARW	ARW	ARW	ARW	ARW	ARW	ARW	ARW
Avg. ARW	23.10	9.39	10.09	6.94	61.67	5.37E-04	0.65	1.29	0.19	1.02	1.06	4.97
Avg. 6v6	23.09	9.30	9.92	6.94	61.02	5.50E-04	0.69	1.25	0.19	1.02	1.05	5.57
	NMM	NMM	NMM	NMM	NMM	NMM	NMM	NMM	NMM	NMM	NMM	NMM
Avg. NMM	16.17	14.27	8.08	6.17	60.46	5.49E-04	0.58	1.61	0.40	1.02	0.98	3.11