An Operating System Designed to Predict the Development, Movement, and Dissipation of Lightning (Cloud-to-Ground and Intra-Cloud) Using Microphysical and Dynamical Data from Cloud Resolving Weather Forecast Models.

Description and Three Case Study Examples

Barry H. Lynn

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Barry.Lynn@weather-it-is.com

This description is excerpted, in part, from a Provisional Patent Application prepared and submitted by Barry Lynn (Weather It Is, LTD; the contents are confidential). The validation was performed as part of a joint research effort between Barry Lynn (also of The Hebrew University of Jerusalem), Yoav Yair (The Open University of Israel), and Colin Price (Tel-Aviv University) with lightning data provided by WSI for these purposes.

Description

The LPI is the volume integral of the total mass flux of ice and liquid water within the "charging zone" (e.g., 0 to -20°C) in a developing thundercloud. It portrays the potential of a thundercloud to separate electrical charge in the relevant depth via the non-inductive ice-graupel mechanism, but it does not calculate the resultant electric field or its evolution. It is derived from the model simulated grid-scale updraft velocity and the mass mixing-ratios of liquid water, cloud ice, snow, and graupel (See Yair et al., 2010; Lynn and Yair, 2010). This approach is in line with many studies showing strong and consistent relationships between lightning flash rates (that can be integrated in time to give total lightning) and the presence of small ice and high precipitation rates. The LPI evolves with time since it is calculated from the microphysical and dynamical model fields at each time step and in every domain grid point of a cloud- resolving model. It is non-zero only within the charging zone.

The LPI has the units of [J kg^{-1}] and is calculated as:

$$LPI = 1/ V \int\int\int \varepsilon w^2 \, d x \, dy \, d z \qquad (1)$$

where V is the model unit volume, w is the vertical wind component in m s^{-1}, and

$$\varepsilon = 2(Q_i Q_l)^{0.5}/(Q_i + Q_l) \qquad (2)$$

Here, Q_l is the total liquid water mass mixing ratio in (kg/kg) and Q_i is the ice fractional mixing ratio in (kg/kg) defined as:

$$Q_i = q_g [((q_s q_g)^{0.5}/(q_s + q_g)) + ((q_i q_g)^{0.5} /(q_i + q_g))] \qquad (3)$$

In essence, ε is a scaling factor for the cloud updraft, and attains a maximal value when the mixing ratios of super-cooled liquid water (Q_l) and of the combined ice species (Q_i) are equal (note, Q_i also obtains a maximal value when the mass mixing ratio of ice, snow, and graupel are equal). It signifies the fact that charge separation requires all these ingredients to operate synergistically within the charging zone.

The advantage of using the LPI compared to other typically used "stability" factors is demonstrated in Figure 1. It shows a three-hour period from a case study conducted for the "FLASH" program (Yair et al., 2010). Fig. 1 shows lightning flashes recorded mostly over the northwest part of the domain. These flashes were associated with a flood event that occurred at Emilia Romagna. In this case study, the corresponding LPI also shows LPI concentrated in the Northwest corner of the domain, coexistent with (but not quite covering) the area with the lightning flashes. The K-Index (Sturtevant, 1995) and CPTP (Williams et al., 1989), in contrast, show widespread areas where convection could occur with lightning. Hence, unlike the LPI, these are very non-specific indexes that most likely lead to a large over-forecast of the areal coverage of lightning. This is typical of indexes derived from coarse (non-cloud-explicit) forecasting grids.

Although the calculation of LPI gives different LPI values during the model simulation (or weather forecast), it cannot be used directly to forecast the number of lightning flashes (cloud-to-ground and intra-cloud) – as it doesn't calculate, as noted, the resultant electric field or its evolution. Hence, the use of the LPI or similar indexes to make lightning "forecasts" is a reactive, rather than proactive approach (e.g, McCaul et al. (2009) and Lynn and Yair (2010)). A reactive approach is not a forecast, but a statistical relationship between the calculated indexes and the observed lightning in *past* case studies. One very important disadvantage of this approach is that the spatial and time characteristics of past study events may have only a small resemblance to one another or future events.

For this reason, I developed a new "Operating System" (OS) to predict the number of lightning flashes (cloud-to-ground (positive-polarity and negative-polarity), and intra-cloud), Traditionally, an operating system is software (programs and data) that provides an interface between the hardware of the computer and other software. Likewise, I designed a set of software routines that interfaces to the microphysical and dynamical fields of a cloud resolving, weather forecast model and produces a prediction of lightning as a forecast field from the *same* model. There is no requirement to run a CPU intensive electric field model that is commonly used to predict lightning. No assumption is made concerning the time and spatial scales of convection in any forecast. Instead, in my OS, I use the predicted microphysical fields in combination with the dynamical data from cloud-resolving weather forecast models *to forecast* the number of lightning strikes.

The OS uses the LPI, but only as one variable in the system of equations required to calculate the number of lightning flashes. The OS also uses a new parameter I invented, referred to as the "Power index" [PI_i; W kg^{-1}]. It is the "specific" instantaneous electric power of the charged cloud fields, and it depends in part on the LPI. The calculation of the instantaneous electric charge is the first step in the operating system to proactively or dynamically forecast the development, movement, and dissipation of lightning in a weather forecast model. The next step is to convert the instantaneous electric charge into charge (or total electric charge, TE). In terms of the nomenclature employed in the WRF model, TE is a "scalar" variable that is created from the collision of ice particles in the presence of water. It is advected horizontally and vertically, and it is dissipated when the electrical power builds up enough to cause a lightning flash.

Validation

Three case studies are briefly described. The date for the first case study was 7 April 2010 (12 GMT) until 9 April 2010 (0 GMT), while the date for the second case study was 24 April 2010 (0 GMT) until 25 April 2010 (12 GMT). The date for the third case was 18 October 2005 until 22 October 2005. In case 1, the environmental conditions were such that rain was from predominately convective clouds. There was initial convection late in the day in the lower Mississippi Valley along a NE-to-SW eastward moving cold front, which was followed by a redevelopment of convection late at night just north of the Alabama coast. The second case study simulates a Mid-West synoptic system. There was rain from mostly stratiform clouds around the low center and from mostly convective clouds in the southeast quadrant of the storm. The third case study details the lightning and ten-meter wind speed development of Hurricane Wilma during a period of explosive deepening.

The forecasts were done using the WRF model modified to include the operating system that predicts lightning from the microphysical and dynamic fields. The first two case study simulations were for 36 hours and a number of simulations were produced for each case to create ensemble forecasts. The forecast domain consisted of an outer grid at 36 km grid spacing, with additional nested grids of 12 km and 4 km grid spacing. The lightning predictions were made on the 4 km grid. The 4 km grid in the first case covered the area where there was the Cold-Frontal passage and redevelopment. The 4 km grid in the second case encompassed the area of the low center and spiraling rain band clouds around it, as well as areas of convection to the southeast of the low center.

The observed lightning data (from USPLN) used for comparison was provided to us by WSI. It consists of the time-span, location, and sign of the peak current of the observed lightning. In the examples shown, below, however, we compare only the total (consisting of the observed positive cloud-to ground, negative cloud-to-ground, and intra-cloud lightning) to the predicted total lightning values.

To put our results in the context of previous work, Figs. 2 and 3 show 3-hourly averaged LPI and predicted three-hour rain amounts for three hourly time-segments during the thirty-six hour ensemble forecast period. The ensemble rain amounts were calculated using "Probability Matching" (Ebert, 2001). During the 07 April case the LPI corresponds in intensity and position quite well to the predicted rain amounts. Higher LPI values are mostly associated with higher rain amounts. However, on 24 April the LPI is large during certain three-hour periods when (apparently) convective rain amounts are high, but LPI is relatively small during other three-hour periods even though rain amounts are still relatively high (but located closer to the center of the low pressure area). The reason LPI is small even though rain amounts are still relatively high in these locations is because the predominant rain during these times is from moist, layered or stratus-type clouds (see, specifically, the three-hour time segments ending 6, 9, and 12 GMT on 25 April). The sensitivity of LPI to microphysical and dynamical properties – previously demonstrated (Yair et al, 2010) makes it a very good candidate to form the basis of the Power Index – as noted above.

Figures 4 and 5 show the observed and forecast lightning values for the 07 April and 24 April cases study events, respectively. The lightning values plotted are the total number of lightning flashes in a three-hour period ending at the time (GMT) shown at the top of each graph. As is typical on weather maps, these figures show a single forecast (as indicated by the color-scale bar) as determined from the most likely distribution from the ensemble forecast (the calculation of the lightning distribution is also a part of the Provisional Patent); these maps also show, however, the potential for lightning strikes to occur as indicated by the gray contour in areas outside the areas indicated by the color-shades (the bounds of this gray-scale that lie between 0.5 and 1 is simply an artifact of the plotting program). The forecast probability for lightning is actually lower in the gray areas outside the colored areas, but as the forecast progresses the spatial extent of the gray areas takes on greater and greater significance (since the forecast is more likely to deviate from the expected evolution – as indicated by the color scale). It is interesting also to note the spatial area covered by the color and gray shades (e.g., on 7 April) is similar to the area encompassed by and outlined by the outer edge of the area covered by the LPI with magnitude greater than 0.1 J kg^{-1} and less than 0.5 J kg^{-1}.

On 07 April, the predicted lightning values correspond quite well in magnitude and spatial coverage during the first twelve hours of the forecast period. The spatial correspondence is less apparent as the forecast time extends into the next day. However, taken together, the color shades (indicating the number of forecast lightning flashes) and the gray contours (indicating where lightning flashes are possible, but not as likely) provide the necessary information required to make informed decisions to protect against the impending occurrence of lightning flashes over the forecast period. For instance, while the ensemble forecast under-estimates, perhaps, the intensity and spatial extent of the secondary convection, the forecast's (hurricane-like map) "cone of uncertainty" evolves, for the most part, to include areas where lightning was observed (outside of the color shades). Moreover, the observed flashes per three hours outside of the shaded areas but within the gray areas were mostly of similar magnitude to the smallest number of flashes forecast by the color shades.

The maps showing the forecast lightning and observations for 24 April show variations in predicted lightning values across the forecast synoptic system. In the center rain bands, the predicted and observed lightning is much less than in the areas of convection in the southeast quadrant. (Note, the number of predicted strikes is higher than observed in the southeast quadrant of the storm, but the proximity to the lateral boundary of the forecast domain most likely has an impact on the predicted intensity of the convection). Emphasizing the unique utility of the PI (and LPI) under different microphysical conditions, steady rain continues to be forecast in the last three (3-hour) periods, but almost no predicted and observed lightning strikes are seen in these graphs.

Figure 6 shows the observed surface pressure minimum for Hurricane Wilma. The simulated WRF minimum surface pressure is also shown. Only a single simulation was done, and the grid spacing was 9 km on an outer, static, and coarse grid, while it was 3 km on an inner moving nested grid. The simulated surface pressure matches quite well the observed surface pressure, although the minimum pressure is not quite as deep as observed and the actual storm weakened just prior to landfall more than the simulated storm.

Figure 7 shows the simulated number of lightning flashes and simulated average wind speed every six hours through this period. Quite remarkably, the number of flashes increases quite significantly from 0 GMT 19 October until 12 GMT 19 October – 12 to 24 hours prior to the most significant deepening (0 GMT, 20 October). The simulated increase in the number of lightning flashes prior to the most significant deepening is consistent with an observational study prepared by Price et al. (2009).

Maps of forecast lightning from a forecast ensemble are similar to those maps depicting predicted rain amounts, but their application is new and novel. The benefit of this approach is that it shows the ensemble's "best" forecast, but also provides information from the ensemble that reflects the potential uncertainty in the forecast as it progresses from its initial time to the end of the forecast period. Similar ensemble forecasts can be prepared for hurricane prediction as well. Here, though, we demonstrate the potential relationship between the number of lightning flashes and hurricane intensity. The predicted number of lightning flashes can be compared against the observed number of flashes as an additional tool in model verification and forecast.

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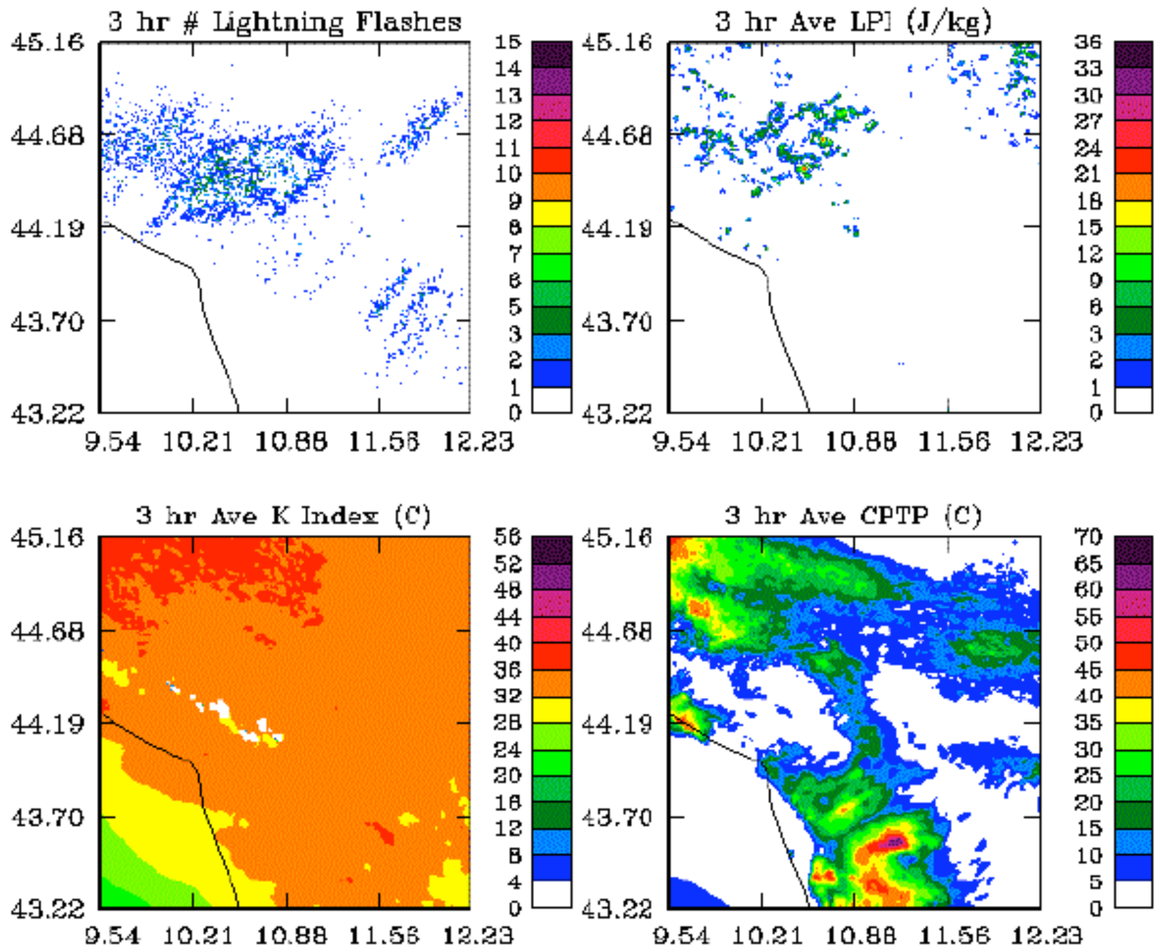
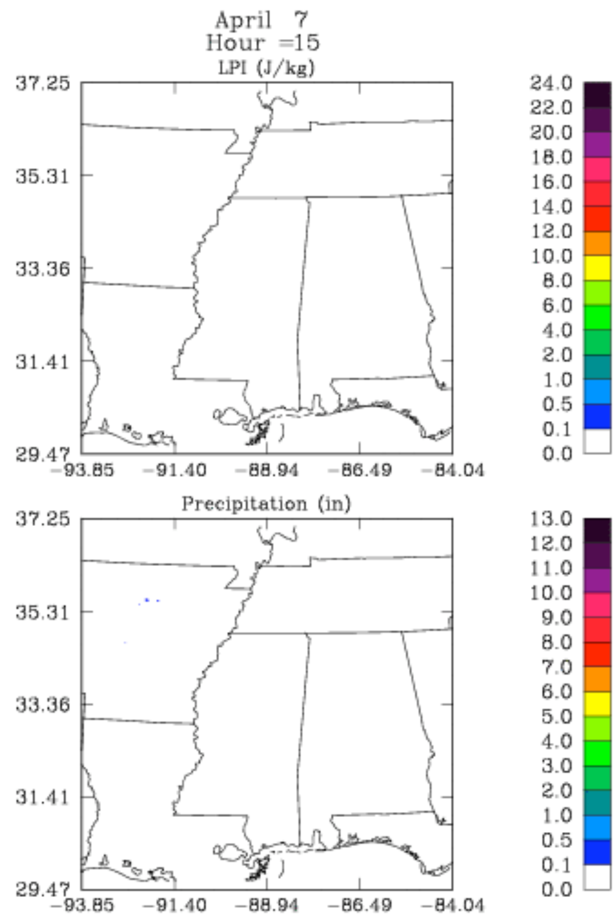
Barry.lynn@weather-it-is.com

Emilia Romagna - Northern Italy --15:00 to 18:00 UTC on 8 September 2006

1



3-hour averages of observed lightning and predicted Lightning Potential Index, K-Index, and CPTP



Barry.lynn@weather-it-is.com

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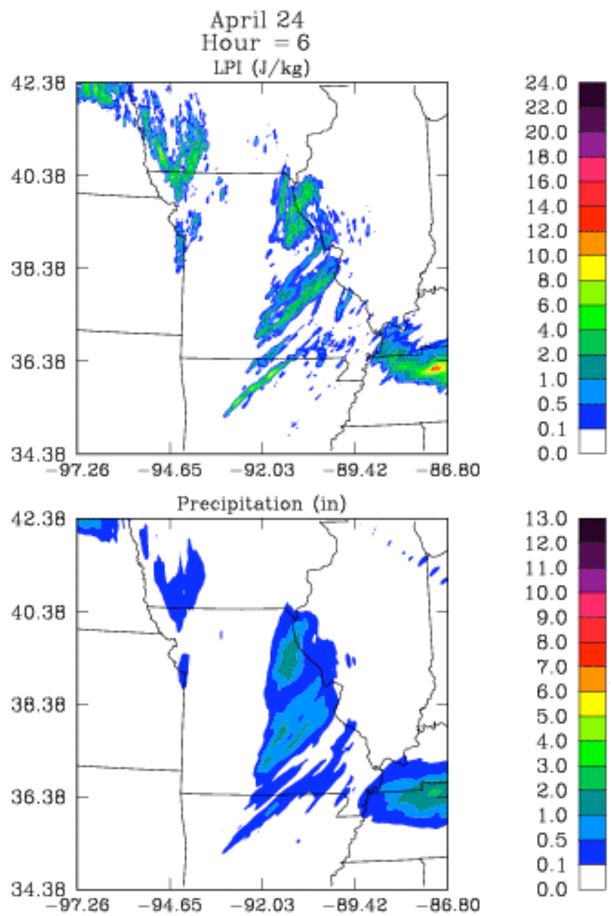

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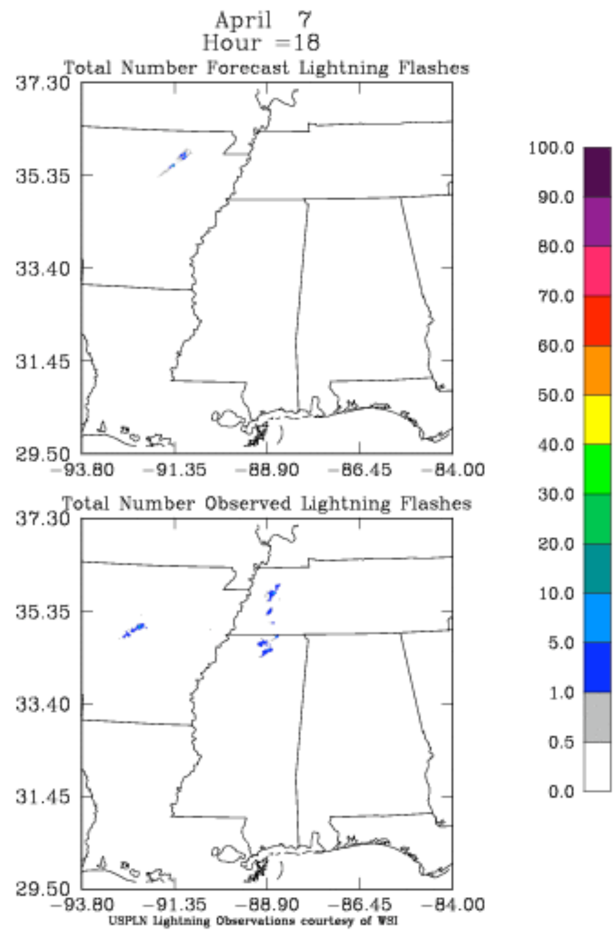

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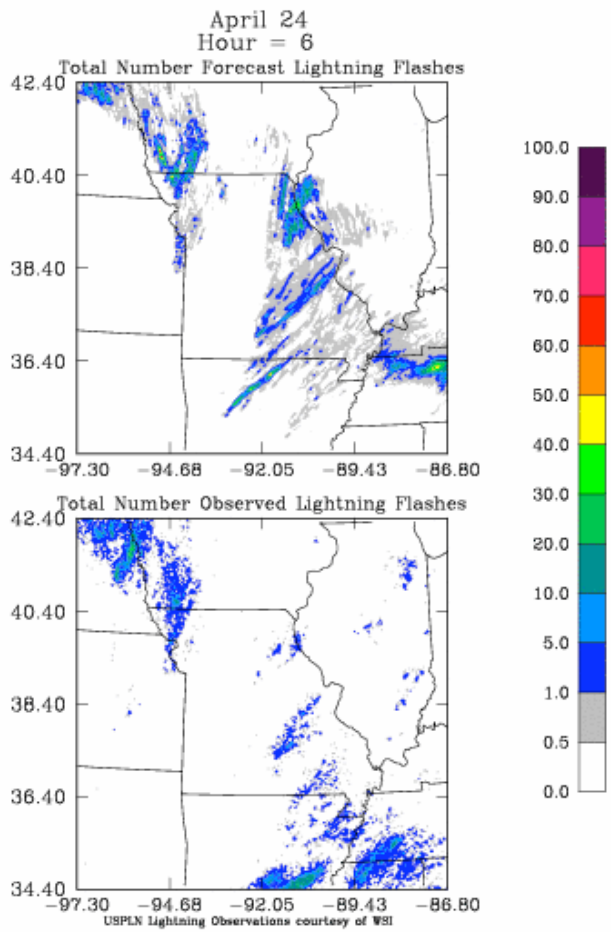

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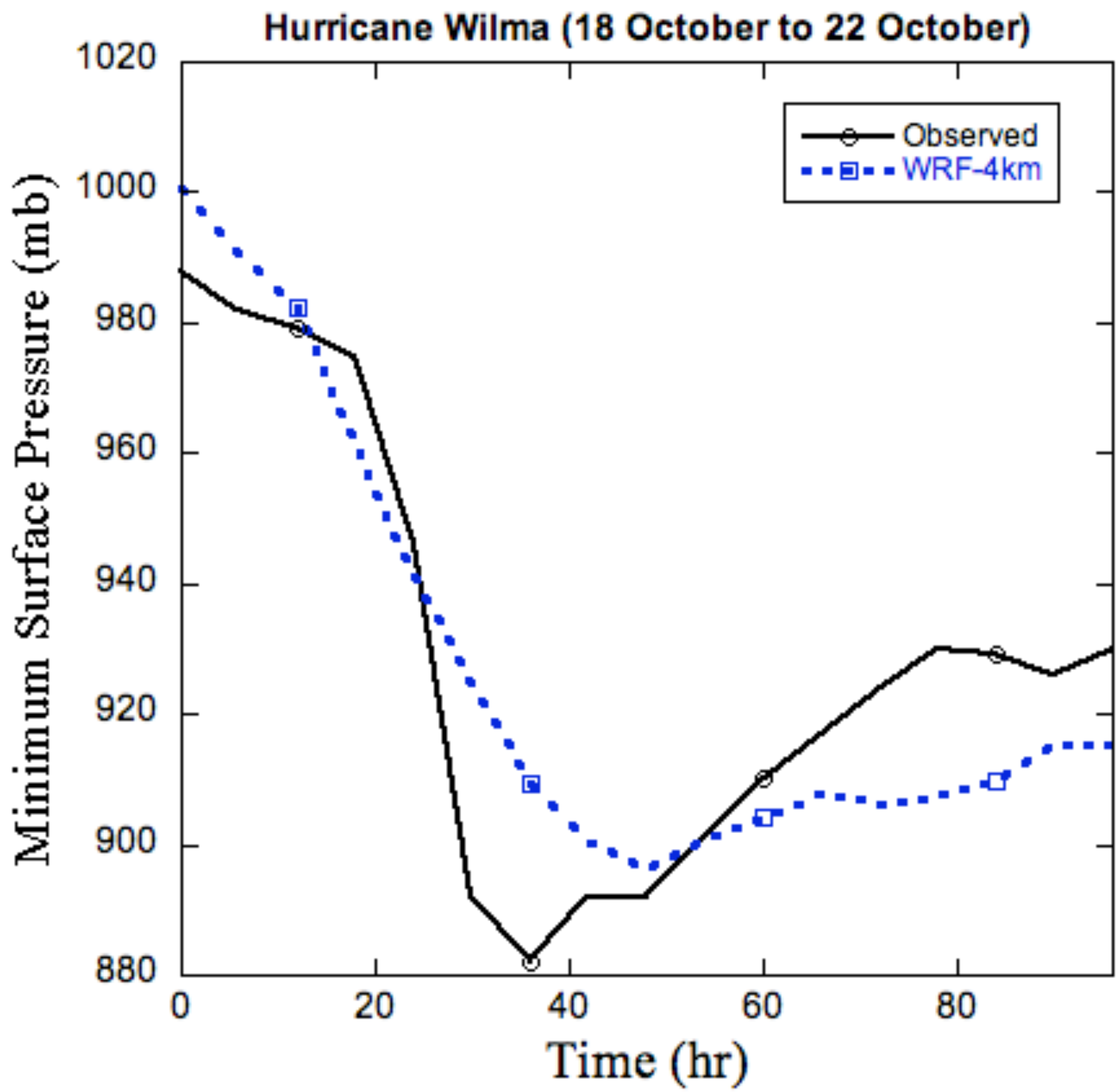
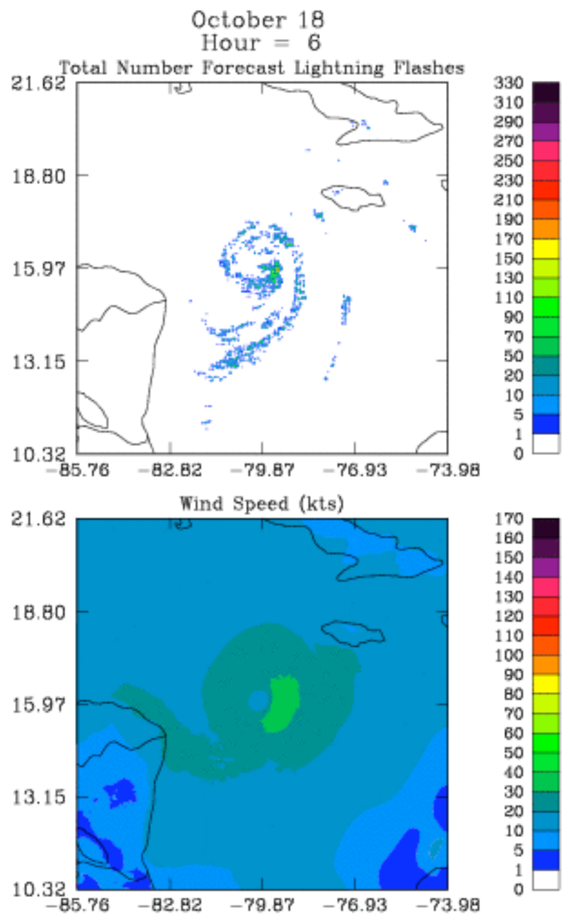

Hurricane Wilma (18 October to 22 October)
Minimum Surface Pressure (mb)
1020
1000
980
960
940
920
900
880
0
20
40
60
80
Time (hr)
Observed
WRF-4km



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