6.2 LIGHTNING PRODUCED BY COLD SEASON OCEANIC EXTRATROPICAL CYCLONES: OBSERVATIONS RELATED TO NOWCASTING STORM DEVELOPMENT, INTENSITY AND PRECIPITATION AMOUNTS

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1. INTRODUCTION

Real-time lightning detection data are used for a variety of meteorological and aviation applications over land areas where cloud-to-ground lightning (CG) networks cover all or part of 40 countries. Real-time CG data are typically combined with radar and other information to identify significant weather over a wide range of time and space scales.

The outer limit of land-based CG flash detection networks is set at 625 km from sensors in the U.S. National Lightning Detection Network (NLDN) and the Canadian Lightning Detection Network (CLDN). This distance is determined by characteristics of the radiation emitted by the ground waves from CG flashes (Section 2). While 625 km is beyond the range of coastal meteorological radars, it is not especially far from land for convective weather systems that often translate and evolve at velocities of 50 km per hour or more.

The primary source of information about thunderstorms over the oceans beyond the 625-km range are satellite imagery, as well as pilot and ship reports. Satellite scans are often collected at 30-minute intervals with a subsequent time delay in availability. Ship reports are sparse, and sporadic pilot reports are often delayed in time. As a result, flights over oceans can enter convective regions with little or no warning. Aircraft can encounter turbulence, icing, direct lightning strikes, and other hazards that can be avoided over and near land regions where there are CG lightning and radar networks (Nierow et al., 2002). Similarly, shipping and other offshore interests have a relatively small amount of information on convective activity beyond the range of the nearest land-based radar.

Vaisala is conducting an ongoing experiment to operate a VLF long-range lightning network over the Atlantic and Pacific Oceans to detect flashes thousands of kilometers from sensors in North America, Europe and Asia. Frequent lightning has been found in oceanic extratropical cyclones during the cold season over the oceans. The detection of lightning within cold-season oceanic extratropical cyclones has shown that flashes within these storms are often an indicator of future storm development, intensification, and precipitation intensity.

This paper will review some of the effects that oceanic convection and latent heat release have on extratropical cyclogenesis, and discuss how lightning data can identify these areas. Other applications are the ability of lightning information to help identify short-wave troughs, the rapid intensification of oceanic extratropical cyclones, and deep tropical moisture transported along a cold front into the cold sector of a storm. The potential for long-range lightning data to improve numerical simulations of extratropical cyclones will also be mentioned. VLF lightning data, GOES infrared satellite images and surface maps will be used to show examples of these applications. A parallel paper on the use of VLF flash data to identify eyewall variations in intense tropical systems is described in Demetriades and Holle (2005).

2. LONG-RANGE VLF LIGHTNING DATA

NLDN and CLDN wideband sensors operate in the frequency range from about 0.5 and 400 kHz where return strokes in CG flashes radiate most strongly. The peak radiation from CG flashes comes near 10 kHz in the middle of the very low frequency (VLF) band of 3-30 kHz. Signals in the VLF band are trapped in the earth-ionosphere waveguide and suffer relatively less severe attenuation than higher frequency signals. Low frequency (LF) and VLF ground wave signals from CGs are attenuated strongly, and are almost imperceptible after a propagation distance of 500 to 1000 km. However VLF signals may be detected several thousand kilometers away after one or more reflections off the ground and the ionosphere. Detection is best when both a lightning source and a sensor are on the night side of the earth, because of better ionospheric propagation conditions at night. The NLDN can easily detect and process signals from lightning at long distances because the standard sensors in the networks detect across a broad band that includes all of the VLF.

Standard NLDN sensors have been part of an ongoing experimental long-range detection network consisting of the combination of the CLDN, the Japanese Lightning Detection Network, the Meteo-France network, and the BLIDS, Benelux, and Central European networks operated by Siemens in Germany. This combination of networks detects CG flashes in sufficient numbers and with sufficient accuracy to identify small thunderstorm areas. The network detects CGs to varying degrees over the northern Atlantic and Pacific oceans, and also over some areas of Asia and Latin America not covered by local ground-based lightning detection networks.

3. OCEANIC EXTRATROPICAL CYCLONE LIGHTNING INTENSITY

The nature of long-range lightning data is shown by two examples off the west and east coasts of the U.S. in December 2002. Figure 1 shows a cyclone as it is

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approaching the west coast during flow with a westerly component. While the NLDN shows some flashes (red) when the storm comes close to land, the long-range VLF network (blue) detects many more flashes much further offshore. Figure 2 shows the rate to exceed 1600 flashes per hour with the long-range data.

Along the east coast, Figs. 3 and 4 indicate how the NLDN depicted a fairly large portion of the flash extent during a cyclone that developed into a nor'easter. However, the long period of flashes and very high rates exceeding 12,000 flashes per hour are much better depicted by the long-range network.

From these examples, it can be seen that long-range flashes compared to land-based CGs:

- Cover a larger area,
- Extend the time periods with lightning,
- Detect many more flashes.

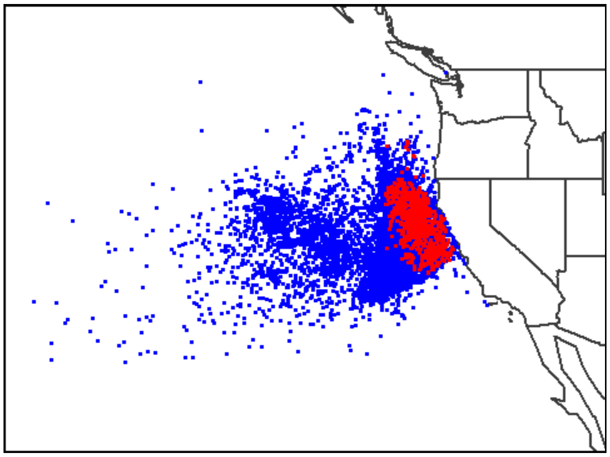

Figure 1. Map of cloud-to-ground (CG) flashes during the approach to the U.S. west coast of a Pacific storm from 17 to 20 December 2002. NLDN flashes are shown in red, and long-range flashes in blue.

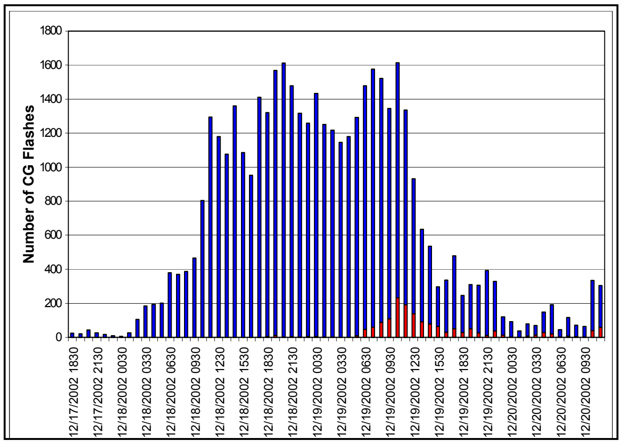

Figure 2. Time series of flashes for Pacific storm in Fig. 1. NLDN flashes are in red, and long-range flashes in blue.

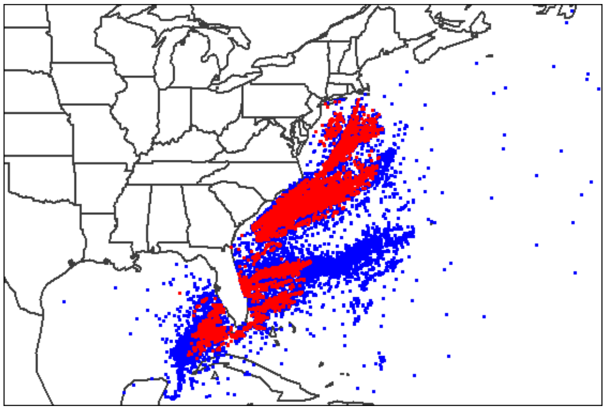

Figure 3. Same as Fig. 1 for Atlantic nor'easter from 24 to 26 December 2002.

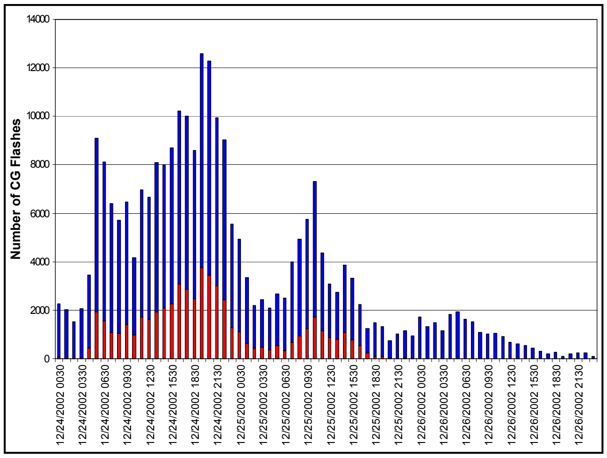

Figure 4. Same as Fig. 2 for storm in Fig. 3.

4. EXTRATROPICAL CYCLOGENESIS

Lightning indicates areas of convection where latent heat release into the troposphere is enhanced. In particular, high flash rates over relatively large areas identify regions of large latent heat release that can cause enhanced vertical motion and pressure falls at the surface. Therefore, large areas of concentrated lightning activity over the ocean may be one of the first signs of extratropical cyclogenesis.

Lightning can also be generated by the enhanced lift and relatively cold air aloft associated with short wave troughs. As these areas of enhanced upward vertical motion and colder air propagate over relatively warm ocean waters during the winter, they often generate lightning. These short wave troughs can then trigger rapid cyclogenesis as they round the base of a long wave trough. As a result, relatively compact areas of lightning activity propagating over the oceans can help identify the existence and intensity of short wave troughs that play a critical role in oceanic cyclogenesis.

The example in Figs. 5 to 8 shows lightning development over a relatively large area preceding surface extratropical cyclogenesis over the oceans in winter. Figure 5 depicts major pressure centers and fronts at 0000 UTC 7 January 2003. A low is east of the southern New England coast, and a long cold front extends through Florida into the Gulf of Mexico. Figure 6 shows substantial lightning activity developing along the cold front between 2053 and 2353 UTC 6 January. Lightning continues 6 hours later as a wave of low pressure developed early on 7 January (Fig. 7). By 0900 UTC, a fairly intense extratropical cyclone had developed with a minimum pressure of 996 mb (Fig. 8).

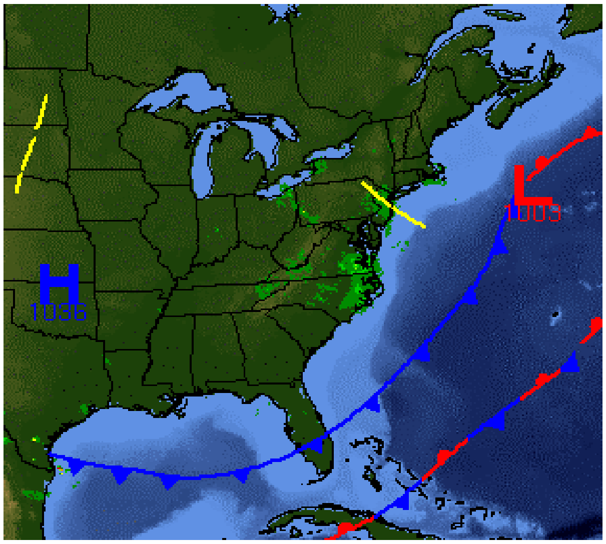

Figure 5. Surface map showing locations of major pressure centers and fronts at 0000 UTC 7 January 2003.

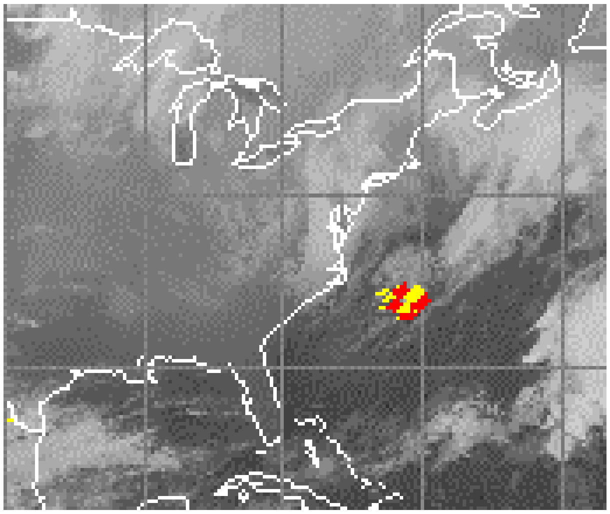

Figure 6. Long range lightning data and infrared satellite image on 6 January 2003. Lightning is for 3 hours from 2053 to 2353 UTC. Yellow dots are flashes from 2053 to 2253 UTC, and red from 2253 to 2353. Satellite image is at 2353.

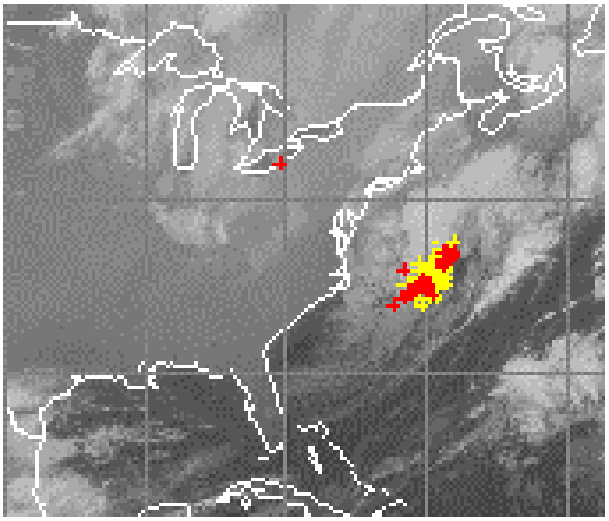

Figure 7. Same as Fig. 6, except for lightning from 0553 to 0853 UTC 7 January 2003. Satellite image is at 0853.

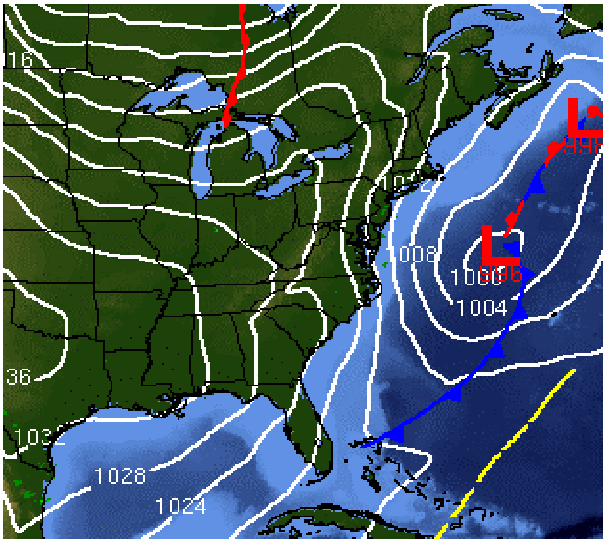

Figure 8. Same as Fig. 5, except for 0900 UTC 7 January.

5. EXTRATROPICAL CYCONE INTENSITY

5.1 Lightning near center of an extratropical cyclone

Latent heat release associated with convection can cause rapid intensification of a system if large areas of convection, and by implication lightning, are present near a developing low (Reed and Albright, 1986; Martin and Otkin, 2004). Similarly, large areas of convection along a frontal boundary will cause enhanced frontogenesis due to the increased lift, and by implication convergence, created by latent heating. As a result, lightning rates over the oceans can help forecasters identify areas where deep cumulus convection may influence storm and frontal development.

Lightning development near an existing extratropical cyclone center sometimes may be a response to rapid intensification, rather than a precursor to subsequent intensification. During explosive cyclogenesis, pressure falls cause increased convergence and lift. Lightning may develop If this lift occurs over relatively warm ocean waters with its ample supply of moisture. This sequence is shown by long-range lightning data near the center of an extratropical cyclone southeast of Newfoundland (Figs. 9 and 10). Lightning in Fig. 9 was detected between 1753 and 2053 UTC on 7 January 2003, and the surface map in Fig. 10 is at 2100. The area of active convection is probably not large enough to cause rapid intensification through latent heating. But the initiation of lightning 3 hours earlier near the center of this storm between 1453 and 1753 UTC (not shown), and its persistence through 2053, was coincident with a 13 mb drop in pressure from 992 to 979 mb from 1500 to 2100 UTC 7 January.

5.2 Lightning in a short wave trough

Short wave troughs can produce lightning through enhanced lift and colder temperatures aloft. Flashes produced by a short wave trough may be an important complement to satellite imagery to help forecasters identify these important impulses. Such impulses will often round the base of a long-wave trough and cause explosive cyclogenesis as they interact with a pre-existing extratropical cyclone center. Figures 11 and 12

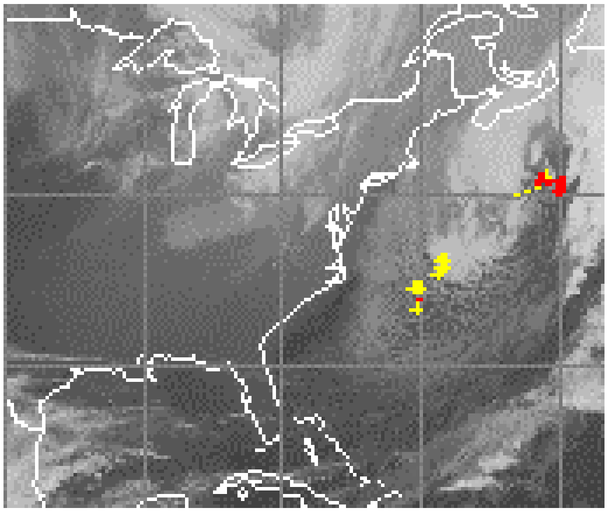

Figure 9. Same as Fig. 6, except for lightning between 1753 and 2053 UTC 7 January 2003. Satellite image at 2053.

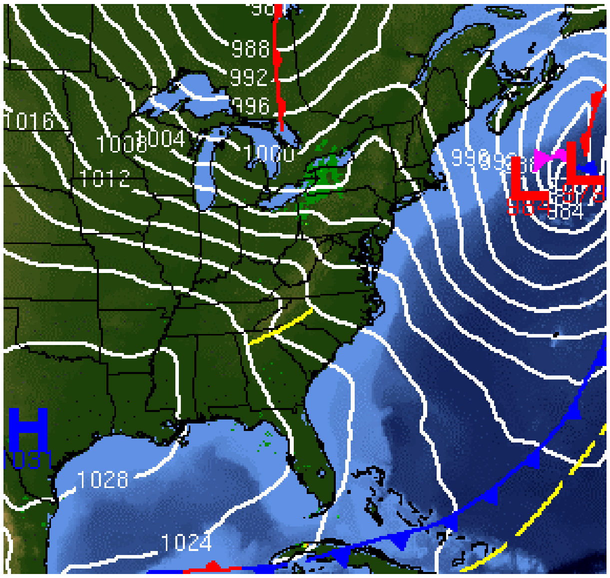

Figure 10. Same as Fig. 5, except at 2100 UTC 7 January.

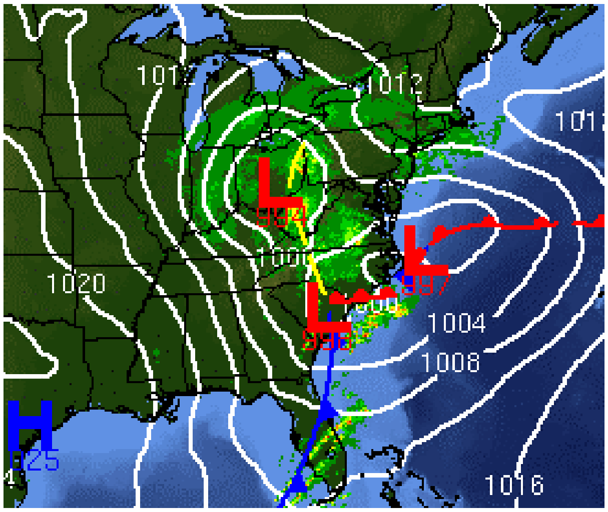

Figure 11. Same as Fig. 5 except for 0900 UTC 25 December 2002. The coastal low is developing just east of North Carolina with a central pressure of 997 mb.

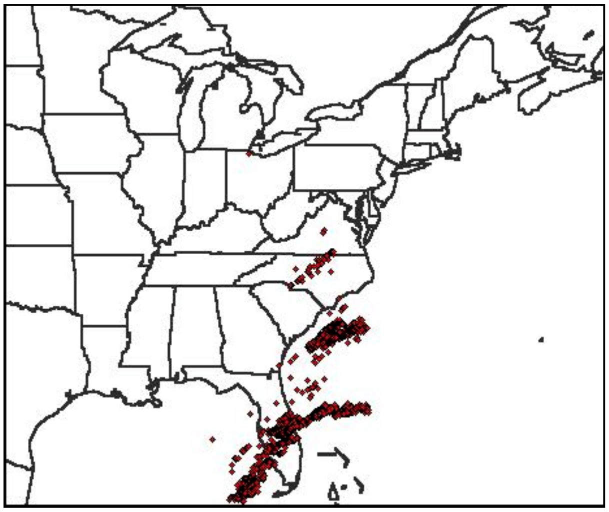

Figure 12. NLDN CG flashes detected between 0600 and 0900 UTC 25 December 2002. The short wave trough over central North Carolina is producing CG lightning.

show lightning produced by a short wave trough that is about to interact with a coastal low located off the North Carolina coast. Figure 11 shows the low with a central pressure of 997 mb at 0900 UTC 25 December 2002, and Fig. 12 shows lightning detected between 0600 and 0900 UTC. In this case, the short wave trough and the lightning it was producing were located over North Carolina. This short wave trough caused explosive deepening of the coastal low and by 1800 UTC, its minimum pressure was 979 mb (Fig. 13).

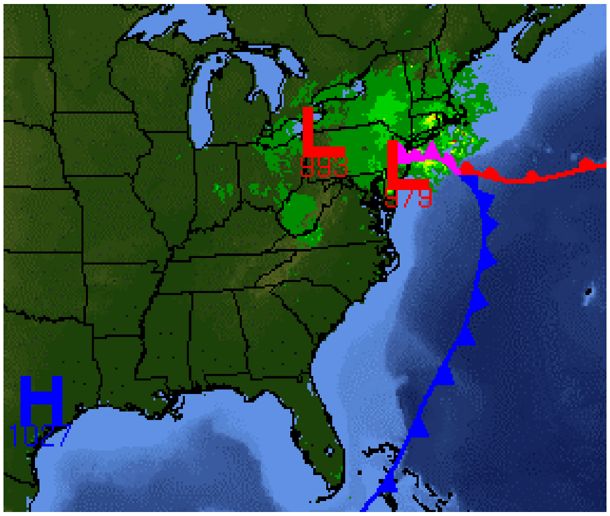

Figure 13. Same as Fig. 5, except for 1800. The coastal low is near southern New Jersey and has a central pressure of 979 mb.

5.3 Role of downstream convection on extratropical cyclone intensify and track

Large areas of convection that develop downstream from an extratropical cyclone can greatly influence the storm's intensity, track and precipitation distribution (Alexander et al., 1999; Atallah and Bosart, 2003; Chang et al., 2001). This convection typically develops between the long wave trough and downstream ridge associated with an extratropical cyclone. The convection releases massive amounts of latent heat that raise the heights of mid- and upper-level pressure fields. Depending on the location of this convection, it can either amplify the trough and downstream ridge, or cause the trough and downstream ridge to deamplify. The amplification or deamplification of the trough and downstream ridge can cause important changes in extratropical cyclone intensity, track and precipitation distribution.

An example in Fig. 14 shows an extremely large area of downstream convection east of the same extratropical cyclone approaching the west coast as was shown by Figs. 1 and 2. Flashes in Fig. 14 occurred during a 3-hour interval from 1452 to 1752 UTC 18 December 2002. The 24-hour ETA model forecast valid at 1200 UTC 19 December had a minimum pressure of 983 mb, while the 12-hour forecast valid at the same time deepened the system to 981 mb. However, the observed central pressure for this system was actually 9 mb lower at 972 mb at 1200 UTC 19 December. This poor forecast may have been caused by the inability of the model to properly simulate bulk upscale effects from this large convective area. It is suggested that assimilation of lightning data may have helped the numerical forecast.

In another example, numerical models incorrectly forecast the magnitude of the 12-14 March 1993 Superstorm along the Gulf of Mexico and east coasts because the models had trouble with the initial explosive development over the Gulf (Alexander et al., 1999). The development resulted from organized deep convection downstream of cyclogenesis over the Gulf. The inability of the models to properly simulate bulk upscale effects of this convection led to central pressure forecasts up to 15 mb too high. Alexander et al. also (1999) demonstrated that model forecasts of surface pressure, as well as the cyclone position and precipitation for the Superstorm were substantially improved through continuous assimilation of NLDN flashes. Forecast errors were greatly diminished when lightning data were combined with SSM/I-IR satellite data. Less frequent assimilation of satellite infrared or passive microwave estimated rainfall rates did not provide comparable improvements.

Latent heating profiles were determined in the model by relating satellite and lightning data over the oceans to rain rate approximations (Alexander et al., 1999). A similar method was successfully used by Chang et al. (2001) with VLF lightning data for a storm that explosively deepened over the Gulf of Mexico in February 1999. Pessi et al. (2004, 2005) are also using a relationship between long-range lightning and rainfall in the northeast Pacific to assimilate lightning into numerical models as a proxy for latent heat release in deep convection. They have confirmed that lightning frequency and convective rainfall rates are relatively well correlated, so that lightning data can indicate latent heat release for assimilation into the MM5 model.

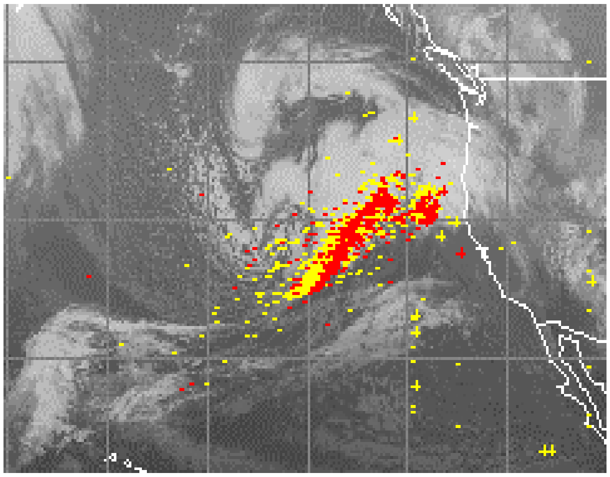

Figure 14. Same as Fig. 6, except for lightning between 1452 and 1752 UTC 18 December 2002. Satellite image is at 1752.

6. COLD FRONT CONVECTION AND WINTER PRECIPITATION

Very intense lightning activity along the cold front of an extratropical cyclone - but not near the center of the storm - can be an indication of deep tropical moisture available to the storm. Such deep tropical moisture can be transported into the cold sector of a storm and cause large amounts of winter precipitation including snow, sleet, freezing rain and rain.

The Presidents' Day Snowstorm of 2003 produced frequent lightning along its cold front, as well as high snowfall totals in the Mid-Atlantic and southern New England states. However, the minimum central pressure never dropped below 1000 mb. Figure 15 shows CG flashes from the long-range lightning detection network within this extratropical cyclone between 0853 and 1153 UTC 16 February. Very frequent lightning was occurring within large areas of convection south of the storm center, along the cold front. The southerly flow associated with this system was transporting moisture northward into the Mid-Atlantic and Southern New England states where temperatures were well below freezing. Snowfall totals were generally between 2 and 4 feet (60 to 120 cm).

This example shows how the location and amount of lightning within extratropical cyclones can help determine its potential impacts. Extremely large amounts of lightning activity may be useful for precipitation nowcasting and forecasting.

7. COLD POOL LOCATION AND INTENSITY

During the winter, the cold pools associated with cold advection behind oceanic extratropical cyclones produce shallow convection and lightning. These flashes are due to the vertical instability generated between the relatively warm oceanic waters near the surface and the cold temperatures associated with the cold pool aloft.

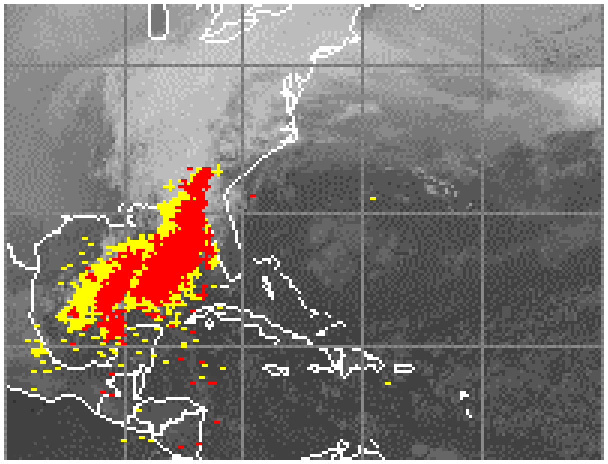

Figure 15. Same as Fig. 6, except for lightning from 0853 to 1153 UTC 16 February 2003. Satellite image at 1153.

Lightning activity complements satellite imagery and can aid forecasters in identifying the location and intensity of cold pools. Figure 16 shows lightning being generated by shallow convection within the cold pool of an extratropical cyclone located over the Central North Pacific Ocean.

Flash data also give an indication of the intensity of the cold pool. In order to generate lightning, updrafts need to reach a velocity sufficient for charge generation and separation. This information can be used with observations of sea surface temperature in order to estimate the temperatures aloft that are needed to create the instability necessary to generate these updrafts.

Lightning detected within the cold pools of oceanic extratropical cyclones can also be an indicator of the amount of modification of the cold pool that is occurring as the result of convective mixing of warmer air located near the ocean surface. This warmer air is transported aloft where it modifies the cold temperatures within the cold pool. Chase et al. (2002) and Tsukernik et al. (2004) have examined the potential role of oceans in modifying cold temperatures aloft at high latitudes.

8. CONCLUSIONS

Lightning data over otherwise data-sparse regions are expected to be valuable for meteorologists. Flash information is especially important for nowcasting and forecasting for aviation and maritime interests. In addition, long-range CG flash data identifies convection that can have significant subsequent impacts on land areas adjacent to oceans.

A variety of situations has been described where lightning data over the oceans have the potential to be very useful sources of information about convection. The existence of CG flashes at specific times and locations over the ocean helps identify features that form and intensify extratropical cyclones. The spatial and temporal extent, and the pattern of such

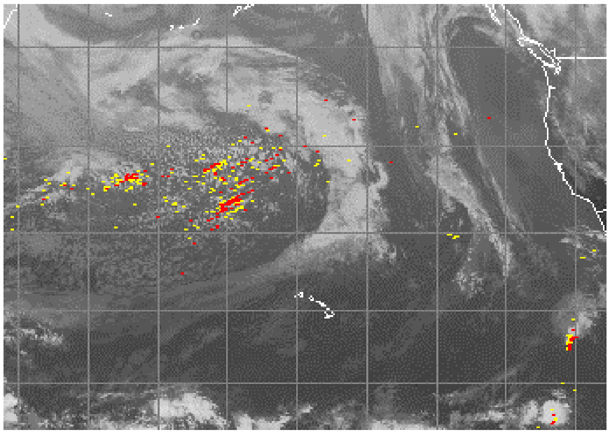

Figure 16. Same as Fig. 5, except for lightning detected between 1752 and 2052 UTC 17 January 2003. Satellite image is at 2052.

flashes can also be useful for diagnosing the stage and extent of development of such systems. Flash data can be assimilated continuously into numerical weather prediction models to better identify the presence of latent heat release that strongly influences the progression of cyclonic systems in the model. In addition the time, location, and amount of upstream lightning may identify deep moisture that can be important in producing heavy downstream precipitation, including frozen precipitation on the ground in winter. The vertical structure of cold pools also may be identified with flash data.

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