National Weather Association, *Electronic Journal of Operational Meteorology,* 2008-EJ4

Use of GIS to Examine Winter Fog Occurrences

BRADEN WARD
Kean University, Union, NJ

PAUL J. CROFT
Kean University, Union, NJ

(Manuscript received 19 December 2007; in final form 15 July 2008)

ABSTRACT

The use of Geographic Information Systems (GIS) to quantify a family of environmental variables associated with specific fog occurrences can improve operational forecasting. Initial results indicate that specific patterns of fog appear as a function of local features and are modulated by prevailing synoptic weather patterns. Combining these patterns with GIS analyses provides for the development of derived risk factors for winter-season dense fog occurrence and coverage based upon land use, elevation, and gradient fields. Results further illustrate that representing local features through GIS datasets can allow for improved definition of fog occurrence and coverage.

This technique was applied to fog occurrences for 15 ASOS sites in the New York Metropolitan region for the 2006−2007 winter season. Fog cases were examined using satellite imagery and surface synoptic maps to assess dense fog occurrence and coverage. Fog events were selectively examined to relate dense fog occurrence and coverage to synoptic weather regimes and environmental features through the application of GIS techniques and fog product imagery. This method has the potential to be a forecasting tool for operational meteorology that accounts for microscale variables related to dense fog occurrence, with results that benefit aviation and public safety.

1. Introduction

Fog events in the northern mid-Atlantic states have been shown to be both prolific and predictable with regard to synoptic development and spatial occurrence (Croft and Burton 2005). The patterns of spatial development and occurrence of dense fog events are anticipated to be in direct relation to the initiating synoptic weather conditions combined with topographic and local surface characteristics.

The study and prediction of dense fog occurrence is relevant for both the Federal Aviation Administration and the National Highway Transportation Administration. Changes in

Corresponding author address: Dr. Paul J. Croft – Professor of Meteorology, Kean University, Department of Geology and Meteorology, 1000 Morris Avenue, Union, NJ 07083.
E-mail: pcroft@kean.edu

expected airport capacities and the problems associated with decreased ceilings and visibilities are of great cost to airlines. It has been estimated by the National Weather Service (Valdez 2000) that more accurate forecasting of these variables could save over 0.5 billion dollars annually of the estimated 2.5 billion in costs from weather delays in the National Airspace System. The same study indicates that, at Chicago O'Hare International Airport, improved forecasting by 30 minutes of events related to cloud ceiling and visibility reduces weather-related delays by 25−30%.

In addition, there are approximately 700 automobile-related deaths annually from driving within dense fog in the United States (Whiffen et al. 2004). The use of METAR surface observations is generally inadequate and ineffective for the generation of highway safety warnings to reduce fatalities given their separation and location relative to major roadways. The necessary data for adequate observations along highways often are absent, as many states have few or no road-weather information systems (Ellrod and Lindstrom 2006).

The dangers posed by fog also extend to marine interests through navigational threats and shipping delays. Within active ports, operations are significantly diminished or halted for visibilities <0.4 km (<¼ mile), and losses can range from $10,000−$25,000 per day, per ship (Croft 2003).

The hazardous impacts are exacerbated in an urban setting, where proportionally large segments of population and systems are affected by a single occurrence of fog. The New York Metropolitan region, consisting of northern New Jersey, southern New York, southwestern Connecticut, and Long Island, is part of the Boston to Washington D.C. megalopolis comprised of a large number of urban and rural sites, and thus prone to significant impacts from visibility limiting fog. The wide varieties of mesoscale and microscale conditions that exist determine the occurrence, intensity, and coverage of fog across the region. These regional variations in fog have been considered in the literature with regard to their attendant forecasting difficulties for many other areas of the United States [e.g., as summarized by Tardif and Rasmussen (2007)]. Urban heat-island interactions also have been established in valley areas, and produce conditions that favor fog clearing. This phenomenon has been quantified by satellite imagery (Underwood and Hansen 2007), and its capability for reducing dense fog occurrences within urban zones of this study has the potential to be realized through climatological summaries.

This study is a preliminary effort to better identify and understand observed variations in fog in the northern mid-Atlantic region. According to prevailing synoptic weather patterns, select cases of dense fog during the 2006–2007 winter season were chosen for further analysis. These selections were made to represent one of each major synoptic pattern according to the most widespread occurrence of dense fog it was associated with. The intent was to provide operational support for the use of satellite imagery [i.e., the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) "fog product"] and satellite-derived products in Geographic Information Systems (GIS) to better depict local fog formation and its areal extent.

When analysis of the datasets above is combined with the synoptic weather pattern and local physiographic features, a forecaster may diagnose fog operationally through a GIS framework. For example, the Shuttle Radar Topography Mission (SRTM)-derived elevation map (Fig. 1a) and surface character map (Fig. 1b) can be used in conjunction with the fog product. This permits analysis of features relevant to fog, and provides for a single event to be discussed with the specific attributes of any location in the area. This integration allows for improved detection and collective understanding of the characteristic patterns and attributes of fog occurrence and coverage.

2. Data collection and methodology

In this study, the region of interest presents a wide variety of physiographic features (Fig. 1a) within and around the high concentrations of residential, industrial, utility, and commercial surface character (Fig. 1b) of the low-lying areas of northeastern New Jersey within the New York Metropolitan region. This area, compared to the rural and varying terrain regions of northwestern New Jersey and northeastern Pennsylvania, creates a wide disparity of sensible weather conditions for forecasters. The unique combinations of urban, rural, surface characteristics, and coastal versus inland locations imply a very complex mix of factors and the simultaneous roles of radiative and advective processes in fog occurrence, maintenance, coverage, and intensity.

In order to examine fog events in the region through a GIS framework, the 2006–2007 winter season (December through February) was selected. Based on 15 Automated Surface

Observations System (ASOS) observation sites (Table 1, Fig. 1c) that had daily data readily available, preliminary local climatological data were gathered [National Weather Service (NWS) form F-6, obtained online at http://www.weather.gov/] to determine days with fog and dense fog.

The period during which fog occurred was determined next in order to obtain corresponding satellite imagery from the NESDIS. While some current issues exist with using remote sensing techniques for fog, the fog product was used in order to reflect an operational environment. Although low-level stratus layers are nearly indistinguishable from the fog itself (Cermak and Bendix 2005), a determination of ground contact can be made using elevation models if the height of the cloud tops and the cloud thickness are determined.

The use of fog product satellite imagery provides a regional representation of the weather conditions at the time of dense fog occurrence. Although the imagery used is limited by low temporal (~hourly) and spatial (2 km at nadir) resolutions, as well as its inability to examine how thick fog is from above, its intent is to provide a more comprehensive spatial view of fog coverage than surface observations alone. It is also known that surface visibility observations have severe limitations in instances of elevated base, towards the dividing line of dense fog and low-lying stratus, as well as the neglect of vertical intensity, as is often the case with dense fog (Bendix 2002). The imagery used in the study displays the fog product simultaneously with surface reports of visibility, ceiling, and weather to determine whether the product is analyzing fog correctly.

An alternative approach is to provide a simulated reproduction of fog occurrence, distribution, and coverage patterns based upon regional characteristics. This was accomplished across the study region using ArcGIS (GIS software by the Environmental Systems Research Institute, or ESRI) and inverse distance-weighting interpolation techniques with observed data.

The ArcGIS mapping software allows for enhanced analysis of several spatial considerations. Comparison of the fog events can be made to overall seasonal patterns of fog and dense fog, and the source or process of fog generation can be hypothesized when compared to physiography. This ultimately will provide for separation by interactions with synoptic patterns that play a role in the observed spatial patterns of the fog event.

Although GIS analysis provides useful integration and layering of data, it does require boundary assumptions that may not reflect the reality of possible biases of a particular station for fog occurrence or intensity. The study area is bounded by such stations as Reading, PA

(KRDG), and Poughkeepsie, NY (KPOU) (Table 1, Fig. 1c); however, the GIS analysis will show a subset of this area for preservation of detail because of the boundary assumptions mentioned. The ability of ArcGIS to show the season of fog visually and contoured over the study region enables direct comparison with surface character and elevation—aided by looking at a small set of figures instead of a group of tables and graphs.

In an effort to distinguish discrepancies and variations observed in the patterns of fog event frequencies, several select cases were isolated according to four major synoptic patterns used by Croft and Burton (2005): high pressure, warm front, low pressure, and cold front. Synoptic maps from the Daily Weather Map (http://www.hpc.ncep.noaa.gov/dwm/dwm.shtml) series were obtained online from the Hydrometeorological Prediction Center (HPC) to identify the prevailing synoptic weather pattern for each dense fog occurrence. This was completed to identify the role of large-scale features in comparison to local effects as related to local physiography (Figs. 1a and 2c).

Given the greater level of impact from severe visibility restrictions, dense fog events were chosen over fog occurrences. Out of the 31 dense fog events identified, those which were observed at the majority of stations were selected for further investigation. In addition, these events were narrowed further by their dominant synoptic pattern in order to focus on the most representative case for high pressure, warm front, low pressure, and cold front that occurred during the study period.

3. Analysis

Out of 90 days observed, there were 65 days (72%) when at least one station in the study region reported fog, and 31 days (34%) when at least one station reported dense fog. Fig. 2a shows the total fog frequency for the study region. Although no information is provided on fog duration in these reports, fog events resulting in visibilities <0.4 km (<¼ mile), defined as dense fog events, were also plotted for consideration (Fig. 2b) and for comparison to all fog events (Fig. 2a). The total numbers of dense and non-dense fog reports are listed by station in Table 2.

When compared with Figs. 1a and 1b, the majority of dense fog events occurred in northeastern Pennsylvania (KMPO, Table 2 and Fig. 2b). A lower incidence of dense fog occurrences were found in the highly urbanized, low-lying, and coastal-influenced area of the

New York Metropolitan region. Specific variations between fog occurrences and dense fog are evident through comparison of Figs. 2a and 2b. For example, John F. Kennedy Airport (KJFK) had the lowest total of fog occurrences (24), but more occurrences of dense fog events (10) than nearby locations. There also exists the issue of elevation discrepancies from Mount Pocono (KMPO) to sites such as Allentown (KABE). While both are in higher elevation areas, KABE is in a valley. In addition, KJFK and Atlantic City (KACY), while both coastal urban zones, are dissimilar in dense fog occurrence.

While the dense fog observed occurs over several synoptic weather setups, in interest of the illustrative nature of this project, the best representation of each class will be discussed. The synoptic weather pattern associated with the most widespread dense fog events were chosen from 16 high pressure cases, five warm front passages, eight low pressure cases, and 11 cold front passages.

a. High pressure system, 13 December 2006—15 December 2006

While all 15 stations observed fog in the selected high pressure case, all but three reported at least one instance of dense fog (Fig. 3a). The coastal and low elevation sites experienced dense fog each day (e.g., compare Figs. 1a and 2b). The synoptic patterns for the 13th to 14th (Fig. 3c) indicated an area of high pressure had passed over the study region, originating on the 13th, and then retreating north-northeast from the Carolinas to Nova Scotia on the 14th while maintaining its intensity. This was followed by another weak high pressure center, and this sequence provided for overnight radiational cooling with light onshore flow from the southeast.

When examined in combination with satellite and GIS, it is clear that a marine-layer was present over the area, with low visibility at stations of interest as depicted in the fog product (Fig. 3b; yellow in the imagery is an indication of low clouds and fog). This relates well with the GIS interpolation of the event, as the areas that experienced dense fog are along the immediate coast and Delaware River Valley (Fig. 2c).

The KJFK, KEWR, and KACY stations, although of similar physiography, experienced unique instances of dense fog. Therefore, in this weather regime, it is necessary to consider the surrounding elevation and surface characteristic changes in order to anticipate the formation of

dense fog according to each location's unique characteristics. GIS applied as a multi-layer analysis could help in determining the correlation between dense fog and local physiography.

b. Warm front passage, 22 December 2006—23 December 2006

During the selected warm front case, seven of 15 stations in the study area experienced dense fog in the time period for at least one day, either in the higher elevations of KMPO, or the coastline of Connecticut (KBDR). KJFK reported no fog on either day, suggesting a connection between elevation and the movement of the front to initiate dense fog. Shifting wind directions and the slope of terrain could have also played a role (south facing in Long Island and southwestern Connecticut), creating shallow cold air damming.

Over this period, an occluded frontal system traversed west of the 15 stations, with a significant warm front pushing up the Eastern Seaboard (Fig. 4c). While the satellite imagery gave a clear indication of low visibility in the area (Fig. 4b), the spatial extent of the fog event was not evident.

The dense fog coverage was limited to the area of higher elevations (towards KMPO) in agreement with the total dense fog events (Fig. 2b). Dense fog reports extended down though KPHL and KILG as the system moved over the region. This observation demonstrates that the total dense fog reports for the season (Fig. 2b) responds to the prevailing synoptic patterns responsible for the most prolific initiation of dense fog.

In Fig. 4a the spatial coverage of each fog event was isolated to regions of varying topographic features, as well as diverse surface character conditions, when compared to Fig. 1a and 1b. It is evident that pre-frontal conditions favorable for dense fog were affected by areas of high elevation that slowed the retreating cooler air mass. This could aid in the creation of precipitation-induced dense fog.

These diagnoses were facilitated by using ArcGIS analyses of variables such as the rate of elevation change and slope direction, which could improve forecasted changes in visibility and cloud ceiling heights. Observed interactions between physiographic features and weather patterns can be included in forecasts.

c. Low pressure system, 25 December 2006—26 December 2006

The selected low pressure system developed and moved directly across the study region with seven station reports of dense fog on at least one day, and KJFK reporting no fog. The satellite imagery (Fig. 5b) from the 26th revealed a narrow corridor of fog over the study region with the onset of the low pressure system. Reports of dense fog over the period were variable (Fig. 5a), with most occurring at KACY and KMPO—two regions of contrasting features (see Figs. 1a and 1b).

The GIS rendering and gradation was dissimilar from satellite imagery (Fig. 5b). This exemplifies the limited recognition of fog through mixed clouds by satellites, and shows where this study provides a useful forecasting approach. KACY was experiencing marine-influenced dense fog due to onshore flow from the low pressure system moving in from the southwest. KMPO experienced the remainder of the occluded front passage, establishing conditions for cold air damming (Fig. 5c). The intensity of the fog events experienced in these locations illustrates a direct relation between the topography of these areas and wind direction influenced by synoptic patterns.

The resulting fog is a combination of factors, and GIS can act as a mediating tool as to prevailing conditions and expected passage location; for example, wind patterns in the region often shifted southeast to northwest, bringing marine and upslope impacts to KACY and KMPO, respectively. GIS can be used operationally to discern where small changes in weather system location and movement have a large impact on the spatial distribution of fog and its intensity as these relate to local features

d. Cold front passage, 28 January 2007—31 January 2007

The Delaware River valley (Fig. 2c) saw sparse dense fog reports with this selected cold frontal case, and the KMPO site reported no dense fog. As this system moved over the 15 stations observed, the dense fog reports were confined to five stations surrounding KPHL.

The fog product imagery captured the event (Fig. 6b) over the Delaware River near KPHL. The frequencies depicted in Fig. 6a match the fog imagery; by comparison to the

elevation model (Fig. 1a), the fog over the region was centered between the higher elevations to the east and west.

Comparing the GIS interpolation of the fog reports to the elevation model, the frequency gradient matches the location of the rising elevation heading north. Based on the surface character display (Fig. 1b), the Philadelphia region shares physiographic elements with the New York Metropolitan region. However, the maritime valley influence in this case with the passing cold front (Fig. 6c) was a deciding factor in the occurrence of dense fog. The cold-air advection processes of the marine-influence area of the Delaware River valley created the necessary conditions for valley and/or upslope fog in and around Philadelphia.

4. Conclusions

The capability of ArcGIS analysis tools to create accurate multi-layer depictions of the fog occurrences with influencing factors is plausible for relating weather patterns to physiographic variables. It is suggested from this study that different synoptic weather events have unique impacts on dense fog coverage and intensity. Compared with satellite fog product imagery, GIS potentially simplifies the phenomenon, and partially captures the nature of the fog intensity directly. This provides a spatial summary of a fog event, where the satellite analysis may be unreliable or unavailable (as in the warm front case).

The changing fog patterns by synoptic regime can be explained by the differences in physiographic features shown across the study area. Capturing these events in relation to specific types of synoptic classes allows for dense fog frequency determinations over the study region. Analyzing the dense fog occurrences with concurrent weather patterns, area surface character, and elevation, allows classifications and conclusions to be made with GIS; and recurring dense fog in similar cases may be anticipated.

Therefore, when derived elevation and surface-character maps are used together, the analysis of the synoptic influence on spatial patterns of dense fog in the region can be more precisely shown. To better isolate the physical relationship to dense fog evolution, future applications may utilize RGB compositing to obtain correlation coefficients of land use and elevation. Such GIS-based calculations will add microscale considerations to the generation of fog forecasts. This can benefit operational forecasting for aviation and public safety, as

numerical predictions do not consider parameters on a local scale. Future development of this tool relies on further case study and quantification of the scale of influence by physiography, which can be portrayed by a GIS-derived variable based upon elevation, surface character, weather patterns, and other factors for dense fog development.

Acknowledgements. The authors are thankful for the help and support provided by the Department of Geology and Meteorology at Kean University and Dr. John Dobosiewicz for GIS guidance and mapping suggestions. The seamless data server provided by the USGS providing NLCD 2001 surface character and SRTM elevation models is appreciated, as is the NESDIS and NWS observational data. Our gratitude is extended for the support of The College of Natural, Applied, and Health Sciences, the Epsilon Corps Program, and the Institute for Urban Ecosystem Studies of Kean University. The authors would also like to thank the reviewers of the NWA Electronic Journal for their comments and suggestions.

REFERENCES

Bendix, J., 2002: A satellite-based climatology of fog and low-level stratus in Germany and adjacent areas. *J. Atmos. Res.,* **64**: 3–18.

Cermak, J., and J. Bendix, 2005: Satellite-based nowcasting of fog and low stratus. Proceedings, *World Weather Research Programme Symposium on Nowcasting and Very Short Range Forecasting, 5-8.5.2005, Touluse (France).* CD Digest 5.06, 4 pp.

Croft, P., 2003: Fog. *The Encyclopedia of Atmospheric Sciences,* J. R. Holton, Ed., Academic Press, 777–792.

____, and A. Burton, 2005: Fog during the 2004-2005 winter season in the northern mid-Atlantic states: Spatial characteristics and behaviors as a function of synoptic weather types. Preprints, *12th Conference on Aviation, Range and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., CD-ROM, P3.3.

Ellrod, G. P., and S. Lindstrom, 2006: Performance of satellite fog detection techniques with major, fog-related highway accidents. *Electronic J. of Oper. Meteor.*, 2006-EJ3, 10 pp.

Tardif, R., and R. M. Rasmussen, 2007: Event-based climatology and typology of fog in the New York City region. *J. Appl. Meteor. Climatol.,* **46,** 1141−1168.

Underwood, J., and C. Hansen, 2007: A method for surveying urban clear islands in radiation fog and low stratus cloud using geostationary satellite imagery: Applications in the San Joaquin Valley of California. Proceedings, *32nd Annual Meeting of the National Weather Association, Reno, NV.*

Valdez, J., 2000: *National Weather Service, a High Impact Agency...We Make a Difference*, *Reinvention goals for 2000*. National Weather Service, National Oceanic and Atmospheric Administration, United States Department of Commerce, Washington, D.C. [Available online at http://govinfo.library.unt.edu/npr/library/announc/npr5.htm].

Whiffen, B., P. Delannoy, and S. Siok, 2004: Fog: Impact on road transportation and mitigation options. National Highway Visibility Conference, Madison, WI, 18−19 May 2004.

ABOUT THE AUTHORS

Braden Ward holds a B.S. degree in Earth Science (Meteorology Option), minor Computer Science, Magna cum Laude from Kean University (2008). Braden is a student member of the National Weather Association and has presented at national, regional, and local conferences. He is currently working with Paul Croft on a COMET-funded study on convection in New Jersey. His interests lie in studies on operational forecasting and studying weather phenomena through computer modeling research.

Paul J. Croft, a Ph.D. graduate of Rutgers University (1991), is a Meteorology Professor and Director of the Center for Earth System Education in the Department of Geology and Meteorology at Kean University and is responsible for teaching, research, and service activities. As a member of the National Weather Association since 1983, he has served in several capacities

(including President in 2004). His interests are in operations-based research and applications in meteorology. He has worked with students and professional meteorologists, particularly in the operational community, for more than 25 years.

TABLES AND FIGURES

Table 1. List of ASOS identifiers (left column) and the corresponding airport/location names with city and state (right column) for ASOS stations used in this study and plotted in Fig. 1c.

KABE	Lehigh Valley International Airport, Allentown, PA
KACY	Atlantic City International Airport, Atlantic City, NJ
KBDR	Igor I Sikorsky Memorial Airport, Bridgeport, CT
KEWR	Newark Liberty International Airport, Newark, NJ
KGED	Sussex County Airport, Georgetown, DE
KILG	New Castle Airport, Wilmington, DE
KISP	Long Island Mac Arthur Airport, Islip, NY
KJFK	John F Kennedy International Airport, New York, NY
KLGA	La Guardia Airport, New York, NY
KMPO	Pocono Mountains Municipal Airport, Mount Pocono, PA
KNYC	Central Park, New York, New York
KPHL	Philadelphia International Airport, Philadelphia, PA
KPOU	Dutchess County Airport, Poughkeepsie, NY
KRDG	Reading Regional Airport/Carl A Spaatz Field, Reading, PA
KTTN	Trenton Mercer Airport, Trenton, NJ

Table 2. Summary of fog events observed at each ASOS station during the period of study. Values are plotted in Figs. 2a (total fog events) and 2b (only dense fog events) using GIS.

Station ID	KABE	KACY	KBDR	KNYC	KEWR	KGED	KILG
Fog Reports (excluding dense)	26	25	22	29	27	41	28
Dense Fog Reports	7	7	6	3	4	4	13
Total	*33*	*32*	*28*	*32*	*31*	*45*	*41*

Station ID	KISP	KJFK	KLGA	KMPO	KPHL	KRDG	KTTN	KPOU
Fog Reports (excluding dense)	28	14	22	20	25	29	33	33
Dense Fog Reports	6	10	2	20	8	12	6	6
Total	*34*	*24*	*24*	*40*	*33*	*41*	*39*	*39*

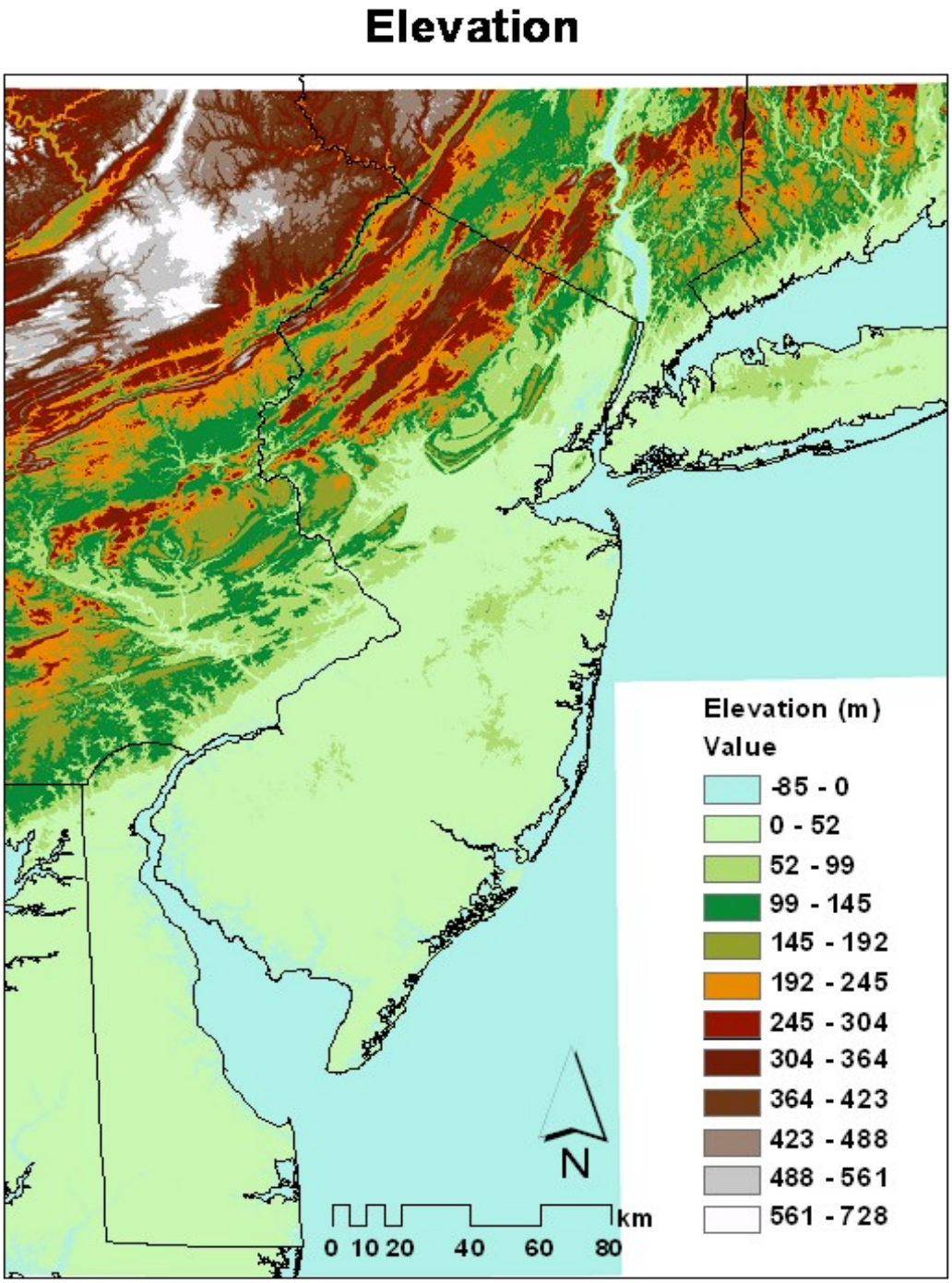

Figure 1a. GIS display of elevation (meters) across the study region. Data were derived from the Shuttle Radar Topography Mission (SRTM).

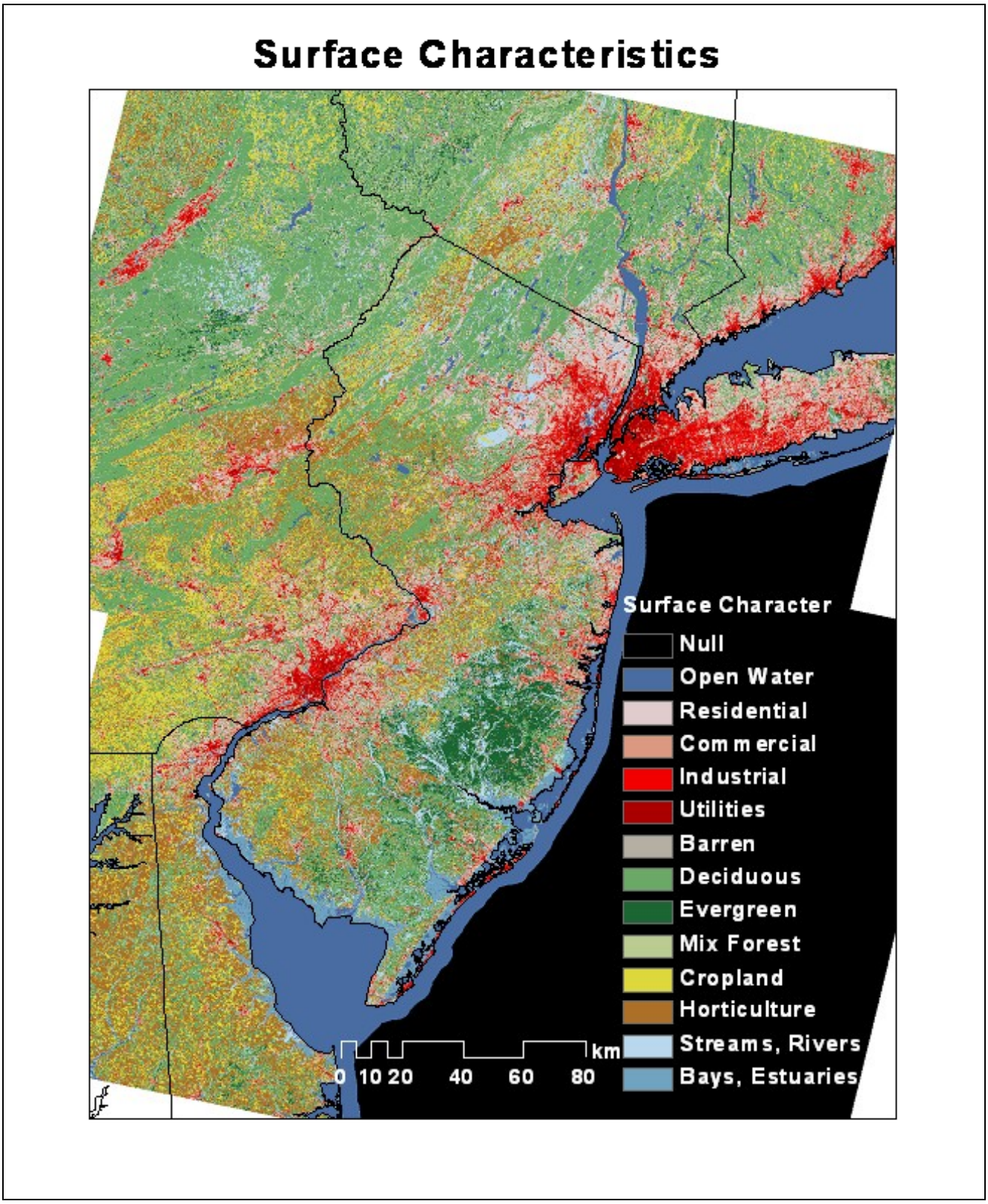

Figure 1b. GIS display of the surface characteristics across the study region. Data were derived from the 2001 National Land Cover Data (NLCD).

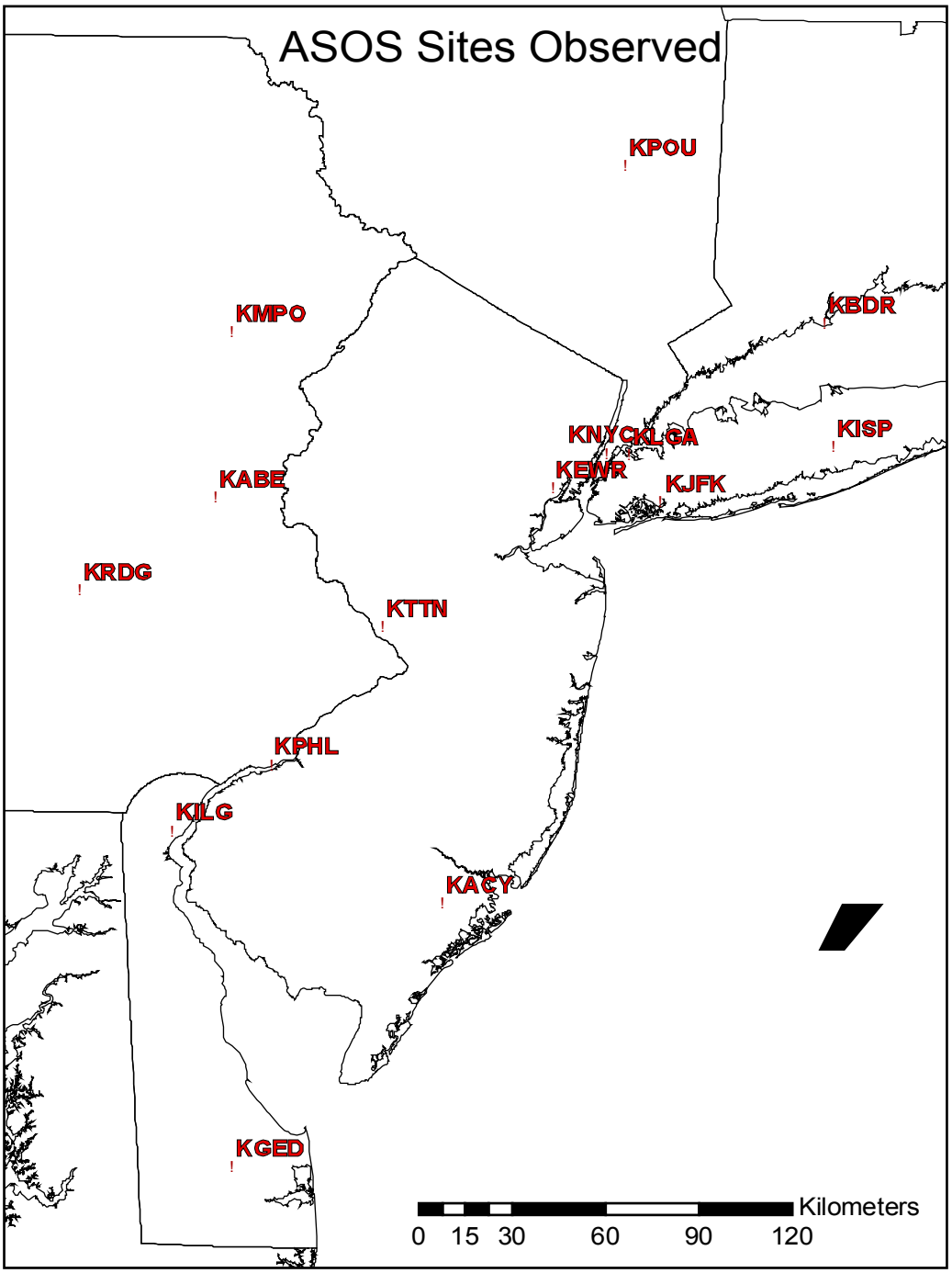

Figure 1c. ASOS stations (by four-letter identifier, and listed in Table 1) used to identify fog reports across the study region.

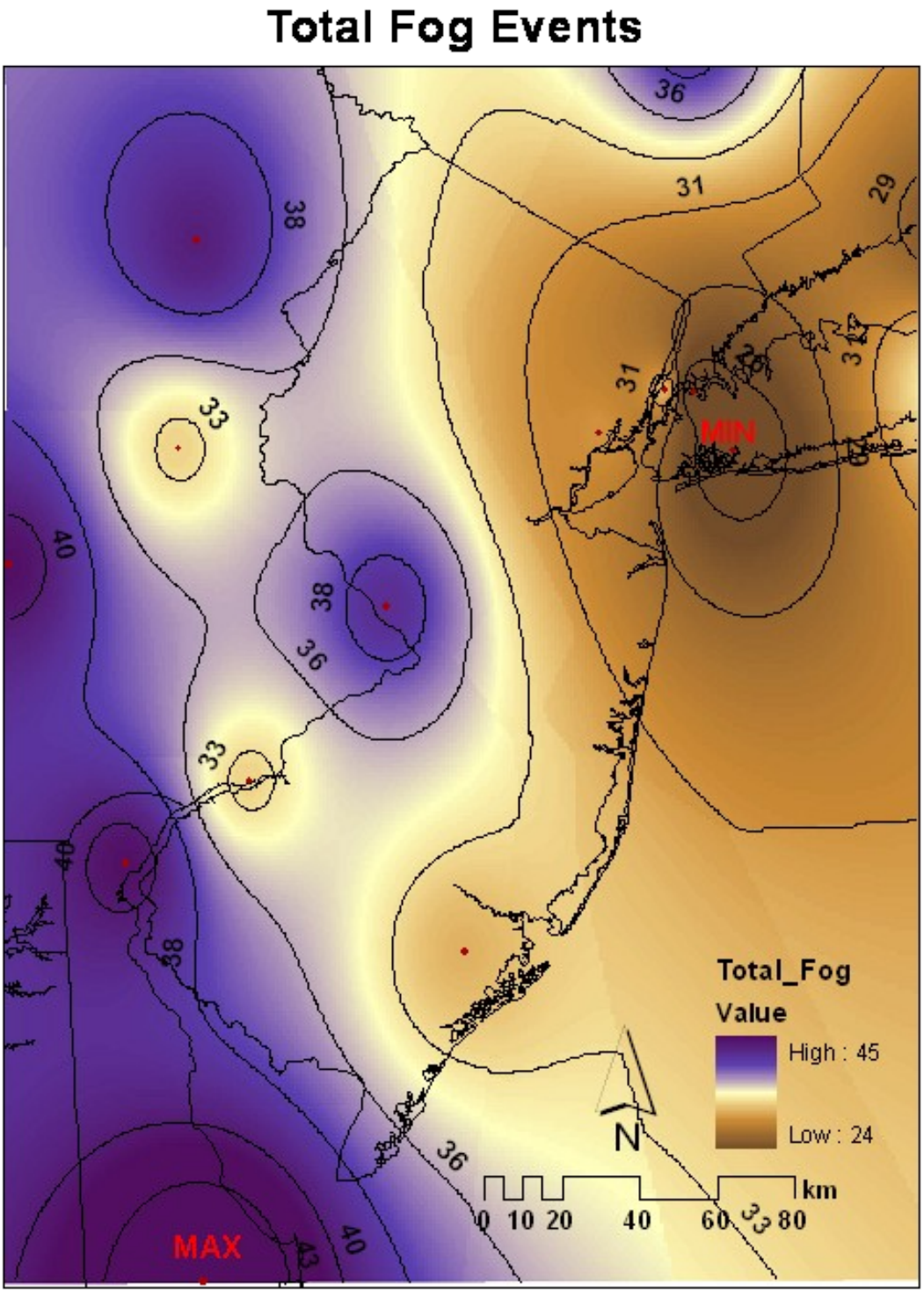

Figure 2a. Total fog event frequencies (dense and non-dense combined) across the study area (GIS-interpolated). Maximum (45 KGED) and minimum frequencies (24 KJFK) are shown in red (MAX, MIN) and appear in Table 2.

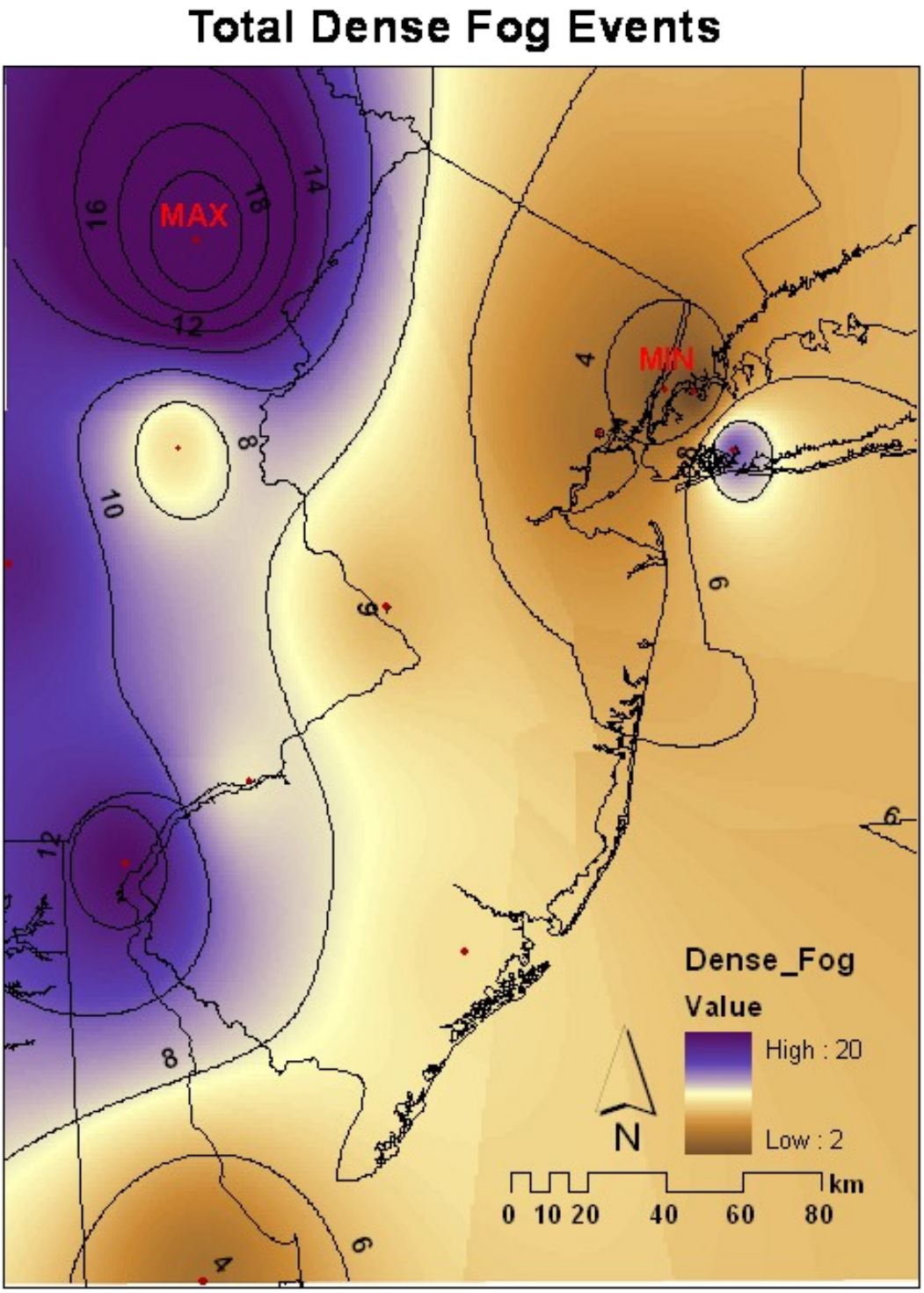

Figure 2b. Total dense fog events for the study area. Maximum (20 KMPO) and minimum (2 KLGA) values are shown in red (MAX, MIN) and appear in Table 2.

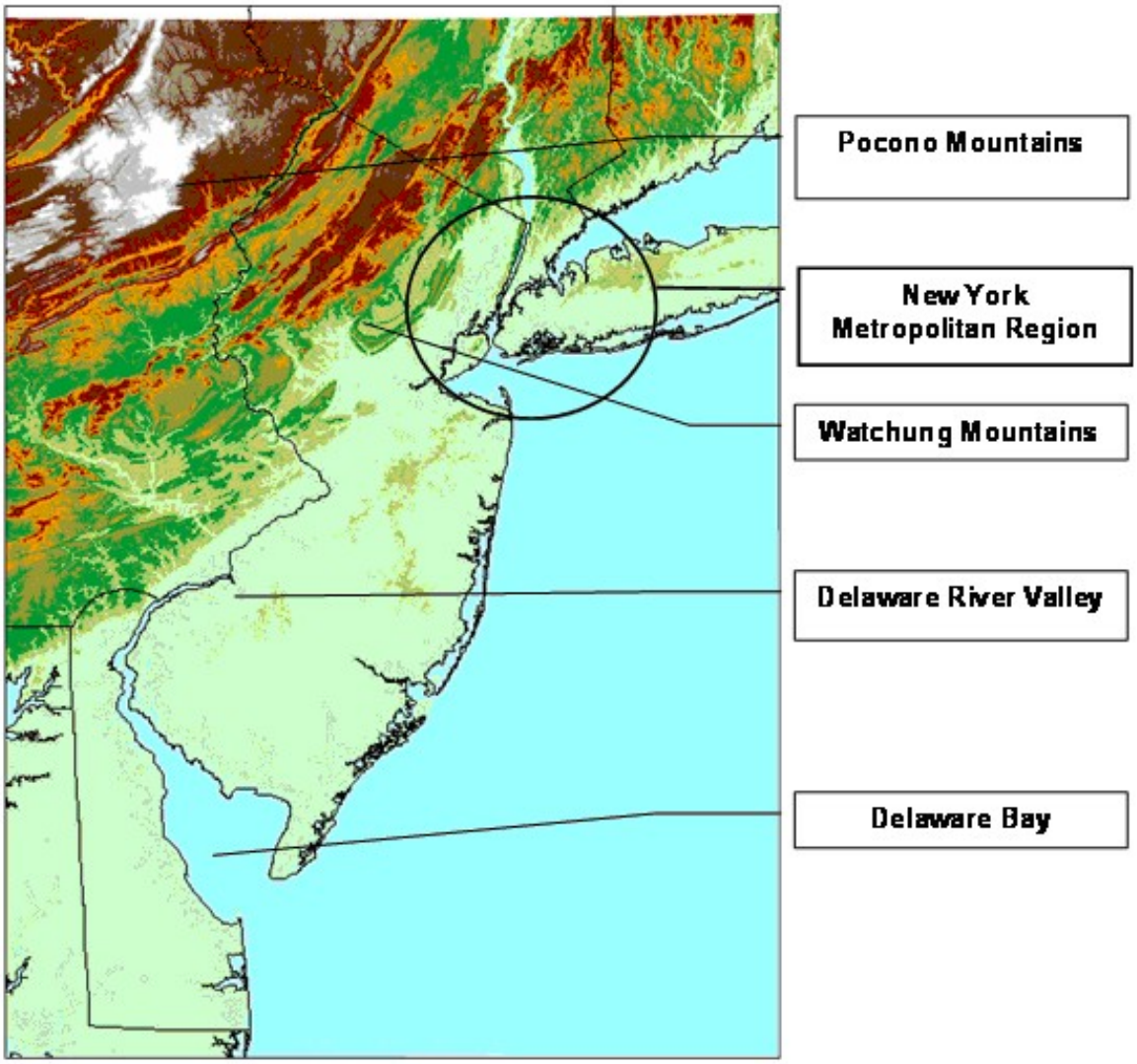

Figure 2c. Similar to Fig. 1c except that certain geographic features have been annotated to highlight areas of interest that are discussed within the analysis section of the paper.

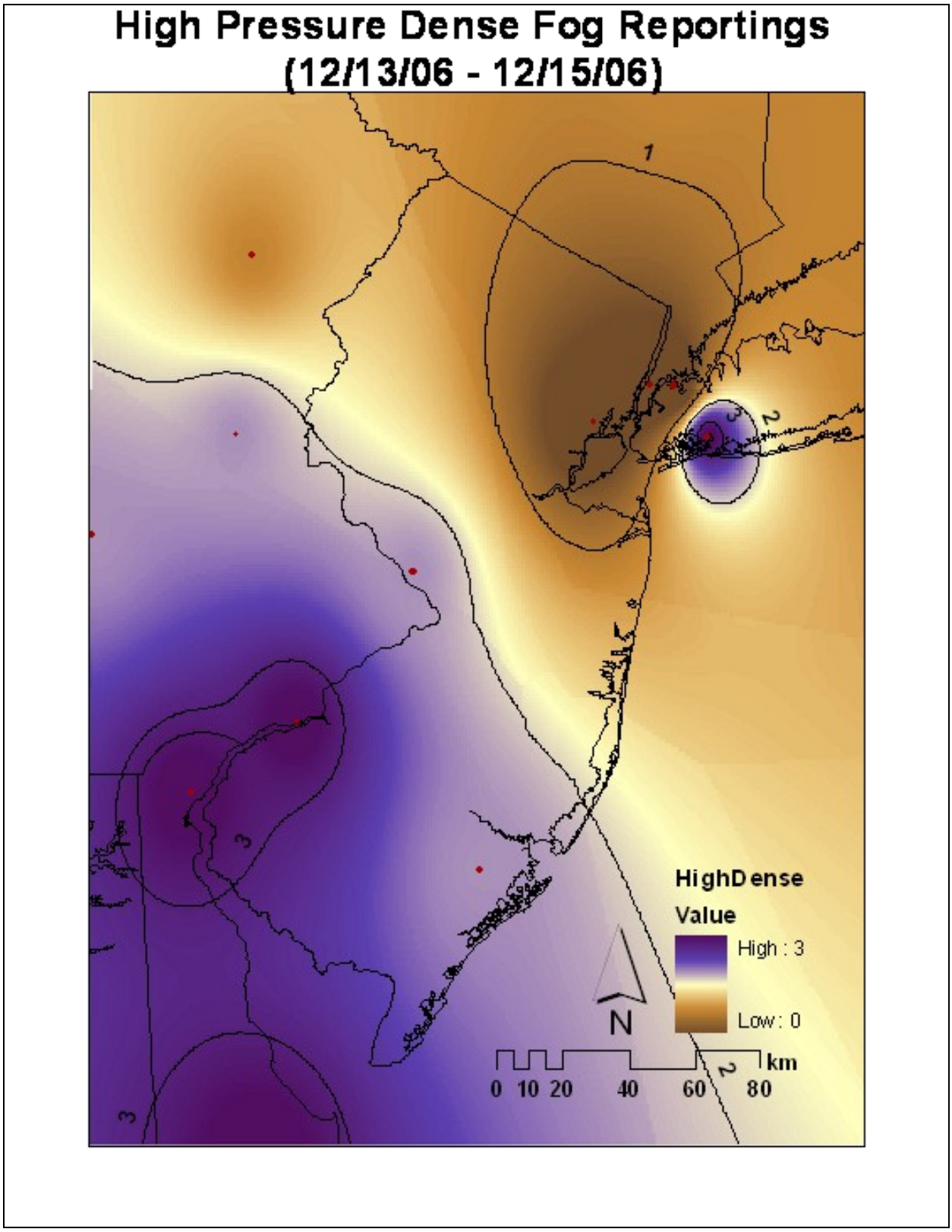

Figure 3a. Dense fog reports for the 3-day period of high pressure (13−15 December 2006).

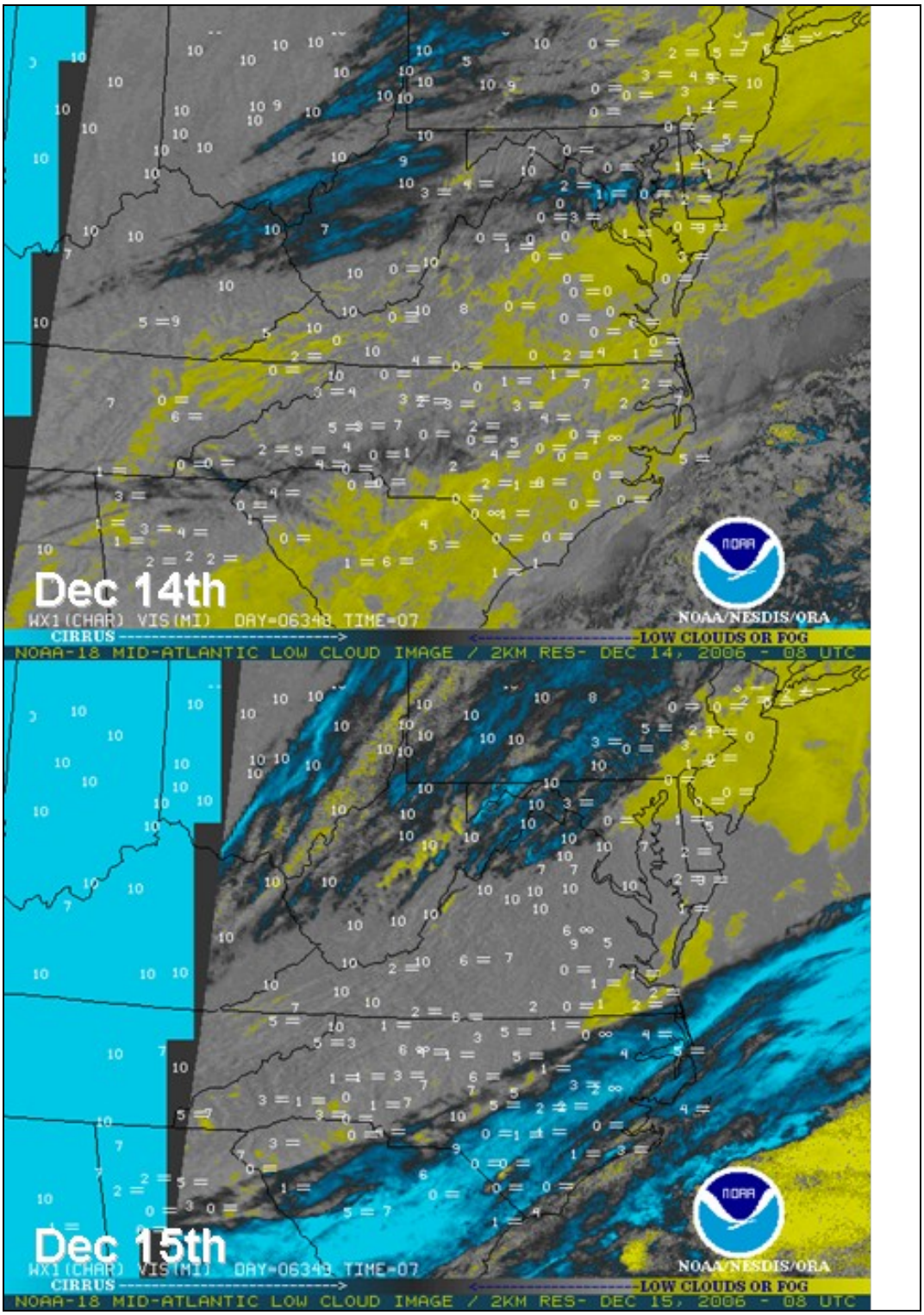

Figure 3b. NESDIS fog-product imagery showing spatial coverage of fog (shown in yellow) and surface weather reports for 0800 UTC 14 December 2006 (top) and 15 December 2006 (bottom).

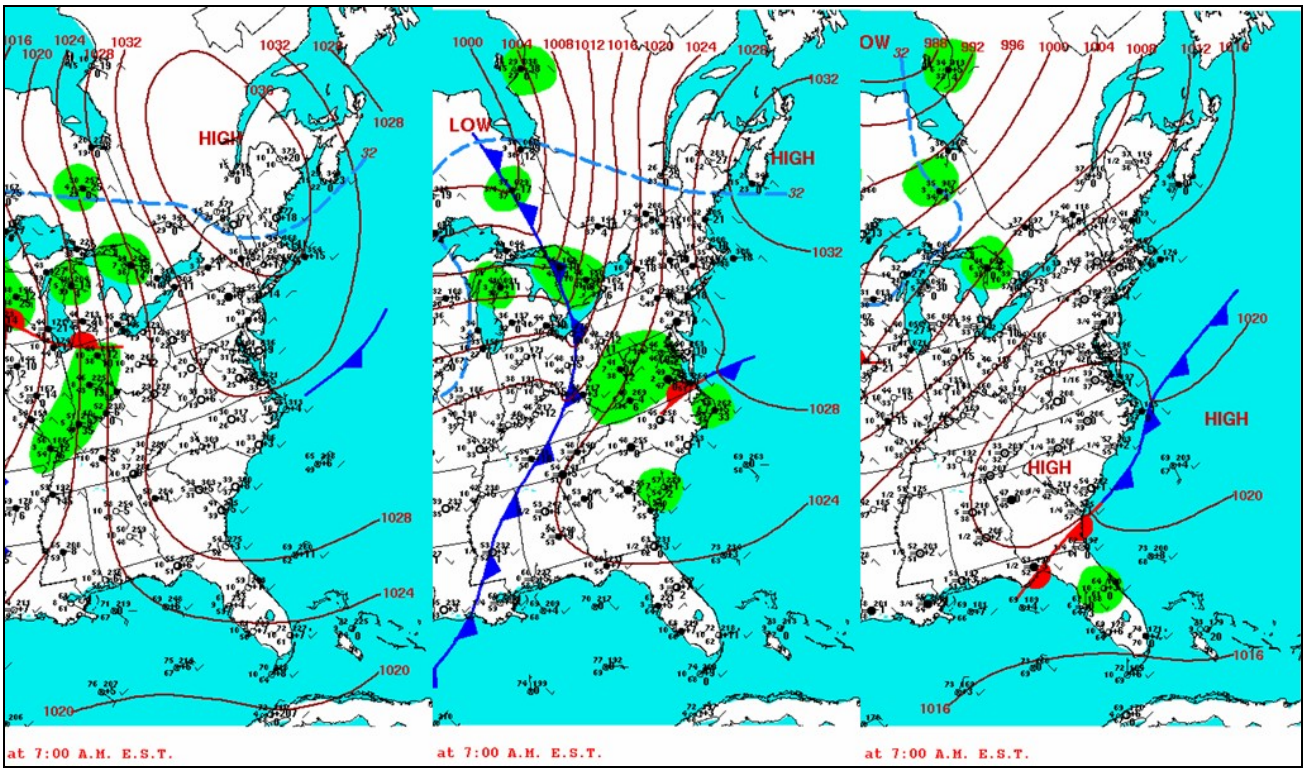

Figure 3c. Daily weather map series from the Hydrometeorological Prediction Center (HPC) for the 13−15 December 2006 event. Sequence illustrates the progression of the synoptic regime during the development and/or maintenance of the dense fog event.

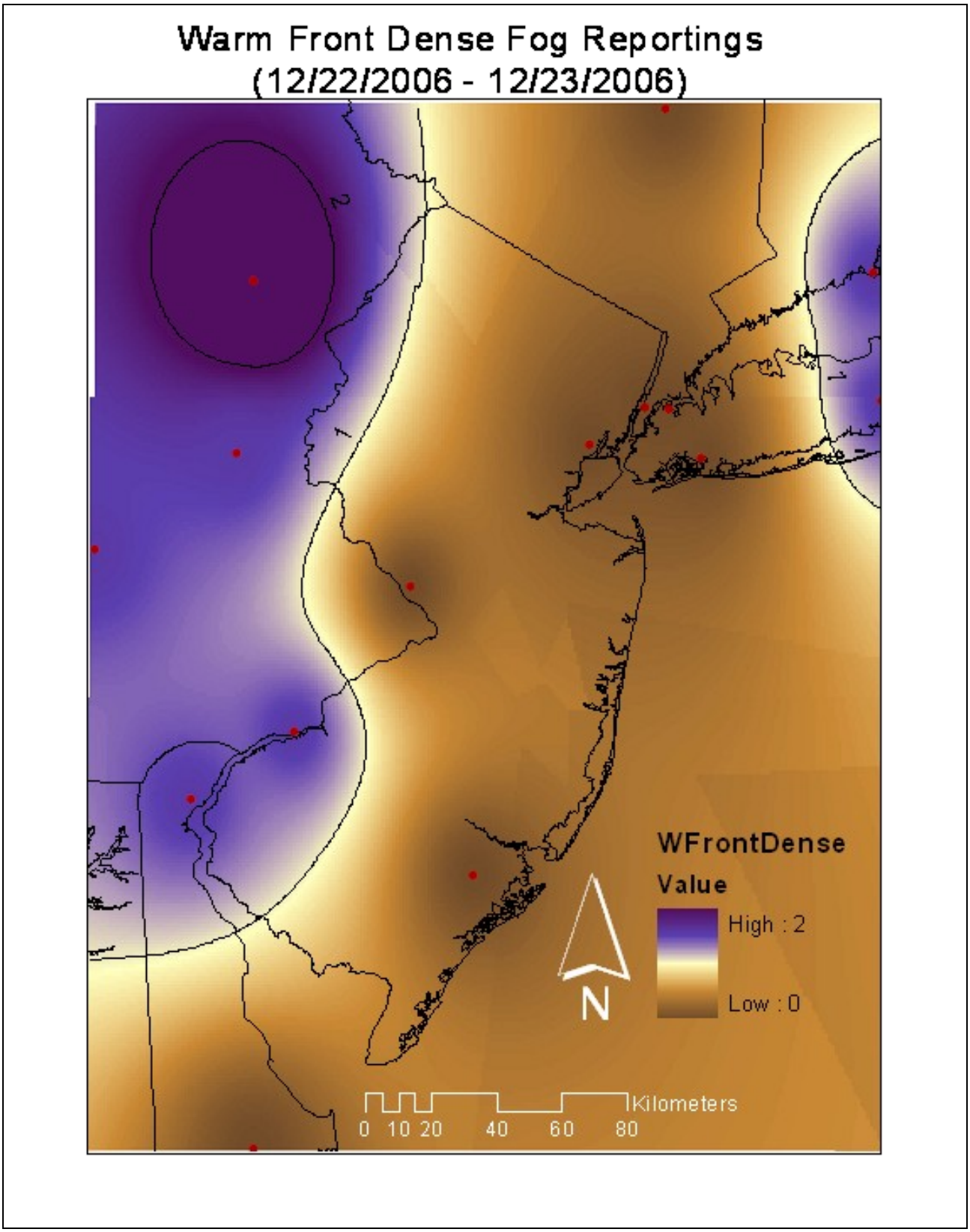

Figure 4a. Dense fog reports for the 2-day period of warm frontal passage (22–23 December 2006).

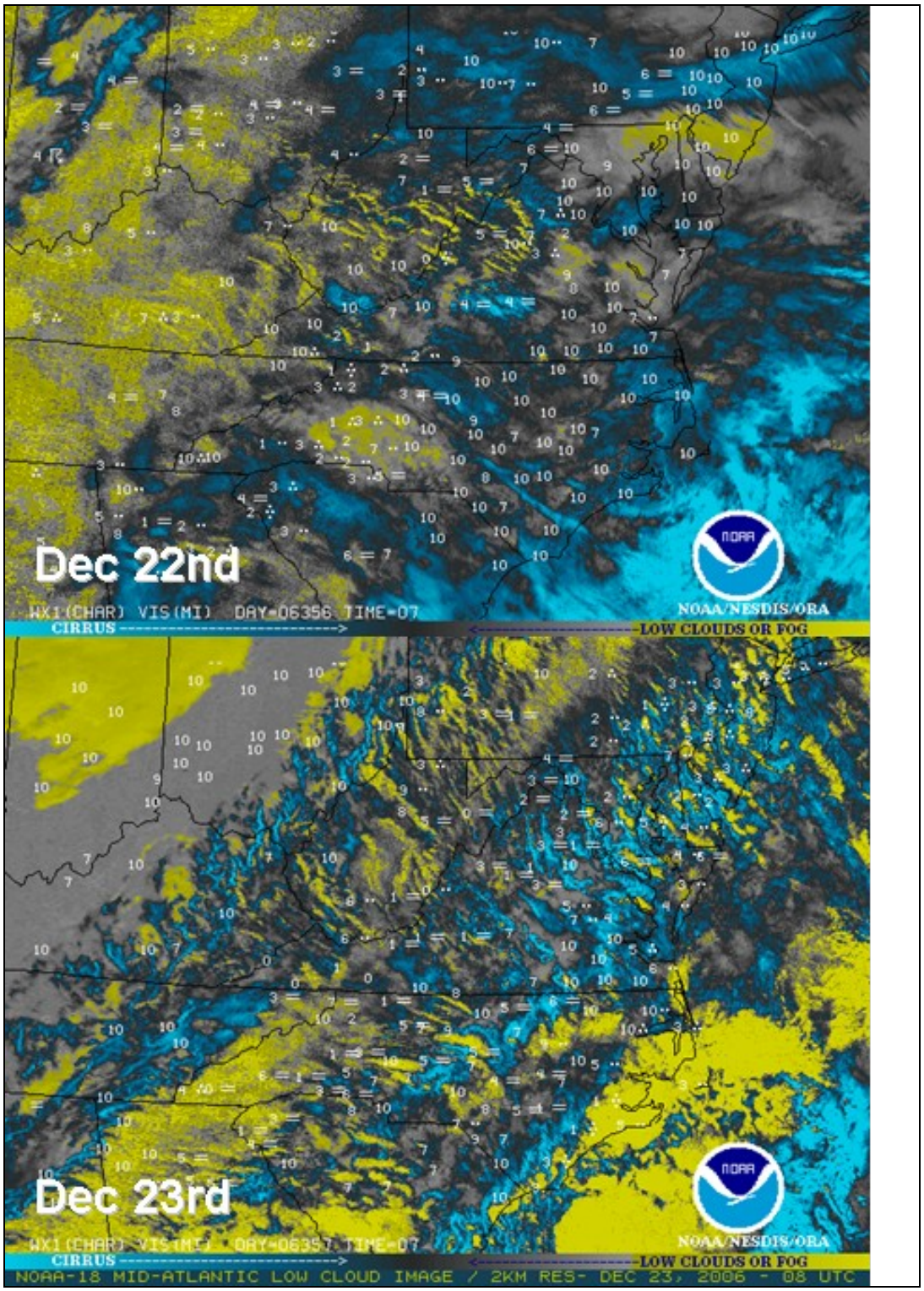

Figure 4b. Same as Fig. 3b but for 0800 UTC 22 December 2006 (top) and 23 December 2006 (bottom).

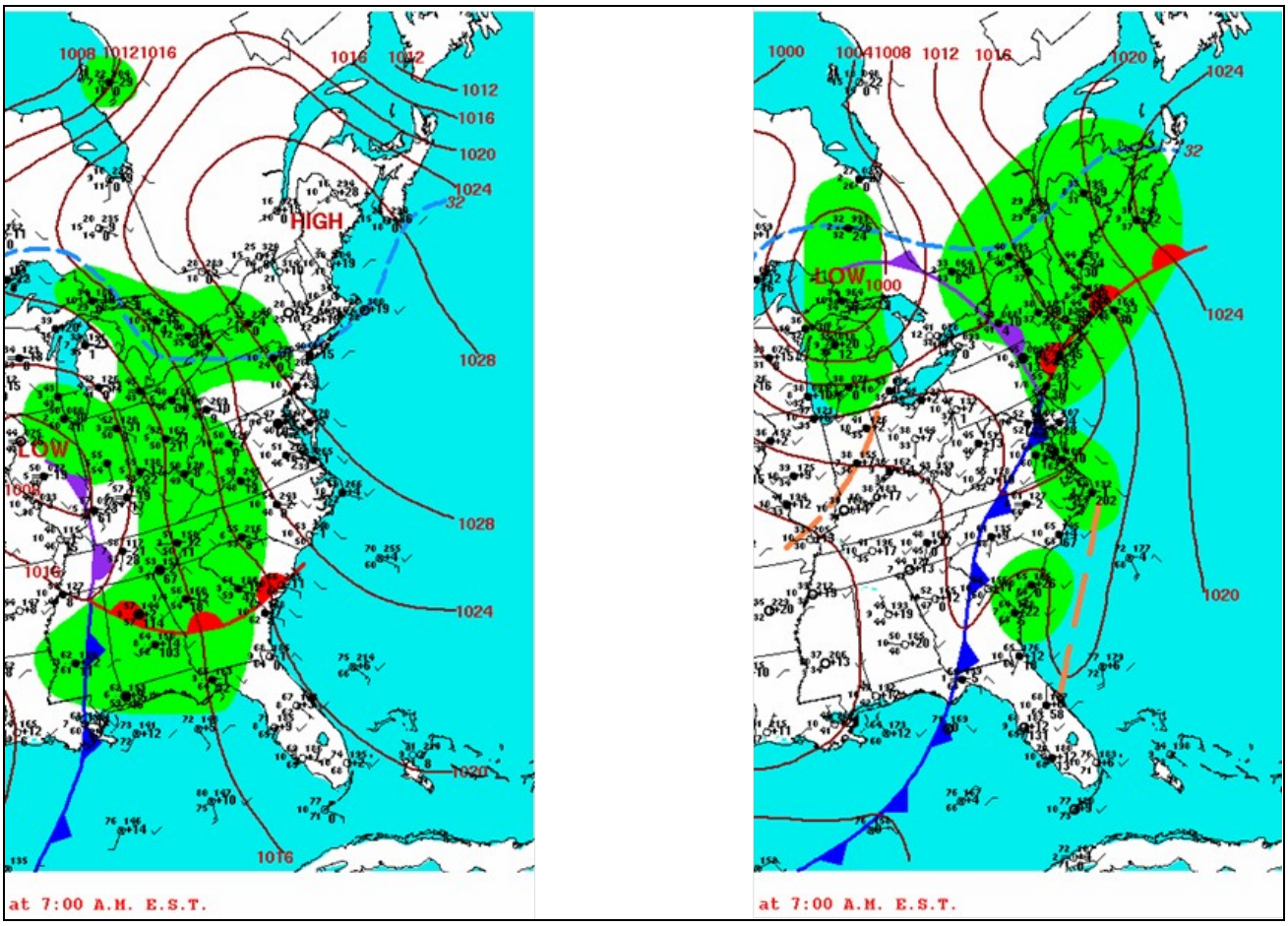

Figure 4c. Same as Fig. 3c but for the 22−23 December 2006 event.

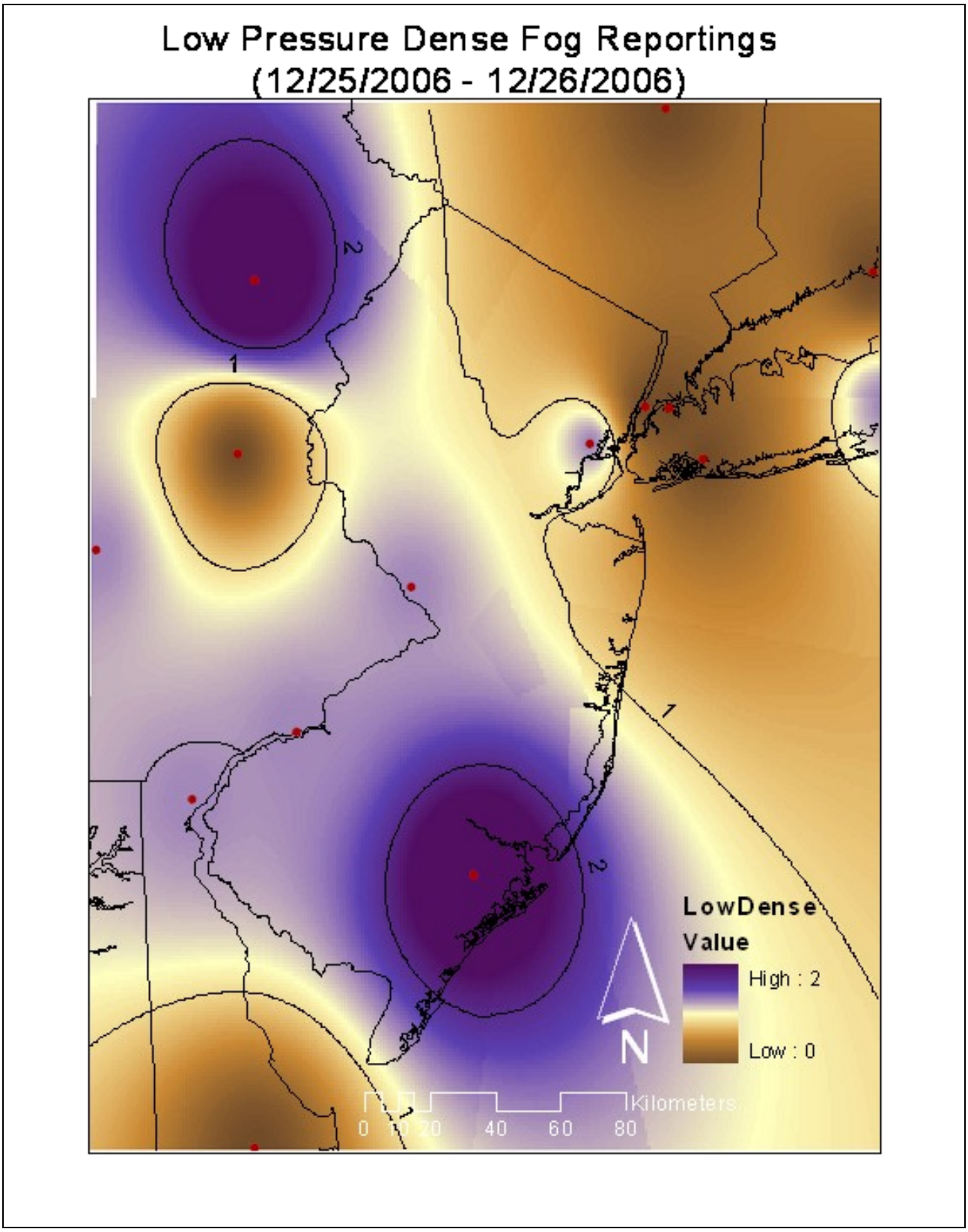

Figure 5a. Dense fog reports for the 2-day period of low pressure (25−26 December 2006).

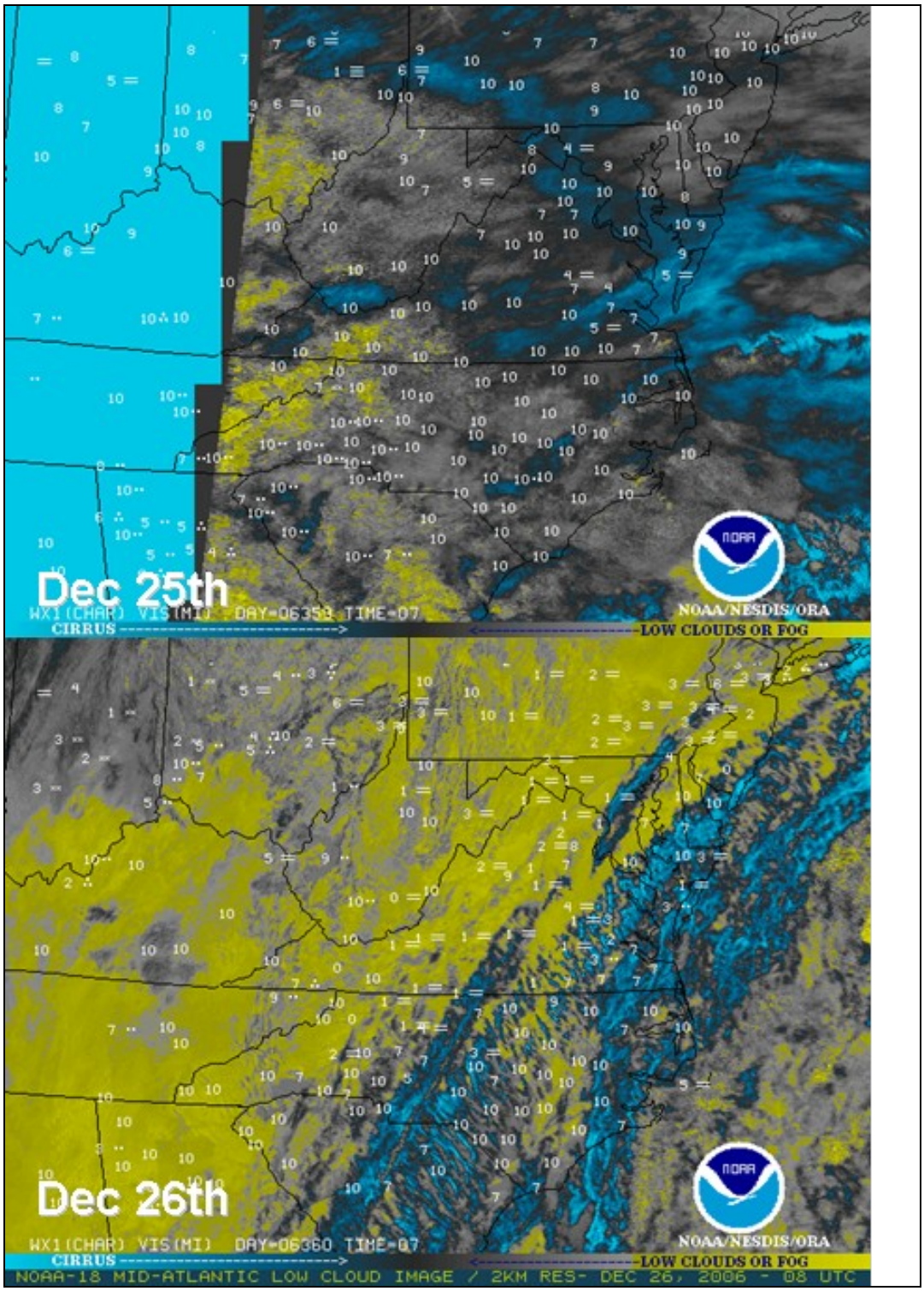

Figure 5b. Same as Fig. 3b but for 0800 UTC 25 December 2006 (top) and 26 December 2006 (bottom).

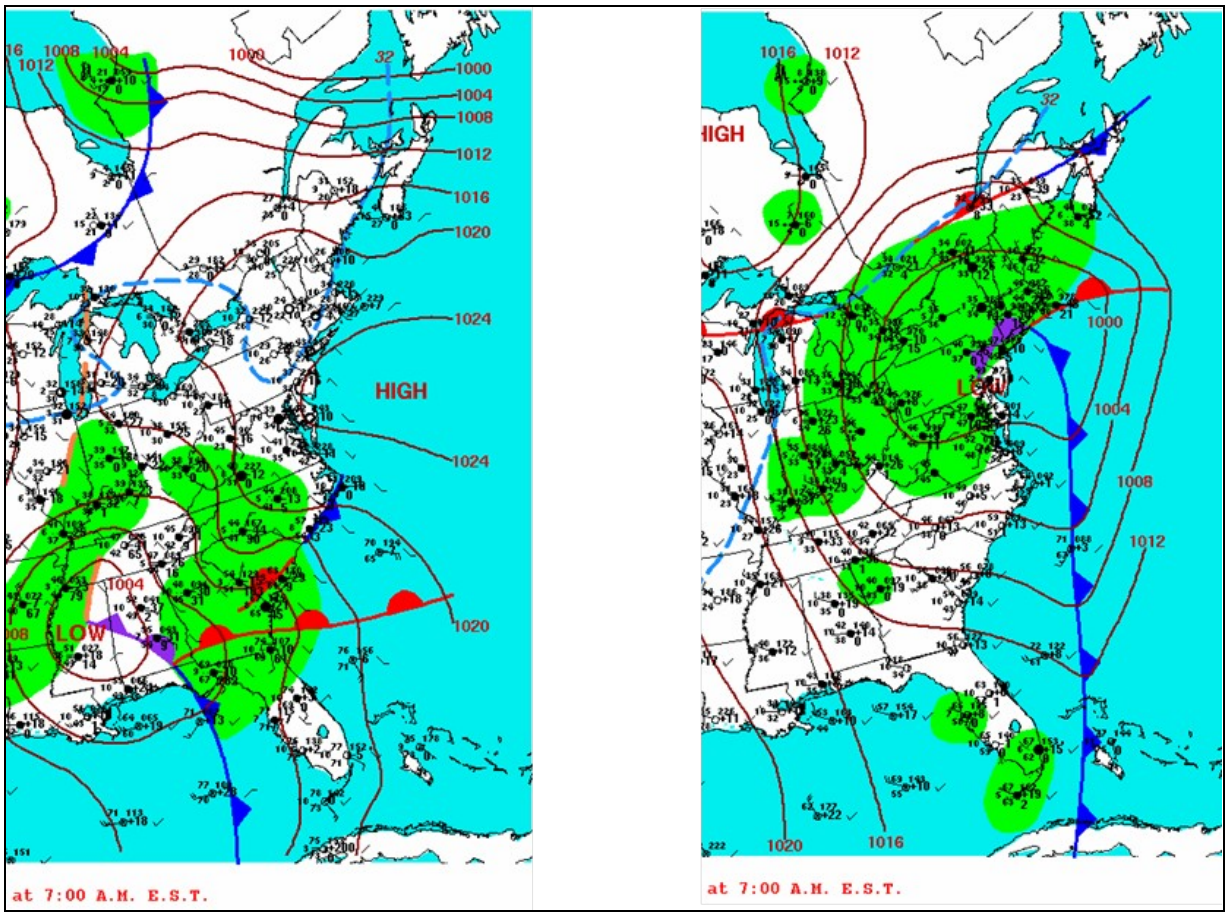

Figure 5c. Same as Fig. 3c but for the 25−26 December 2006 event.

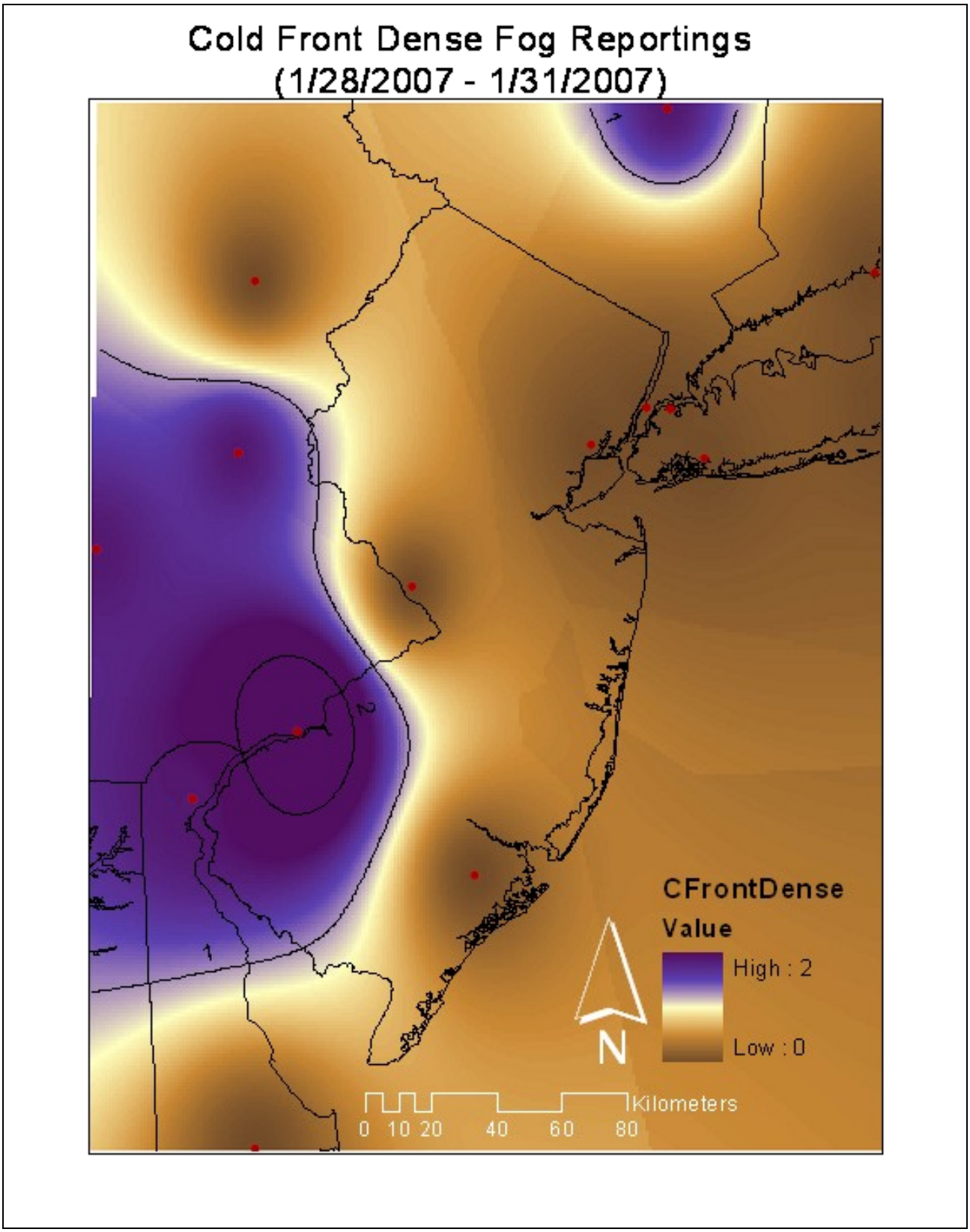

Figure 6a. Dense fog reports for the 4-day period of cold frontal passage (28−31 January 2007).

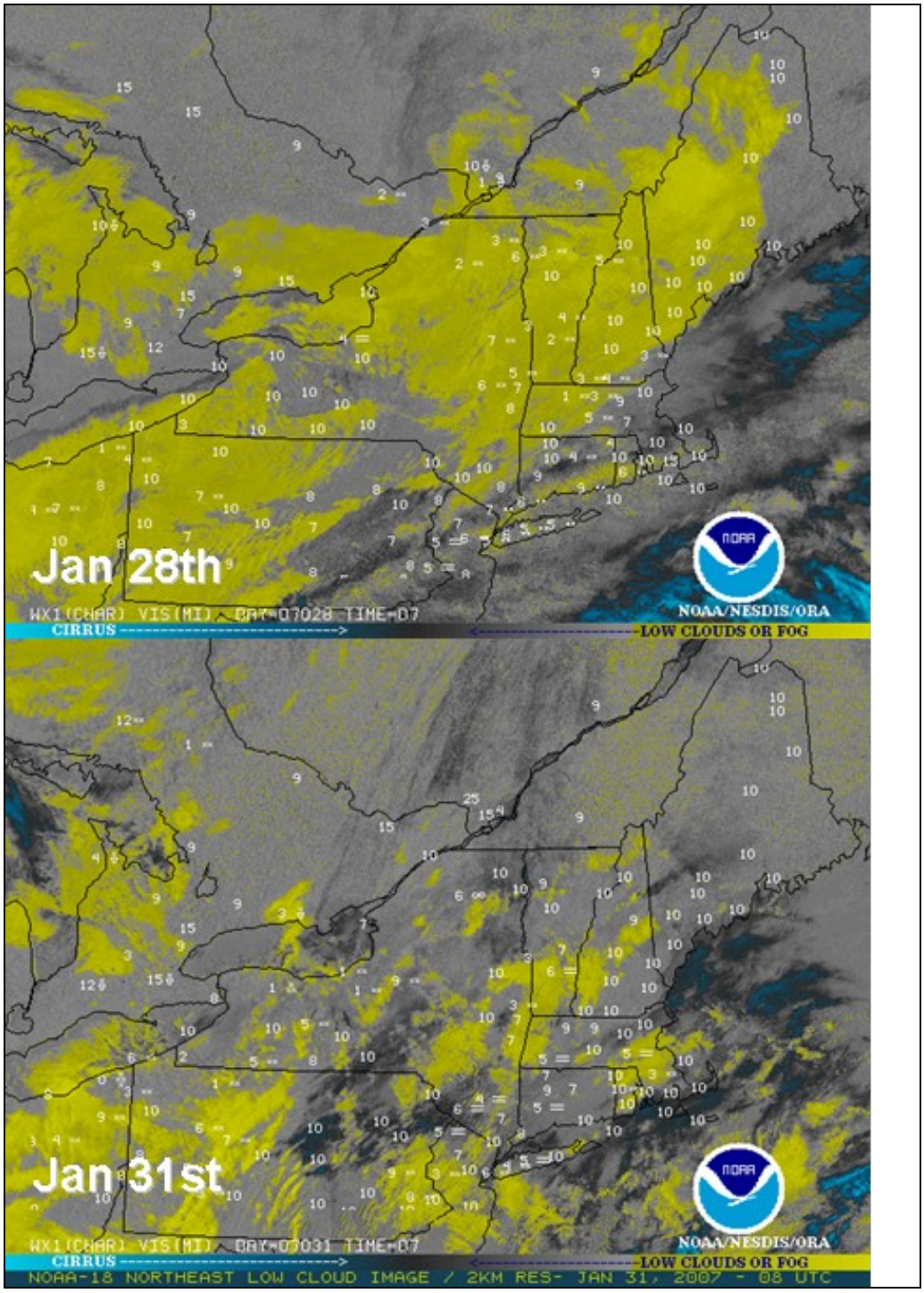

Figure 6b. Same as Fig. 3b but for 0800 UTC 28 January 2007 (top) and 31 January 2007 (bottom).

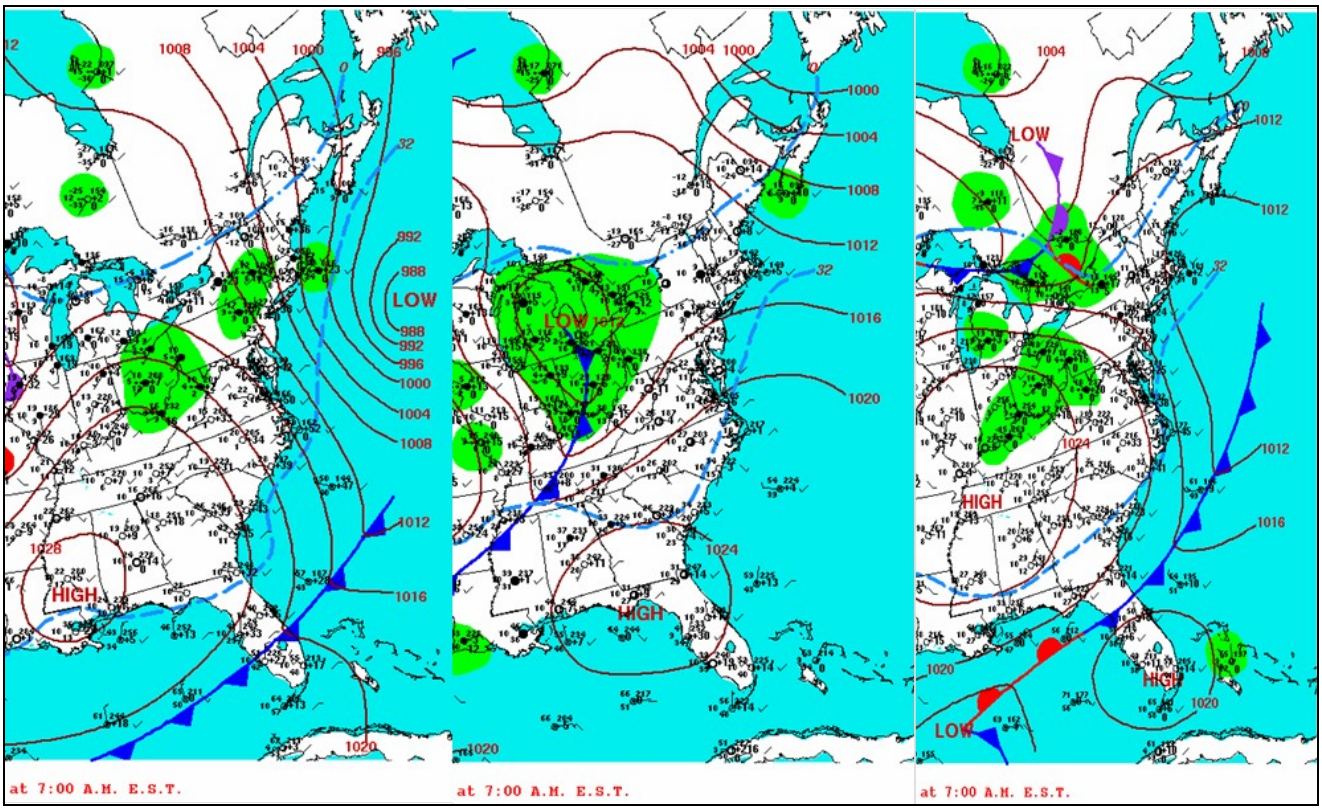

Figure 6c. Same as Fig. 3c but for the 29–31 January 2007 event.