P10.6 CHARACTERIZING FOG OCCURRENCES IN THE NORTHEASTERN UNITED STATES USING HISTORICAL DATA

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1. INTRODUCTION

Advances in the understanding of the physics of fog have been made through numerous field experiments and modeling studies. Nevertheless a complete understanding of the processes and interactions influencing its life cycle remain elusive. This is particularly true for fog and other boundary layer clouds occurring in areas characterized by a complex landscape. One such region is the New York metropolitan area, where fog is a common occurrence. This area is of particular interest since it is heavily populated and thus is characterized by heavy air and road traffic. In fact, low ceilings and visibility is identified as important causes of delays at the major airports in the area (Allan et al., 2001). The complexity of the landscape, with a complex coastline and significant variations in land surface characteristics (urban, suburban, rural areas, rivers and lakes), along with high levels of pollution, provides for a wide range of influences which can potentially affect the dynamical behavior and microphysical characteristics of fog and stratus clouds.

As first steps toward a greater understanding of the fog phenomenon in the northeastern United States, the emphasis of the present study is on identifying and describing the various fog regimes affecting several locations in a region centered on New York City. This is in contrast with the study of Meyer and Lala (1990) (hereafter referred to as ML90), which concentrated on a single type of fog for one location in the Hudson Valley, New York. The analysis is performed based on the identification of *events* from hourly observations following a simple set of rules. Focusing on fog events, rather than evaluating statistical parameters based on individual hourly reports, is useful in determining the nature of the fog a particular location may experience. Once events have been identified, an analysis of conditions at the time of onset, as well as a few hours before, can help identify mechanisms that contributed to the formation of fog. As such, a “fog type” classification of events is performed based on conditions at and before onset, seeking a more quantitative assessment of the likelihood with which expected mechanisms leading to fog formation may be occurring in various parts of the region. This type of analysis has already been performed for advection-radiation and sea fogs in the Los Angeles basin by Baars et al. (2003).

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2. DATA AND PROCEDURE

2.1 *Historical data*

The main data used to establish the fog climatology were taken from the National Oceanic and Atmospheric Administration (NOAA) Techniques Development Laboratory (TDL) Surface Hourly Observations dataset archived at the National Center for Atmospheric Research (NCAR). Hourly surface observations of visibility, temperature, dew point temperature, wind speed and direction, ceiling height, cloud cover, coded obstruction to vision, precipitation type and intensity, were gathered for the period corresponding to 1977 to 1996 inclusively. A total of 17 stations are considered. The locations of were chosen such that various influences characterizing the region are represented. Stations located within heavily urbanized areas, along the coastlines of the Atlantic Ocean and Long Island Sound, as well as stations located farther inland in Connecticut, southern New York, central New Jersey and eastern Pennsylvania were chosen. Only stations reporting during the whole diurnal cycle (24 hours) and with a high percentage of data availability were retained. Table I presents the list of stations used in this study.

Table I. List of stations from which data is used to establish the fog climatology for the northeastern US, and their elevation above mean sea level.

Station ID	Station name	Elevation (m)
EWR	Newark, NJ	7
JFK	John F. Kennedy, NY	9
LGA	LaGuardia, NY	11
ISP	Islip/McArthur, NY	43
TEB	Teterboro, NJ	7
HPN	White Plains, NY	121
POU	Poughkeepsie, NY	46
BDR	Bridgeport, CT	7
BDL	Hartford, CT	60
PVD	Providence, RI	16
ABE	Allentown, PE	114
WRI	McGuire AFB, NJ	41
PNE	North Philadelphia, PE	28
PHL	Philadelphia, PE	18
ACY	Atlantic City, NJ	23
MIV	Millville, NJ	23
ILG	Wilmington, DE	28

2.2 *Identification of fog events*

The usual definition of fog requires the observed horizontal visibility to be below 1 km. Here, a slightly different definition is used by considering the various flight categories as defined in the United States. Events are defined as long enough periods during which the visibility is less than 1 statute mile (1.6 km). This threshold partly corresponds to the definition of Low Instrument Flight Rules (LIFR). The onset of a possible event is identified as the first hour at which the visibility goes below 1.6 km in association with fog. This means that fog, ground fog or ice fog must be reported at the same time visibility is reduced. If the subsequent observations indicate a visibility at or below 1.6 km for at least three consecutive hours and at least one of these visibility reports indicate a value below 5/8 of a mile (1 km), then a potential event is flagged. This condition is used to retain only the events characterized by *dense* fog. Then, visibility observations are checked to determine if at least one hourly report is characterized by reduced visibility without the presence of precipitation. If this is verified, then an event has been formally identified. This check is done to avoid periods where precipitation is the main phenomenon impacting visibility throughout the event. The end of an event is defined as a report of reduced visibility followed by three or more consecutive reports of visibility with values above 1.6 km. The criteria used here are somewhat arbitrary but provide a simple mean of capturing the more significant reduced visibility events in association with the presence of fog.

2.3 *Fog type classification*

Once identified, fog events are classified according to fog types reflecting the main mechanism leading to their formation. After an extensive review of observations, five different types of fog were identified: precipitation fog, radiation fog, advection fog, fog occurring through the lowering of cloud base and fog forming due to evaporation at the surface at sunrise.

Fog events are first divided into precipitation and non-precipitation events. An event induced by precipitation is defined when some type of precipitation is observed at the onset of the event and/or during the previous two hours. The hypothesis is that the moistening of the lower atmosphere by the evaporation of precipitation is the main factor leading to fog onset. For the non-precipitation events, observations at the time of onset and the previous five hours are used in order to identify the possible mechanisms leading to onset.

A radiation fog event is identified whenever fog onset is characterized by cooling of the 2-m temperature with light wind speeds and absence of a ceiling the hour before. Light winds are defined here as speeds below 2.5 m s^{-1}. In order not to be too restrictive, a radiation fog event is also identified if cooling is observed as the ceiling height is increasing, again under light wind conditions, or when a very low ceiling appears before onset in association with a significant and sudden downward jump in ceiling height, also under light wind conditions. This is done to consider cases when light fog forms before a denser fog. As indicated by ML90, light and patchy fog often occurs hours before the onset of dense radiation fog. In some instances, it has been found that due to the hourly resolution in the data, some radiation fog events seem to be associated with some warming in the hour onset occurs. This can occur if dense fog forms after an observation was taken and sufficiently long enough before the next one. Then, IR radiation emission by fog droplets can lead to an increase in the near-surface temperature. Thus the classification scheme also allows for some warming in the hour during which onset occurs, if a significant period of cooling characterizes the time period before, under cloudiness conditions outlined above.

In general terms, advection fog occurs as moist air flows over a cold surface. The most common occurrences of advection fog occur at sea and are usually referred to as sea fog. Advection fog can also occur over land, although it is observed less frequently. This type of fog is expected to appear as an incoming “wall” of fog, formed upstream as moist air is cooled over a cold surface. In terms of surface observations, this would translate into a sudden reduction in visibility in association with flow at a significant speed. Here, a wind speed above 2.5 m s^{-1} is considered to be significant. Following an extensive review of observations, it also appears that advection fog may appear in the data as an initial and sudden appearance of a ceiling at heights below 300 m followed closely by a reduction in visibility. In the classification scheme used here, the low ceiling must not appear more than two hours before the onset of dense fog.

The onset of fog related to the lowering of cloud base is identified whenever a reduction in visibility below 1.6 km is observed to occur following a gradual lowering of ceiling heights over the 6 previous hours, regardless of wind direction or speed. Ceiling heights must be observed to be below 1 km during that time period in order for the event to be classified as a fog resulting from cloud base lowering.

The formation of fog related to the evaporation of surface water at sunrise (morning evaporation fog) is identified whenever an event begins after nighttime cooling within an hour of sunrise, as warming of the near-surface temperature occurs in conjunction with a larger increase in the dew point temperature. No conditions on wind speed or direction are applied. If a fog event does not meet all the criteria outlined above, or if there is insufficient valid data before onset, it is classified as “indeterminate”.

3. RESULTS

Using the rules described in section 2.2, fog events are identified from time series of surface observations at the 17 stations listed in Table I. A total of 5904 events were identified in the dataset composed of data taken from 1977 to 1996 at all stations.

3.1 *Spatial distribution of events*

The total number of events identified in the dataset is presented for every station in Figure 1. Results indicate a significant variability in the occurrence of fog events within the region. For instance, locations more directly influenced by the marine environment (e.g. ISP, ACY, MIV, JFK and PVD) have the highest number of events. In contrast, the more urbanized locations (e.g. EWR, TEB, LGA, and PHL) clearly exhibit the lowest number of fog events. This is likely related to the weaker cooling rates that such areas experience during the night, leading to the formation of an urban heat island, thus diminishing the likelihood of fog forming as a result of radiative cooling (Sachweh and Koepke, 1995). Furthermore, minima in the number of fog events in the urban core of New York City and around Philadelphia (PHL) correspond very well to the nocturnal temperature pattern shown in Gedzelman et al. (2003), with the highest temperatures found in these urban areas.

White Plains (HPN) stands out as a positive anomaly among stations in the region with 647 events. This is related to local effects such as moisture sources and topography, as the station is located near an important reservoir and experiences a slight upslope flow when the wind is blowing from Long Island Sound. The data also shows a maximum in fog events in the coastal plain of New Jersey, where nocturnal cooling over land and advection of moist air from the ocean are likely to interact to enhance the likelihood of fog formation. The overall features of the resulting spatial distribution are consistent with the larger scale analysis presented by Peace (1969) although the present analysis provides a greater degree of details.

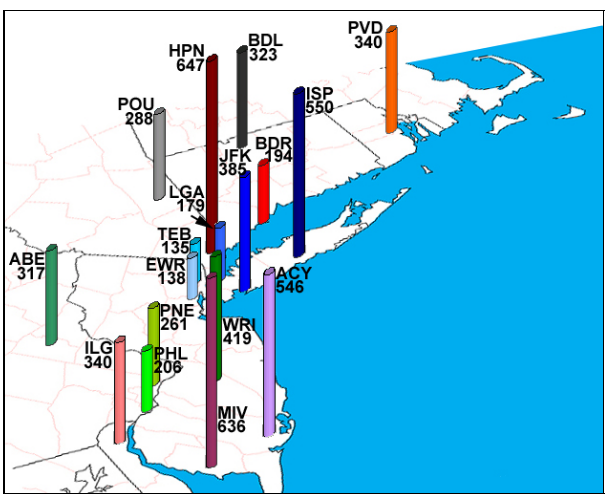

Figure 1. Number of fog events identified from surface observations taken over the 1977-1996 period, for stations located in Rhode Island, Connecticut, southern New York, New Jersey, eastern Pennsylvania and northern Delaware. The lengths of bars on the graph are proportional to the number of fog events.

3.2 *Conditions at onset*

Near-surface conditions are examined to identify potential influences enhancing the likelihood of fog formation. Of all the surface observations, wind speed and direction exhibit the clearer trends associated to fog onset. This is illustrated using the stations closest to the urban core of New York City (Fig. 2). The plots show the frequency with which fog events began while wind was blowing from a specific direction (in 10^{o}-wide bins). The frequency of events with calm wind at onset is also shown. The results suggest distinct flow regimes leading to fog onset within the region. The most striking feature is for stations located close to a significant water body to experience a larger number of fog events when the near surface flow is characterized by over-water trajectories. In essence, this suggests the important role of the cool and moist marine environment, through either the formation of advection fog out at sea and subsequently advected over the coastal land areas, or simply through the increased levels of moisture expected during onshore flow, which would enhance the likelihood of other types of fog. Stations such as LGA and JFK have very narrow distributions of wind direction defining fog onset. For LGA, flows coming from the Long Island Sound produce the majority of fog events, while JFK experiences flows mostly from the south at fog onset. The Newark airport (EWR) shows a more complex distribution, but the influence of the marine environment is again suggested, this time by a secondary maximum associated with flows from Raritan Bay. Although results for Islip (ISP) show a wider range of wind directions, onshore flow is still the predominant regime defining fog onset. Bridgeport (BDR) also experiences fog onset mostly with over-water low level trajectories. Similarly, Providence (PVD) also experiences fog under onshore flow conditions from Narragansett Bay/Rhode Island Sound (not shown). Another interesting feature concerns the flow regime at HPN. Given the fact that this location is the highest in the region (121 m above mean sea level) and that fog onset is mostly characterized by flows coming from Long Island Sound, a slight upslope flow thus prevails, leading to an additional contribution to cooling from adiabatic processes.

For stations located farther inland (not shown), a common pattern emerges. Apart from POU and BDL located in valleys, stations such as EWR, TEB, ABE, PNE, PHL, MIV and WRI have peaks in the wind direction distribution corresponding to northeasterly winds at fog onset. Most of these stations, such as POU, ABE, TEB, WRI and MIV, also experience a fair amount of fog onset under calm wind conditions. For coastal locations, ISP and HPN also experience a fair amount of fog onset under calm wind conditions. It is also worthwhile noting that hours without fog throughout the region are mostly characterized by northwesterly near surface flows, generally bringing dry continental air to the coastal area.

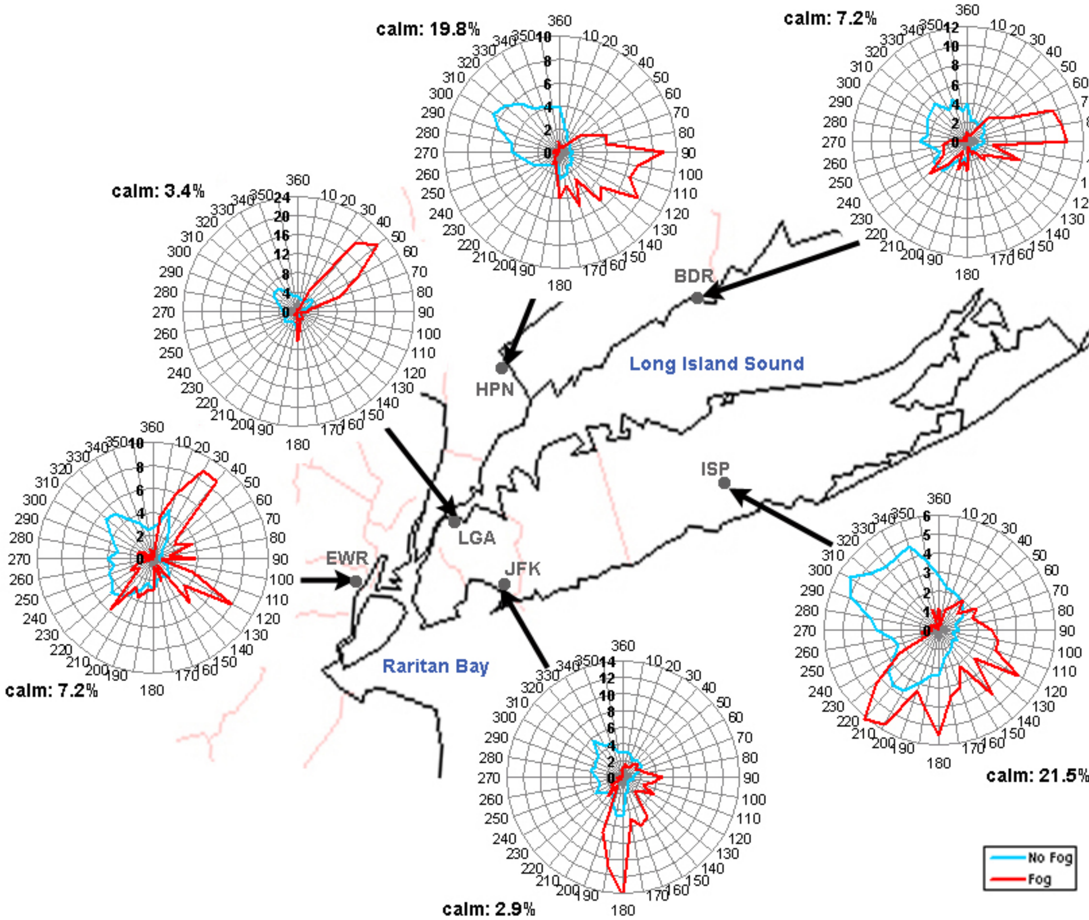

Figure 2. Plots of the frequency distribution of wind direction at the time of fog onset (red) for stations located in the general vicinity of New York City. Frequencies are calculated from data collected from 1977 to 1996. The distributions corresponding to the hours for which no fog was reported are also shown (light blue) to represent the overall wind climatology at each station. The frequency of events with calm wind at onset is also provided.

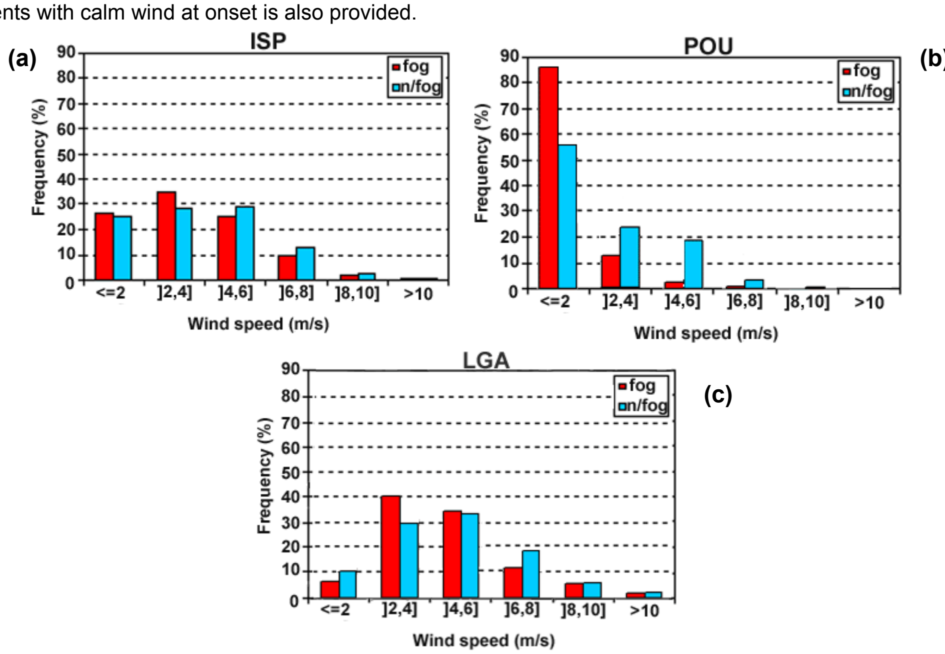

Figure 3. Frequency distribution of near surface wind speed at fog onset (red) for (a) ISP, (b) POU and (c) LGA. Blue bars indicate the overall wind climatology during hours without fog.

In terms of wind speed, the overall results show that the onset of fog events is most frequently associated with wind speeds in the 2 to 4 m s^{-1} range. Events characterized by weaker or stronger wind tend to be less likely to some degree. This is well illustrated by conditions at ISP (Fig. 3a). These features bare some resemblance with the overall wind speed climatology for most stations. Stations that depart somewhat from this picture are Poughkeepsie (POU) and LaGuardia (LGA) (Figs. 3b and 3c). For POU, a large majority of fog events occur under light wind conditions (wind speed below 2 m s^{-1}). In fact, 80% of all events began while winds were reported to be calm. This is also consistent with the previous study of ML90, who characterized the occurrences of radiation fog for Albany, also located in the Hudson Valley, New York. In contrast to this, LGA shows a significant number of events with stronger wind speeds. The frequency of events with wind speed greater than 4 m s^{-1} at onset is equal to 53.6%, the highest among all stations considered. In fact, there is a tendency for coastal stations (LGA, BDR, JFK and ISP to some extent) to experience a greater proportion of fog events characterized by significant wind speed. This could be the consequence of thermally driven mesoscale coastal circulations, such as sea breeze or land breeze circulations, that tend to occur in cases where the synoptic scale pressure gradient is weak.

3.3 *Fog type analysis*

To help understand the characteristics of fog events discussed in the previous sections, a classification of all fog events is performed for the seventeen stations considered using the algorithm outlined in section 2.3. The frequency of occurrences for each type is presented for each station in Table II. Results indicate that precipitation related events are generally the most common in the area. In fact, 11 of the 17 stations have their highest fog type frequency corresponding to precipitation related events, while the six other stations have precipitation fog ranking as the second most likely fog type. Radiation fog is most common at suburban and rural locations, in the coastal plain of New Jersey (ACY, MIV and WRI), eastern Pennsylvania (ABE), northern Delaware (ILG), southern New York (POU) and Connecticut (BDL). The more urbanized locations of PHL and PNE in eastern Pennsylvania also show radiation fog as a dominant fog type. Radiation fog is most common at POU and WRI. In contrast, coastal locations (JFK, BDR and LGA) experience few radiation fog events. Fog related to the lowering of cloud base occurs with significant frequencies throughout the region. Ten stations have this type of fog ranking as, or close to, the second most likely fog type. The highest frequencies of this type occur at EWR and LGA, while lowest frequencies occur at the two locations for which radiation fog dominates (POU and WRI). Not surprisingly, advection fog is most frequent at locations under the direct influence of the marine environment such as JFK, LGA, ISP and BDR to some extent. Other locations experiencing significant advection fog are ACY, PVD and HPN, also under the influence of moist marine air. Fog formation related to surface evaporation at sunrise is of minor importance compared to the other types but still some events do occur in the region. This is particularly true at locations prone to radiation fog. This suggests that nights where radiation fog didn't quite form due to sufficient dehydration of the surface layer by the deposition of dew at the surface, may in fact lead to conditions conducive to morning evaporation fog.

3.4 Synoptic weather patterns

Large-scale analyses of mean sea-level pressure (MSLP) from the NCEP-NCAR Reanalysis project (Kistler *et al*., 2001) were used to characterize the synoptic weather patterns associated with fog in the NE. The focus is on fog events identified at Islip/MacArthur (ISP). This station has been chosen since every fog type discussed in this study occurs with a fairly significant frequency. NCEP-NCAR reanalyses are available every 6 hours from the NOAA-CIRES Climate Diagnostics Center. The analyses corresponding to the time closest to the observed time of fog onset were examined for all events for which a fog type could be assigned with confidence. A total of more than 400 patterns were examined and classified into distinct types showing the more common large scale characteristics observed at the onset of fog events. A total of seven distinct, but recurring, synoptic patterns were identified. The main weather patterns are illustrated through the use of subjective composites of the reanalyses (Fig.4).

The most common pattern (37% of events) is characterized by a high pressure system centered offshore with a ridge extending over the coastal areas (Fig. 4a). With this MSLP pattern, the surface flow is onshore. Another common pattern (frequency of 19%) is characterized by a low pressure center generally located over the Great Lakes or in eastern Canada, with a well defined trough (cold front) extending southward to the west of the New York region (Fig. 4b). The associated surface flow in the region of interest is generally from the south (onshore). A less common pattern (8% frequency) consists of a low pressure center located over the mid-west, with a trough (warm front) extending to the south of the region (Fig. 4c). With this pattern, the flow is from the southeast or east over Long Island. A scenario involving a weak trough located over the region (Fig. 4d) was found to occur 17% of the time. Another fairly common pattern (11%) is characterized by a low pressure center approaching the region from the south or southwest (Fig. 4e). Under the influence of this type of MSLP pattern, the surface flow over New York is from the east or northeast. The least common pattern (3%) is associated with light winds over the region and is characterized by a ridge generally extending southward from a high pressure system centered over southeastern Canada (Fig. 4f). Some fog events (5%) took place as the New York region was located in the warm sector of mid-latitude low pressure systems (Fig. 4g), with a surface flow from the south or southwest.

TABLE II. Frequency of occurrence (%) of the various fog types considered in this study, for the locations listed in Table I.

Station ID	Radiation	Advection	Cloud base lowering	Morning evaporation	Precipitation	Indeterminate
EWR	18.8	4.3	29.0	2.2	39.9	5.8
TEB	24.4	0.7	23.7	1.5	46.7	3.0
LGA	3.9	25.7	32.4	0.0	36.3	1.7
JFK	7.3	30.1	19.0	0.2	40.0	3.4
ISP	18.2	18.5	21.3	1.1	36.7	4.2
HPN	17.9	10.5	15.8	1.9	49.6	4.3
BDR	5.2	14.9	19.6	0.0	48.5	11.8
PVD	20.6	11.2	21.8	2.1	38.8	5.5
POU	45.1	0.0	12.2	4.9	29.5	8.3
BDL	32.2	2.5	24.8	4.0	28.8	7.7
WRI	44.2	1.0	13.4	3.6	31.0	6.8
PNE	33.3	3.1	18.0	3.4	30.7	11.5
PHL	30.1	4.9	21.4	2.4	31.1	10.1
ABE	36.9	0.6	17.4	2.8	36.6	5.7
MIV	40.1	2.2	16.7	2.5	30.7	7.8
ACY	36.1	12.6	16.7	2.7	25.8	6.1
ILG	31.5	4.4	21.8	3.8	32.6	5.9

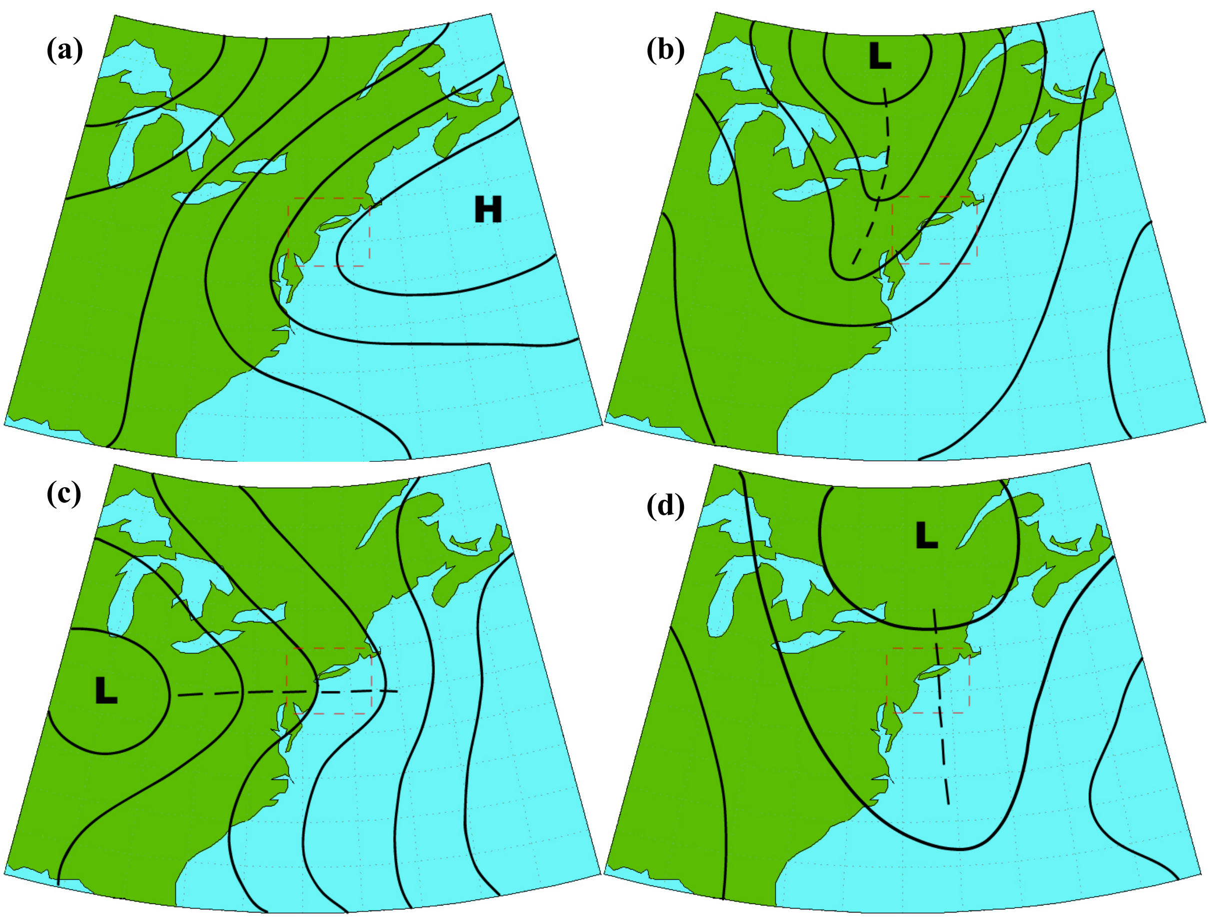

Figure 4. Examples of common surface synoptic weather patterns associated with fog onset at the Islip/MacArthur airport (ISP) in central Long Island, NY. (a) Coastal high pressure system with ridge, (b) approaching cold front from the west, (c) approaching warm front from the south, (d) weak trough. The region encompassing the stations used in this study is highlighted by a dashed rectangle.

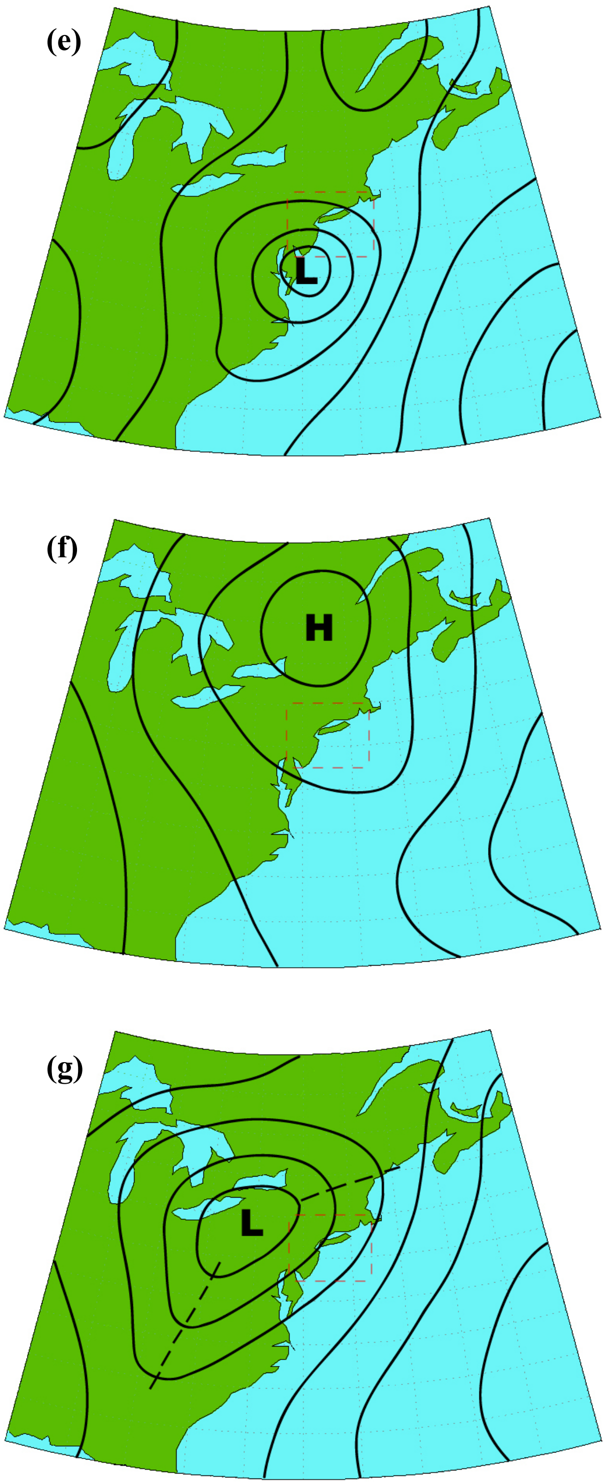

Figure 4 (continued). (e) Approaching low pressure system from south, (f) ridge, (g) warm sector of a low pressure system.

The frequency of occurrence of every identified synoptic pattern is shown in Table III for the main fog types discussed here. The most common synoptic pattern ("coastal ridge") is associated with every fog type discussed in the previous section. As the region remains in the anti-cyclonic circulation on the western edge of the high, the coastal marine boundary layer is likely to be capped by a subsidence inversion. Thus precipitation fog under this scenario has a tendency to be associated with lightly precipitating (drizzling) stratiform boundary layer clouds. Also, fog related to the lowering of cloud base occurs with a significant frequency as marine stratiform clouds are advected over the coastal areas. With such a pattern of MSLP, the flow at the surface is generally from the south or southeast (onshore). Since the sea-surface temperature (SST) of the coastal waters in the western Atlantic is typically characterized by a significant gradient oriented toward the south (Fig. 5), the occurrence of southerly or southeasterly surface flows is conducive to sea fog formation as warm moist air flows over a colder surface (Taylor, 1917). Radiation fog events also occur with a significant frequency under that weather pattern. Light winds prevail when the pressure gradient on the western edge of the high pressure system is weak or if the region is closer to the ridge axis. If marine boundary layer clouds do not develop, fog can form over land as radiative cooling occurs at night in conjunction with moist conditions related to the light onshore flow.

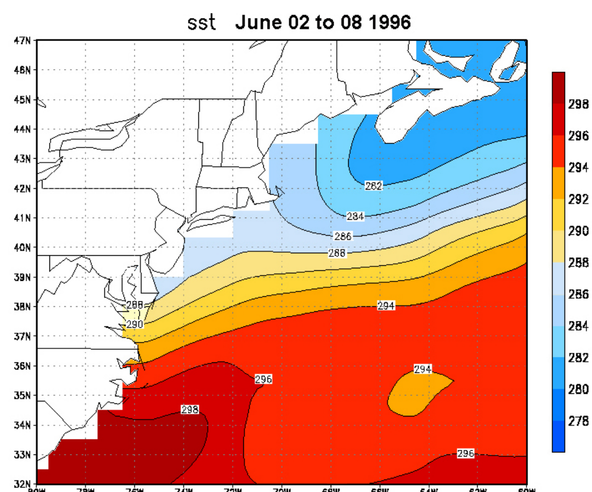

Figure 5. Objective analysis of sea surface temperature (in Kelvin), following Reynolds et al. (2002), over the western Atlantic for the week of June 2nd to June 8th 1996.

Table III. Frequency (%) of occurrence of synoptic weather patterns for the various fog types considered. PCP: precipitation, CBL: cloud base lowering, ADV: advection and RAD: radiation fog.

Pattern	PCP	CBL	ADV	RAD
Coastal ridge	20	31	55	63
Cold front	32	17	10	0
Warm front	11	12	3	0
Weak trough	7	28	20	24
Low	22	5	2	1
Ridge	0	0	5	12
Warm sector	8	7	5	0

With the scenario characterized by a trough approaching from the west ("cold front"), precipitation fog occurs more frequently, followed by fog resulting from cloud base lowering and some advection fog in association with the northerly surface flow over colder water. With a trough approaching from the south ("warm front"), some precipitation fog and fog resulting from the lowering of frontal clouds do occur. Under a "weak trough" scenario, the occurrence of fog types driven by boundary layer dynamics (cloud base lowering, advection and radiation) is predominant. When a ridge extends over the area from a high pressure system centered to the north, radiation fog has a tendency to occur as light winds prevail. With an intense low pressure center approaching the area, precipitation fog is the dominant type. A small number of precipitation, cloud base lowering and advection fog events occur in the warm sector of a low pressure system, as a surface flow from the south or southwest prevails over the area.

4. CONCLUSIONS

Based on the results obtained from an analysis of historical data, a complex picture of the fog phenomenon in the NE emerges. This general conclusion is along the same line as the one suggested by a preliminary analysis of field data (Tardif et al., 2004). A significant variability in the character of fog exists in the region.

For instance, the distribution of the number of occurrences found over a 20-year period shows a marked minimum in the urban areas, while the maximum number of events is generally found at coastal locations. These facts point toward the role of surface interactions at the local scale, as the urban island effect seems to limit the likelihood of fog formation. The maximum at coastal locations, in conjunction with the finding that fog events tend to occur under the influence of onshore flow, suggests the important influence of conditions within the coastal marine environment.

An analysis based on the classification of events into distinct fog types indicates the wide variety of influences under which fog forms in the region. Fog events associated with the moistening of the boundary layer by the evaporation of light precipitation generally dominate throughout the region, followed by fog forming as a result of cloud base lowering. This latter type seems to occur either with stratiform marine boundary layer clouds of with frontal clouds. Radiation fog is one of the dominant fog types for suburban inland locations, while the number of advection fog occurrences is significant at coastal locations.

The large-scale conditions associated with the formation of fog were examined using NCEP-NCAR reanalyses. The identification of seven major synoptic weather patterns associated with fog further illustrates the wide variety of scenarios under which fog events occur in the region.

Acknowledgments

The author would like to thank Ben Bernstein of NCAR-RAP for providing some of the historical data and the original version of the analysis software used to establish the fog climatology. This research is in response to requirements and funding by the Federal Aviation Administration (FAA). The view expressed are those of the author and do not necessarily represent the official policy of the FAA.

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