5.1 A CLIMATOLOGICAL STUDY OF LOW CEILING AND FOG EVENTS ASSOCIATED WITH THE OCCURRENCE OF PRECIPITATION IN THE NORTHEASTERN UNITED STATES

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1. INTRODUCTION

A previous study has shown that a significant fraction of fog events in the northeastern United States occur in the presence of precipitation. Tardif (2004) found that 25% to 50% of fog events at various locations in a region around New York City were associated with the presence of some type of precipitation at their onset. Other authors have also pointed out the common occurrence of fog in precipitation (Byers 1959, Westcott 2004). It is also found that a large fraction of precipitation events are also associated with low level cloud ceilings. Thus precipitation seems to play a significant role in the formation of low ceiling and visibility (C&V) conditions, yet relatively little is found in the literature about the mechanisms and interactions leading to changes in ceiling height and the appearance of fog in precipitation. Goldman (1951) lists some factors thought to be linked to the lowering of cloud ceilings in continuous precipitation and proposes empirical rules to forecast the rate of decrease of cloud ceilings. Factors cited are the rate of moistening of the subcloud layer by the evaporation of rain drops, mechanical turbulence and the advection of temperature and moisture. Some limited success was obtained with ceiling forecasts obtained through the application of the proposed rules. A few other studies describe fog in precipitation as a phenomenon associated with warm rain falling into colder air in areas ahead of warms fronts (Byers 1959, Petterssen 1969) or in regions of extra-tropical cyclones characterized by a transition in precipitation type (Stewart 1992, Stewart and Yiu 1993, Stewart et al. 1995). Therefore, a relatively few studies are found which aim to further our understanding of the relationship that exists between the occurrence of precipitation and cloud ceilings and visibility in fog.

Given the frequent occurrence of low C&V conditions in precipitation and the lack of a comprehensive description of the mechanisms involved, a more complete understanding of the underlying influences leading to the occurrence of such events is desirable toward the improvement of short-term C&V forecasts. In this paper, a look into the phenomenology of low C&V conditions in precipitation is taken, with a focus on the northeastern United States. A general description of the relationship between the occurrence of precipitation and low ceiling and fog conditions is first presented, followed by a more detailed analysis of the environmental conditions associated with fog events occurring under the influence of precipitation.

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2. DATA AND ANALYSIS PROCEDURE

2.1 *Historical data*

The main dataset used in this study is the same as in Tardif (2004). Historical surface observations 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) are used. Hourly surface observations of visibility, precipitation type and intensity, temperature, dew point temperature, wind speed and direction, ceiling height, cloud cover, and coded obstruction to vision were gathered for the period corresponding to 1977 to 1996 inclusively. A total of 17 stations 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) were retained. Table I presents the list of stations used in this study, while Fig.1 shows their location.

For the more detailed study of fog events, this dataset is complemented by some radiosoundings performed close enough in space and time to be representative of conditions at fog onset, while data from NCAR-NCEP re-analyses are used to identify the main synoptic weather patterns associated with the events of interest.

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

Figure 1. Geographical location of the 17 stations used in this study. The location of the Upton NY sounding site (OKX) is also indicated (red dot), as well as buoys off the southern shore of Long Island. ACY also indicates the location of a sounding site.

2.2 *Identification of precipitation, low ceiling and fog events*

The identification of precipitation, low ceiling and fog events in time series of observed weather parameters is performed based on the concept of "M-of-N" constructs (Setiono et al. 2005). For example, the "fog present" attribute is defined as an observation of visibility below 1 statute mile (1.6 km), reported at the same time as fog (FG), ground fog (GF) or ice fog (IF). A potential fog event is identified whenever a minimum of M "fog present" attributes is detected within N consecutive hourly observations. This is referred to as a positive construct. Here, values of M = 3 and N = 5 were chosen. The end of the potential event is defined by the first reported visibility value above 1.6 km contained in a negative M-of-N construct. A fog event is then formally identified if at least one of these visibility reports found between the onset and end of the potential event indicates a value below 5/8 of a mile (1 km) in the absence of precipitation or in light to moderate liquid precipitation, or below the thresholds proposed by Rasmussen et al. (1999) in snow. The threshold used in the presence of heavy rain or freezing precipitation is chosen as 800 m (1/2 mile). These conditions are used to minimize chances of taking into account reduced visibility events solely related to the presence of precipitation. Fog events associated with precipitation are then identified if some type of precipitation is reported at fog onset or the hour prior. 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.

A similar methodology is used for the identification of precipitation events. "M-of-N" constructs are again used, with M = 3 and N = 5, except that a positive attribute is here defined as a report of the presence of any type of precipitation. For the identification of low ceiling events, a positive attribute is an observation of a cloud ceiling below 500 m.

3. LOW CEILINGS AND FOG VS. PRECIPITATION

First looking at the relationship between precipitation events and low C&V conditions, precipitation events were identified in the 20-year dataset and the proportion of those that led to low ceiling and/or fog conditions compiled. Fog conditions associated with precipitation events are identified when a single "fog present" attribute is detected, while a positive low ceiling is counted when a single "low ceiling present" attribute is detected within the duration of the precipitation event.

It is found that the proportion of precipitation events leading to foggy conditions ranges from 11% to 39% depending on the location (see Table II), with an average of 18.1%. For low ceilings, frequencies range between 52% and 74%, with an average of 60.8%. Therefore a significant fraction of precipitation events are associated with low cloud ceilings while a smaller fraction of precipitation events in fact lead to foggy conditions. Of those that did not lead to foggy conditions, 46% were characterized by high levels of relative humidity (RH > 95%). So, a little over half of the non foggy precipitation events are simply the result of a non sufficient moistening of the lower atmosphere. However, high levels of relative humidity characterize the remaining events. This suggests that particular conditions need to be met in order for fog to form in precipitation; the presence of precipitation alone is evidently not sufficient to explain the onset of foggy conditions by having reached saturation through the evaporation of precipitation particles.

TABLE II. Number of precipitation events identified in the 20-year dataset for the 17 stations considered, and the fraction of those events leading to the formation of low ceilings and foggy conditions.

Station	Number of precipitation events	Percent of events with fog	Percent of events with low ceilings
ISP	1847	22.0	72.8
JFK	1865	19.7	60.1
LGA	1774	13.4	58.5
EWR	1942	11.3	53.8
TEB	1812	13.4	60.4
HPN	1773	38.5	74.2
POU	1707	13.6	56.6
BDR	1677	17.9	57.5
BDL	1953	16.3	58.7
PVD	2038	18.4	70.0
ABE	1962	17.4	53.7
WRI	1973	20.4	53.2
ACY	1793	18.9	66.2
MIV	1754	27.6	66.9
PHL	1772	13.0	52.3
PNE	1727	17.9	61.8
ILG	1748	19.4	56.4

The appearance of foggy conditions at the surface in precipitation is intimately tied to the low ceiling problem. Indeed, close to 90% of the fog events were associated with the presence of cloud ceilings below 500 m the hour prior to the onset of fog. Fog at the surface is thus mostly the result of a low cloud base further lowering to the surface in precipitation. To gain a higher degree of understanding of the processes responsible for this scenario, conditions at the onset of fog events associated with precipitation are analyzed in more details in the next section.

4. ENVIRONMENTAL CONDITIONS AT FOG ONSET

The work presented in this section seeks to confirm and/or add to the previously published findings by examining environmental conditions associated with the onset of precipitation fog events, and therefore better identify specific conditions leading to the formation of this type of fog in the northeastern United States. The database of fog events established by Tardif (2004) is the basis for the remainder of this study, with a focus on those associated with precipitation at fog onset.

4.1 Synoptic weather patterns

When considering the overall fog phenomenon, mechanisms leading to its formation are in many ways conditioned by the large-scale environment (flow conditions, cloudiness, presence of precipitation etc.). Therefore, characterizing the large-scale weather patterns associated with the onset of events represents a useful baseline in establishing the character of environmental conditions leading to fog.

The synoptic weather patterns are identified through a subjective classification of the mean sea-level pressure (MSLP) analyses from the NCEP-NCAR reanalyses. Locations representative of the various regions characterized by distinct fog characters were chosen for this analysis. The synoptic scale MSLP patterns corresponding to fog events at the Newark airport (EWR) (urban environment), John F. Kennedy (JFK) (coastal), Allentown (ABE) (inland) and Millville (MIV) (coastal plain of New Jersey) are examined in order to gain a comprehensive view on the synoptic scale features. Surface weather patterns are subjectively classified into categories loosely based on the work of Meyer and Lala (1990), Westcott (2004) and Keim et al. (2005). A total of 14 categories are used to accommodate the distinct and recurring synoptic weather patterns associated with all occurrences of fog events. Categories are defined through the relative position of relevant features in the MSLP (centers of high or low pressure systems, well-defined frontal boundaries or less defined troughs and ridges) with respect to the location of target stations. The patterns identified are illustrated in figure 2. A weather pattern is labeled as *low center* (LC) when the station where fog onset occurs is located within the first or second closed isobar around the lowest pressure represented on typical weather maps. The *pre-cold front* (PreCF) synoptic weather scenario occurs as a well-developed mid-latitude cyclone is centered over the Great Lakes or over eastern Canada, with a well-defined trough (cold front) extending southward just west of the region of interest. The *post-cold front* (PostCF) scenario is identified when fog onset occurs shortly after the passage of a cold front. A typical example of the *pre-warm front* (PreWF) scenario involves a well-developed low pressure system centered over the Midwest with a warm front extending eastward just south of the location where fog onset is observed (Fig 2d). Some events begin shortly after the frontal passage, defining the *post-warm front* (PostWF) pattern. A number of fog events occur within the *warm sector* (WS) of mid-latitude cyclones. Another category associated with mid-latitude cyclones is labeled as *northeast sector* (NES). It is used to characterize fog forming at locations found in the northeast quadrant of an approaching low pressure center, but without the presence of distinct fronts in the vicinity of the station where a fog event is detected. The *northerly return flow* (NRF) describes fog appearing under northeasterly flow conditions as the area is under the influence of a low pressure center located to the S or SE, moving in a general eastward direction. Cases where fog formation takes place within a trough characterized by weak pressure gradients are identified as the *weak trough* (WT) pattern. Three categories are used to describe weather patterns associated with high pressure systems. Similarly to cyclonic weather patterns, the *high center* (HC) pattern is used to categorize fog events forming within a closed-isobar anti-cyclone. Fog events sometimes occur within an open *ridge* (R) extending over the region from a well-defined high pressure center, often located over eastern Canada. The *Atlantic return flow* (ARF) pattern is used to describe situations where the region is located on the western side of a high pressure system centered over the western Atlantic. Some fog formation events occur at locations found in-between features, such as in a *col* found between two low pressure centers. Finally, the *weak synoptic forcing* (WSF) category is used to describe various weather scenarios characterized by an ambiguous synoptic pattern, defined by the absence of distinct features in the MSLP.

The analysis of the frequencies of the patterns under which fog forms in precipitation reveals that one of the dominant scenario is the pre-warm front (PreWF) pattern with a little over 15% of these events (81 out of 515 events) (Table III). This is consistent with previously published work pointing out that the region ahead of warm fronts is prone to fog formation as warm rain falls and evaporate into the colder air near the surface (Byers 1959, Petterssen 1969). The other leading synoptic weather scenario is the weak trough (WT) pattern with 79 events (15%). Fog forming in precipitation as a cold front is approaching (PreCF) also occurs with a significant frequency (59 events, 11%), as well as when a low pressure system is centered over the region (48 events, 9%). Fog onset in the warm

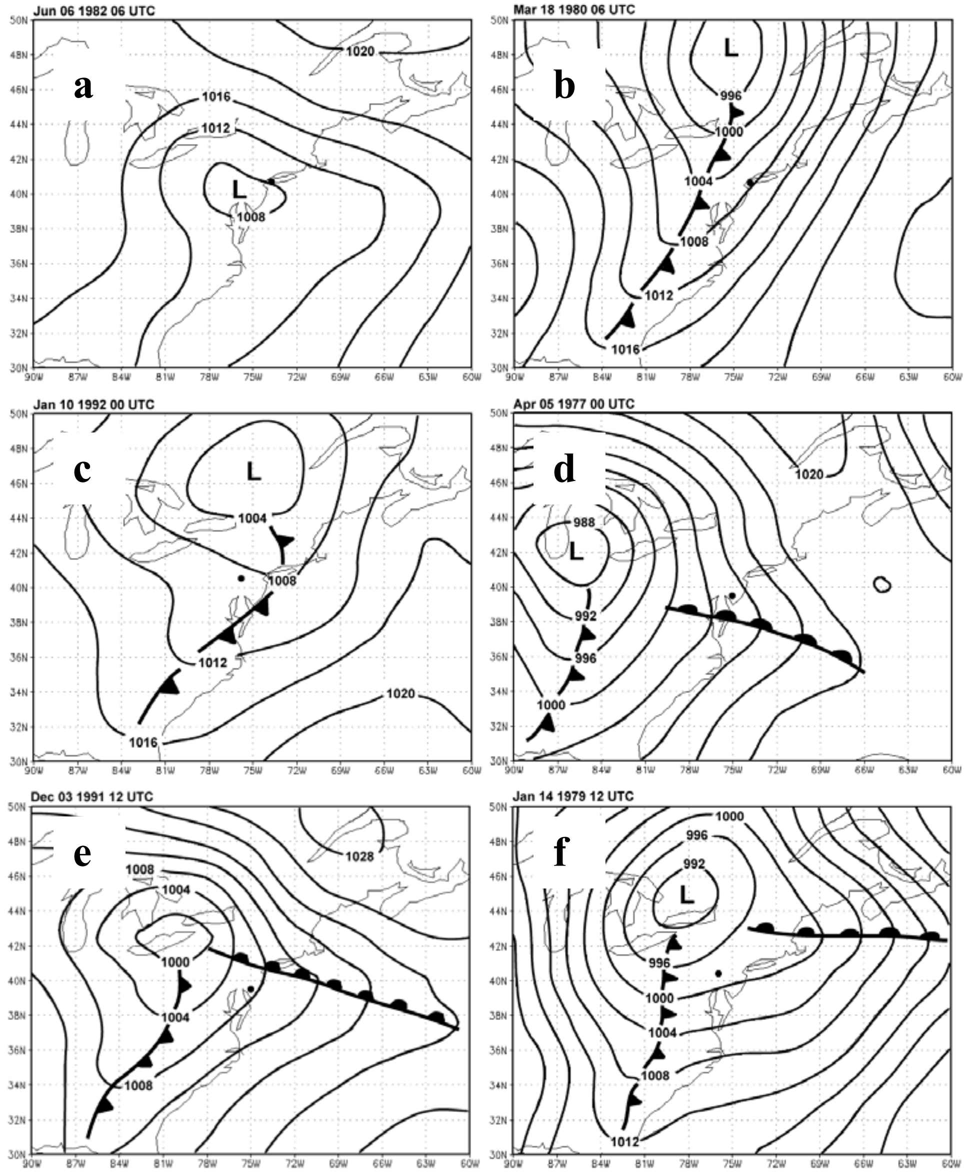

Figure 2. Synoptic weather patterns associated with fog events. a) Low center (LC) weather pattern, with fog onset at JFK (black dot) on June 6th 1982 06 UTC, b) pre-cold front (PreCF), fog onset at JFK on March 18th 1980 06 UTC, c) post-cold front (PostCF), fog onset at ABE on January 10th 1992 00 UTC, d) pre-warm front (PreWF), fog onset at MIV on April 5th 1977 00 UTC, e) post-warm front (PWF), fog at MIV on December 3rd 1992 12 UTC and f) warm sector (WS), fog at ABE on January 14th 1979 12 UTC.

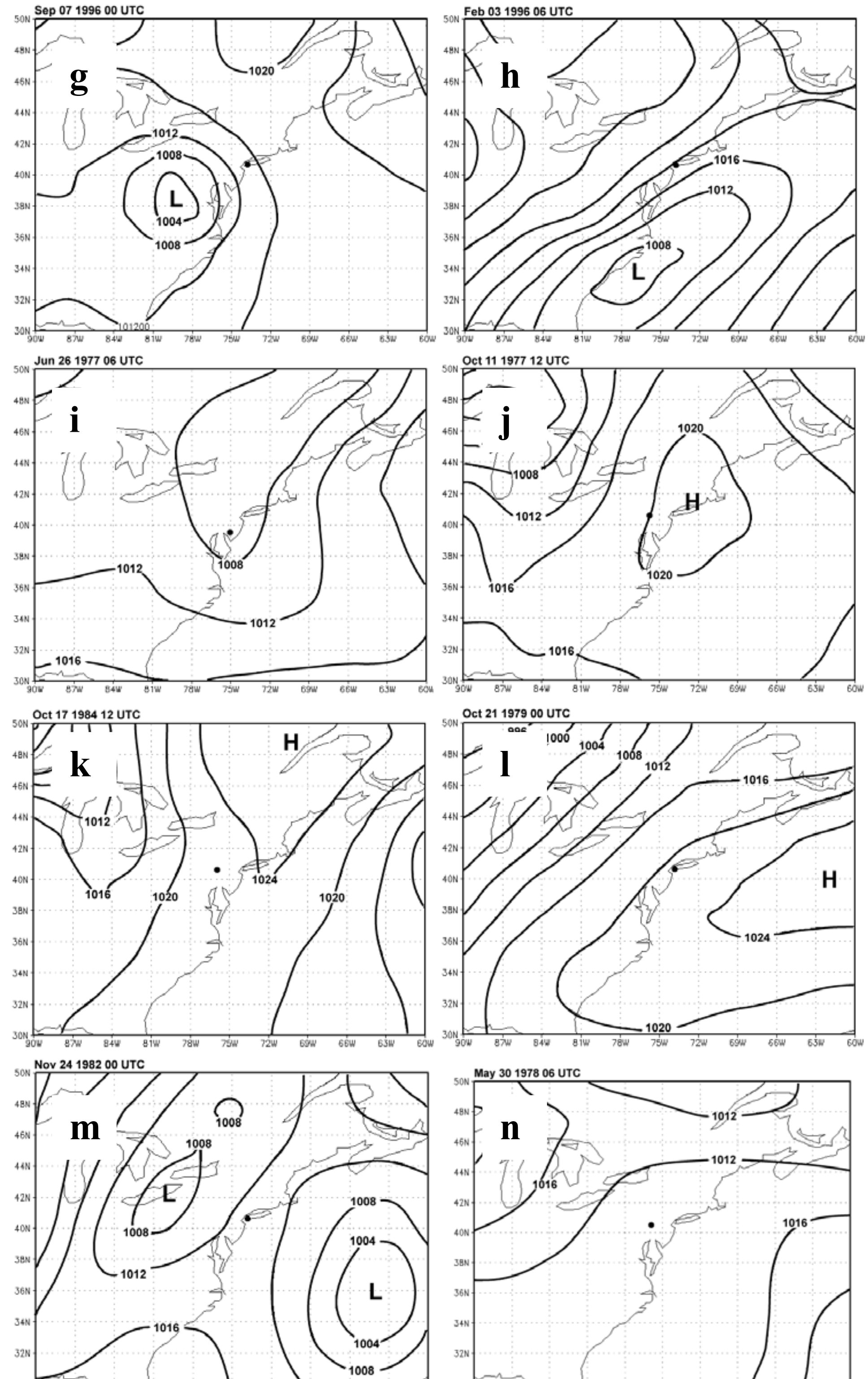

Figure 2 (continued). g) Northeast sector (NES) synoptic weather category, fog onset at JFK on September 7th 1996 00 UTC, h) northerly return flow (NRF) pattern, fog at JFK on February 3rd 1996 06 UTC, i) weak trough (WT), fog at MIV on June 26th 1977 06 UTC, j) high center (HC), fog at MIV on October 11th 1977 12 UTC, k) ridge (R), fog at ABE on October 17th 1984 12 UTC, l) Atlantic return flow (ARF) pattern, fog at JFK on October 21st 1979 00 UTC,). m) Col weather pattern on November 24th 1982, where a fog event began at JFK at 22 UTC on the 23rd, and n) weak synoptic forcing (WSF) on May 30th 1978, where a fog event began at ABE at 09 UTC.

sector (WS), in the northeast sector (NES) of a cyclone or behind a warm front (PostWF) occurs with significant frequencies (8%, 7% and 7% respectively), as well as in a col (7%), within a ridge (7%) and under the influence of the return flow from the Atlantic on the western edge of an anti-cyclone (5%).

Table III. Number of fog events by synoptic weather patterns for all precipitation fog events identified at John F. Kennedy (JFK), Newark (EWR), Allentown (ABE) and Millville (MIV). Numbers are provided for the various fog types observed in the region around New York City.

Pattern	Number of events
LC	48
PreCF	59
PostCF	10
PreWF	81
PostWF	34
WS	40
NES	36
NRF	13
WT	79
col	34
HC	1
R	38
ARF	28
WSF	14
Total:	515

4.2 Precipitation character

Relationships between precipitation type and intensity at the onset of fog and low clouds are examined, as well as transitions in precipitation character. The frequency of the various precipitation types and intensities (in categories defined as light, moderate and heavy) associated with the onset of precipitation fog events is compiled.

The results indicate that the clear majority of events are associated with liquid precipitation light in intensity (Fig. 3). 38% of precipitation fog events began as light drizzle (L-) was observed, while 39% began as light rain (R-) was reported. Light rain showers (Rw-) were reported for 6% of the events. Some events also have an onset as snow is reported, with 7% of events associated with light snow (S-) and 3% with moderate snow (S). Events with freezing precipitation represent a minor component, with only 2% of events being associated with freezing drizzle (ZL) or freezing rain (ZR).

The possible relationship between fog formation and a transition in precipitation type is tested by examining the frequencies of observed variations in precipitation character (if any) during the hour leading to fog onset. The results indicate that the majority of cases (55%) are characterized by the absence of any transition in precipitation type and intensity, at least in a categorical sense (Fig. 4).

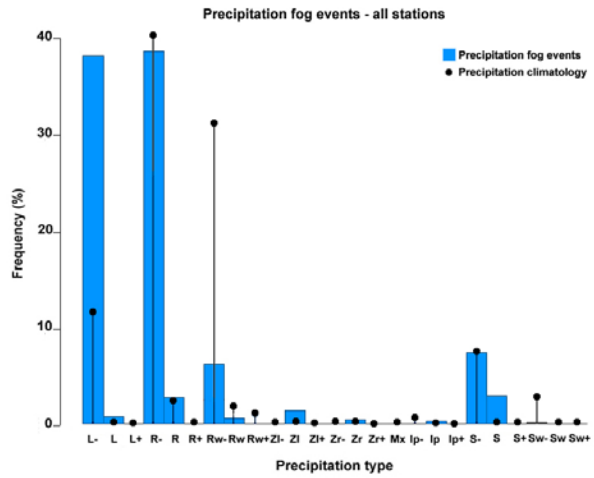

Figure 3. Histogram showing the frequency of various precipitation types and intensity associated with the onset of fog events. "L" denotes drizzle, "R" rain, "Rw" rain showers, "Zl" freezing drizzle, "Zr" freezing rain, "Mx" combination of liquid and frozen precipitation, "IP" ice pellets, "S" snow, and "Sw" snow showers. "-" and "+" denote light and heavy precipitation respectively. The overall frequency of precipitation per type is also shown as a reference (dots). The data cover the 1977 to 1996 period.

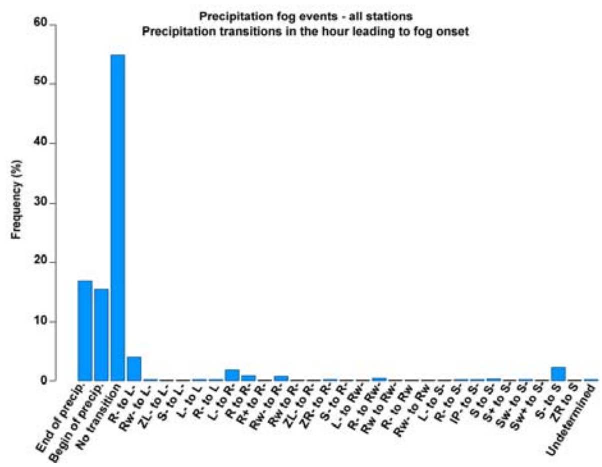

Figure 4. Histogram showing the frequency of observed transitions in precipitation characteristics (type and intensity) corresponding to the onset of fog conditions, for fog events identified at the 17 stations for the period from 1977 to 1996.

Other relatively common scenarios are characterized by fog onset occurring at the very end of precipitation or during a break in precipitation (17%) or as precipitation begins (15%). The most common transitions during continuous precipitation are light rain transitioning to light drizzle (4%) and inversely from light drizzle to light rain (2%). A transition from light to moderate snow accounts for 2% of the events. Of all the events characterized by the absence of a transition in precipitation character during the hour leading to onset, 62% are also characterized by an absence of transition during the period between 2 hours to 1 hour before fog onset. This suggests that the preferred scenario leading to fog forming under the influence of precipitation in the northeastern United States is not characterized by transitions in precipitation type.

4.3 Surface flow conditions, thermodynamic tendencies and vertical profiles

Since an important fraction of precipitation fog events occur under steady conditions in precipitation character, an analysis of other surface weather parameters is presented next to identify more specific conditions associated to fog formation in precipitation. The focus of the analysis will hereafter be placed on the four stations for which synoptic weather patterns were identified.

Flow conditions can potentially influence the formation of this type of fog through their relationship with patterns of horizontal advections of temperature and moisture, as well through their influence on the generation of mechanical turbulence in a near-saturated lower atmosphere. Specific patterns in the wind direction are found (Fig. 5). The majority of events at coastal locations (of which JFK is representative) begin as an onshore flow is observed. Further evidence of the effect of onshore flow is also seen in the wind distribution at EWR and MIV with maxima in the frequency distribution corresponding to low level winds from Raritan Bay for EWR (flow from SE) and from Delaware Bay for MIV (flow from the S). Inland locations generally experience precipitation fog under the influence of a northeasterly flow (ABE is a representative example).

In terms of wind speed, the maximum in the distribution corresponds to speeds in the 2 m s^{-1} to 4 m s^{-1} range for most stations (Fig. 6). A greater proportion of precipitation fog events begin at coastal locations as wind speeds are reported to be moderate to strong (in excess of 6 m s^{-1}), while inland locations have a greater number of events beginning under calm wind conditions.

Tendencies in near-surface humidity and temperature are examined next. More specifically, changes in specific humidity (q) and saturation specific humidity (q_{sat}) during the hour leading to fog onset are examined to infer mechanisms leading to an increase in relative humidity (RH) and fog formation. It is noted that due to the exponential dependence of saturation vapor pressure on temperature, changes in saturation specific humidity mostly reflects changes in temperature.

Tendencies in temperature (Δq_{sat}) and moisture (Δq) for fog events are grouped in four distinct categories representing the main influence leading to fog onset. Events for which $\Delta q_{sat} \geq 0$ and $\Delta q \geq \Delta q_{sat}$ are characterized by *moistening* during the hour leading to fog onset, while events with $\Delta q_{sat} < 0$, $\Delta q < 0$ and $\Delta q \geq \Delta q_{sat}$ are said to result from the main influence of *cooling*. A number of events are characterized by $\Delta q_{sat} < 0$ and $\Delta q > 0$ and are thus associated with *moistening and cooling* in the hour prior to onset. The fourth category includes events for which *no apparent trends* in temperature and moisture are observed ($\Delta q_{sat} = \Delta q = 0$). The distribution in the number of events in each category is broken down by the main flow regimes characterizing fog onset and the results are shown in figure 7. First of all, it is shown that events are distributed with frequencies corresponding to 44% of events with NE flows, 41% with onshore flow at coastal locations and 15% with calm wind conditions. Also, 43% of these events are characterized by moistening, 26% by the absence of perceptible trends, 22% with cooling and 9% with the combined influences of moistening and cooling. Results also show that the most common scenarios are characterized by moistening of the lower atmosphere under NE flow at inland locations and onshore flow conditions at coastal locations. In terms of synoptic weather patterns, these scenarios are predominantly associated with the pre-cold front environment (PreCF) at coastal locations under the influence of onshore flow and the pre-warm front environment (PreWF) for locations under the influence of NE flow (Fig. 7).

Conditions associated with these two scenarios are studied in more details in order to identify important influences. For instance, an examination of the vertical structure of the lower troposphere from the few available soundings performed close enough in time and space to locations and times where fog onset was observed to occur in scenarios discussed above indicates the presence of a common feature. The presence of a strong stably stratified layer is observed within the lowest few hundred meters of the atmosphere in the majority of cases. This is illustrated in figure 8, where observed profiles of temperature, dew point temperature and wind from the 12 UTC sounding at Upton NY (OKX) on April 16th 1996 are shown. Foggy conditions appeared at JFK (80 km SW of the sounding site) at 12 UTC as light rain was observed for numerous hours on April 16th, as a cold front was approaching from the W (pre-cold front scenario). The 2-m temperature was increasing slightly at the time of fog onset, indicating that the "moistening" scenario was occurring under the influence of a southerly flow.

The vertical structure of the lower atmosphere was characterized by a well-mixed layer in the first 200 m, superimposed by a shallow layer with strong static stability between 200 m and 350 m. The whole lower troposphere was moist as shown by the small dew point depression. The atmosphere above 1 km was characterized by a moist-adiabatic lapse rate. Such profiles suggest that the scenario of warm rain drops evaporating in the colder air near the surface was at play in this case. The presence of a well-mixed layer near the surface along with a strong wind shear in the lowest 200m (Fig. 8c) is indicative that shear induced turbulent mixing was taking place at fog onset. Therefore, the role of turbulent mixing of saturated (from rainfall evaporation) air parcels of different temperatures was also a potentially important mechanism in this case.

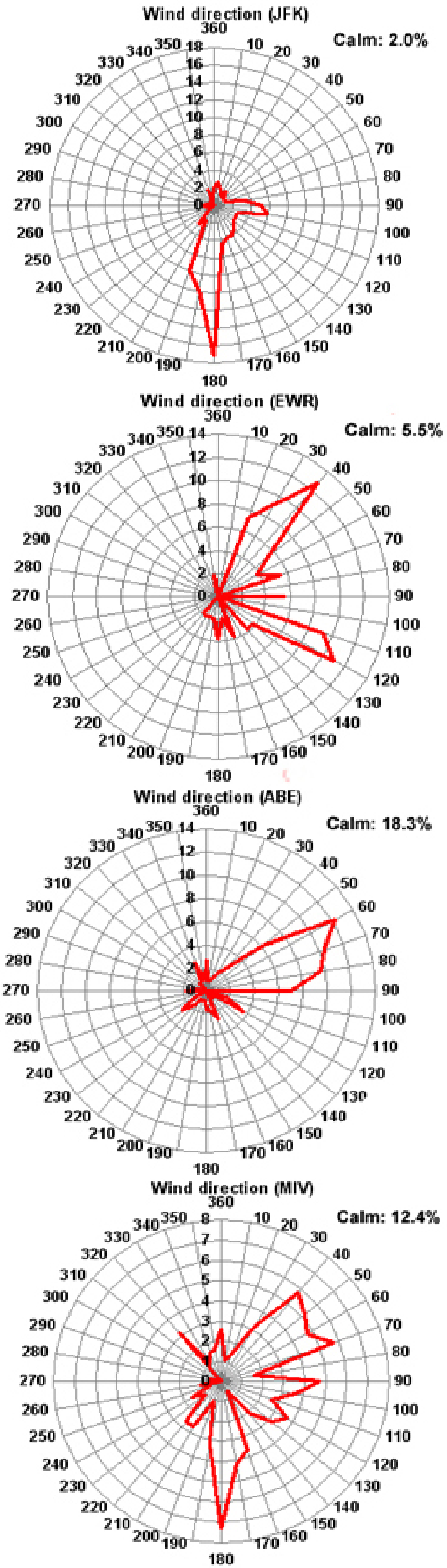

Figure 5. Frequency distributions of wind direction observed at the onset of precipitation fog events at various locations (JFK, EWR, ABE and MIV).

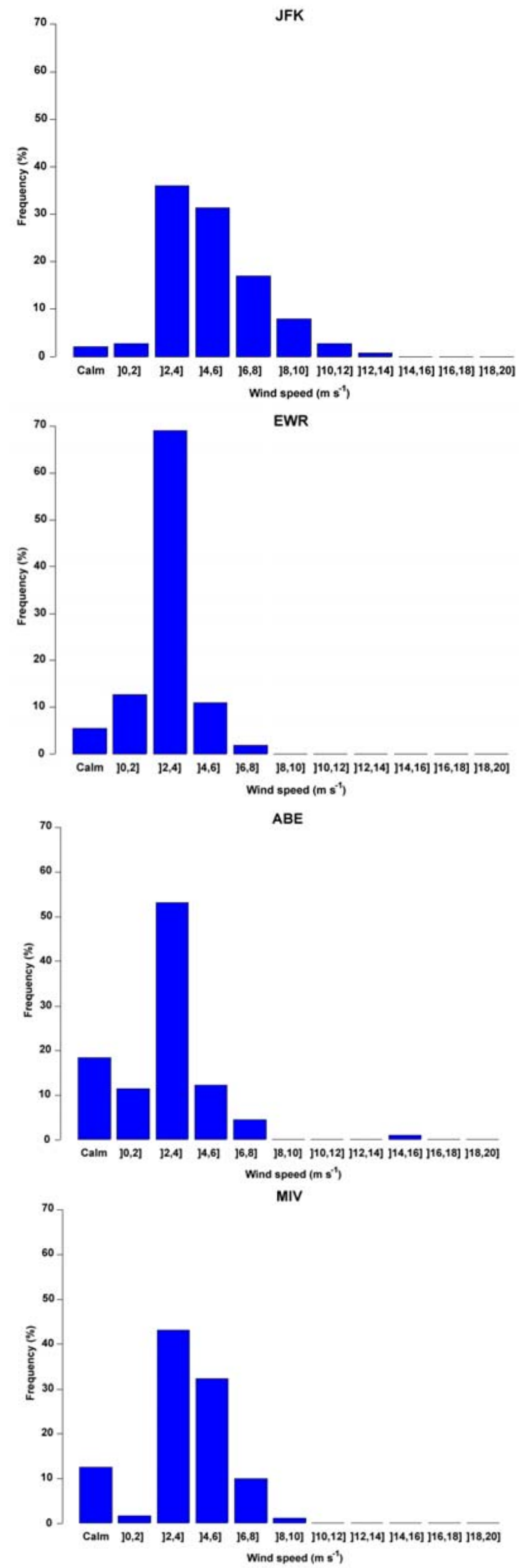

Figure 6. Frequency distributions of wind speed observed at the onset of precipitation fog events at various locations (JFK, EWR, ABE and MIV).

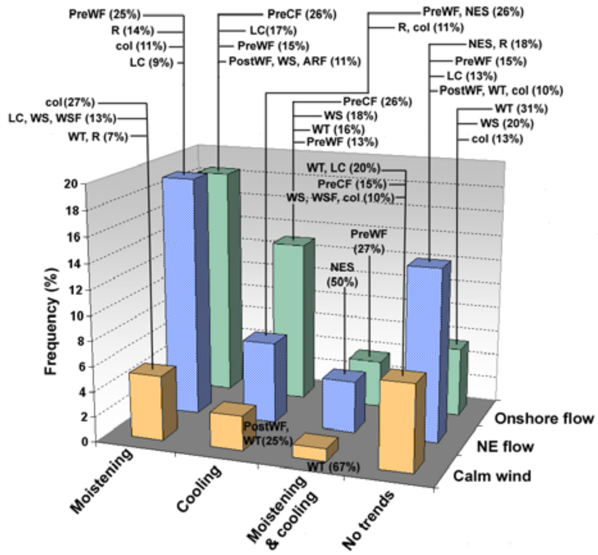

Figure 7. Frequency distribution of precipitation fog events characterized by moistening, cooling or absence of changes (trends) in temperature and moisture in the hour prior to fog onset, for various flow regimes (onshore, northeasterly flow and calm wind). The frequency of occurrence of the main synoptic weather patterns is also indicated for each category.

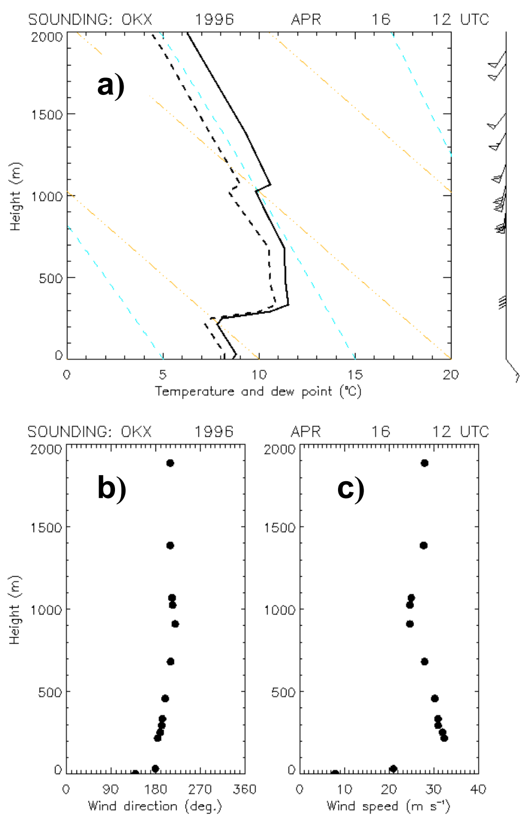

Figure 8. Observed profiles from the 12 UTC OKX sounding on April 16th 1996 for a) temperature and dew point, b) wind direction and c) wind speed. The dashed blue line in (a) represent moist-adiabatic lapse rate, while the dot-dashed orange line represent the dry-adiabatic lapse rate.

The presence of a layer with stable stratification near the surface under such a scenario seems to be the result of the interaction of the warm air from the south flowing over the colder surface of the coastal Atlantic. Evidence of this is provided by the fact that for all of the precipitation fog cases at JFK examined, for which the flow was from the S, observations at coastal buoys showed that the air temperature was warmer than the sea surface temperature (SST), with differences of the order of +2^{o}C to +4^{o}C (Fig. 9). In the case discussed above, the observed difference between the air temperature and the water temperature at the ALSN6 buoy upstream from JFK was ~ +4^{o}C, which is of the same order as the temperature contrast that existed between the 200m-deep layer near the surface and the lower free troposphere aloft (Fig 8a), all within a layer characterized by a strong flow with a southerly component.

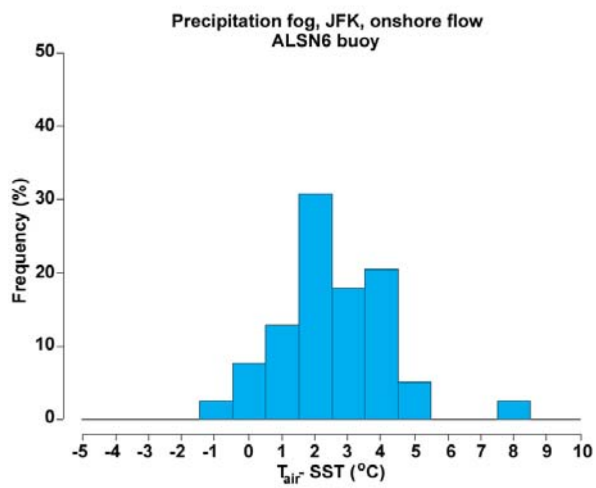

Figure 9. Histogram showing the frequency distribution of the difference between the air temperature and water temperature at the ALSN6 buoy, from measurements taken at the onset of precipitation fog events observed at JFK.

In the case of the pre-warm front scenario, the thermal contrast between the atmosphere adjacent to the surface and the air aloft is the result of differential temperature advection associated with a significant baroclinity of the lower troposphere and the presence of directional wind shear. This is illustrated using conditions observed in southern New Jersey on April 13th 1994. A transition to foggy conditions occurred at MIV at 02 UTC as visibility lowered to a value below 1 km as light drizzle was reported. The low level wind was blowing from the NE at about 3.5 m s^{-1}. During the hours leading to fog onset, overcast conditions prevailed with periods of light drizzle. Humidification, reduced visibility (below 5 km) and lowering of cloud ceiling height occurred during that period. Visibility decreased further with the reappearance of light drizzle starting at 00 UTC. Visibility conditions remained obscured for several hours thereafter, even after the end of precipitation. The vertical profiles obtained from the 00 UTC April 13th sounding performed in the vicinity of nearby Atlantic City (ACY) (44 km NE of MIV) shows the presence of a complex thermal vertical structure in a moist layer that extended up to about 1 km (Fig. 10a). A well-mixed layer about 100m-deep was adjacent to the surface, superimposed by a stably stratified layer from 100 m to 400 m and a nearly moist adiabatic layer between 400 m and 750 m. This vertical structure seems to have been related to the directional wind shear (Fig. 10c) and its relation to temperature advection. The flow had an easterly component near the surface veering to the SW aloft, with the colder layer near the surface corresponding to the layer with an easterly flow. The NCEP-NCAR re-analysis of the mass and temperature fields shows that the flow at the surface was up the temperature gradient (cold air advection of about -0.2°C h^{-1}) while the flow at 850 hPa was down-gradient (warm air advection of about +0.4°C h^{-1}) (Fig. 11). This differential advection of temperature contributed in the creation of stably stratified conditions in the lower atmosphere. Thus in this case, the drizzle drops, likely created in the upper portion of the cloudy layer, eventually fell into the colder air in the lowest 200 m of the atmosphere.

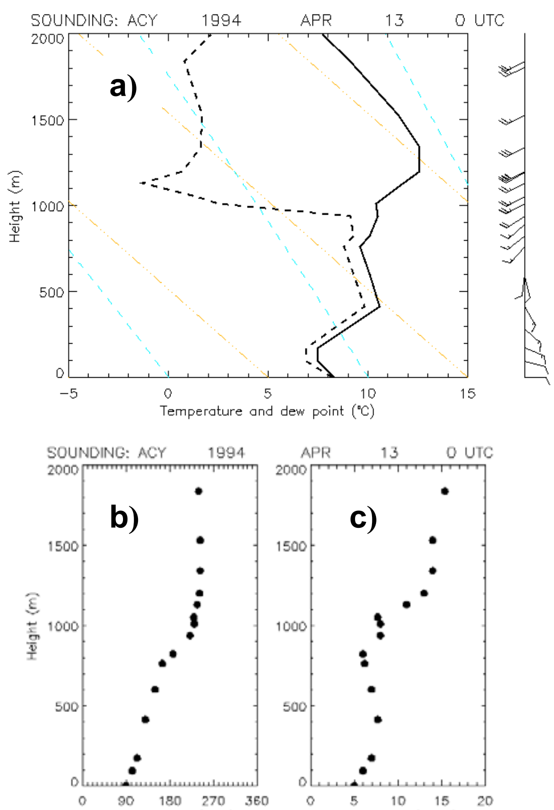

Figure 10. Observed profiles from the OO UTC ACY sounding on April 13th 1994 for a) temperature and dew point, b) wind direction and c) wind speed.

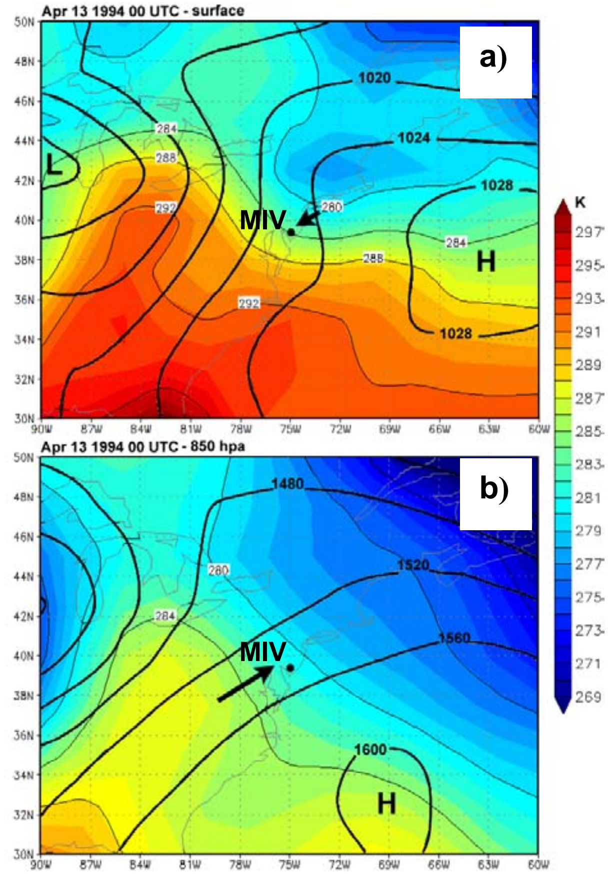

Figure 11. Synoptic conditions at 00 UTC on April 13th 1994, from the NCAR-NCEP re-analyses. a) Mean sea-level pressure (solid lines) and surface temperature (colored contours) and b) geopotential height (solid lines) and temperature (colored contours) at 850 hPa. Arrows indicate the general direction of the flow at both levels.

The presence of a well-mixed layer near the surface in the sounding profiles (Fig. 10) once again suggests that turbulent mixing of air parcels with different temperatures could have been an important mechanism in the formation of fog at the surface.

5. SUMMARY AND CONCLUSIONS

An analysis of routine historical surface observations focusing on the characterization of conditions associated with low ceiling and fog occurrences in precipitation in the northeastern United States has been presented. It has been shown that low ceiling conditions occur on the majority of precipitation events, while fog occurs on fewer occasions as a result of cases of low ceilings lowering all the way to the surface. This provides evidence that fog in precipitation represents extreme cases of cloud base lowering. Therefore, the formation of fog in precipitation and associated reduction in visibility is in essence a low ceiling problem, where the crucial forecasting problem is to accurately predict the future behavior of low cloud ceilings in precipitation.

An examination of the observed precipitation character around the time of onset of fog indicated that the preferred precipitation regime leading to these events is characterized by continuous light liquid precipitation (light rain and drizzle). The observed tendencies in temperature and moisture prior to fog formation indicate that fog production is most often associated with moistening of the near-surface atmosphere (constant temperature or warming trend, with a sufficient increase in water vapor to create or maintain saturated and then possibly supersaturated conditions). Such conditions seem to occur at inland locations in the northeasterly flow ahead of warm fronts (classic scenario discussed in textbooks), but also at coastal locations in onshore flow conditions sometimes associated with approaching cold fronts from the west. In both scenarios, the presence of a stably stratified layer in the lower atmosphere has been observed. In the warm front case, the inversion is related to the warm air aloft overrunning the cold air near the surface. In the onshore flow case, a key factor is the temperature contrast between the air flowing from the south and the colder waters of the coastal Atlantic leading to the creation of a stably stratified internal boundary layer (IBL).

In conclusion, evidence points to the main mechanisms leading to cloud bases lowering to the surface (fog) being the evaporation of warm precipitation particles in the colder air in the subcloud layer, as well as possibly the shear induced turbulent mixing of saturated air parcels of contrasting temperatures. A more in-depth analysis of detailed observations is required to confirm these preliminary conclusions obtained from the analysis of historical data. Particular attention should be put on the microphysical processes associated with the evaporation of warm precipitation particles in the near saturated or saturated environment, as well as the boundary layer processes associated with the possible generation of supersaturation by turbulent mixing. This will be the subject of future work.

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