

# Atmospheric circulation structures associated with freezing rain in Quebec City, Quebec

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## ABSTRACT

**Introduction:** An analysis of freezing rain (FZRA) events in Quebec City (YQB), Quebec, Canada, a climatologically active area, is counted over a 30 year period (1979-2008) in an attempt to better understand the synoptic patterns, severity, and frequency of such events. **Methods:** Of the 218 individual events, 48 are classified as severe and are given a more in depth analysis at various pressure levels. Events are partitioned into five categories based on synoptic patterns, including the location and organization of surface features, 500 hPa trough location and length, and instantaneous geostrophic wind direction at YQB at the first hour of reported FZRA. Composite analyses of atmospheric variables are then created for each category, and the latter are then compared. **Results:** Each of the five categories has a unique thermodynamic and dynamic signature. Identifying these signatures within forecast models may significantly improve the prediction of freezing rain events. **Discussion:** FZRA events have not been studied extensively in the SLRV and so identifying these aforementioned signatures within forecast models may significantly improve the prediction of freezing rain events.

## KEYWORDS

*Meteorology, freezing rain (FZRA), severe weather, synoptic scale, Quebec City.*

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Received: 1 January 2011

Revised: 12 March 2011

## INTRODUCTION

### MOTIVATION

The St-Lawrence River Valley (SLRV) is one of the more climatologically active areas for freezing rain (FZRA) in North America. Associated inconveniences with freezing rain range from small scale disruption of ground transportation and aircraft operations to a large scale regional shut down (8). Quebec City (YQB) is located in the St-Lawrence River Valley (SLRV), a primary topographic feature of eastern Canada, extending in a southwest-northeast direction from Lake Ontario, past Montreal (YUL) and Quebec City (YQB) to the Gulf of St-Lawrence (7). The 1998 ice storm was the most devastating natural disaster in Quebec history. Data provided by the National Oceanic and Atmospheric Administration indicates that the storm killed 44 people and caused nearly \$4 billion of damage in the United States and Canada (6).

## OBJECTIVES AND MOTIVATION

This paper attempts to identify synoptic-scale, a horizontal length scale on the order of 1000km, circulation structures associated with ice storms in Quebec City. Current forecasting techniques include analyses of the expected vertical profile of the atmosphere using skew-t diagrams or tephigrams, in conjunction with surface and upper level movement of low-pressure systems as they approach the province of Quebec. However, the dynamics and thermodynamics of these events within the SLRV have not been studied extensively. Although Quebec City escaped most of the devastating effects of the 1998 ice storm, it shares a similar history of FZRA occurrences with its southwestern counterpart, Montreal (YUL). Quebec City is a large metropolitan area, housing almost 500,000 people. It is imperative to increase understanding of the physical processes occurring in these freezing rain events, to increase the safety of the public.

## PREVIOUS WORK

Freezing precipitation can form through two microphysical paths (9): the melting process and the collision-coalescence process. The first path forms FRZA, and the second creates freezing drizzle. This paper will focus solely on FZRA as previous research shows (5,3,11) that the synoptic-scale patterns associated with freezing drizzle may differ from those associated with freezing rain (6).

Few studies conducted in eastern Canada examine the type and frequency of synoptic-scale weather patterns associated with freezing precipitation (9). Most studies that are conducted revolve around either a climatology or case studies of one severe event. Since YQB is located in the SLRV, it is subject to pressure-driven channeling of surface winds throughout all seasons. YUL and YQB exhibit countercurrents where the direction of the wind within the valley is opposite to the wind above the valley (7). Pressure-driven channeling refers to valley winds that are driven by the pressure gradient along the valley axis.

## RESULTS

### APPROACH

In order to adequately investigate freezing rain occurrences, it is necessary to define a severe event. The 30-year period (1979-2008), analyzed using hourly surface observations from Environment Canada's Digital Archive of Canadian Climatological Data, had a total of 218 individual events. Individual events are defined as continuous or intermittent freezing rain precipitation lasting at least one hour. If non-freezing rain reports between FZRA events exceed six hours, the next FZRA report is considered a new event. A severe event is categorized as having six or more hours of freezing rain using the same guidelines as

set for individual events. Of the 218 total events recorded, 48 were found to be severe. Events are classified using partitioning methods, discussed below, and composites are created for each category. Composites consist of an average field of analyses taken for individual events over the first hour of reported FZRA. The partitioned synoptic-scale composite identifies potential triggers and signatures, which may be used by forecasters to identify future freezing rain events at YQB.

## DATA

Freezing rain events at the Jean Lesage International Airport in Quebec City (YQB) were identified using hourly surface observations from Environment Canada's Digital Archive of Canadian Climatological Data. Events occurred from the months of November and April, inclusively, throughout the 30 specified years (1979-2008).

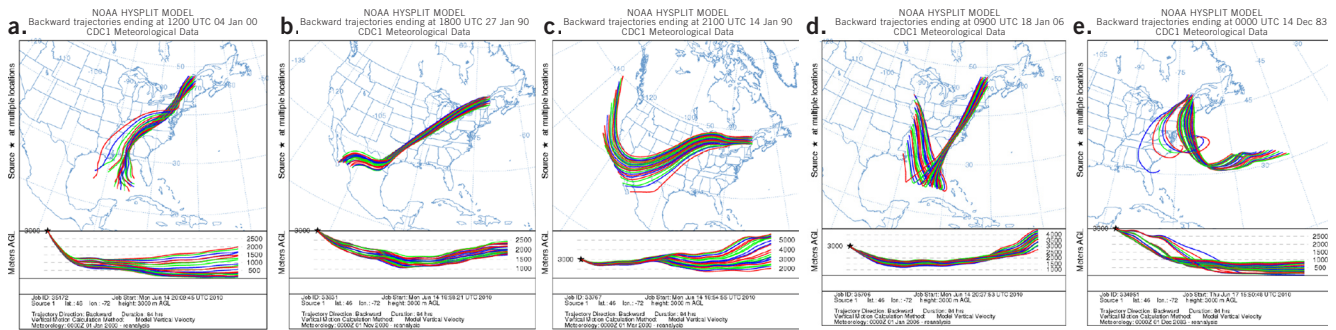
The North American Regional Reanalysis (NARR) dataset (2) was then used in conjunction with the General Meteorological Package (GEMPAK) version 5.7.11 to produce most of the analyses and graphics. The NARR uses the NCEP North American Mesoscale model, which has a 32-km horizontal grid with 45 vertical layers and analyses performed every three hours (4).

The Air Resources Laboratory Hysplit Trajectory Model was employed with a matrix grid of two-degree latitude-longitude separation to illustrate the paths of 24 trajectories at three different levels. Levels were chosen at 300m, 3000m, and 5500m corresponding to the approximate respective pressure levels of 1000hPa, 700hPa, and 500hPa. These levels were found to best represent incoming air parcels in the distinct low-level cold layer and mid-level warm layers of a FZRA event. Backward trajectories traced back in time to 84 hrs prior to the first report of freezing rain were chosen to better understand the origins of the air parcels.

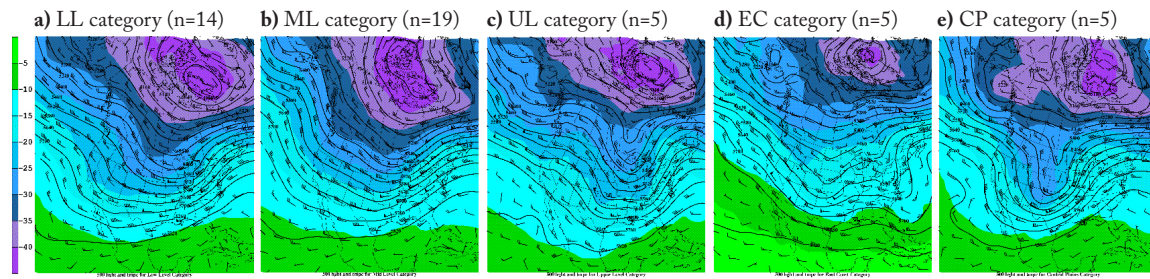
## METHODS AND PARTITIONING TECHNIQUE

We constructed Fig. 1 using the Air Resources Laboratory Hysplit Trajectory Model. The upper panel of each category displays horizontal parcel displacement and the lower panel displays vertical displacement as a function of time. The 3000m level, coinciding with the warm layer, provides a basis for partitioning. Categorization is based on the range of altitudes at which air parcels begin.

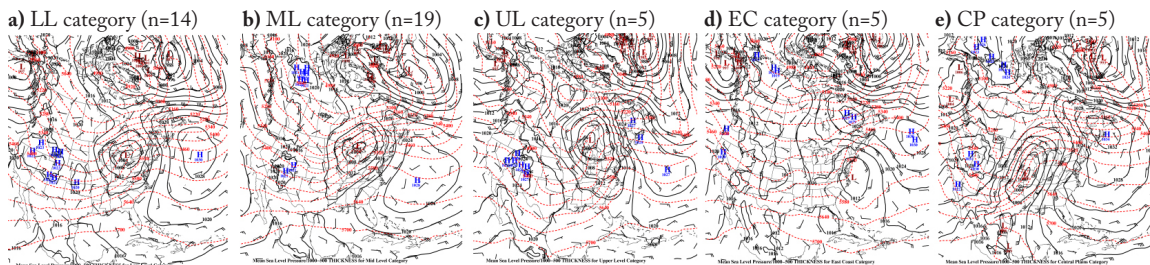
A large-scale analysis of various atmospheric variables at different levels which track the progression of the system responsible for the freezing rain in Quebec City yields a better understanding of its development and life cycle. Furthermore, the partitioning technique employed when categorizing severe events allows for a more dynamic, comprehensive, time-integrated approach



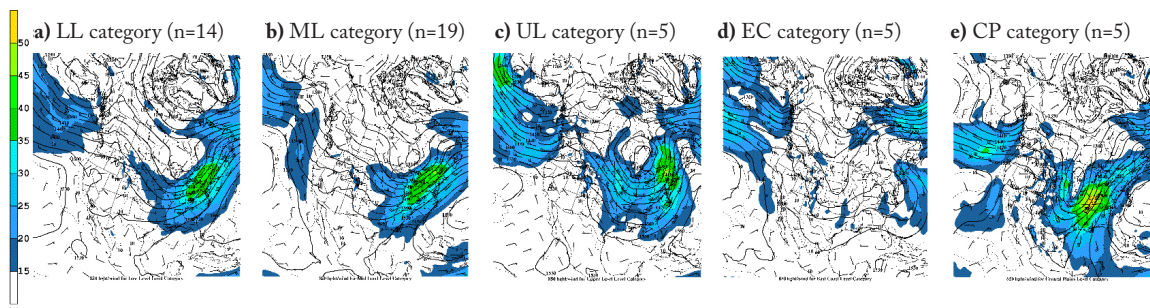
**Fig 1.** From left to right: LL, ML, UL, EC, CP parcel trajectories, one event taken from each category. The lower panel provides the approach for partitioning based on the range of altitudes at which air parcels begin.



**Fig 2.** Composite analyses of 500hPa height (black contours, interval: 40m) and temperature (°C, shaded).

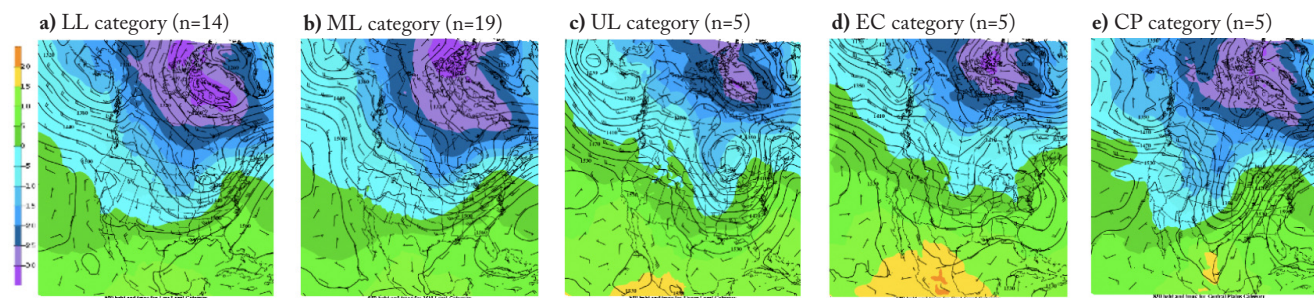


**Fig 3.** Mean sea level pressure (hPa, black contours are isobars with interval 4 hPa) composites illustrate the spatial pattern of couplets associated with each category. Wind barbs indicate surface wind speeds, red dashed lines indicate 1000-500 hPa thickness (contour interval of 60m).



**Fig 4.** 850 hPa Temperature (°C, shaded) and 850 hPa height (contour interval of 30m) composites for each category.





**Fig 5.** 850 hPa Temperature (°C, shaded) and 850 hPa height (contour interval of 30m) composites for each category.

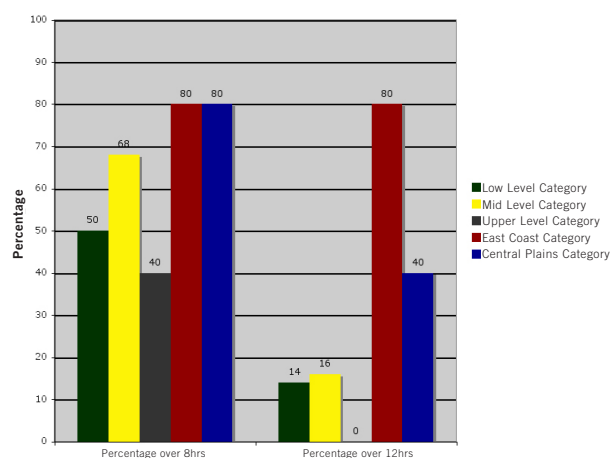
compared to specifically looking at one time frame of the system's development. By looking at parcel trajectories, we get an 84h progression on both the horizontal and vertical planes. The progression is then correlated to two synoptic spatial patterns observed at the initial onset of FZRA at YQB, explicitly at the surface and at 500 hPa. Surface observations also indicate that a specific instantaneous geostrophic wind direction is present within each category. Geostrophic winds blow parallel to isobars, contours of constant pressure, and refer to winds balanced by the pressure gradient and coriolis forces. Categorization is therefore based on both a static and dynamic approach, here providing a sound and diverse method of partitioning, the most important step in the research of FZRA at YQB. Five examples, one from each category, are given in Fig. 1 (a,b,c,d,e shown as Low Level (LL), Mid Level (ML), Upper Level (UL), East Coast (EC), and Central Plains (CP), respectively).

## COMPOSITES

Composites consist of an average of individual analyses of events present in each category. Each individual analysis is constructed at the onset of FZRA precipitation at YQB. The 500 hPa height temperature field (Fig. 2) shows all five categories with an environment conducive to synoptic-scale ascent over YQB—situated downstream of a height trough. The UL category is centered over Ontario whereas the CP category is centered over Manitoba. The EC category is most notably distinguished by a negatively tilted short-wave trough along the East Coast of the United States.

The sea-level pressure and 1000–500 hPa thickness fields (Fig. 3) exhibit cyclone–anticyclone couplets providing distinct instantaneous geostrophic winds at YQB. These winds coincide with air parcel trajectories at both 300m and 3000m for their respective events. The EC category is uniquely characterized by easterly geostrophic flow at YQB, with a north–south anticyclone–cyclone couplet. The other composites are primarily characterized by southerly geostrophic flow at YQB, with a west–east cyclone–anticyclone couplet.

**Percentage Thresholds for Duration of Freezing Rain Events per Category in Quebec City, QC (1979–2008)**



**Fig 6.** Threshold Duration of FZRA per category.

A 850hPa wind speed (kts) isotach analysis (Fig. 4) pinpoints the presence of a low level jet, defined by speeds exceeding 15kts, in each category. The strongest winds, 30 kts above the climatological average, are associated with the CP category. All categories, except for that of the EC, have winds that are 1 to 2 standard deviations above the normal range (15–25kts), indicating large amounts of warm air and moisture transport from the south. The EC category retains its high moisture transport due to the trajectories' proximity to the Atlantic Ocean.

Geostrophic warm advection at 850–hPa over YQB (Fig. 5) provides favorable conditions for ascent. The persistence of warm air advection, the temperature increase associated with the transport of warmer air into the region of interest, and moisture transport over YQB supports FZRA formation and maintenance. The UL and EC categories have the warmest associated mean (ranging to 5°C). Owing to the UL category's meridional flow, FZRA duration is shortest with respect to all other categories, regardless of the presence of much higher maximum 850 hPa temperatures.

Figure 6 presents percentage threshold duration of FZRA events per category. Thresholds are set at 8 and 12h respectively. The EC category has the longest duration of events, with 80% of events lasting over 12h. On the other hand, the UL category has no events lasting over 12hrs, as well as only 40% of all events lasting over 8 hrs.

## DISCUSSION

A major focus of our research is to determine synoptic patterns that influence the duration of FZRA. Ideal conditions require a deep warm layer, with temperatures above 0°C, maintained with warm air advection. This yields a constant influx of moisture and above zero temperatures. The progression of spatial patterns at the surface, 850 hPa, and 500 hPa, bracket the potential interval of duration of each event. As outlined by Cheng *et al.* (1), duration thresholds, chosen to be 8 and 12h, are used to determine variability among the categories. The longest events are found in the EC and CP categories. Moreover, 80% of all EC events last over 12h, coinciding with conclusions reached by Rauber *et al.* (9): “processes occurring on the cold side of moving and stationary warm fronts and deep within EC air masses were most efficient at producing freezing precipitation per unit area.”

The EC category produces ideal conditions to allow the maintenance of this structure. A time-scale analysis of events tracking up the coastal United States provides markers that depict constant and persistent moisture and temperature transport at 850 hPa, and constant low-level influx of cold air. The influx of cold air is significant as microphysical processes related to the release of latent heat associated with freezing rain often disrupt this layering process. The essentially meridional track of low pressure systems within this category, as opposed to the more typical zonal track, allows for eastward-located warm sector to be maintained at mid levels for a longer period of time. Furthermore, the anticyclone located over Northern Quebec channels near-surface arctic air, representing the lowest portion of the Earth's atmosphere, with a depth ranging from 8 to 17km in the mid-latitudes, into the SLRV providing the cold air necessary for the maintenance of FZRA. The North-South couplet of mean sea level pressure provides a basis for a blocking pattern, while the negatively-tilted shortwave trough allows for the intense deepening of the low pressure system. Though low level jet winds are closely approximated by the climatological mean, moisture trajectories stemming from the Atlantic travel a short distance to YQB, allowing for an availability of substantial precipitable water.

Additionally, the CP category also yields events of especially long duration. Specifically, this category is characterized by 40% of its events lasting over 12h. Synoptic patterns indicate that moisture

and warm air advection originate in the Gulf of Mexico. Although this is a significant distance to cover, it is quite feasible given that this category is characterized by the highest 850 hPa wind speeds among all categories, with top speeds exceeding 50 kts. For comparison purposes, a 60 kt wind transports moisture in the atmosphere for a distance of approximately 110 km in an hour. The trajectory of the low pressure system allows for the maintenance of the mid level warm layer, as the warm air mass ahead of the low air mass covers much of the Eastern United States. This results in a warm sector whose area has more coverage in Canada than the LL, ML, and UL categories. The Southwest-Northeast couplet at sea level also provides ideal wind channeling conditions to maintain the surface cold layer's maintenance.

Unlike the LL and ML categories, which hold similar duration intervals, the UL category yields no events lasting over 12h. Analysis of 500 hPa, 850 hPa, and surface composites provides a synoptic reasoning for this result. The meridional shortwave trough present at 500hPa in UL cases is not conducive for a long-term maintenance of the mid level influx of warm air, as the track of the associated surface low quickly brings about the encroaching arctic air on the backside of the cold front. Loss of mid level influx of warm air results in a phase change in precipitation from FZRA to snow. Furthermore, although 850 hPa temperatures and wind speeds are warmer and stronger than those of the other categories, their small coverage of area yields a shorter duration of FZRA.

## CONCLUSION

Severe FZRA events in the Quebec City area are associated with specific synoptic patterns, partitioned into five categories. The intensity and duration of these events are connected to the spatial distribution of the associated atmospheric patterns. East Coast cases are associated with particularly long durations, with 80% of these events lasting longer than 12h. Events in the Central Plains category represent a large portion of longer lasting events, with 40% lasting over 12h.

A major limitation of this study is the lack of FZRA accumulation values. Environment Canada does not directly record accumulation amounts for freezing rain. Instead, they use a chart which consists of light ( $< 2.5 \text{ mmh}^{-1}$ ), moderate ( $2.5\text{--}7.5 \text{ mmh}^{-1}$ ), and heavy ( $> 7.5 \text{ mmh}^{-1}$ ) precipitation. It was therefore necessary to employ a less precise method of categorization based on total duration instead of precipitation rates.

This analysis of synoptic signatures associated with FZRA events in Quebec City provides meteorologists and researchers with a new documentation of synoptic-scale patterns over the area.

These results are an important step in better understanding the formation, progression, and duration of a severe natural phenomenon that can wreak havoc on major cities, infrastructure, and citizens.

## ACKNOWLEDGEMENTS

This research has been supported by a grant from the Natural Sciences and Engineering Research Council of Canada, and in part by the Ouranos Consortium on Regional Climatology and Adaptation to Climate Change. Thanks to the National Climatic Data Center for providing access to the NARR, and NCEP Global Reanalysis, and to the NOAA Air Resources Laboratory for access to their HYSPLIT trajectory model. Finally, thanks to Environment Canada for access to their online climate information database.

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