The role of anticylones in replenishing surface cold air and modulating freezing rain duration

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ABSTRACT

Introduction: Freezing rain (FZRA), a hazardous meteorological phenomenon, is associated with airflows from both cyclones and anticyclones. Though researchers have placed primary emphasis on the cyclone's role in FZRA, we intend to examine the anticyclone's role in transporting near-surface cold air. More specifically, we study its impact on the duration of FZRA in a region of orographically enhanced vulnerability, namely at Quebec City (YQB), located in the St-Lawrence River Valley (SLRV). This region is an active zone of freezing rain due to orographic influences that promote pressure-driven channeling. **Methods**: Within the SLRV region, we define a severe event using a minimum duration threshold of six hours and found 47 severe freezing rain cases during a 30-year period (1979-2008). We then partitioned these cases into categories based on precipitation phase change and 850hPa geostrophic relative vorticity. **Results**: We found that the duration of freezing rain is determined in large part by the intensity and location of the anticyclone. **Discussion**: The anticyclone enhances pressure-driven channeling, and this channeling provides the replenishment of cold air at the surface required to maintain FZRA. Identifying these anticyclonic features provides a novel approach to determine the potential duration of FZRA events.

Keywords

Severe weather: Any weather phenomena related to the disruption of social services, property damage, and/or loss of life. Freezing rain: A meteorological phenomenon characterized supercooled water freezing on contact due to a shallow layer of sub-zero temperatures at the surface and a warm layer aloft. Anticyclone: A large scale, clockwise-rotating (northern hemisphere) weather system characterized by generally calm weather and high pressure at its center. St-Lawrence River Valley: A low-lying topographical region encompassing the Montreal and Quebec City areas, extending into southern Ontario and eastward to the Gaspé Peninsula. Pressure-driven Channeling: Valley winds that are driven by the pressure gradient aligned along the axis of the St-Lawrence River Valley.

KEYWORDS

Severe weather, freezing rain, anticyclone, St-Lawrence River Valley

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INTRODUCTION

MOTIVATION

Freezing rain (FZRA) is a meteorological phenomenon that poses many hazards to the general population and resources, including damage to crops and city infrastructure *(1)*. It occurs when the vertical structure of the atmosphere has a shallow layer of sub-zero temperatures at the surface and a warm layer of above zero temperatures aloft. The warm layer must be thick enough to entirely melt snowflakes falling from the clouds, which then freeze upon contact with the surface. The occurrence of FZRA in

SLRV is significant because the SLRV is one of the most climatologically active areas for FZRA in North America *(3)*. Severe FZRA events have inflicted billions of dollars in damage to the province of Quebec *(4)*. It is therefore of significant importance that research be conducted to better understand their occurrence.

OBJECTIVES

FZRA forecasts given by Environment Canada utilize models issued by the Canadian Meteorological Centre. Splawinski *et al.* *(2)* introduce the importance of the SLRV in pressure-driven channeling and identify the general synoptic structure of severe FZRA events in YQB. This paper attempts to further identify the influence of specific features, namely the low-level jet and anticyclone, on the duration of severe FZRA events. Knowledge of these features' impact on duration may enable better forecasting techniques, thereby significantly improving watches and warnings issued to the public for FZRA events.

PREVIOUS WORK

While most past research on FZRA in eastern Canada has focused mainly on climatology and case studies of specific events, only Ressler *et al*. (2012), Splawinski *et al*. (2011), and Rauber *et al*. (1994, 2001) focus on the frequency of synoptic scale weather patterns associated with freezing participation. And though Splawinski *et al*. (2011) provide an overview of conditions necessary for FZRA formation, the vertical structure and significance of individual features associated with FZRA were not examined.
Following the work of Splawinski *et al*. (2011), this research focuses solely on the small structures of freezing rain, as opposed to freezing drizzle, whose synoptic-scale structures are distinctively different from those of freezing rain *(1, 4, 5, 6)*.

RESULTS

APPROACH AND DATA

The data set and initial parameters of this study are the same as those used in Splawinski *et al*. (2011) *(2)*. A 30-year period (1979-2008) was chosen and analyzed using hourly surface observations at Jean-Lesage International Airport in Quebec City, QC. Events with a minimum duration of six hours were categorized as severe events; of the 218 individual cases, 47 were determined to be severe.

Analyses were conducted using the North American Regional Reanalysis (NARR) dataset *(6)*, and the associated graphics were then created using the General Meteorological Package (GEMPAK) version 5.7.2 *(8)*. Finally, WRPlot View *(9)* was used in conjunction with Environment Canada surface data to create wind roses, which plot the distribution of magnitude and direction of winds at a location for a specific time.

METHODS AND PARTITIONING TECHNIQUE

Specific precipitation phase changes are associated with distinct vertical structures of the atmosphere; therefore, the 47 individual severe events were partitioned into six categories (Table 1) based on the observed phase change over a three-hour period at the end of FZRA.

Phase Change	P (SLRV)	PN (SLRV)	UP (NS)	UP (EW)	Total
Rain (RA)	2	7	9	0	18
Snow (SN)	5	0	1	0	6
FZDZ (freezing drizzle)	1	1	5	2	9
CLD+ve (no precipitation with an increase in temperature at phase change)	1	3	3	0	7
CLD-ve (no precipitation with a decrease in temperature at phase change)	2	1	1	0	4
CLDst (no precipitation with no change in temperature at phase change)	0	1	0	2	3

Table 1. Partitioning of the 47 severe events, based on categories (Phase change) and sub-categories (850hPa flow).

Flow	Description
P(SLRV)	Perturbed flow, within the St-Lawrence River Valley
PN(SLRV)	Perturbed flow, north of the St-Lawrence River Valley
UP (NS)	Unperturbed, meridionally-oriented (South-North) flow
UP (EW)	Unperturbed, zonally-oriented (West-East) flow

Table 2. Definitions of the four flows obtained using geostrophic relative vorticity. Table 1 initially categorizes events based on phase change, then on the 850hPa geostrophic relative vorticity.

These events were then further partitioned into four sub-categories, based on 850 hPa cyclonic geostrophic relative vorticity (Table 2). This quantity is proportional to the horizontal Laplacian of the geopotential height field, as shown by equation (1),

$$\xi_g = \frac{1}{f_0}\nabla_p^2\Phi \quad (1)$$

Where ξg is the geostrophic relative vorticity, f0 the Coriolis parameter, and Φ the geopotential height field. In simpler terms, ξg refers to the local spin of air parcels, and Φ describes elevation-adjusted force of gravity. These four distinct flows (Fig. 1a-1d) were observed using a minimum threshold of $24\text{x}10^{-5}\text{s}^{-1}$. Perturbed flow, characterized by vorticity maxima and maximum curvature at 850hPa, is observed in two distinct patterns. Perturbed flow within the valley (P (SLRV)) is categorized by vorticity maxima and maximum curvature centered along the axis of the SLRV. (Fig. 1a). There is also a distinct perturbed flow and associated vorticity and curvature maxima (PN (SLRV)) centered to the North of the SLRV around the James Bay region (Fig. 1b). Surface pressure patterns were used to distinguish the two flows; the P(SLRV) category having a SW-NE oriented axis relative to the SLRV in contrast with the NW-SE axis of orientation of the PN(SLRV) category. Unperturbed flow, characterized by a lack of organized vorticity maxima and associated with a straight-line 850hPa flow, was also observed in two categories. The meridional flow (UP(NS)) has a southerly wind flow and an east-west anticyclone-cyclone couplet (Fig. 1c), whereas the zonal flow is characterized by an easterly flow with a north-south couplet.

For the purposes of this paper, specific cases were chosen from each of the four subcategories mentioned above. To be able to provide a representative choice, wind roses of actual wind speed (ms^{-1}) and direction, as well as the 1000-850hPa critical thickness lines (1300m) were created for all events in each subcategory. The 1000-850 hPa critical thickness line of 1300m is a winter precipitation index based on a climatological-mean value. The coherence among individual cases allows for one case to be chosen at random, while remaining representative of each sub-category.

Sub-categories display weakening wind speeds at the time of phase change (Fig. 2b, f), and/or a distinct wind shift (Fig. 2d,h). This is significant because it relates back to the pressure-driven channeling *(12, 13)* responsible for the required shallow layer of cold air at the surface.

METEOGRAMS (THICKNESS AND TEMPERATURE PLOTS)

We examined specific changes in temperature, winds, and thicknesses over YQB, prior to analyzing surface and upper level graphics. The thickness of a column of air relates to the virtual

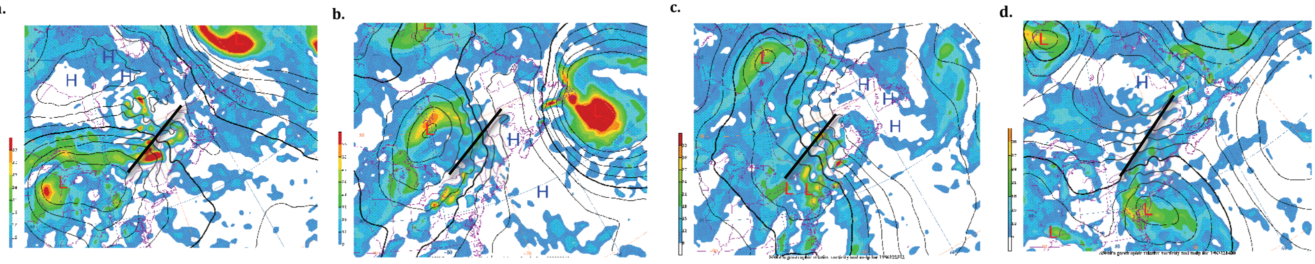
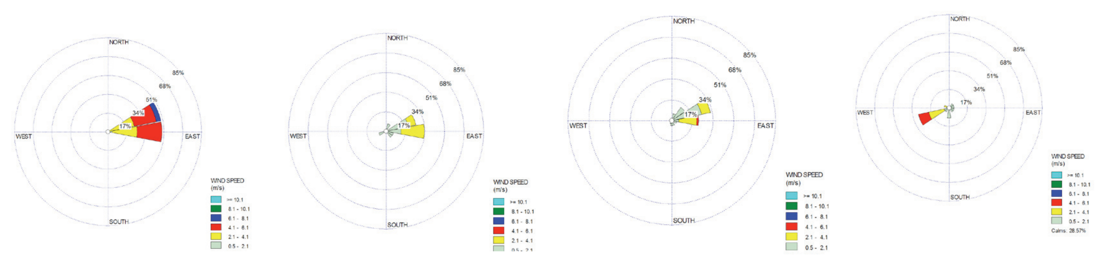
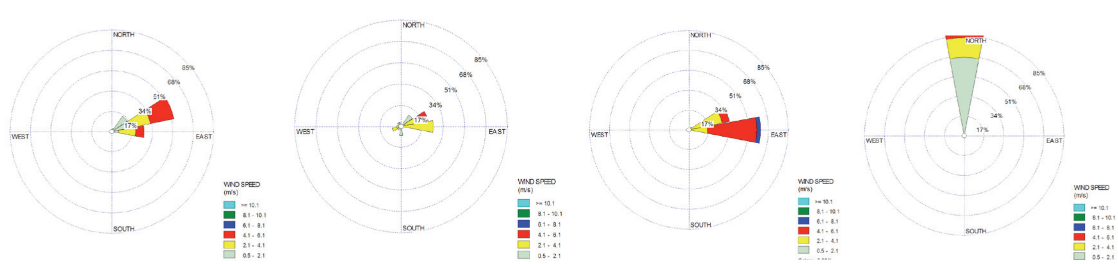


Figure 1. 850hPa Geostrophic Relative Vorticity (10-5s-1) and Sea-Level Pressure (SLP, solid black contour of 4 hPa). The black arrow defines the axis of the SLRV. The minimum threshold of 24x10^{-5}s^{-1} is shaded in lime green. **1a.** P (SLRV): Maxima of cyclonic vorticity located within the SLRV. **1b.** PN (SLRV): Maxima of cyclonic vorticity located N of the SLRV. **1c.** UP (NS): Straight-line north-south oriented geostrophic flow with small, disorganized vorticity maxima. 1d. UP (EW): Straight-line east-west oriented geostrophic flow with a north-south couplet of high and low pressure.



2a,b. SN P(SLRV) *2 c,d. RA PN(SLRV)*



2 e,f. RA UP(NS) *2 g,h. FZDZ UP(EW)*

Figure 2. Wind roses of surface winds at YQB comprised of all events within that subcategory for at the time of onset and phase change of FZRA, respectively. The rose points in the direction from which the wind is blowing, the concentric circles showing the percentage of time associated with each direction, smaller circles indicating small percentages. The various shades of the rose depict associated wind speeds (ms^{-1}) with darker shades showing successively stronger winds.

temperature (adjustment applied to actual temperature to take into account reduction in air density due to the presence of water vapor[1]) of that column through the hypsometric equation (2),

$$ln\left(\frac{p_1}{p_2}\right)\frac{R\langle T_v\rangle}{g} = z_2 - z_1 \quad (2)$$

where z_2-z_1 is the thickness of the column, g is gravity, R is the gas constant for dry air, and p1 and p2 are the pressures of the given layers. As the mean virtual temperature of the column increases, the thickness of the column bounded by p1 and p2 increases, and vice versa.

Fig. 3a. SN P(SLRV) case (1997.01.05/12Z-1991.01.06/12Z)

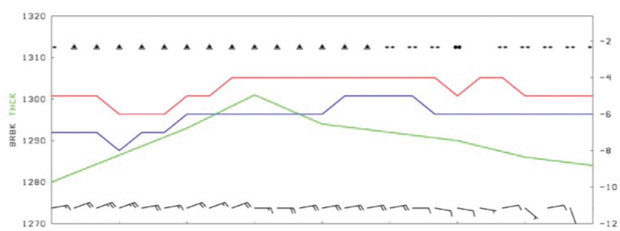


Fig. 3b. RA P(NSLRV) case (1988.03.09/12Z-1988.03.10/12Z)

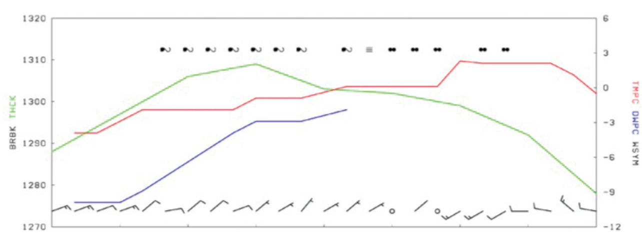


Fig. 3c. RA UP(NS) case (1989.12.31/00Z-1999.01.01/00Z)

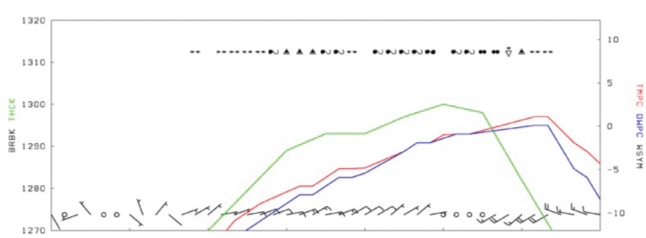
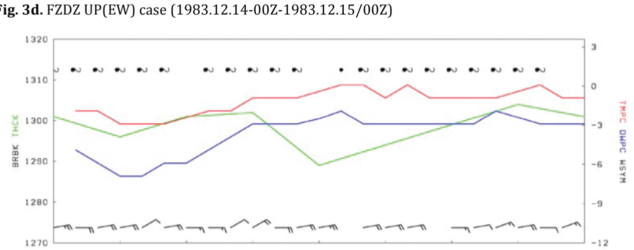


Fig. 3d. FZDZ UP(EW) case (1983.12.14-00Z-1983.12.15/00Z)



Figures 3a-d. Meteogram analyses: 1000-850hPa thickness (green line, m, with scale on left), surface temperature (red line, deg C, scale on right), dewpoint temperature (blue line, deg C, scale on right), wind barbs of standard meteorological convention, weather symbols at the top of the plot. Vertical lines coincide with figures shown below.

Figure 3a, showing the meteogram for the SN P(SLRV), indicates that 1000-850hPa thickness remains between 1280-1300m. Temperatures and winds do not vary substantively throughout the entire period. The thickness declines at the end of FZRA, coinciding with a phase change to snow. Figure 3b depicts the meteogram for the RA PN(SLRV). At the time of phase change into rain, winds predominantly from the NE throughout the event become calm and show a distinct shift to the SW after the changeover occurs. Temperatures then increase from 0 to 3 deg C as the rain continues. However, thicknesses continuously decrease at phase change.

The RA UP(NS) case (Fig. 3c) shows temperature variations of as much as 10 deg C throughout the duration of the event. Thickness trends are positive throughout the event, and only decrease once phase change occurs. At phase change, there is a distinct wind shift once again from the NE to the SW, indicating the loss of pressure-driven channeling.

Finally, in the FZDZ UP(EW) event (Fig. 3d), we see consistency among all variables. Especially noteworthy is the maintenance of northeasterly winds throughout the entire event, allowing for temperatures to remain below zero with the maintenance of cold air replenishment at the surface. The 1000-850 hPa thickness also remains almost constant (between 1290-1305m).

CASE STUDY MAP ANALYSES

To assess the influence of the anticyclone on the duration of freezing rain, we focus primarily on the atmosphere's height difference (or thickness) between the 850 and 1000 levels, more typically 1500m AGL. The shallow layer of cold air at the surface is often decoupled from the warm layer at 850hPa aloft, with each layer having unique thermodynamic structures.

Each of the four case studies chosen is partitioned into four time intervals, starting with the onset and ending at the time of phase change. This allows for the analysis of the synoptic scale flow progression, and for the importance of the SLRV and the anticyclone in the maintenance of FZRA to be highlighted.

Figure 4a identifies a P(SLRV) event with a changeover to snow. At the onset of FZRA (4a.1), the 850hPa flow depicts the presence of a low-level jet (LLJ), with its attendant warm air advection and tropical moisture transport. At the surface, YQB is situated within the warm sector of the cyclone, and is flanked to the north by an anticyclone whose clockwise rotation provides the replenishment of cold air required to maintain FZRA. As the cyclone progresses to the NE, the ridge gradually weakens over northern Quebec as it retreats over northern Hudson Bay. At phase change (Fig. 4a.4), the passage of a cold front and its associated large thickness falls provide a changeover from FZRA to SN. The anticyclone, meanwhile, has weakened and is no longer in a position to provide wind channeling.

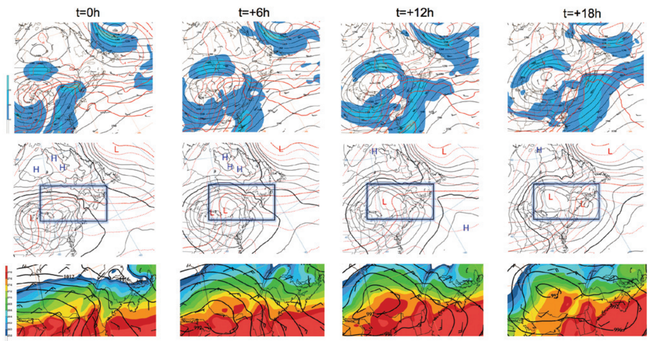


Figure 4a: Time evolution of the SN P(SLRV) event. The onset of the event is depicted by t = 0 h, and the phase change occurs in the 4^{th} panel. Top row: shaded regions indicate 850hPa wind speeds greater than 30knots ($15ms^{-1}$), 1000-850hPa thickness (solid black contour interval of 30m), 850 hPa isotherms (contour interval of 4 deg C, with red solid indicating values greater than or equal to 0 deg C, red dashed indicating temperatures colder than 0 deg C), with plotted winds in the standard meteorological convention. Middle row: Sea-level pressures (solid black contour interval of 4 hPa, with bold contour showing the 1008 hPa isobar), and 1000-500hPa thickness (dashed contour interval of 60m, with the bold contour indicating the 5400m value). The blue box identifies the region shown in the bottom row. Bottom row: Surface potential temperature (shaded, in K), sea-level pressure (solid contour interval of 4 hPa), and plotted surface winds of standard meteorological convention.

Figure 4b identifies a P(NSLRV) event with a changeover to rain. In this case (Fig. 4b.1), the 850 hPa low center is located farther north and temperatures at YQB at the same level are still above the melting point. At the surface, the anticyclone is structured meridionally and as the low tracks eastward, the anticyclone gradually weakens. At phase change (Fig. 4b.4), there is a loss of pressure-driven channeling along the SLRV due to the weakening of the anticyclone and the passage of the center of the low over YQB. This translates into a wind shift seen in the wind roses (Fig. 2d), from NE to SW. The loss of channeling, combined with the latent heat of fusion from the surface, and the lack of a cold front passage, triggers the changeover from FZRA to rain (RA).

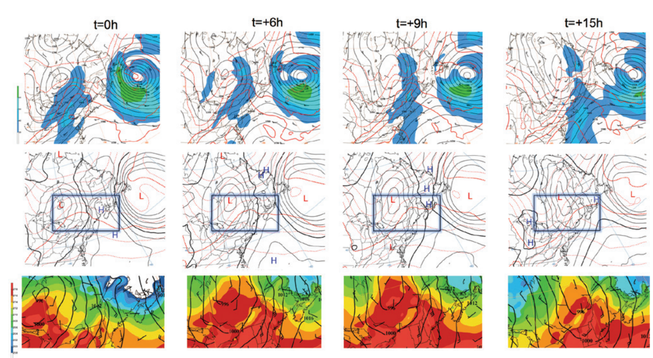


Figure 4b: Time evolution of the SN P(SLRV) event. The onset of the event is depicted by t = 0 h, and the phase change occurs in the 4^{th} panel. Top row: shaded regions indicate 850hPa wind speeds greater than 30knots (15ms-1), 1000-850hPa thickness (solid black contour interval of 30m), 850 hPa isotherms (contour interval of 4 deg C, with red solid indicating values greater than or equal to 0 deg C, red dashed indicating temperatures colder than 0 deg C), with plotted winds in the standard meteorological convention. Middle row: Sea-level pressures (solid black contour interval of 4 hPa, with bold contour showing the 1008 hPa isobar), and 1000-500hPa thickness (dashed contour interval of 60m, with the bold contour indicating the 5400m value). The blue box identifies the region shown in the bottom row. Bottom row: Surface potential temperature (shaded, in K), sea-level pressure (solid contour interval of 4 hPa), and plotted surface winds of standard meteorological convention.

An UP(NS) event with a changeover into rain is shown in Fig. 4c. Unperturbed categories are associated with strong LLJs that penetrate deep into northern QC. However, the strong anticyclone is anchored just offshore of the Maritime provinces, which manages to offset the warm air advection aloft and latent heat of fusion at the surface, once again with pressure-driven channeling. Sea-level pressure fields indicate that the low deepens without moving eastward, maturing into a well-developed cyclone by phase change (Fig. 4c.4). This intensification also leads to an increase in LLJ speeds throughout the period. Furthermore, the anticyclone gradually travels farther into the Atlantic, where it can no longer sustain the pressure gradient required to maintain cold air replenishment at the surface. The loss of cold air advection at the surface combined with YQB remaining in the warm sector of the cyclone at phase change allows for a change of phase into rain.

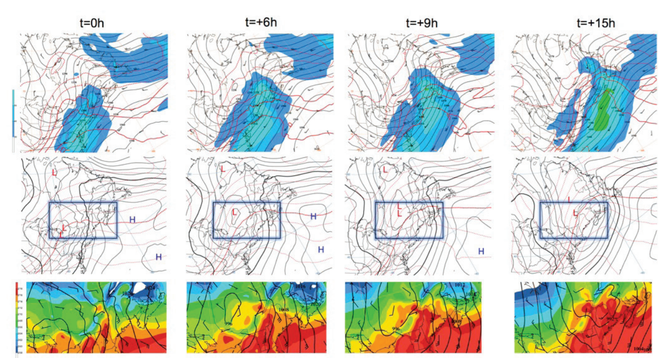


Figure 4c: Time evolution of the SN P(SLRV) event. The onset of the event is depicted by t = 0 h, and the phase change occurs in the 4^{th} panel. Top row: shaded regions indicate 850hPa wind speeds greater than 30knots ($15ms^{-1}$), 1000-850hPa thickness (solid black contour interval of 30m), 850 hPa isotherms (contour interval of 4 deg C, with red solid indicating values greater than or equal to 0 deg C, red dashed indicating temperatures colder than 0 deg C), with plotted winds in the standard meteorological convention. Middle row: Sea-level pressures (solid black contour interval of 4 hPa, with bold contour showing the 1008 hPa isobar), and 1000-500hPa thickness (dashed contour interval of 60m, with the bold contour indicating the 5400m value). The blue box identifies the region shown in the bottom row. Bottom row: Surface potential temperature (shaded, in K), sea-level pressure (solid contour interval of 4 hPa), and plotted surface winds of standard meteorological convention.

Figure 4d identifies an UP(EW) event with a changeover to freezing drizzle (FZDZ). The synoptic pattern at the onset of FZRA (Fig. 4a.1) shows a well-developed cyclone along the eastern coast of the United States, coupled with an anticyclone over northern Quebec. The duration of the event is 24h, which stems from both the anticyclone and cyclone's relatively static position, creating a blocking pattern. This pattern allows for continuous replenishment of cold air in the SLRV at the surface from the anticyclone, and warm air advection at 850hPa from the cyclone. As the event progresses, the anticyclone slowly tracks off the coast of Labrador, while the cyclone continues its northerly track. At phase change (Fig. 4d.4), the anticyclone is no longer in a position to maintain the pressure-driven channeling at the surface, cutting off the source of cold air. YQB remains south of the 5400m critical thickness threshold used to differentiate between rain and snow, and a change of phase into FZDZ occurs. Evidently, during the process of weakened channeling, the atmospheric structure becomes more conducive to facilitating FZDZ.

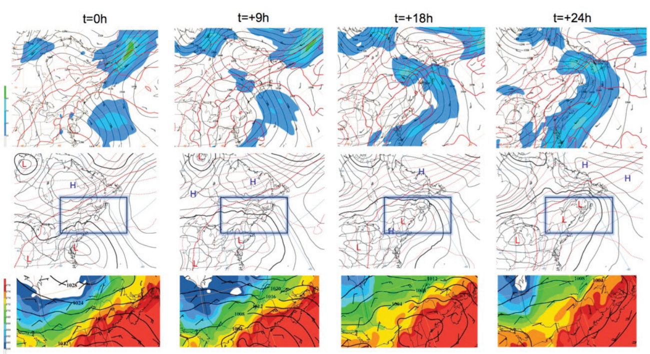


Figure 4d: Time evolution of the SN P(SLRV) event. The onset of the event is depicted by t = 0 h, and the phase change occurs in the 4^{th} panel. Top row: shaded regions indicate 850hPa wind speeds greater than 30knots ($15ms^{-1}$), 1000-850hPa thickness (solid black contour interval of 30m), 850 hPa isotherms (contour interval of 4 deg C, with red solid indicating values greater than or equal to 0 deg C, red dashed indicating temperatures colder than 0 deg C), with plotted winds in the standard meteorological convention. Middle row: Sea-level pressures (solid black contour interval of 4 hPa, with bold contour showing the 1008 hPa isobar), and 1000-500hPa thickness (dashed contour interval of 60m, with the bold contour indicating the 5400m value). The blue box identifies the region shown in the bottom row. Bottom row: Surface potential temperature (shaded, in K), sea-level pressure (solid contour interval of 4 hPa), and plotted surface winds of standard meteorological convention.

DISCUSSION

Given its SW-NE axis, the SLRV orography allows for pressure-driven channeling of cold air, and thus the maintenance of a prolonged FZRA event even while YQB resides in an area of the low that facilitates warm air intrusions aloft. This pressure-driven channeling is predominantly governed by the location and intensity of the anticyclone, as it is this feature that determines the pressure gradient along the valley. Pairing the wind roses with the meteograms and surface analyses properly depicts this interaction. If conditions aloft do not change, then FZRA will continue as long as the 850 hPa warm air advection continues, and there is enough cold air advection at the surface to offset the effects of latent heat of fusion. At phase change, there is a distinct weakening of winds in each category and a shift in others, depending on where the low pressure system tracks. Lows tracking north of YQB will effect a substantial wind direction shift, whereas wind shifts associated with lows centered south of YQB are less significant. Both the changes in the magnitude and direction of the winds at YQB can be attributed to the loss of pressure-driven channeling. Since low pressure systems within each category are either strengthening or relatively unchanging, we can therefore say this is due primarily to the weakening or translation of the anticyclone. And though the low does obviously play a large role in FZRA precipitation, we focus predominantly on surface flow and the maintenance of CAA. The latter is only possible through the anticyclone, and to first order, we can therefore say that the anticyclone plays an inherent role in maintaining surface cold air and the inversion that facilitates freezing rain. This is also shown in the time evolution of surface potential temperature, with the shading indicating the cold pool of air within the SLRV.

CONCLUSION

The duration of severe FZRA events in Quebec City is predominantly based on the location and intensity of the anticyclone. This anticyclone provides the basis for pressure-driven channeling which replenishes the cold air required at the surface to maintain a vertical profile conducive to FZRA precipitation. Stationary patterns hold the greatest potential for long duration events, as long as the instability aloft is maintained, as was the example with the great Ice Storm of 1998 *(14)*.

The limitations of this study are similar to those performed by Splawinski *et al.* (2011), and arise in the recording of FZRA accumulations. This method, employed by Environment Canada, does not directly measure accumulations, but rather uses precipitation rates.

However, results still clearly depict the role the anticyclone plays in FZRA events, more so than discussed in past literature. Given this, meteorologists are provided with a novel, insightful approach to forecasting severe FZRA events, which can be used in conjunction with current forecasting techniques. This may provide better forecasts that enable city officials and the general public time to adequately prepare and take all necessary precautions.

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