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A Study of the Meteorological Conditions Associated with Anomalously Early and Late Openings of a Northwest Territories Winter Road

K. EMMA KNOWLAND,[1,2] JOHN R. GYAKUM[1] and CHARLES A. LIN[1]

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ABSTRACT. In the Canadian Arctic, winter roads are engineered across the frozen land, rivers, and lakes. The strength and longevity of these roads depend on particular weather conditions. Our research focuses on the winter road between Tulita and Norman Wells, Northwest Territories, which has been maintained officially by the territorial government since 1982. Statistical analysis of the opening dates for the winter road showed five seasons with extremely early dates and five with extremely late dates. The extremely early-opening seasons are distinguished by anomalously high sea-level pressures, anomalously cold tropospheric air, and northwesterly surface winds during the November prior to the road opening. The extremely late-opening seasons are characterized by an anomalously strong Aleutian low in the preceding November. The extremely late-opening years are correlated with strong El Niño seasons, whereas the extremely early-opening years are not systematically associated with teleconnection patterns. Our analysis of meteorological conditions near Norman Wells, associated with the extreme opening dates for this winter road, may provide planners with more precise information germane to this road construction.

Key words: Northwest Territories weather, winter roads meteorology, interannual variability, regional climate

RÉSUMÉ. Dans l'Arctique canadien, les routes hivernales sont construites sur le sol, les lacs et les rivières gelées. La solidité et la durabilité de ces routes dépendent de conditions météorologiques particulières. Nos recherches mettent l'emphase sur la route hivernale officiellement entretenue par le gouvernement territorial depuis 1982, entre Tulita et Norman Wells dans les Territoires du Nord-Ouest. L'analyse des statistiques relativement aux dates d'ouverture de cette route ont permis de dénoter des dates d'ouverture très hâtives dans le cas de cinq saisons, et très tardives dans le cas de cinq autres saisons. Les années où l'ouverture est extrêmement hâtive sont distinguées par une pression au niveau de la mer irrégulièrement haute, de l'air troposphérique irrégulièrement froid, et des vents de surface du nord-ouest durant le mois de novembre précédant l'ouverture de la route. Les cinq années dont l'ouverture est extrêmement tardive sont précédées par un mois de novembre où la basse pression des Aléoutiennes y est irrégulièrement forte. Les résultats démontrent que les années où l'ouverture est extrêmement tardive sont des saisons influencées par El Niño tandis que les années dont l'ouverture est extrêmement hâtive ne sont pas systématiquement associées avec des signaux de téléconnexions. L'analyse des conditions météorologiques près de Norman Wells, associée avec les dates d'ouvertures extrêmes pour cette route, procure aux planificateurs de ces routes de l'information plus précise pour la construction de celles-ci.

Mots clés : conditions climatiques des Territoires du Nord-Ouest, météorologie des routes hivernales, variabilité interannuelle, climat régional

INTRODUCTION

Every winter, roads cross the frozen lakes, rivers, and tundra in the Canadian Arctic. These transportation corridors are known as *winter roads* if they are mainly over land and *ice roads* if they traverse frozen lakes and rivers (ACIA, 2005:933). Such temporary winter transportation routes connect the remote communities and the oil, mining, and gas industries with the all-season paved or gravel roads. They are used to bring in heavy machinery, fuel, and supplies that otherwise could be transported only by air—an expensive alternative (ACIA, 2005; Hinzman et al., 2005). There is pressure from industries to open the roads as soon as possible, but the weather conditions play a major part in efficient and safe road construction.

In the Northwest Territories (NWT), the Department of Transportation is in charge of the networks of winter and ice roads. Depending on the road and the weather conditions, construction can begin as early as November, and the roads may be maintained until April. The Government of the Northwest Territories has compiled opening and closing dates for the winter and ice roads since 1982 (GNWT, 2007a).

Given the substantial interannual variability in the documented durations of the winter and ice road seasons, our objective is to determine, and to understand, the synoptic-

[1] Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, Quebec H3A 2K6, Canada
[2] Corresponding author: ktm321@gmail.com

scale atmospheric circulation structures and the meteorology associated with the varying winter road opening dates. Though we might consider studying the meteorological conditions associated with varying winter and ice road closing dates, such an exercise would not be useful, because the closures are often associated with non-meteorological factors, such as early completion of annual shipping or other economic issues. Considering that there is typically much pressure to open the winter and ice roads as soon as possible in the early winter, the meteorology is the dominant factor in determining the opening of the roads. Therefore, we focus on the meteorology associated with the opening dates.

For this study, we selected the winter road, approximately 88 km in length, between Norman Wells (65˚18′ N, 126˚48′ W) and Tulita (64˚54′ N, 125˚36′ W), NWT, (see Fig. 1), located in the Mackenzie River Basin (MRB), because there is a reliable, long-term record of both surface and upper-air (radiosonde) meteorological observations at Norman Wells. The objective of this study is to identify physically relevant meteorological features associated with years of extremely early and late openings of this particular road.

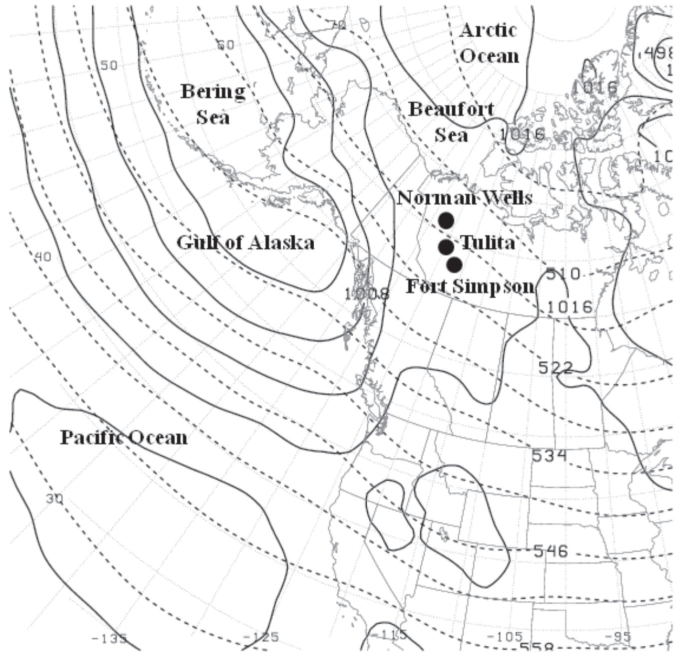

FIG. 1. November climatology for northwestern North America and surrounding water bodies. Solid lines show sea-level pressure (contour interval = 4 hPa) and dashed lines indicate 1000–500 hPa thickness (contour interval = 6 dam). Latitude and longitude lines are five degrees apart. Dots indicate weather stations at Norman Wells, Tulita, and Fort Simpson.

Winter Road Construction

Our analysis requires an understanding of both winter road construction and the meteorological factors that are generally accepted to be most crucial in this construction.

Initially, a predetermined path over land that connects the different frozen bodies of water is cleared of all trees and bush. Then, year after year, this same trail is used. The crossings over water are known as ice bridges and can traverse a frozen lake, river, or creek (Lafrance, 2007). Crucial factors influencing the start of the winter road season include air temperature, solar radiation, wind speed, and snow cover, as well as the currents, size, and depth of the water body, which affect initial ice freeze-up and the rate of ice growth (ACIA, 2005; Williams and Stefan, 2006). Freeze-up is usually fastest for shallow, slow-moving bodies of water (Lafrance, 2007).

Ice thickness varies throughout the frozen surface, so it is important to measure its depth accurately. The ice must reach a minimum thickness (typically 10 cm) before construction (techniques to speed ice growth) of an ice bridge can begin and another crucial minimum thickness (typically 100 cm) before public travel across the bridge is allowed (ACIA, 2005). Testing and flooding stop when the ice reaches a depth of 127 cm (R. Gunderson, pers. comm. 2007). A crucial issue for tundra regions is the protection of the existing vegetative cover, so that any active layer must be frozen to a depth sufficient to avoid damage to the vegetation from the vehicular traffic (ACIA, 2005). Once established, this frozen layer is covered with a combination of snow and water for in situ freezing (ACIA, 2005). Ten centimeters of compacted snow is required on all of the winter road surfaces, including all ice bridges and permanent bridges, in order to provide better traction and to maintain a sufficiently high albedo (Lafrance, 2007; R. Gunderson, pers. comm. 2007).

It is important to have very cold temperatures when constructing ice bridges. Initial ice formation occurs on freshwater lakes when daily mean temperatures are less than -5˚C with weak winds (Williams and Stefan, 2006). As temperatures continue to drop, the strength in the ice gradually increases until -18˚C, after which point the strength of the ice remains constant (Lafrance, 2007). Techniques to increase ice thickness as part of the ice bridge construction process include flooding ice bridges with water (Lafrance, 2007). Flooding pumps water from below the ice over the ice bridge (Lafrance, 2007). Lafrance (2007) provides general guidance for flooding a bridge between 45 and 60 m wide. At a daily mean temperature of -18˚C, 5 cm can successfully freeze overnight, and at a daily mean temperature of -31˚C or lower, 9 cm can freeze overnight. Significant snow pack early in the season insulates the underlying cryosphere, resulting in unsafe ice conditions throughout the year (Lafrance, 2007). During construction, therefore, the snow is either cleared or packed down to remove its insulating abilities (GNWT, 2007b).

Background Climate of the Northwest Territories

During the cold season (October through April), the Aleutian Low appears in the Gulf of Alaska, transporting moisture at upper levels into the MRB from the southwest (e.g., Smirnov and Moore, 1999, 2001). An example of the Aleutian Low is shown by the November mean sea-level pressure (SLP) and 1000 – 500 hPa mean temperature (thickness) field in Figure 1. The moisture-laden air is forced to rise over the Rocky Mountains, often loses much of its water vapor to condensation, and subsequently warms dry adiabatically (through compressional warming of unsaturated air) on its lee-side descent. The moisture at upper levels is either transported out of the basin or remains in the atmosphere to precipitate later (Smirnov and Moore, 1999). Despite the fact that precipitation amounts are particularly low in the cold season (Bjornsson et al., 1995), this frozen precipitation plays an important role in conditioning the surface for winter road construction. Generally, significant precipitation in the MRB is preceded by an extended period during which the tropospheric air becomes saturated with water vapor from precipitation aloft (Lackmann and Gyakum, 1996). However, because air is drier at lower tropospheric levels, sub-cloud evaporation and sublimation reduce the amount of precipitation reaching the ground (Szeto et al., 1997; Smirnov and Moore, 1999; Stewart et al., 2004). Fort Simpson (61˚30; N, 121˚0′ W) lacks low-level moisture in the cold season (Liu and Stewart, 2003; Hudak et al., 2004; Stewart et al., 2004) because it is located inland, in the lee of the Rocky Mountains. Although Fort Simpson is located about 550 km to the south (Fig. 1), similar scenarios could affect precipitation amounts in Norman Wells.

Little literature exists related to weather systems affecting the MRB region surrounding Norman Wells. Pacific-origin disturbances and subsequently lee cyclogenesis could occur over the Mackenzie Mountains and affect weather in Norman Wells, just as they do in the southern MRB (e.g., Lackmann and Gyakum, 1996) or in the northern MRB (Asuma et al., 1998, 2000). However, the amount of precipitation would be affected by the presence or absence of low-level moisture (e.g., Asuma et al., 1998, 2000; Stewart et al., 2004).

Figure 1, which shows the November synoptic climatology, also illustrates two opposing processes that affect winter roads. The Aleutian Low in the Gulf of Alaska facilitates the transport of heat and moisture from the Gulf of Alaska into the MRB. The cold anticyclone in the Arctic Ocean and Beaufort Sea has the potential to enhance cold, dry flow into the Tulita/Norman Wells region. As we will see later in this study, November is a particularly crucial month for meteorological conditioning for winter road construction: it happens to be the month when the mean daily surface temperatures typically cool to -18˚C, a critical temperature for ice bridge construction.

Bonsal et al. (2006) investigated how large-scale teleconnection patterns affect freeze-up and breakup dates of lakes and rivers across Canada. Their results related to river ice freeze-up are of interest here, since the winter road between Tulita and Norman Wells crosses only rivers and creeks. They found that the rivers in most of the NWT are freezing five days later in years with a positive autumn (September through December) Pacific–North American (PNA) pattern (Wallace and Gutzler, 1981) than in years with a neutral PNA pattern, a result that is statistically significant from that of the Norman Wells region.

The influence of the PNA is often well correlated with the El Niño/Southern Oscillation (ENSO) (e.g., van Loon and Madden, 1981; Renwick and Wallace, 1996; Bonsal et al., 2006). A positive PNA accompanied by positive ENSO produces an anomalously strong southerly flow in the eastern North Pacific–western North America region (van Loon and Madden, 1981) owing to the stronger Aleutian Low (Szeto et al., 2007) and extensive ridge over western Canada (Wallace and Gutzler, 1981). The result is warmer, drier conditions in the MRB. On the other hand, when the PNA and ENSO are both negative, the frequency of blocking high-pressure events in the North Pacific increases (Renwick and Wallace, 1996). The result is a split flow, with Pacific cyclones passing to the west of Alaska (Szeto, 2008) and colder conditions in the MRB (Szeto et al., 2007).

Data

This study used opening and closing dates for winter roads and hourly and daily weather observations. The public NWT winter road opening dates were obtained for the period 1982–2007 (GNWT, 2007a). Hourly and daily surface weather observations at Norman Wells were obtained for the period of 1971–2007 (Environment Canada, 2007). As discussed earlier, our reasons for choosing the Tulita-to-Norman Wells winter road include the fact that Norman Wells has consistent records of hourly and daily surface observations since 1943 (Environment Canada, 2007) and upper-air soundings since 1955. An archive of upper-air soundings since 1973 may be found at http://weather.uwyo.edu/upperair/sounding.html. As the meteorological station at Tulita reports observations only during its usual operating hours (typically 8–9 hours a day), these observations were not used in this study. The daily weather observations that were used from Norman Wells include maximum, minimum, and mean temperature, total rain, total snow, and total precipitation (rain and snow-water equivalent). Relative humidity, cloud cover, wind speed, and wind direction were taken from the hourly reports at Norman Wells.

The analysis of synoptic conditions prior to winter road opening dates used the National Centers for Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR) global reanalysis with an approximate horizontal resolution of 250 km (Kalnay et al., 1996). Additionally, the sounding analysis is derived from the North American Regional Reanalysis (NARR, Mesinger at al., 2006), with an approximate horizontal resolution of 32 km.

METHODS

Opening Dates

We used the opening dates of the winter road from Tulita to Norman Wells for the years 1982 through 2006. We identified 10 extreme opening dates, namely those that were more than 0.9 standard deviations earlier or later than the

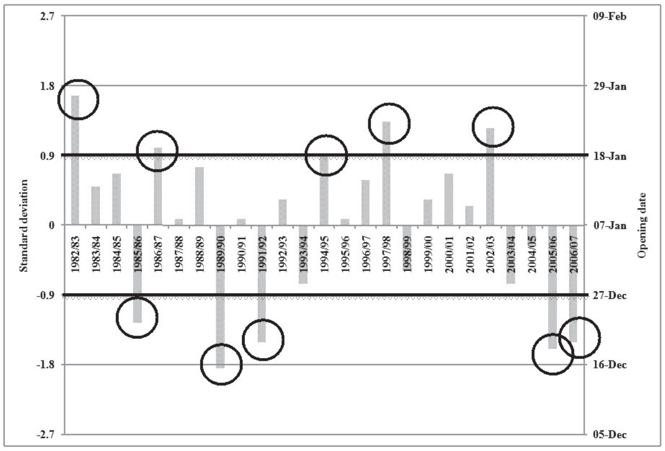

FIG. 2. Time series of opening date anomalies for the winter road from Tulita to Norman Wells between 1982–83 and 2006–07. The average opening date is 7 January. Solid lines show criteria for extreme early and late opening dates. The circles highlight the seasons of the anomalously early- and late-opening dates discussed in this paper.

mean opening date. To analyze the extreme years, we examined how temperature, precipitation, winds, and synoptic structures (for the study period 1 October through 31 January) differed between early-opening years and late-opening years, as well as how they differed from the 30-year climatology (1971–2000).

As only five extreme early-opening years and five extreme late-opening years existed in our small sample of 25 years, the few degrees of freedom generally preclude our demonstrating statistically significant differences. Only comparing the early-opening years to the late-opening years produced a few statistically significant results. However, comparison of composite means of the different weather parameters for the five extreme early opening years to those for the late-opening years showed physical differences that were clearly important, though not statistically significant. It should also be noted that variability in the sensible weather parameters increases as the season changes from summer to winter (Hudak et al., 1995).

Temperature

To assess the relationship of temperature on the opening dates of the anomalously early- and late-opening years, we produced composite time series from the Norman Wells daily mean surface air temperatures for each of these extreme samples and for the differences between them. Additionally, we computed the climatological time series of daily mean surface air temperatures and the associated confidence intervals, with magnitudes defined by one standard deviation.

Precipitation

To assess the possible role of precipitation in contributing to conditions associated with extreme winter road openings, we used daily amounts for each precipitation type (snow and rain) at Norman Wells to compute the monthly amounts for the different composites (early-opening years, late-opening years, and the 1971–2000 climatology). The monthly values for the composite of early-opening years, the composite of late-opening years, and the 1971–2000 climatology were then compared.

Sea-level Pressure and 1000–500 hPa Thickness Analyses

To assess large-scale atmospheric circulations associated with each class of extreme winter road openings, we computed November composite fields of SLP and 1000–500 hPa thicknesses for each set of extreme values (anomalously early- and late-opening years). The mean 30-year November climatological values were then subtracted from the corresponding values for the early- and late-opening years to produce SLP and 1000–500 hPa thickness anomalies.

Wind Roses

Surface winds reported at Norman Wells were used to construct a 30-year climatology of November wind vectors. The November wind vectors in each of the five-case samples of anomalously early- and late-opening years were collected and graphed as wind roses, which are graphical displays of frequency of wind speed and direction (Lakes Environmental, 2007). The wind roses were then compared to corresponding conceptual models based upon our composite fields of SLP.

Soundings

Composite soundings for Norman Wells of temperature, dewpoint, and wind were computed from the NARR (Mesinger et al., 2006), and from the NCEP/NCAR global reanalyses (Kalnay et al., 1996) data for November of the anomalously early- and late-opening year samples.

RESULTS

Opening Dates

The mean opening date for the Tulita-to-Norman Wells road is 7 January. An extreme early-opening year is defined as a year when the road opens on or before 27 December, and an extreme late-opening year as one when it opens on or after 18 January (Fig. 2). We identified five extreme early-opening years: 1985–86, 1989–90, 1991–92, 2005–06, and 2006–07 and five extreme late-opening years: 1982–83, 1986–87, 1994–95, 1997–98, and 2002–03 (Fig. 2).

Relationship of PNA and ENSO Indices to Opening Dates

Table 1 shows both PNA and ENSO indices, beginning in August of the preceding summer, for the late- and early-opening seasons. The late-opening years were all

TABLE 1. Monthly Pacific-North American (PNA) and three-monthly Oceanic Niño Index (ONI) indices as a function of the extremely early (rows in bold) and extremely late opening dates.

Extreme Year	Opening Date	PNA August	PNA September	PNA October	PNA November	PNA December	PNA January	ONI August to October	ONI September to November	ONI October to December	ONI November to January
1982–83	27 Jan 83	0.34	1.05	-0.93	-0.48	0.75	1.18	1.5	1.9	2.2	2.3
1985–86	**23 Dec 85**	**-0.5**	**-0.71**	**-1.51**	**-1.9**	**1.39**	**0.97**	**-0.5**	**-0.4**	**-0.3**	**-0.4**
1986–87	19 Jan 87	-1.45	-0.29	0.92	-0.73	1.37	1	0.7	0.9	1.1	1.2
1989–90	**16 Dec 89**	**-0.24**	**0.54**	**-1.13**	**-0.72**	**0.87**	**-0.34**	**-0.3**	**-0.3**	**-0.2**	**-0.1**
1991–92	**20 Dec 91**	**-0.25**	**1.43**	**-2.28**	**0.24**	**0.47**	**1.28**	**0.9**	**1**	**1.4**	**1.6**
1994–95	18 Jan 95	-1.34	-2.38	-0.23	-1.67	0.69	0.66	0.7	0.9	1.2	1.3
1997–98	23 Jan 98	-0.52	0.31	-0.26	0.91	1.16	0.74	2.2	2.4	2.5	2.5
2002–03	22 Jan 03	0.64	0.77	-0.65	1.54	1.59	1.29	1.1	1.3	1.5	1.4
2005–06	**19 Dec 05**	**0.72**	**1.63**	**0.9**	**-0.76**	**1.38**	**0.43**	**0.2**	**-0.1**	**-0.4**	**-0.7**
2006–07	**20 Dec 06**	**-1.41**	**0.42**	**-0.84**	**-1.39**	**1.86**	**0.72**	**0.6**	**0.9**	**1.1**	**1.1**
Late Composite		-0.466	-0.108	-0.23	-0.086	1.112	0.974	1.24	1.48	1.7	1.74
Early Composite		**-0.336**	**0.662**	**-0.972**	**-0.906**	**1.194**	**0.612**	**0.18**	**0.22**	**0.32**	**0.3**

characterized by strong El Niño (positive ENSO) episodes (NOAA, 2010) occurring as early as April in the preceding spring. The existence of an El Niño several months prior to opening is consistent with the likelihood that it takes several months for this tropical forcing to influence the high-latitude regions. The positive PNA indices become apparent for the late-opening years only during the months of December and January. El Niño/La Niña events are monitored by the National Oceanic and Atmospheric Administration (NOAA) through the Oceanic Niño Index (ONI) (NOAA, 2010). ONI is the three-month running mean of sea-surface temperature departures from the average for the central equatorial Pacific Ocean Niño 3.4 region (5˚ N to 5˚ S, 120˚ W to 170˚ W) (NOAA, 2010). An El Niño (or La Niña) event is defined as a period with ONI greater than + 0.5˚C (or less than - 0.5˚C) for at least five consecutive three-month averages (NOAA, 2010). Since 1980, there have been nine El Niño events according to this definition. When related to the winter road opening dates, five of the El Niño events occurred during the winter of an extreme late-opening year, three occurred during the winter of an extreme early-opening year, and one occurred during the spring and summer. However, the ONI values were highest for the El Niño events that corresponded to the late-opening years.

The territorial government opened the winter road for the first time in 1982–83. However, the federal government had already started Mackenzie Valley winter roads in the early 1970s (R. Gunderson, pers. comm. 2008). Therefore, the trail for the road did not need to be cleared during the construction period for the 1982–83 season. Such a clearing operation would have delayed the opening date.

During the spring of 1982, the El Chichón volcano in Mexico erupted. At the time, it was the largest influx of sulfur dioxide into the atmosphere during the 20th century, second now to Mt. Pinatubo in 1991. Normally, with a volcanic eruption, there is a cooling effect. However, the 1982 El Niño episode, with ONI values greater than 0.5 beginning in the spring, had been the strongest El Niño on record (second now to 1997–98). The two phenomena counterbalanced each other, producing no general cooling or warming effect at the global level. However, a more limited warming effect was observed in North America (Angell and Korshover, 1984).

The late-opening seasons of 1997–98 and 2002–03 were both especially warm seasons. During the construction period, which we define as 1 November through 15 December, there was not a single day at Norman Wells when the mean air temperature was below -30˚C. The mean air temperature was below -18˚C for only 16 days in 1997–98 and 5 days in 2002–03, two especially warm seasons. This made ice bridge construction a long process.

In the falls of 1997 and 2002, large spikes in the daily temperature profiles, with temperatures above freezing, were experienced at Norman Wells. These spikes were due to the "pineapple express," a transport of warm moist air from the tropics near Hawaii to the northwestern United States, which leads to intense precipitation on the windward side of the Rocky Mountains and large increases in temperature from chinook winds on the lee side (Lackmann and Gyakum, 1999). Roberge et al. (2009) defined a pineapple express as northward moisture transport greater than two standard deviations from the 57-year mean (1948 to 2005) for at least a day within the region of 45˚ to 55˚ N and 160˚ to 120˚ W. This region covers the northwestern United States, the southern half of British Columbia, and the neighboring Pacific Ocean. Only two events during the construction period of the extremely late-opening years, on 8 November 1997 and 25 November 2002, met the Roberge et al. (2009) criteria for a pineapple express. On these particular pineapple express days, temperatures at Norman Wells began to rise. Two days later they reached their maximum warming, as similarly observed by Lackmann and Gyakum (1999). Temperatures returned to pre-event levels two days after the spike for the 1997 event and four days after the spike for the 2002 event. Rain was associated with the pineapple express event in 2002, but no precipitation was observed during the event in 1997.

There was no particular relationship between the early-opening years and the occurrence of negative PNA or La Niña events (see Table 1). In fact, three of these early-opening years were El Niño seasons (Table 1).

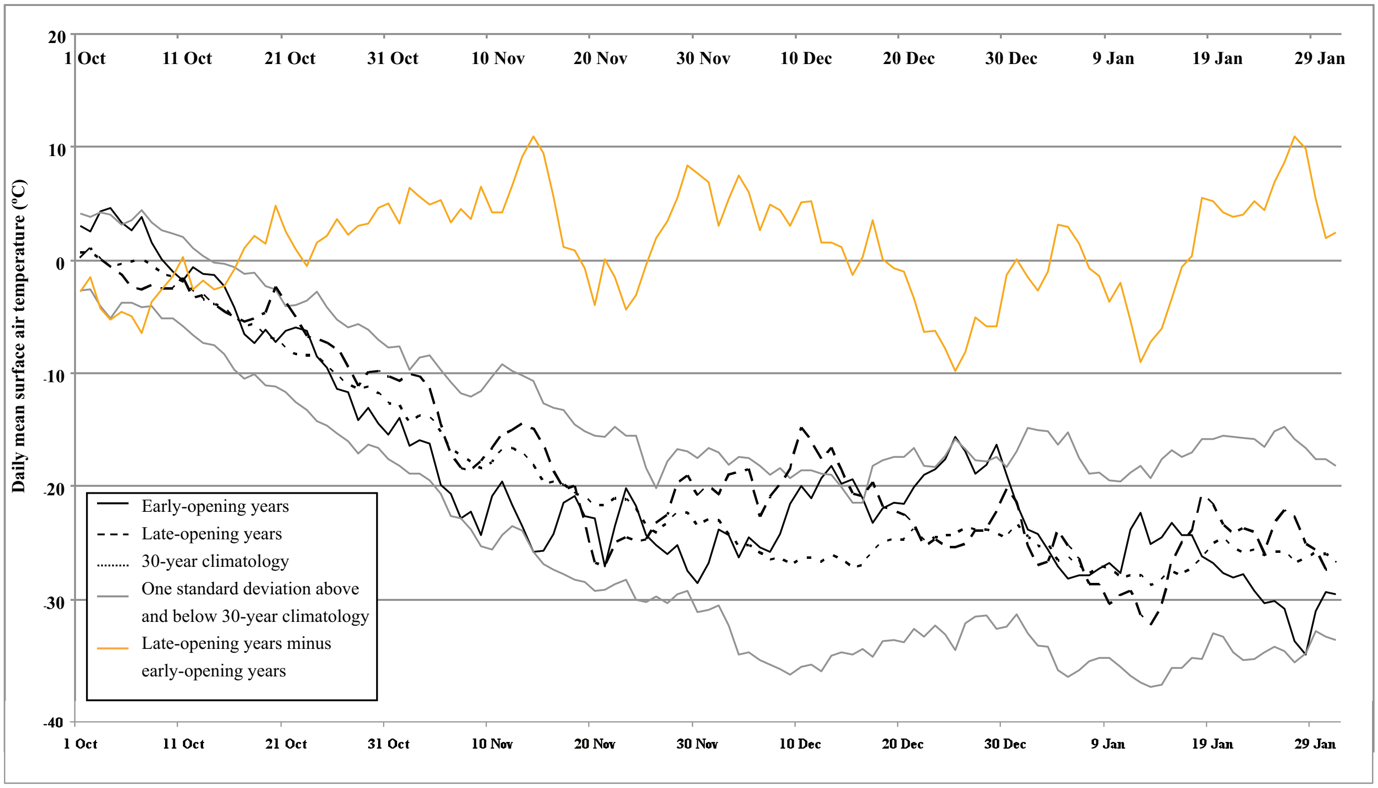

FIG. 3. Time series of composites of daily mean surface air temperatures at Norman Wells for early-opening years (heavy solid line), late-opening years (heavy dashed line), and the 30-year period (dotted line). Light solid lines indicate one standard deviation above and below the 30-year mean. The orange solid line shows the difference between the late and early composites (late-opening years minus early-opening years).

The 1991–92 winter road season was an El Niño season, but it was not a late-opening year. We hypothesize that the cooling effect on the atmosphere of an increase in sulfuric aerosols from the Mt. Pinatubo volcanic eruption was the cause. A cooling trend in the monthly mean temperatures at 700 hPa (as compared to the 1982–91 mean) can be seen in the Northern Hemisphere shortly after the Mt. Pinatubo eruption, simultaneously with an El Niño event (Dutton and Christy, 1992). Without the effects from the Mt. Pinatubo eruption, the El Niño event would likely have caused a warming trend (McCormick et al., 1995).

The most recent years considered in this study, 2005–06 and 2006–07, were early-opening years and also had El Niño episodes. The strong El Niño episodes corresponding with the late-opening years began in spring or early summer and lasted about a year (NOAA, 2010). The 2005–06 and 2006–07 El Niño episodes were weaker and did not last as long (NOAA, 2010). With the permanent bridge structures completed by the 2005–06 season, some effects from the weak El Niño episodes would have been missed. Since 2003, 23 permanent bridge structures have been built in the Northwest Territories over rivers and creeks (R. Gunderson, pers. comm. 2007), and three of these bridges are on the road from Tulita to Norman Wells. These structures are intended to reduce the influence of weather on the winter road seasons by limiting the need for ice bridge construction (Infrastructure Canada, 2004).

Further Analysis of Opening Dates

Figure 3 shows time series (1 October–31 January) of the composite daily mean surface air temperatures at Norman Wells for the early-opening years and the late-opening years, as well as the 30-year climatological mean and one standard deviation above and below that mean. The climatological mean falls below -18˚C starting in mid-November, which gives more than a month for constructing the winter roads before the average opening date of 7 January. Note the predominantly positive difference between the late-opening years and early-opening years (mean = +3.48˚C) in the crucial period from 20 October to 15 December. The persistence of either relatively warm, or relatively cold, temperatures affects winter road construction (ACIA, 2005).

The composite of daily mean surface air temperature for early-opening years (heavy solid line) is higher than the 30-year climatological mean (dotted line) through the beginning of October, and then lower from the last week of October until the beginning of December (Fig. 3). For the early-opening years, daily mean temperatures were below -18˚C for 75% of the construction period and below -30˚C for 11% of that period. For late-opening years, the daily mean temperatures were below -18˚C for less than 54% (and below -30˚C for only 9%) of the same construction period.

Daily mean temperatures below -18˚C are crucial to the formation of ice bridges. For early-opening years, this level is achieved for the entire construction period, including the period in December when temperatures are above the 30-year mean. For late-opening years, the composite of daily mean surface air temperatures (heavy dashed line) is colder than the 30-year mean in the beginning of October (Fig. 3), but then becomes warmer until mid-November.

This late-opening pattern of a colder October and a warmer November is opposite to the pattern for the composite of early-opening years (Fig. 3); it therefore appears to be a crucial factor in the meteorology leading up to the extremely early winter road opening dates. The differences between the daily temperatures for late-opening and early-opening years are statistically significant at the 95% level on 4–6 October, 4 and 5 November, and 13–15 November.

The composite temperatures for late-opening years are more than one standard deviation above the 30-year mean for the eight-day period starting 9 December and are above -18˚C for four of these days, negatively affecting ice bridge construction. The pattern of temperatures above the climatological mean continues from the end of November through mid December.

Precipitation

Figure 4 illustrates the importance of precipitation with monthly totals for October, November, December, and January. The difference in monthly total precipitation between composites of late- and early-opening years is statistically significant at the 95% level for November only. Not shown in the figure is the differentiation between rain and snow. In October, the early-opening years received more rain but less snow than either the late-opening years or the 30-year period. In November, no rain was observed during the early-opening years, but rain was observed for the late-opening years. On average, the early-opening years received over twice as much snow as the late-opening years and just under twice as much snow as the 30-year period. Ten centimeters of snow is required on all portions of a winter road for traction and to avoid damage to the ice bridges and tundra (Lafrance, 2007). Any excess snow is removed or compacted to avoid the insulating properties of snow (GNWT, 2007b).

Sea-level Pressure and 1000–500 hPa Thickness Analyses

The synoptic maps show the November composites of SLP (Fig. 5a and b) and 1000–500 hPa thickness values (Fig. 5c and d) calculated for the extreme opening years (light solid contours). The anomalies from the 30-year climatology are also shown (heavy contours).

The November composite for the early-opening years has a strong high-pressure region over the northern Yukon and Alaska (light solid contour, Fig. 5a) that is not observed in the climatological field (Fig. 1). The associated, anomalously high SLP (greater than 8 hPa) evident throughout northwestern Canada extends westward to its center over the Bering Sea (heavy solid contours; Fig. 5a). The anomalously strong SLP and ridging of that center are associated

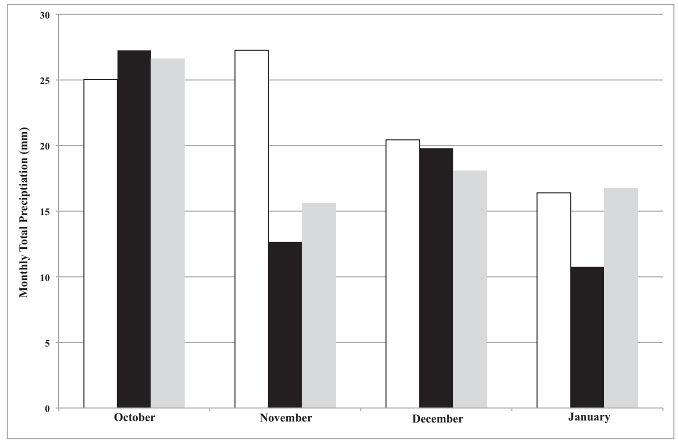

FIG. 4. Monthly total precipitation (mm) in October, November, December, and January for the composite of early-opening years (white) and the composite of late-opening years (black) compared to the 30-year mean (grey).

with anomalously cold air situated in the area of the NWT and the Yukon, with a peak cold anomaly over the Norman Wells region of nearly 6 dam—nearly 3˚C colder than average in the 1000–500 hPa layer (Fig. 5c). Cold air from the Arctic Ocean also arrives on the back side of the low situated over the Eastern Arctic region.

The late-opening years are characterized by two small SLP negative anomalies (Fig. 5b), one over the Bering Sea and the majority of Alaska and the other over a portion of Nunavut. The Aleutian Low is deeper in the composite of late-opening years than in either the composite of early-opening years or the 30-year climatology. The composite Arctic high, which extends inland in Figure 5a, is weaker and remains over the Beaufort Sea in Figure 5b. This pattern will result in less cold air coming in over the NWT from the Arctic Ocean. There is a large area of small positive thickness anomalies (Fig. 5d), with a positive 1 dam anomaly over Norman Wells.

There is, as would be expected, some variability among the years within each sample. However, this variability is not so substantial as to refute the basic conclusions made from the composites. Indeed, each of the late-opening years is characterized by an anomalously strong Aleutian low, and each of the early-opening years is associated with anomalously strong surface ridging in the vicinity of the winter road. We have tested the sensitivity of our composite results to the removal of individual years from the sample. This testing reveals that our synoptic-scale SLP and 1000–500 hPa thickness structures, as depicted in Figure 5, do not change substantively as a result of such changes in the sample's members.

Wind Roses

We hypothesize, from the results of the synoptic composites, that anomalous sources of warm or cold air might be seen through monthly wind rose frequencies. The 1971–2000 climatological wind roses for Norman Wells (Fig. 6) show bimodalities in the northwest/southeast directions. Pressure-

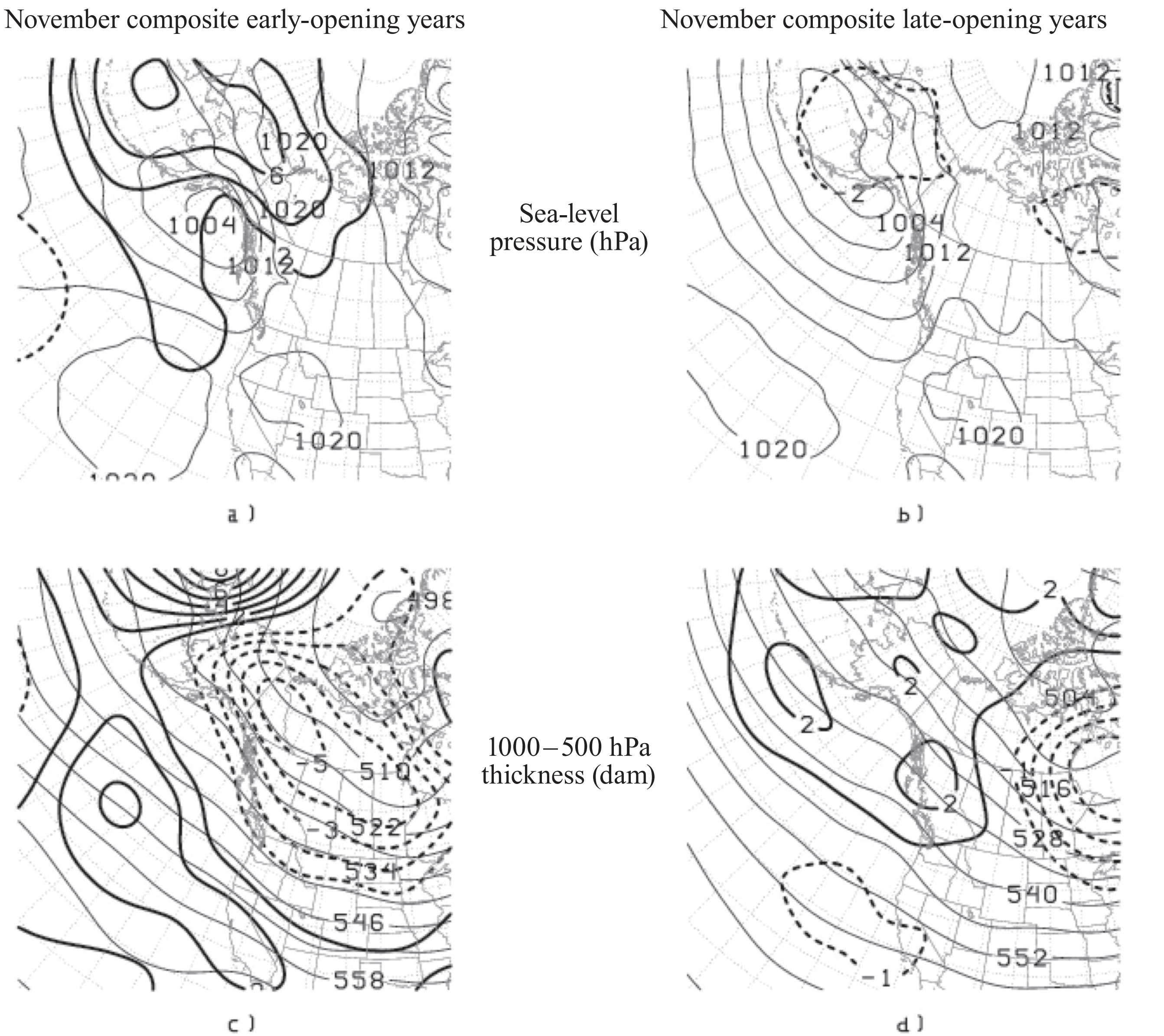

FIG. 5. November composites of sea-level pressure (a, b; hPa; light solid contours) and 1000–500 hPa thickness (c, d; dam; light solid contours) with anomalies from the 30-year climatology (bold) for early-opening years (a, c) and late-opening years (b, d), where positive contours are solid and negative contours are dashed.

driven channeling, associated with synoptic-scale pressure gradients, is likely to be a major factor associated with these bimodalities. Norman Wells is located on the Mackenzie River, between the Norman Mountain range 10 km to the northeast and the Mackenzie Mountain Range 40 km to the southwest (see Fig. 6). The winds of the early-opening years (Fig. 7c) had a greater frequency of northerly-component winds than those of the late-opening years (Fig. 7d), which correlates to the anomalous high-pressure system in the composite of early-opening years (Fig. 7a). The presence and extent of the Arctic high-pressure region (Figs. 5a, 7a) could also account for the increased frequency of calm winds in the early-opening years (Fig. 7c). The radiative cooling that occurs over snow-and ice-covered regions with clear skies and nearly calm winds is associated with conditions near such an Arctic anticyclone. The late-opening years composite has a greater frequency of southerly-component winds (Fig. 7d), which is associated with the deeper Aleutian Low present in the November of the late-opening years (Figs. 5b, 7b). The difference between early-opening years and late-opening years in the frequencies of northerly component winds and southerly component winds in November is statistically significant at the 99% confidence level.

Soundings

For November, composite soundings were plotted for Norman Wells for early-opening years and late-opening years using the NARR (Mesinger et al., 2006), shown in Figure 8, and using NCEP/NCAR global reanalysis (with similar results, which are therefore not shown). These plots illustrate the differences between the extreme opening years with regard to winds and temperatures at the surface, as shown in the wind roses (Fig. 7) and temperature time series (Fig. 3), as well as the amount of moisture throughout the troposphere, especially below 700 hPa, which affects the amount of precipitation observed at the surface (Fig. 4).

The November composite soundings for the early-opening years and the late-opening years (Fig. 8) are different. The composite temperatures are colder for the early-opening years, not just at the surface, but throughout the troposphere (heavy solid line). Composite November precipitation in the early-opening years was twice that in the late-opening years (Fig. 4). Figure 8 reflects this difference, in that the layer below 700 hPa is more saturated in the composite of early-opening years (Fig. 8a) than in that of late-opening years (Fig. 8b). The surface wind for early-opening years (Fig. 8a) also shows a northwesterly component, which corresponds to the increase in frequency of winds with northerly components (or decrease with southerly components) seen in Fig. 7c. The surface wind for the composite of late-opening years (Fig. 8b) is a light wind from the southwest, which represents the average of the winds seen in Figure 7d.

The deep tropospheric winds and wind shear are generally stronger in the late-opening composite (Fig. 8b). This pattern is consistent with the synoptic setting at Norman Wells (Fig. 5c, d), in which the Novembers of the late-opening years are associated with preferentially strong 1000–500 hPa thickness gradients (Fig. 5d).

SUMMARY AND DISCUSSION

Statistical analysis of the opening dates of the winter road between Tulita and Norman Wells led us to the selection of five extremely early-opening years and five extremely late-opening years. Weather parameters, including air temperature, precipitation, and wind, and synoptic patterns were studied for these extreme opening years. Knowledge of winter road construction was used to analyze the results of the extreme opening year composite comparisons. Natural ice growth is sensitive to surface air temperature, precipitation amounts and type, wind speed, insolation, evaporation, and convection (Williams and Stefan, 2006). According to Williams and Stefan (2006), initial ice formation on freshwater lakes requires daily mean air temperatures less than -5˚C and winds less than 5 m s^{-1}. Temperatures remain below -5˚C from 17 October onward for the composite of early-opening years and from 23 October onward for the composite of late-opening years. We found that late-opening years had surface temperatures averaging 3.48˚C warmer than those of the early-opening years from 20 October to 15 December (Fig. 3). An empirical calculation performed by Williams et al. (2004) for a sample of 143 North American freshwater lakes finds that

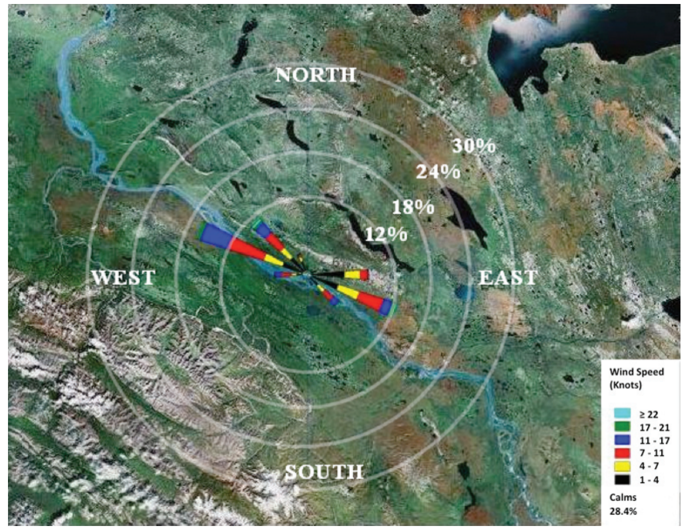

FIG. 6. November wind climatology at Norman Wells (1971–2000). Wind speed (in knots; 1 knot = 0.52 m s^{-1}) is divided into six bins: 1–4 (black), 4–7 (yellow), 7–11 (red), 11–17 (blue), 17–21 (green), and greater than 22 knots (cyan). Wind direction is shown as compass points, and wind directions are separated into 16 different directions. North is oriented towards the top of the page.

a 1˚C increase in mean air temperature in a climate-change scenario delays a lake's ice-in date by approximately five days. Although our study did not explicitly address the climate-change issue, our computed temperature difference of 3.48˚C between our two samples of anomalously late- and early-opening dates suggests approximately a 17-day delay in the ice-in date for the winter road. This time difference is less than our observed 33-day difference between the mean opening dates of the extreme early- and late-opening years (Table 1 and Fig. 2). Though we should not expect any more of a quantitative agreement between our results and the empirical results of Williams et al. (2004), because of the differing regions of analysis and the very different criteria for determining dates, we have established the qualitative inference that surface temperature anomalies contribute to anomalies in winter road opening dates. It is important to have cold temperatures not only to freeze the lakes and rivers, but to penetrate into the ground, allowing it to harden to support large loads of over 64 000 kg. During November, early-opening years experience daily mean temperatures colder than those of the late-opening years or the 30-year climatology.

Another difference in the ice formation forcings is the amount of precipitation received. It is important to consider precipitation because it plays an important role in the construction of both ice bridges and winter roads. Snow can insulate the underlying surface. If snow falls on freshly formed ice early in the season, then the ice below it will not grow as quickly. In October, our data suggest (though this result is not statistically significant), more precipitation occurs in late-opening years than in early-opening years (Fig. 4), insulating the ground and the initial ice formation. Later on, snow is necessary on the winter roads to protect the underlying vegetation (ACIA, 2005). In November,

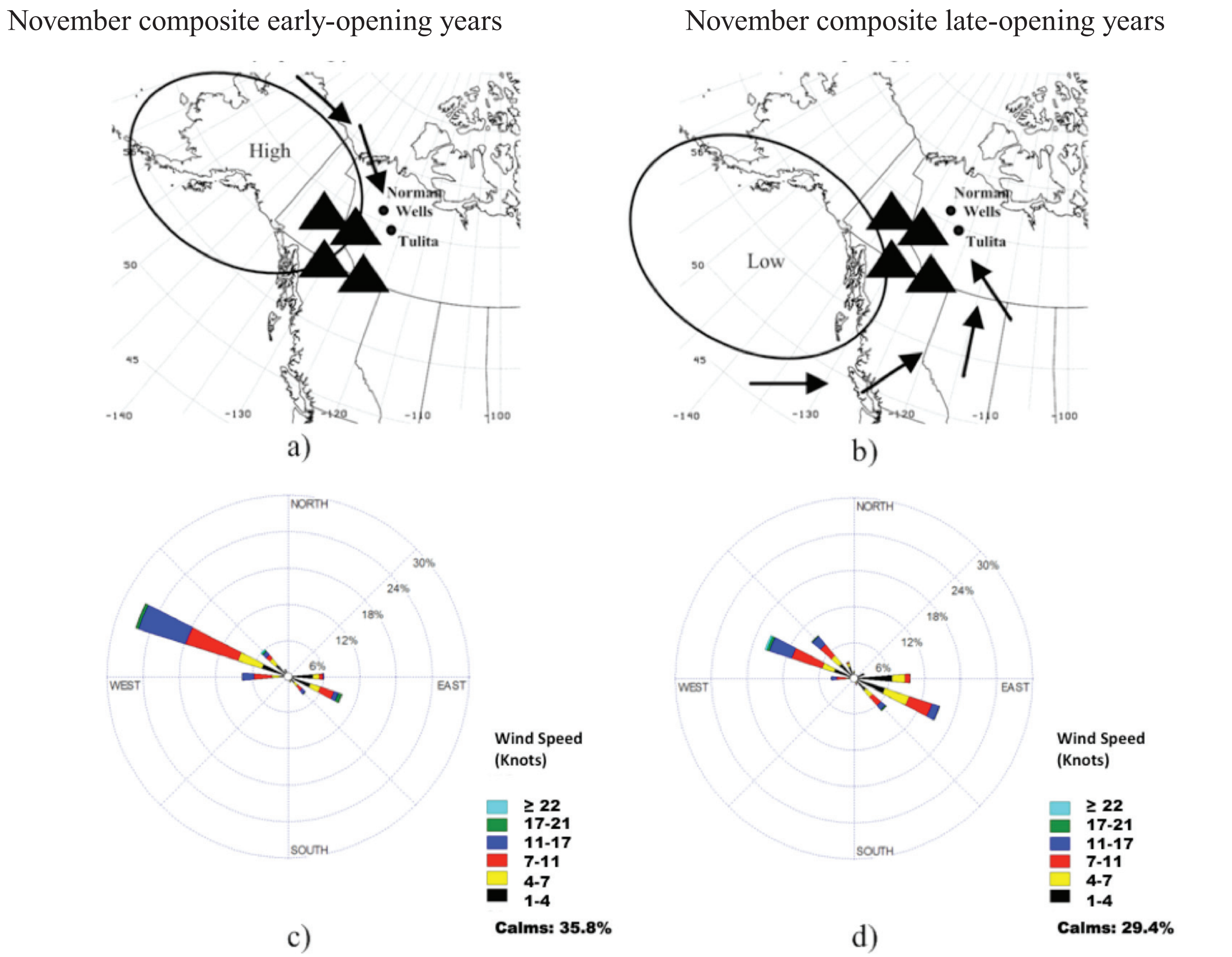

FIG. 7. Schematics for November of extreme opening years with corresponding wind rose. (a) Cold conditions at Norman Wells in early-opening years are caused by an influx of northerly component winds. High represents the Arctic high in the Beaufort Sea, to the north of the Mackenzie Mountains (solid triangles), with northwesterly winds (arrows) channeled along the Mackenzie River past Norman Wells. (b) Warm conditions at Norman Wells in late-opening years are caused by an influx of southerly component winds. Low represents the Aleutian Low, to the southwest of the Mackenzie Mountains (solid triangles), with winds (arrows) channeled along the Mackenzie River past Norman Wells. November wind roses (plotting convention as in Fig. 6) for (c) early-opening years and (d) late opening years.

precipitation was greatly reduced for the composite of late-opening years. For the composite of early-opening years, precipitation (all snow) was twice that of late-opening years and nearly twice that of the 30-year period.

During November in early-opening years, there was a statistically significant increase in the amount of winds with a northerly component and a corresponding decrease in winds with a southerly component. Ice growth is faster if wind can blow off the snow and keep the air moving above the ice surface, allowing for more heat to be exchanged with the colder air above (Williams and Stefan, 2006). There is also a higher frequency of calm conditions in the early-opening years. This fact likely reflects the relatively calm conditions occurring in the region of anomalously cold surface anticyclones that compose the climatology of early-opening years (Fig. 5a, 5c). We speculate that optimal meteorological conditions for ice formation involve relatively strong winds at the periphery of an anomalously cold surface anticyclone that blows away snow, followed by a period of cold, calm conditions as the anticyclone approaches the region. These calm conditions allow enhanced interactions between the atmosphere and water below the ice, which are conducive to ice growth.

Synoptic structure anomalies correspond to the differences in surface observations at Norman Wells. For the composite of early-opening years, there was higher SLP in the Gulf of Alaska in October (not shown) and higher SLP stretching from the Bering Sea to Nunavut in November (Fig. 5a), resulting in lower 1000–500 hPa thicknesses (Fig. 5c). Particularly in November, the high-pressure region over the Beaufort Sea extended southward to the northern coast of Alaska/Yukon/NWT (Fig. 5a), bringing more cold air from the north to Norman Wells. Complementary results were seen also in the November soundings, as the troposphere was colder in the composite of early-opening years than in that of late-opening years (Fig. 8).

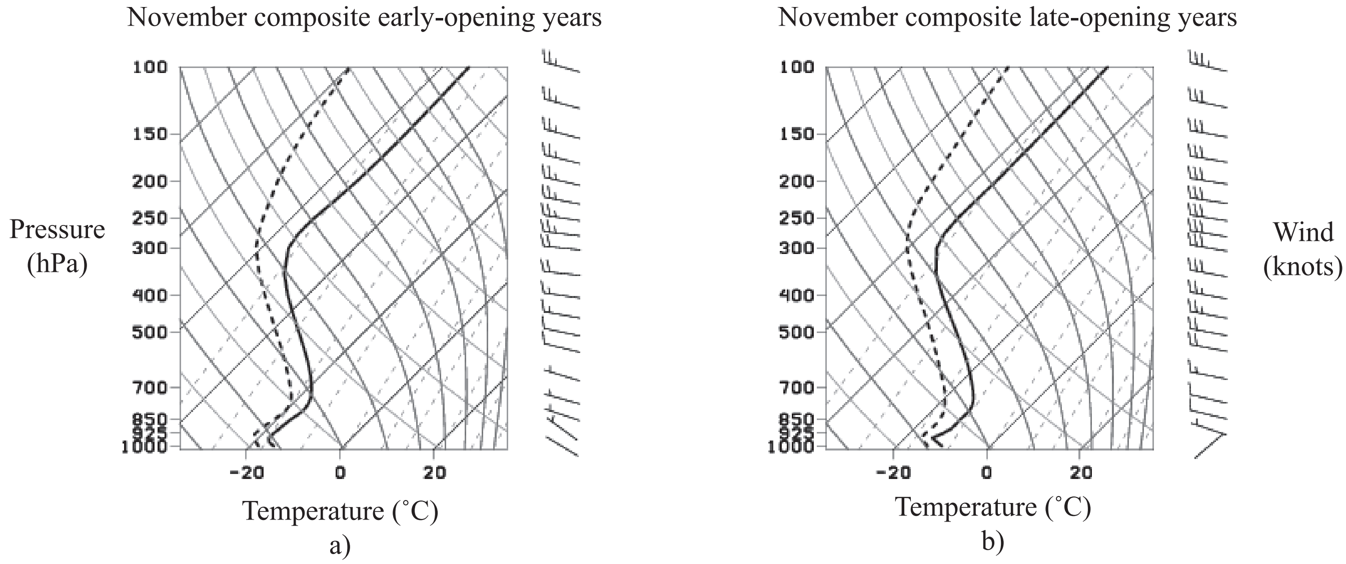

FIG. 8. November composite skew-T soundings of temperature (solid line) and dew point (dashed line) using the North American Regional Reanalysis for (a) early-opening years and (b) late-opening years. For panel b, the 1000 hPa wind barb is the southwest wind.

The anomalously cold Novembers with a relative preponderance of northwesterly surface winds are associated with a flow from cold surface anticyclogenesis to the north. In the significant precipitation events, cold, northwesterly flow linked with a deep surface cyclone to the east is associated with an upshear thickness trough that dominates the forcing for synoptic-scale ascent. For the composite of late-opening years, lower SLP was observed in October over the Pacific Ocean (not shown) and in November over the Bering Sea (Fig. 5b). An anomalously strong Aleutian Low is common for El Niño events and positive PNA episodes (Table 1 and Fig. 5b). The relatively dry air in the late-opening cases may arise from the descent associated with cross-barrier flow.

In the context of the larger network of winter and ice roads in the Northwest Territories, Knowland (2008) points out that the various road networks all indicate varying secular trends in length of season, with season length generally increasing in the north and decreasing in the Yellowknife region, south of our study area. This substantial regional variability in any secular trend suggests the need for a more comprehensive study of winter and ice road meteorology to improve our understanding of meteorology and climate in the region.

Given our results for the relatively small sample of extreme winter road opening dates, it appears that the month of November may provide the most comprehensive set of meteorological precursors that would be either favorable or unfavorable to the construction of winter roads in the Norman Wells region. A more comprehensive analysis of the complete winter road network, using the techniques discussed in this paper, will provide systematic insight into the impacts of interannual variability, possibly improvements in seasonal forecasting, and perhaps a better understanding of climate change throughout the Northwest Territories.

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