Gale-force downslope winds in Hurricane Alley, north Dempster Highway, Yukon

by

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Abstract

Strong, downslope winds commonly disrupt traffic on the Dempster Highway near the Yukon-NWT border; road closures occur on 25% of winter days. Wind characteristics from regional and local weather stations were analysed and associated with synoptic conditions. Downslope winds form due to a mountain ridge along the territorial border. The ridge is a boundary for wind characteristics: easterlies prevail in the Yukon, westerlies in the NWT, and both in Wright Pass where the highway crosses the border. The ECCC Rock River weather station has recorded 672 easterly windstorms since 2006 and a maximum wind speed of 137 km h\(^{-1}\). Just 12% of the windstorms occurred in summer, with the remainder equally distributed during the other seasons. Easterly windstorms were commonly associated with extratropical cyclones in the Gulf of Alaska and north-south pressure gradients, and westerly windstorms with south-north gradients and cyclones over the Beaufort Sea.
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Chapter 1: OVERVIEW AND OUTLINE

1.1 Introduction

This thesis considers the occurrence and development of strong downslope winds in northern Yukon and adjacent Northwest Territories that present hazardous conditions to traffic on the Dempster Highway. The north Dempster Highway (Fig. 1.1) passes through a range of Richardson Mountains near the Yukon-Northwest Territories border where high winds commonly occur. The terrain of the northernmost 15 kilometres of the highway within Yukon (km 450-465) has become known as Hurricane Alley\(^1\) (Figs 1.1, 1.2). Through much of Hurricane Alley, the road is aligned north-south, parallel to a ridge 1-3 km east of and 4-500 m higher than the road. In all seasons, but especially outside of summer, easterly winds accelerate downslope from the ridge, and blow perpendicular to the road. In contrast, strong westerly winds may be encountered on the other side of the ridge in the Northwest Territories (Humphries et al. 2019). The Environment & Climate Change Canada (ECCC) Rock River meteorological station (Fig. 1.3a) at YT km 457 has hourly wind records at a height of 10 m available since July 2006. A maximum sustained wind speed of 137 km h\(^{-1}\) recorded in February 2014 at Rock River suggests the Hurricane Alley name is apt, as hurricane-force winds exceed 118 km h\(^{-1}\) on the Saffir-Simpson wind scale (Stull 2017). Near gale-, gale-, and storm-force winds on the Beaufort Scale, covering

\(^1\) This is the name given by highway crews to the section of the north Dempster Highway which experiences the high winds. The name applies to the final 15 km of the highway within Yukon (YT kms 450-465), although the strongest winds occur from about YT km 452 to NT km 6. This term should not be read as implying that hurricanes (or tropical cyclones) contribute to the strong winds, since the study area is too far from the tropics and too far inland to experience their effects.
Figure 1.1. Maps of the study area including (a) the western Arctic, (b) Richardson Mountains, and (c) Hurricane Alley. Basemap data from the Government of Canada (2023b), Natural Earth Data (2023), Statistics Canada (2019; 2022), and the United States Census Bureau (2021). Road network data from the Alaska Department of Transportation & Public Facilities (2023) and the Government of Yukon (2023b). Elevation data from the Government of Canada (2023a).
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wind speed ranges of 50-61, 62-88, and 89-118 km h\(^{-1}\), respectively (Table 1.1, ECCC 2021), have been recorded for 4.3, 4.0 and 0.7% of observations at Rock River. Hurricane-force winds (>118 km h\(^{-1}\)) have been recorded during a total of 24 hours (0.02%) in the record. For the purposes of this thesis, wind speeds are reported in units of km h\(^{-1}\) rather than m s\(^{-1}\) (1 km h\(^{-1}\) ≈ 0.28 m s\(^{-1}\); 1 m s\(^{-1}\) = 3.6 km h\(^{-1}\)). Additionally, near gale- and gale-force winds representing the wind speed range of 50-88 km h\(^{-1}\) are collectively referred to as gale-force winds within this thesis.

The high winds that disrupt safe travel on the Dempster Highway are especially problematic in winter as they are associated with blowing and drifting snow, reducing visibility and obscuring the road surface. Vehicles travelling on the road during high winds risk leaving the driving surface and becoming stuck off the embankment. In very high winds, transport trucks may be blown off the road as their flat sides effectively act as a sail (e.g., Rébillon 2014). Inclement weather in Hurricane Alley often results in road closures between Eagle Plains at YT km 369 and James Creek at NT km 14 (highway markers restart at km 0 at the territorial border). For the purposes of this thesis, the territory will not always be given before the kilometre marker since higher values will naturally be in the Yukon and lower values will be in the Northwest Territories. Approximately 70% of road closures in the Eagle Plains Maintenance Division (YT kms 286-465) are a result of high winds and blowing snow in Hurricane Alley (Humphries et al. 2019). Based on road status reports available from 511Yukon (Government of Yukon 2023a), the road was closed on approximately 25% of all days between November 2022 and March 2023.

Hourly weather forecasts are available from ECCC (2023b) for the Rock River area, but often underpredict the strongest winds. These forecast models operate with grid cell
Table 1.1. Beaufort Wind Scale (following ECCC 2017 and 2021; Humphries et al. 2019) and frequency of occurrence (%) as recorded at ECCC Rock River.

<table>
<thead>
<tr>
<th>Descriptive Term</th>
<th>Force</th>
<th>Thesis Term</th>
<th>Wind Speed (km h(^{-1}))(^a)</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>0</td>
<td>Calm</td>
<td>&lt;1</td>
<td>6.38</td>
</tr>
<tr>
<td>Light Air</td>
<td>1</td>
<td>Breeze</td>
<td>1-5</td>
<td>25.46</td>
</tr>
<tr>
<td>Light Breeze</td>
<td>2</td>
<td>Breeze</td>
<td>6-11</td>
<td>25.54</td>
</tr>
<tr>
<td>Gentle Breeze</td>
<td>3</td>
<td></td>
<td>12-19</td>
<td>11.21</td>
</tr>
<tr>
<td>Moderate Breeze</td>
<td>4</td>
<td></td>
<td>20-28</td>
<td>8.97</td>
</tr>
<tr>
<td>Fresh Breeze</td>
<td>5</td>
<td></td>
<td>29-38</td>
<td>7.56</td>
</tr>
<tr>
<td>Strong Breeze</td>
<td>6</td>
<td></td>
<td>39-49</td>
<td>5.88</td>
</tr>
<tr>
<td>Near Gale</td>
<td>7</td>
<td>Gale</td>
<td>50-61</td>
<td>4.28</td>
</tr>
<tr>
<td>Gale</td>
<td>8</td>
<td></td>
<td>62-74</td>
<td>2.60</td>
</tr>
<tr>
<td>Strong Gale</td>
<td>9</td>
<td></td>
<td>75-88</td>
<td>1.37</td>
</tr>
<tr>
<td>Storm</td>
<td>10</td>
<td>Storm</td>
<td>89-102</td>
<td>0.62</td>
</tr>
<tr>
<td>Violent Storm</td>
<td>11</td>
<td></td>
<td>103-118</td>
<td>0.11</td>
</tr>
<tr>
<td>Hurricane(^b)</td>
<td>12</td>
<td>Hurricane</td>
<td>≥119</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\(^a\) Depending on the unit given, conversions to other units may not completely match given range.

\(^b\) The Saffir-Simpson Hurricane Wind Scale places the threshold for hurricane-force winds at ≥119 km h\(^{-1}\) (NOAA 2023). This is the criterion for hurricane-force winds which has been used in this thesis rather than the Beaufort Scale criterion of ≥118 km h\(^{-1}\)
spacings of 10 or 15 km (ECCC 2020b) – too coarse to accurately capture the topographic effects of the (relatively) finer-scale ridge. However, recent modelling at the University of British Columbia (Ribberink et al. 2020) was able to accurately represent historic high wind events using smaller grid cells, suggesting that forecast accuracy may be greatly improved at finer resolutions.

1.2 Downslope winds

The strong winds encountered in Hurricane Alley and the surrounding area are downslope winds, commonly arising from interactions between synoptic-scale weather systems – on the order of a few hundred to a few thousand kilometres – and topography (Barry 2008, Stull 2017, Abatzoglou et al. 2020). The windstorms in Hurricane Alley are believed to be foehn (föhn) winds (Ribberink et al. 2020). One common foehn mechanism follows the damming of cold, statically-stable air layers behind a topographic feature (Barry 2008, Stull 2017, Abatzoglou et al. 2020, Ribberink et al. 2020). Slightly warmer and higher-altitude layers override these lower-altitude layers, spill over the topography, and accelerate downslope. In Hurricane Alley, this means that cold air layers pool behind the ridge and fill up the valley before spilling over the ridgetop and accelerating downslope. The same is believed to be the case when strong winds occur on the NT side of the border: cold air pools in Hurricane Alley before spilling over the ridgetop across the territorial border. In this thesis, surface pressure charts (ECCC 2023a) will be used to suggest the strong winds in Hurricane Alley are associated with extratropical cyclones (low-pressure systems) moving northeast through the Gulf of Alaska and across the St. Elias Mountains into southern Yukon (Chapter 4). In conjunction with high-pressure systems further north
(often in the Beaufort Sea), north-south pressure gradients and regional easterly flow occur in the Hurricane Alley area. The opposite appears to be true for the strong wind events in NT: high-pressure centres over the western Arctic mainland and low-pressure centres over the Beaufort Sea, with a south-north pressure gradient and regional westerly flow.

Strong winds may also sometimes be caused by mountain (or gravity) waves due to low-altitude jet streams interacting with the ridge (Ribberink et al. 2020). Mountain waves are a result of buoyancy after statically stable air encounters a topographic feature (Whiteman 2000; Chow et al. 2013; Stull 2017). The air is displaced vertically upwards over the topography and a restoring force accelerates the air downward on the lee side of the obstacle. The restoring force then may switch direction to move the air to its original elevation. Several oscillations of the air mass may occur downflow of the topographic feature. These mountain waves may reach the surface as lee waves resulting in downslope windstorms. Other downslope winds include boras, katabatic winds, and gap winds (see Chapter 2).

1.3 Seasonality

While the strongest winds in Hurricane Alley occur in winter, high winds may still occur in autumn and spring. Windstorms are rare in summer, though average wind speeds are highest in late spring and early summer and lowest in winter (Humphries et al. 2019). In winter, the strong winds are a feature of intermittent extratropical cyclones. Wind speeds tend to be lower between these cyclones. In summer, winds are influenced by convective activity and the daily cycle of insolation, with moderately strong and steady winds during the day and calmer winds at night (Stull 2017). As detailed in Section 4.2, mean wind
speeds at Rock River are highest in May and June (23.7 and 22.8 km h\(^{-1}\)) and lowest in February (13.1 km h\(^{-1}\)). For March 2022-February 2023, the seasonal total hours of gale- and storm-force winds were, respectively, 195 and 11 in spring, 129 and 0 in summer, 145 and 6 in autumn, and 152 and 22 in winter at a height of 10 m. For the new station at km 457, these respective values were 144 and 3, 41 and 0, 94 and 0, and 121 and 0 at a height of 3 m. The difference in high winds at these two stations is likely due to the logarithmic increase of wind speed with height (Section 2.4). Storm-force winds have not been recorded at Rock River in June-August and mainly occur between November and February.

### 1.4 Methodology

A number of meteorological data sources were used to investigate the characteristics of high winds in the Hurricane Alley region. Principal among these are ECCC historical data records from the Rock River meteorological station (Fig. 1.3a; ECCC 2023f). Additionally, seven new meteorological stations (Fig. 1.3b) were installed at kms 450, 453, 454, 457, 459, 465 in the Yukon and km 4 in the Northwest Territories and report data via satellite to the Campbell Cloud (Campbell Scientific Canada 2023). These stations were installed in October 2021 and report wind speed and direction with the stations at kms 453 and 4 also reporting temperature and humidity. Wind records at Transport Canada stations at YT km 421 and NT km 8.5 (installed as part of the Northern Transportation Adaptation Initiative or NTAI) were assessed to determine regional wind characteristics. ECCC synoptic weather charts (ECCC 2023a), upper air analysis charts (University of Wyoming 2023) and composite wind speeds (NOAA Physical Sciences Laboratory 2023) were investigated to identify synoptic conditions associated with the high winds.
1.5 Research objectives

The main purpose of this thesis is to use a variety of meteorological tools and records to improve understanding of the development and progression of strong winds and windstorm events occurring in Hurricane Alley. Several key objectives are associated with this overarching goal:

1) Determine the historic properties of high winds at Rock River and identify any trends on differing temporal scales (monthly, seasonally, annually);
2) Determine how high wind events vary spatially within the Hurricane Alley area;
3) Identify synoptic weather patterns which are associated with the high wind events;
4) Evaluate the positioning of the newly installed weather stations and identify which are in important locations for measuring the high winds in Hurricane Alley.

1.6 Thesis layout

This thesis is organized into six chapters. Following this overview, Chapter 2 presents a discussion of wind conditions in the western Arctic before focusing on a more detailed explanation of local downslope winds. Chapter 3 describes the project methodology and rationale as well as the study region. Chapter 4 presents results from the analysis and data sources described in Chapter 3. These results are then discussed in further detail in Chapter 5 which also includes reflection on the objectives of this thesis. Finally, Chapter 6 provides a summary of the key findings with a brief note containing suggestions for further research.
Chapter 2: WINDS

2.1 Introduction
Understanding the downslope windstorms that occur within Hurricane Alley requires knowledge of the interactions between synoptic-scale weather systems and topographic features. To develop this understanding, the following sections of this chapter present a discussion of synoptic weather systems affecting the Arctic. Consideration is subsequently given to the wind patterns throughout Yukon drawing on Wahl et al. (1987). Finally, this chapter discusses localized downslope winds after an examination of the influence of topographic features on atmospheric flow. A broader overview of the forces creating and affecting general wind types, and weather system basics are presented in Appendix 1.

2.2 Arctic highs and lows
The main air masses affecting the western Arctic and Yukon are the moist and cool mA and mP (maritime Arctic and Polar) air masses which develop in the Bering Sea and Gulf of Alaska, or the mid-latitudes of the Pacific Ocean; and cold and dry cP and cA (continental Polar and Arctic) air masses which develop across northern North America and the Canadian High Arctic, respectively (Wahl et al. 1987; Ross 2013; Stull 2017). The mA and mP air masses often move east or southeastward from the Pacific Ocean onto the west coast of North America, while the cP and cA air masses move southwestward from higher latitudes across the continent. An mcA (modified continental Arctic) air mass often develops outside of winter (Wahl et al. 1987). This air mass is warmer and moister than cA air masses as it forms when some of the region is covered by open water.
In addition to the varying air masses that affect the western Arctic, the discrepancy between average temperatures over the continents and oceans gives rise to average seasonal pressure patterns (Fig. 2.1) (Ross 2013; Stull 2017). In summer when the continents are warmer than the oceans, the Pacific (or Hawaiian) High develops over much of the North Pacific Ocean, with lower pressure developing over much of North America. In winter when the oceans are warmer than the continents, the Canadian High develops over much of North America, while the Aleutian Low develops in the Bering Sea, over the Aleutian Islands, and in the Gulf of Alaska. The Arctic High is also strong in the winter months over the Canadian Arctic. For Yukon, this means that low pressure is common in summer (Fig. 2.1c), while high pressure prevails over central Yukon in the winter (Fig. 2.1a) (Wahl et al. 1987). In spring, the high-pressure region shifts northward (Fig. 2.1b). In autumn, the summer low pressure pattern dissipates as the Arctic High and Aleutian Low develop (Fig. 2.1d). Enhanced extratropical cyclone development in the north Pacific Ocean and Gulf of Alaska in autumn and winter leads to the development of the Aleutian Low. The development of the Aleutian Low and Arctic High lead to a strong pressure gradient and high winds across southwestern Yukon (Fig. 2.1a). The extratropical cyclones responsible for the Aleutian Low also appear to be associated with the strong winds in Hurricane Alley when their presence brings low pressure, warming, and moisture into the continental interior. However, the bulk of the storm systems commonly stall in the Gulf of Alaska and are blocked from reaching the interior. This is because the Coast and St. Elias mountains in southwestern Yukon entirely block or greatly diminish maritime air flow from the Pacific Ocean (Wahl et al. 1987). Similarly, the Mackenzie, Richardson, Barn, and British mountains in north Yukon may block cA air from entering, but if such air does establish in
Figure 2.1. Mean sea-level pressure patterns across Yukon for (a) January, (b) April, (c) July, and (d) October (Wahl et al. 1987, figs 7.1-7.4). This reproduction is a copy of an official work published by Environment Canada and has not been produced in affiliation with, or with the endorsement of, Environment Canada. Figure labels added to original.
the region, it commonly lingers, trapped within valleys under anticyclonic conditions. These topographic effects are responsible for the continental climate of much of Yukon exemplified by large temperature ranges and relatively low precipitation.

### 2.3 Winds of Yukon

*Climate of Yukon* (Wahl *et al.* 1987) was published before the construction of most weather stations in the Richardson Mountains region (Sections 3.4 and 3.5). ECCC stations at Old Crow, Eagle Plains, and Fort McPherson predate the publishing, but are too far from Hurricane Alley to provide information on the localized high winds. Nevertheless, Wahl *et al.* (1987, p. 38) still noted strong winds in Hurricane Alley and reported that “fierce winds can occur in Wright Pass where the Dempster Highway passes through the western Richardson Mountains.” They noted that, in general, wind and turbulence may be locally severe within valleys of the northern Yukon mountain ranges. An additional report describes a highway crew being trapped during a blizzard in December 1979 in the Richardson Mountains (Gates 2015).

Largely calm conditions are prevalent in winter at most Yukon meteorological stations with local winds commonly controlled by topography: either aligned with valley orientations or blowing downslope as in Hurricane Alley. Wahl *et al.* (1987) noted that average and extreme wind speeds are generally highest at the stations on the Beaufort Sea Coast (Shingle Point and Komakuk Beach) due to southerly outflow winds on the North Slope. Elsewhere in the territory, they probabilistically estimated that extreme downslope winds with a return period of 30 years are highest at Burwash (115 km h⁻¹), Aishihik (100 km h⁻¹), and Whitehorse (82 km h⁻¹). Apart from the single anecdote regarding Hurricane
Alley, Wahl et al. (1987) had no observations from the area, and so did not discuss the high wind environment described in this thesis.

The preceding sections have outlined the pressure systems and air masses affecting the western Arctic and Yukon. Differential heating between the ocean and continents (i.e., monsoonal flow) leads to the development of low pressure over the western Arctic in summer and high pressure in winter. Extratropical cyclones responsible for the development of the Aleutian Low in winter also commonly affect Yukon and are associated with high winds in Hurricane Alley. Strong downslope winds are observed elsewhere in Yukon but are not nearly as high as those observed in Hurricane Alley. In the following sections, the influence of topography on local wind conditions is examined.

2.4 Wind speed profile

The atmospheric boundary layer is the lower layer of the atmosphere – within 0.3 to 3 km of Earth’s surface. It is affected by friction and exchanges of energy, mass, and momentum (Gallagher 2010; Ross 2013; Stull 2017). Near the base of this layer, there is strong wind shear (i.e., change in wind speed with height) due to friction between the atmosphere and surface, and between air layers (McIlveen 1986; Oke 1987; Stull 2017). This results in a power or logarithmic wind profile above the surface (Fig. 2.2; Patton et al. 2007; Barry 2008). The wind shear near the surface is greater over smoother surfaces because less friction over such surfaces results in a more rapid change in wind speed with height (Oke 1987). At greater reference wind speeds, friction and drag forces are increased, thus increasing wind shear and the absolute difference in wind speed with height (Fig. 2.2; Wang and Emmerich 2010; Stull 2017).
Figure 2.2. Representation of the logarithmic wind speed ($u$) profile with height ($z$) in the lower sections of the atmospheric boundary layer. With increasing wind speeds at the reference height ($z_{\text{ref}}$), wind shear increases (red, blue, and green profiles). These profiles extrapolate to wind speeds of zero at the roughness length ($z_o$).
The equation representing the logarithmic wind speed profile follows eq. 2.10 in Oke (1987):

\[ u_z = \left( \frac{u^*}{k} \right) \ln \left( \frac{z}{z_0} \right) \]

where \( u_z \) is the average wind speed at height, \( z \), \( u^* \) is the friction velocity and represents the drag force or shear stress from the surface, \( k \) is the von Kármán constant, and \( z_0 \) is the roughness length. The roughness length indicates the height at which the wind profile extrapolates to a speed of 0 (Fig. 2.2). In the Hurricane Alley area, summer roughness lengths are possibly on the order of 3-10 cm due to the short tundra vegetation (Oke 1987; Stull 2017). The roughness length decreases in winter – to a value on the order of 1 mm or less – due to the smooth snowpack. However, the presence of a snowpack also raises the effective ground surface, meaning that the anemometers record wind speeds at a lower height. In order to estimate the wind speed when it is known at a reference height, the following equation can be used (eq. 18.14a, Stull 2017):

\[ u_2 = u_1 \times \left[ \frac{\ln(z_2 / z_0)}{\ln(z_1 / z_0)} \right]^{2.5} \]

2.5 Topographic influence on atmospheric flow

2.5.1. Overview

Motion of air in the atmosphere is similar to water flow in that both are fluids. When considering the effects of Earth’s surface on atmospheric flow, two major regions are identified: the atmospheric boundary layer and the free atmosphere (Gallagher 2010; Stull 2017). Above the atmospheric boundary layer (Section 2.4) is the free atmosphere where effects of Earth’s surface are less pronounced, and atmospheric motion is based on synoptic-scale weather patterns. When the logarithmic wind profile in the atmospheric
boundary layer (Section 2.4) encounters an isolated hill or mountain (i.e., a topographic feature), the flow is disrupted and constrained (Fig. 2.3; Ayotte and Hughes 2004; Patton et al. 2007; Barry 2008). Near the bases of both the windward and leeward slopes, there is excess pressure and a slight reduction in wind speed, but near the summit of the mountain, there is a pressure deficit, and the wind accelerates. This is a result of the Bernoulli effect whereby fluid that is constrained (near the summit) encounters lower pressures and higher speeds, while fluid that is not constrained (near the bases of the mountain) encounters slightly higher pressures and reduced speeds (Fig. 2.3) (Giambattista et al. 2016).

The Froude Number (Fr) is the ratio between inertial forces and gravitational or buoyancy forces (Atkinson, 1981; Barry 2008) and can also be thought of as the ratio of the fluid speed to the speed with which energy and information travels (wave group velocity, Stull 2017). Flow types can be classified depending on Fr: sub-critical (Fr < 1), critical (Fr = 1), and supercritical (Fr > 1) (Stull 2017). These categories describe whether upstream (upwind) air can ‘feel’ the effect of downstream (downwind) conditions. For subcritical flow, wave motion and downstream effects may propagate upstream faster than the fluid is moving. For supercritical flow, the fluid is moving faster than these wave motions and downstream effects. That is, in subcritical (supercritical) flow, upstream fluid does (does not) experience the effect of downstream features.

Atmospheric conditions and flow result in differing Froude numbers which in turn affect the response when wind interacts with a topographic feature. Generally, mountain (or gravity) waves form when wind encounters topography (Durran 1990; Stull 2017). In a statically stable atmosphere, where flow tends to remain laminar, mountain waves are produced due to the restoring force of buoyancy. When statically stable air encounters a
Figure 2.3. Effect of an isolated hill (h) on the wind regime. In (a), the typical logarithmic wind profile ($U_o$) is shown to the left of the figure. At the top of the hill, this profile is altered such that wind speed is increased ($U_o + U$). In (b), the slight pressure excesses near the slope bases and pressure deficit near the summit of the hill are depicted. Reproduced following Fig. 2.31 from Barry (2008).
mountain, it is displaced vertically upwards. The restoring force attempts to return the air back to its initial position which may lead to the air being displaced vertically below its initial position. A restoring force again tries to return the air to equilibrium, but again overshoots this equilibrium position. These oscillations continue until they are dampened by friction and turbulence. The mountain waves oscillate at the Brunt-Väisälä frequency, $N_{BV}$. The Brunt-Väisälä frequency is also known as the buoyancy frequency and represents the natural frequency of these oscillations considering a compressible medium without effects from pressure or friction (Barry 2008; Chow et al. 2013). The Brunt-Väisälä frequency increases with increasing atmospheric stability and may be defined by the following equation (eq. 5.4b, Stull 2017):

\[
N_{BV} = \left( \frac{|g|}{T_v} \times \frac{\Delta \theta_v}{\Delta z} \right)^{1/2}
\]

where $g$ is the gravitational acceleration constant, $T_v$ is the virtual temperature, and $\Delta \theta_v/\Delta z$ is the virtual potential temperature gradient (Chow et al. 2013; Stull 2017). This temperature gradient – and thus the Brunt-Väisälä frequency – is higher with stronger atmospheric stability.

The form of the mountain waves and topographic effects on the air movement depend on the Froude number and are also influenced by atmospheric stability, wind speed, and mountain geometry (Fig. 2.4) (Barry 2008; Stull 2017). When winds are light or conditions are highly statically stable, $Fr \approx 0.1$ and air movement may be blocked by the topography. If the topographic feature is an isolated hill or mountain, the air might flow around it. At a slightly higher $Fr$ – around 0.4 – lee wave separation occurs (Fig. 2.4a). In this case, air layers at higher altitudes clear the ridge and form small mountain waves, while lower altitude air layers are either blocked by larger features or flow around isolated
Figure 2.4. Effect of Froude number (Fr) on lee mountain waves: (a) Fr ≈ 0.4, (b) Fr = 1, (c) Fr ≈ 1.7, and (d) Fr >> 1 (see text for explanation). Fig. 17.30 from Stull (2017) redistributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. Figure labels adjusted compared to original.
features. For moderate static stabilities, Fr ≈ 1 and intense lee waves are formed (Fig. 2.4b). These conditions are associated with downslope windstorms and near-surface turbulent rotors within wave crests. Due to Fr being close to 1, this class of mountain waves is associated with hydraulic flow (Durran 1986; Whiteman 2000; Chow et al. 2013). Upstream of the mountain, flow is subcritical, but transitions to supercritical on the lee slope resulting in strong downslope winds. Further downslope, a hydraulic jump may occur as flow transitions back to subcritical (Section 2.5.2). For weak static stabilities or strong winds, Fr ≈ 1.7 and weak mountain waves are formed (Fig. 2.4c) (Barry 2008; Stull 2017). A cavity with reversed flow may occur on the leeward slope. Finally, for statically neutral conditions, Fr increases towards infinity and a large turbulent wake is produced (Fig. 2.4d).

In the case of mountain waves, Fr may be calculated with the following equation:

\[ Fr = \frac{\lambda}{2W} \]

where \( \lambda \) is the resulting wavelength produced by a topographic feature of width, W (eq. 17.32, Stull 2017). The width of the topographic feature is measured at the location where the elevation is halfway between the peak and neighbouring valleys (R. Stull, pers. comm. 2022). Accordingly, for a topographic feature of a fixed width, the wavelength of the mountain waves is proportional to and increases or decreases with Fr. \( \lambda \) may itself be calculated taking the form of the following equation:

\[ \lambda = \frac{2\pi U}{N_{BV}} \]

where U is the wind speed and \( N_{BV} \) is the Brunt-Väisälä frequency (eq. 17.30, Stull 2017). The wavelengths are longer when the wind speed is greater or atmospheric stability is weaker (the Brunt-Väisälä frequency increases with increasing stability). This is also evident on Fig. 2.4 and the relevant discussion where shorter wavelengths are associated
with high atmospheric stability and low Fr.

2.5.2. Hydraulic jumps

Hydraulic jumps occur when the fluid motion changes from supercritical (Fr > 1) to subcritical (Fr < 1) flow (Fig. 2.5) (Barry 2008; Chanson 2009; Stull 2017). In the case of downslope winds, cold air may accelerate down a slope under the influence of gravity and reach supercritical conditions (Barry 2008; Stull 2017). Because this air layer is cold, it is denser than overlying layers and is thus constrained against the slope. Eventually the air will decelerate after reaching the foot of the slope or encountering an obstacle. As the flow decelerates, it returns to subcritical flow. The decrease in speed and transition back to subcritical flow are associated with increases in both vertical depth and turbulence (Chow et al. 2013; Stull 2017). Hydraulic jumps lead to much calmer winds, or even reversed flow near the surface (Cao and Fovell 2016).

2.6 Downslope winds

2.6.1. Development and types of downslope winds

Downslope winds typically develop due to the interactions between synoptic weather systems and topography and are common in mountainous areas, especially in the mid-latitudes during winter (Barry 2008; Stull 2017; Abatzoglou et al. 2020). Mountain waves, katabatic winds, foehn winds, and bora winds, are all classes of downslope winds. Mountain waves (Section 2.5.1) result from the oscillation of statically stable air layers after encountering a topographic feature (Whiteman 2000; Barry 2008; Chow et al. 2013; Stull 2017). Katabatic winds form at night during clear, calm conditions from radiative
Figure 2.5. Development of a hydraulic jump. The flow regime in (a) displays how cold air flowing down a mountain slope in (b) accelerates to supercritical flow. When the air layer reaches the foot of the slope, it decelerates. This eventually results in a return to subcritical flow and sudden increase in both vertical depth and turbulence. Fig. 17.18 from Stull (2017) redistributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. Figure labels added to original.
cooling of mountain slopes and surface air layers (Chow et al. 2013; Stull 2017). These cool layers accelerate downslope under the influence of gravity. Katabatic wind speeds are usually quite light (~10-30 km h\(^{-1}\)) except in Antarctica or Greenland where downslope distances are hundreds of km and winds may accelerate up to 70 km h\(^{-1}\) or higher (Speirs et al. 2010; Stull 2017; Abatzoglou et al. 2020). The strong winds experienced across the continental North Slope are katabatic outflow winds (Wahl et al. 1987; Mackay and Burn 2005). Gale-force and stronger winds are encountered here especially in winter.

Foehn (or fohn) winds have a variety of regional names: chinook (east of The Rockies), zonda (Argentina), Santa Ana (California), aspre (France), or austru (Romania) (Barry 2008; Stull 2017; Abatzoglou et al. 2020). Foehn winds are associated with warm, dry downslope flows (Whiteman 2000; Barry 2008; Chow et al. 2013; Stull 2017). A common mechanism leading to development of foehn winds is the damming of cold, statically-stable air layers by a mountain or ridge (Fig. 2.6a), resulting in higher-altitude air layers overriding the stable layers to flow over the mountain ridge and downslope. During descent, these layers accelerate, and with sufficient descent, adiabatically warm.

Bora winds are similar to foehn winds but are cold and dry instead of warm and dry (Fig. 2.6b) (Whiteman 2000; Barry 2008; Stull 2017). They develop when a deep layer of cold air encounters a mountain. If this cold air layer is deeper than the peak elevation of the mountain, portions near the top of the layer may pass over the ridge. Sections closer to the surface are mechanically lifted up the mountain slope and the entire cold air layer is constrained near the ridge and on the lee slope. The downslope winds thus accelerate as described by the Bernoulli effect (section 2.5.1). Draw-down of higher-altitude warm layers by the mountain also helps constrain the cold air layer to the lee slope.
Figure 2.6. Development of downslope winds: (a) a foehn wind and (b) a bora wind. Figs 17.36 and 17.37 from Stull (2017) redistributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. Figure labels added and descriptive text adjusted from original.
Mountains often act as a barrier to air flow, but gap winds may develop in regions where the topography is lower such as mountain passes, river valleys, and fjords (Whiteman 2000; Chow et al. 2013; Stull 2017). When cold air approaches a mountain range, it may be blocked and produce high pressure. With lower pressure on the opposite side of the mountain range, a pressure gradient will develop driving the air through any gaps in the mountains. Gap winds may also be enhanced by gravity when driven downslope through mountain passes.

2.6.2. Effects of downslope winds

As previously noted, the main concern with the strong downslope winds in Hurricane Alley is the safe operation of the Dempster Highway. The specific hazards in Hurricane Alley are related to winter conditions as the strong winds result in reduced visibility due to blowing snow and large snow drifts blocking the road surface (Fig. 2.7). The strong winds themselves are a hazard to larger vehicles (Rébillon 2014). However, downslope winds may also cause a variety of other effects such as infrastructure damage in populated areas (e.g., Abatzoglou et al. 2020; Lawson and Horel 2015), vegetation damage (e.g., Lawson and Horel 2015), extreme warming events (e.g., Speirs et al. 2010; Schwarz et al. 2020), intensification of wildfires (e.g., Nauslar et al. 2018), increased pollutant concentrations which can cause adverse respiratory health effects (e.g., Aguilera et al. 2019; Leibel et al. 2019), severe turbulence which is hazardous to aircraft (Stull 2017), and opportunities for wind energy generation (e.g., Romanić et al. 2015).
Figure 2.7. A plowed snow drift at km 440 of the Dempster Highway following a windstorm in March 2022. High winds resulted in this snow drift blocking the road. Photograph taken in March 2022 facing north.
2.7 Summary

Depending on the configuration of the topography and atmospheric conditions, a variety of downslope wind types occur which can have a myriad of effects on downslope locations. Yukon is commonly influenced by mA, mP, cA, and cP air masses with high pressure dominant in winter and low pressure in summer. Extratropical cyclones produce the Aleutian Low and affect the western Arctic in the winter. Throughout Yukon, winds are not particularly strong except for the katabatic winds on the North Slope (Wahl et al. 1987). In Hurricane Alley, the high winds pose a significant hazard to safe and continuous operation of the north Dempster Highway.
Chapter 3: STUDY AREA & METHODOLOGY

3.1 Introduction

In this chapter, consideration is given to the regional setting of Hurricane Alley, its topography, and its climate. Next, the project design, including installation of the new meteorological stations and their surroundings is described. Finally, a critical discussion of additional data sources, data obtained, and methods of analysis is presented.

3.2 Project scope

Following reports of strong winds in the early years of operation of the Dempster Highway (Wahl et al. 1987; Gates 2015), instrumentation of the Hurricane Alley area with weather stations began with ECCC Rock River in 1995. The station is approximately 200 m west of the highway at km 457 (Fig. 1.3a) (66.98 °N, 136.22 °W, elevation 731.0 m). The data record (ECCC 2023f) began with daily temperatures in late February 1995. Hourly data, including wind speed and direction measurements at a height of 10 m, have been recorded since July 2006. Wind speed was recorded prior to this with maximum daily wind gusts and their associated direction available intermittently from 1995 through 1998. Additional weather stations were installed along the Dempster Highway near the territorial border by NorthwesTel, Transport Canada (TC), and the Government of Yukon’s Transportation Engineering Branch and their partners. At most of these stations, wind data is measured at a height of 3 m. The NorthwesTel stations have recorded some intermittent wind data since July 2009, the TC stations have largely continuous data since February 2014, and the Government of Yukon stations have been recording since November 2021.
There has been little research on the regional and local wind characteristics in Hurricane Alley, even though there is public knowledge and interest regarding the winds. The high winds have been a concern of Yukon Highways and Public Works and the Government of Northwest Territories Department of Transportation. The installation of regional weather stations at kms 421, 8.5 and 51.5 as part of Transport Canada’s Northern Transportation Adaptation Initiative (NTAI) (Idrees et al. 2015), increased the ability to examine the aeolian regime of the area. Humphries et al. (2019) and Kokelj et al. (2022) outlined the wind characteristics at these and other local stations. Research related to the strong winds investigated the effects of snow fences on near-surface ground temperatures within Hurricane Alley (Humphries 2020).

ECCC provides publicly available hourly weather forecasts (ECCC 2023b) for Rock River, although the high winds are commonly underpredicted (Fig. 3.1). These forecast models operate with grid cell spacings of 10 or 15 km (ECCC 2020b), and while the mountain ridge east of Hurricane Alley is of a similar size to these spacings in the north-south direction (Fig. 1.1c), it is much narrower from east to west (Fig. 3.2). Accordingly, the topographic details of the ridge are poorly represented within the forecast models and downslope wind speeds are underpredicted. Wind forecasts from a variety of models are also available on Windy.com (Lukačovič 2023) including some at finer spatial resolutions than ECCC: ECMWF at 9 km (European Centre for Medium-Range Weather Forecasts), NAM at 5 km (North American Model produced by NOAA’s National Centers for Environmental Prediction), and HRRR at 3 km (High-Resolution Rapid Refresh produced by NOAA’s National Centers for Environmental Prediction). Though these models may more accurately capture the topographic effects of the ridge, they still commonly
Figure 3.1. Comparison between ECCC forecasted and recorded wind speeds at Rock River (ECCC 2023b; 2023f) during a windstorm in December 2019.
Figure 3.2. Elevation profile within Hurricane Alley from ECCC Rock River near km 457 towards the ridge to the east of the Dempster Highway. Elevation data at 50-metre intervals obtained from Google Earth. Elevation data is vertically exaggerated compared to horizontal distance at a ratio of 1:5.
underestimate high winds in Hurricane Alley. In November 2021, seven new simple meteorological stations were installed in the Hurricane Alley region to add to the overall data capacity with the goal of improving the understanding of the high wind events, especially with respect to their spatial characteristics (Section 4.4) (Figs 1.1c, 1.3b).

3.3 Study area

3.3.1 Regional description

Hurricane Alley is located along the Dempster Highway roughly halfway between Eagle Plains (km 369) and Fort McPherson (km 86) within Richardson Mountains physiographic region (Fig. 1.1b) (Fig. 3.1 in Wahl et al. 1987). The mountains are composed of closely-spaced hills oriented in a north-south direction with a series of flat and smooth ridgetops and broad valleys (Mathews 1986; Catto 1996; Scudder 1997). The underlying geology is composed mainly of deformed sedimentary rocks with some smaller granite intrusions (Smith et al. 2004, p. 98). Near the border, the ridges contain sandstones and quartzite with shales and siltstones underlying the valleys (Catto 1996). The mountain range narrows from widths of 80 km north of the territorial border crossing to 35 km in its southern reaches with its narrowest width of 15 km near the headwaters of the Vittrekwa River in the Hurricane Alley area (Fig., 1.1b; Catto 1996; Humphries 2020).

Within Hurricane Alley itself, the Dempster Highway climbs northwards from an elevation of 578 m at km 450 to 957 m at Wright Pass (Fig. 3.3). From the territorial border, the road continues northeast, descending towards Peel Plateau with elevations of 865 m at km 4 and 660 m at km 8.5. For much of Hurricane Alley – between kms 453 and 460 – the road is between 650 and 750 m asl with a gentle slope to the south. The gradient increases
Figure 3.3. Elevation profile of the Dempster Highway between kms 450 and 8.5 with the locations of weather stations marked. Elevation data at 250-metre intervals obtained from Google Earth.
close to the border. The narrow ridge to the east of the road represents one of the north-south trending ridges of Richardson Mountains. It extends approximately 17 km south of Wright Pass with a ridgetop elevation generally between 950 and 1,150 m. At its southern end east-southeast of km 450, the ridge elevation descends below 800 m. Directly east of ECCC Rock River, the ridge reaches its maximum elevation near 1,200 m (Fig. 3.2). Within Hurricane Alley, the road and ridge gradually converge (Table 3.1). Near km 453, the ridge is approximately 3.3 km east of the road, and near km 459, it is 2.4 km east of the road. North of Wright Pass, the ridge gains elevation as it becomes part of a larger range of the Richardson Mountains. Here, peak elevations are as high as 1,574 m (Mount Sittichinli; Catto 1996). South of Hurricane Alley, elevations are typically in the range of 800-1,000 m, but the mountain range is also wider (Fig. 1.1b). The combination of wider mountains both south and north of and greater elevations north of Hurricane Alley suggest that the area might act as a gap through which air masses may more easily pass and winds may strengthen (Section 2.6).

Richardson Mountains physiographic region is a part of the Taiga Cordillera ecozone (Smith et al. 2004, p. 4). This ecozone contains tundra vegetation with alpine sedges, grasses, shrubs, and mosses (Zoltai and Pettapiece 1973; Wahl et al. 1987; Smith et al. 2004). Birch and alder shrubs may be found in areas with a warmer microclimate, while trees are only found in the lowest-lying or most-protected valleys (Zoltai and Pettapiece 1973; Wahl et al. 1987). Hurricane Alley itself is at a high enough elevation that it is located within the tundra (Fig. 1.2), but the Dempster Highway north of Eagle Plains and the Arctic Circle passes through the taiga with isolated tree stands (Fig. 3.4) or taller forests in the lower, protected valleys (Fig. 3.5).
Table 3.1. A selection of metadata for the seven new weather stations, ECCC Rock River, and the two TC stations. Elevations and distances obtained from or measured in Google Earth.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Elevation (m)</th>
<th>Distance From Break in Slope (km)</th>
<th>Distance From Ridge (km)</th>
<th>Elevation of Ridgetop (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YT km 421 (TC)</td>
<td>66.701</td>
<td>-136.358</td>
<td>635</td>
<td>1.1</td>
<td>1.6</td>
<td>770</td>
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<td>YT km 450</td>
<td>66.937</td>
<td>-136.295</td>
<td>578</td>
<td>5.0</td>
<td>6.5</td>
<td>1,090</td>
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<tr>
<td>YT km 453</td>
<td>66.945</td>
<td>-136.224</td>
<td>698</td>
<td>1.1</td>
<td>2.9</td>
<td>1,105</td>
</tr>
<tr>
<td>YT km 454</td>
<td>66.957</td>
<td>-136.229</td>
<td>650</td>
<td>2.0</td>
<td>3.1</td>
<td>1,110</td>
</tr>
<tr>
<td>ECCC Rock River</td>
<td>66.981</td>
<td>-136.221</td>
<td>727</td>
<td>2.3</td>
<td>3.0</td>
<td>1,195</td>
</tr>
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<td>YT km 457</td>
<td>66.982</td>
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<td>742</td>
<td>2.1</td>
<td>2.8</td>
<td>1,190</td>
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<tr>
<td>YT km 459</td>
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<td>1.3</td>
<td>2.4</td>
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<td>YT km 465 (Border)</td>
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<td>956</td>
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<td>-</td>
<td>-</td>
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<td>NT km 4</td>
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<td>NT km 8.5 (TC)</td>
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<td>-136.088</td>
<td>659</td>
<td>3.0</td>
<td>6.2</td>
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</tr>
</tbody>
</table>
Figure 3.4. Isolated, short trees along the Dempster Highway north of the Arctic Circle. Note the flagged nature of the trees with increased growth on the lee (right) side of the trunks. The trees are leaning with the prevailing direction of the wind. Photograph taken in March 2022 facing southwest by C.R. Burn.

Figure 3.5. A dense, tall forest near km 446. Google Streetview imagery from August 2009 facing northeast.
High winds in the Hurricane Alley region result in a thin, dense snow cover (Fig. 3.6). During winter 2018-19 at km 456, snowpack depths in undisturbed tundra reached 11, 23, and 30 cm respectively at the ends of October, December, and March (Humphries 2020). In March 2019, snow densities were on average 0.26 g cm\(^{-3}\) in the tundra, though individual measurements varied between approximately 0.15-0.45 g cm\(^{-3}\). Another consequence of high winds in the region is the occurrence of ‘flagged’ trees with branches disproportionately on the lee side of tree trunks (Fig. 3.4) (Barry 2008).

### 3.3.2 Regional climate

At broad scale, the climate of Yukon can be described as subarctic continental (Wahl et al. 1987). The continental climate results in relatively dry conditions and large temperature ranges. Wahl et al. (1987) consider the Hurricane Alley area to be contained within the Northern Mountains climate region. This region of Richardson and British mountains experiences long, cold winters lasting from mid-October through May (Wahl et al. 1987; Klock et al. 2001). Annual mean temperatures in the study area are slightly higher than in the surrounding Porcupine and Peel river basins due to atmospheric inversions over the low-lying regions. The low winter temperatures are occasionally punctuated by the introduction of mild, moist air from the Pacific Ocean when storms move inland from the Gulf of Alaska (Wahl et al. 1987). Summers are short (July-August) with warm periods and fair weather interrupted by intrusions of Arctic air from the Beaufort Sea (Wahl et al. 1987; Klock et al. 2001). Annual precipitation is low – on the order of 2-400 mm – with the majority occurring as convective precipitation during the summer months. Average monthly winter snowfall is below 10 cm per month (Klock et al. 2001). The snow that does
Figure 3.6. Snowpack near km 456 in Hurricane Alley. Dense, shallow snow with visible vegetation is present in the foreground of the image. The snowpack is deeper in the midground of the image due to snow fencing, visible in the centre right of the image. Photograph taken in March 2022 facing northeast.
accumulate is redistributed by wind due to the absence of trees and large shrubs in the mountains (Wahl et al. 1987). Strong winds, poor visibility, and low ceilings are common in the mountains especially in winter (Klock et al. 2001).

The nearest ECCC meteorological stations to Hurricane Alley with long-term, continuous data are Fort McPherson, NT, and Old Crow, YT, respectively located approximately 80 and 170 km from Rock River. The most recent climate normals published by ECCC (2023c) are for 1981-2010 (Fig. 3.7). Fort McPherson (elevation 35.4 m) recorded a mean annual air temperature (MAAT) of -7.3 °C and mean total annual precipitation (MTAP) of 298 mm. Mean total annual rainfall (MTAR) was 146 mm and mean total annual snowfall (MTAS) was 152 cm. For Old Crow (elevation 250.2 m) the values are similar over the same climate normal: MAAT was -8.3 °C, MTAP was 279 mm, MTAR was 155 mm, and MTAS was 141 cm. Homogenized temperature data (ECCC 2023d) yield a MAAT of -7.6 °C for the most recent climate normal (1991-2020) at Old Crow (Vincent et al. 2020; Schetselaar et al. 2023). Homogenized data are not yet available for Fort McPherson.

Annual mean air temperatures were also compiled for the regional NTAI stations by Stockton et al. (2019; 2014-15 through 2017-18) and Kokelj et al. (2022; 2015-2020). From Stockton et al. (2019), MAATs are -4.8 and -5.2 °C at kms 421 and 8.5, respectively. Kokelj et al. (2022) reported similar values for other stations in the Northwest Territories. These values are higher than those for Old Crow and Fort McPherson due to the effects of winter atmospheric inversions (Burn et al. 2015; O’Neill et al. 2015; Stockton et al. 2019) whereby the higher elevation NTAI stations record warmer conditions than the ECCC stations at lower elevations.
Figure 3.7. ECCC (2023c) mean monthly temperature and total precipitation data for Fort McPherson, NT for the climate normal of 1981-2010.
3.3.3 Winds

Wind records at the closest regional ECCC meteorological stations of Fort McPherson and Old Crow are incomplete for the 1981-2010 climate normals (ECCC 2023c). Only maximum hourly wind speeds for each month are provided in the published data (Table 3.2). At Fort McPherson, the maximum sustained hourly wind speed during 1981-2010 was a westerly wind of 56 km h\(^{-1}\) on 16 March 1990. Maximum wind speeds in other months were either northerlies or westerlies but did not commonly reach gale force (Table 3.2). At Old Crow, a maximum sustained hourly wind speed of 74 km h\(^{-1}\) was recorded on 14 January 1993. This wind was westerly in contrast to the other maximum wind speeds in each month which were either northerly or southwesterly gale-force winds (Table 3.2). The wind conditions at both Old Crow and Fort McPherson are not commonly described in the literature except in discussions concerning the oriented lakes of the Old Crow Flats which note prevailing northeasterlies in the summer months (e.g., Roy-Léveillé and Burn 2010; 2015). With the limited ECCC data available at the time, Wahl et al. (1987) noted prevailing northeasterlies in all months at Old Crow with higher average wind speeds in late spring and summer, and lower average wind speeds in the winter months.

Using data from the NTAI meteorological stations, regional winds were studied in Richardson Mountains (Humphries et al. 2019) and the Peel Plateau region (Kokelj et al. 2022). Humphries et al. (2019) reported that for 2014-2018, prevailing wind direction was easterly on the Yukon side of Richardson Mountains and southwesterly on the Northwest Territories side. The highest winds on the Yukon side were also easterlies, demonstrating the topographic effect of the Richardson Mountains in producing high winds in Hurricane Alley and further south. Weaker winds had variable directionality. Gale- and storm-force
Table 3.2. Maximum hourly wind speeds (km h\(^{-1}\)) and associated cardinal or ordinal directions recorded at a height of 10 m in each month at Fort McPherson, NT, and Old Crow, YT. Data from ECCC (2023c) for the 1981-2010 climate normal.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Fort McPherson</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Speed (km h(^{-1}))</td>
<td>52</td>
<td>41</td>
<td>56</td>
<td>33</td>
<td>37</td>
<td>46</td>
<td>33</td>
<td>37</td>
<td>37</td>
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<td>46</td>
<td>37</td>
</tr>
<tr>
<td>Direction</td>
<td>N</td>
<td>W</td>
<td>W</td>
<td>N</td>
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<td>N</td>
<td>N</td>
<td>N</td>
<td>W</td>
<td>N</td>
<td>N</td>
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</tr>
<tr>
<td><strong>Old Crow</strong></td>
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</tr>
<tr>
<td>Speed (km h(^{-1}))</td>
<td>74</td>
<td>56</td>
<td>65</td>
<td>59</td>
<td>48</td>
<td>56</td>
<td>46</td>
<td>65</td>
<td>50</td>
<td>56</td>
<td>63</td>
<td>61</td>
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<tr>
<td>Direction</td>
<td>W</td>
<td>SW</td>
<td>N</td>
<td>NE</td>
<td>N</td>
<td>N</td>
<td>S</td>
<td>SW</td>
<td>SW</td>
<td>N</td>
<td>N</td>
<td>SW</td>
</tr>
</tbody>
</table>
winds accounted for 8.3% and 0.8% of observations at Rock River, respectively; but were rare or absent at the NTAI stations. Mean wind speeds at Rock River (17.6 km h\(^{-1}\)) recorded at a height of 10 m were approximately twice as high as at the NTAI stations (8.3-11.5 km h\(^{-1}\)) where wind speeds were measured at a height of 3 m. Kokelj et al. (2022) reported similar mean wind speeds at two NTAI stations in the Northwest Territories for 2014-2021. The strongest winds have been recorded in winter, but average wind speeds are higher during summer (Humphries et al. 2019), probably due to daytime convective activity compared with intermittent cyclonic activity during winter (Section 2.2) (Stull 2017). This is in line with the analysis of Wahl et al (1987), which notes calmer winds throughout much of Yukon in winter due to prevailing anticyclonic stability and weaker pressure gradients.

Recognizing the need for improved forecasts of the high winds in Hurricane Alley, a proof-of-concept modelling project was undertaken by the Weather Forecast Research Team at the University of British Columbia. Ribberink et al. (2020) back-casted five high wind events during winter 2019-20 using models at four different grid cell spacings: 0.33, 1, 3, and 9 km. The model with a resolution of 9 km performed similarly to the ECCC forecasts, and the 3 km model also underpredicted the observed conditions at Rock River. The simulations at 1 and 0.33 km grid spacings performed substantially better than all others, more accurately matching the recorded wind speeds at Rock River. Ribberink et al. (2020) noted that the easterly high winds in Hurricane Alley are commonly a result of the foehn mechanism, though westerlies may sometimes occur by mountain waves due to low-altitude jet streams interacting with the ridge. During some of the cases, hydraulic jumps were simulated downslope and to the west of the road.
3.4 Field sites

3.4.1 Site selection

Positions for the seven new meteorological stations within and near Hurricane Alley were selected in summer 2021 before installation in late October 2021. Data collection was initiated in November 2021. The specific locations for each site were selected based on then-current understandings of the winds and identification of sites where wind data were most important. Initially, three potential locations were identified as most important: km 453 upslope of the road, the border (km 465/0), and km 4. The suggested positioning of km 453 closer to the ridge came from Ribberink et al (2020). Their modelling results suggested that strong winds may initially develop southeast of kms 452-454. A station was installed in this area to determine if it provided an advanced warning of developing windstorms which later spread throughout Hurricane Alley. Km 4 was identified as a station site on the basis of many reports from highway crews and motorists of strong westerly winds around this location (e.g., Rébillon 2014). Furthermore, ECCC Rock River records only the strong easterlies on the Yukon side, and NTAI km 8.5 is too far downslope to record the strongest westerly winds on the Northwest Territories side (Humphries et al. 2019; Kokelj et al. 2022). The border was initially identified as a potential location due to evidence that the wind regime could be variable near Wright Pass. For example, during a March 2020 windstorm, winds were calm within Hurricane Alley itself, but beginning a few metres below the pass, rapidly increased to strong westerlies at the border (C.R. Burn, pers. comm. 2020). Analysis of the limited wind data from NorthwesTel’s North Vittrekwa site (in Wright Pass) had also suggested that strong westerlies and easterlies occur in the
pass. This contrasts with other stations in the region which typically recorded either prevailing easterlies or westerlies (Humphries et al. 2019).

Further site selection occurred when the number of stations to be installed was confirmed at seven. Km 457 near ECCC Rock River was identified as a suitable location to cover potential data gaps at ECCC Rock River. The installation of a new station close to Rock River would also allow for comparison of wind speed at different heights because the new stations record wind at 3 metres, while the anemometer at Rock River is 10 metres above the surface. Additionally, there have been suggestions from highway crews that the specific location of ECCC Rock River may experience reduced wind speeds during windstorms compared to areas just to the north and south. Kms 454 and 459 were selected as additional sites for the new stations to provide more spatially detailed data on the development and variation of winds within Hurricane Alley. Km 450 was selected as the final site for a new weather station as this location is commonly considered to be the southern boundary of Hurricane Alley, though reports suggested that the winds here were weaker than at other points in Hurricane Alley.

3.4.2 Site instrumentation

These seven new meteorological stations were installed in the Hurricane Alley area in late October 2021 at kms 450, 453, 454, 457, 459, the border (km 465/0), and km 4 (Fig. 1.1c). The stations were installed by contractors at Northern Avcom Ltd. for the Government of Yukon’s Transportation Engineering Branch. Shortly thereafter in early November, the stations began recording and transmitting data. The anemometer at each of the seven stations is a Campbell Scientific 05108-45-L Wind Monitor-HD, Alpine Version (Fig.
These anemometers are designed with alpine recording environments in mind and as such have a black housing and ice-resistant coating to help reduce ice build-up. The specifications for this anemometer are presented in Table 3.3. The anemometers have been programmed to record the mean wind speed and direction in the final 10 minutes of each hour, as well as the maximum wind speed and associated direction at any time during the hour. The anemometers record data at a height of 3 m.

The stations at kms 453 and 4 also contain temperature and humidity sensors. These are Campbell Scientific CS215-L Temperature and Relative Humidity Probes (Fig. 3.8; Campbell Scientific, Inc. 2023c). The specifications of this probe are presented in Table 3.3. These probes are encompassed within a white radiation shield to prevent erroneous readings in direct sunlight. The probes have been programmed to record the mean ambient air temperature (°C) and relative humidity (%) in the final minute of each hour, as well as maximum and minimum temperature and relative humidity at any time during the hour.

The data recorded at each station are logged on a Campbell Scientific CR310 Measurement and Control Datalogger (Campbell Scientific, Inc. 2023b), and transmitted via the GOES satellite network in near-real time to be available on Campbell Cloud (Campbell Scientific Canada 2023). To facilitate this, each station features GOES modems and antennas and GPS antennas. Batteries, solar panels, and further core infrastructure are also included on each station.

### 3.4.3 Site characteristics in March 2022

A selection of metadata including co-ordinates, elevation, etc. for each of the seven new meteorological stations and ECCC Rock River are presented in Tables 3.1 and 3.4.
Table 3.3. Data specifications for the wind, temperature, and relative humidity sensors installed at the new weather stations.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Measurement Range</th>
<th>Output Resolution</th>
<th>Accuracy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Campbell Scientific 05108-45-L (Wind Speed)</strong></td>
<td>0 to 100 m s(^{-1}) (0 to 360 km h(^{-1}))</td>
<td></td>
<td>±0.3 m s(^{-1}) (±1.08 km h(^{-1})) or 1% of reading</td>
</tr>
<tr>
<td><strong>Campbell Scientific 05108-45-L (Wind Direction)</strong></td>
<td>0 to 360°</td>
<td></td>
<td>±3°</td>
</tr>
<tr>
<td><strong>Campbell Scientific CS215-L (Air Temperature)</strong></td>
<td>-40° to +70°C</td>
<td>0.01°C</td>
<td>±0.3°C (at 25°C) ±0.4°C (5° to 40°C) ±0.9°C (-40° to +70°C)</td>
</tr>
<tr>
<td><strong>Campbell Scientific CS215-L (Relative Humidity)</strong></td>
<td>0 to 100% RH (-20° to +60°C)</td>
<td>0.03% RH</td>
<td>±2% (10% to 90% range) at 25°C ±4% (0% to 100% range) at 25°C</td>
</tr>
</tbody>
</table>
Figure 3.8. The new weather station at km 4. The temperature and humidity probes are installed below the white radiation shield at the centre top of the apparatus. Note that the propellor from the anemometer is missing due to damage sustained earlier in the winter. Photograph taken in March 2022 facing southwest.
Table 3.4. Wind characteristics recorded by station type. The TEB stations at kms 453 and 4 also record temperature and relative humidity (Section 3.4.2), and ECCC Rock River and the TC stations record a variety of additional meteorological data. Note that depending on the source, the stated measurement period for wind speed at ECCC stations varies (ECCC 2020a; 2021; and 2023e).

<table>
<thead>
<tr>
<th>Organization</th>
<th>Station Locations</th>
<th>Anemometer Type</th>
<th>Anemometer Height (m)</th>
<th>Wind Speed Measurements</th>
<th>Wind Direction Measurements</th>
<th>Recording Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment &amp; Climate Change Canada (ECCC)</td>
<td>Rock River (near km 457)</td>
<td>U2A</td>
<td>10</td>
<td>Average during final one, two, or 10 minutes of the hour</td>
<td>Average during final two minutes of the hour</td>
<td>Jul. 2006 – present</td>
</tr>
<tr>
<td>Government of Yukon Transportation &amp; Engineering Branch (TEB), Northern Avcom Ltd.</td>
<td>YT km 450</td>
<td>Campbell Scientific 05108-45-L Wind Monitor-HD, Alpine Version</td>
<td>3</td>
<td>Average during final 10 minutes of the hour (mean)</td>
<td>Average during final 10 minutes of the hour (mean)</td>
<td>Nov. 2021 - present</td>
</tr>
<tr>
<td>Transport Canada (TC)</td>
<td>YT km 421</td>
<td>RM Young 05103AP-10-L</td>
<td>3</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Feb. 2014 – present</td>
</tr>
<tr>
<td>NorthwesTel</td>
<td>North Vittrekwa (near border)</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Aug. 2012 – May 2015</td>
</tr>
</tbody>
</table>
Appendix 2 presents additional information and images of specific site conditions. On 13 March 2022, a brief field trip took place with visits to each of the sites. A few days prior to this visit on 9-10 March 2022, an easterly windstorm had occurred in Hurricane Alley. Sustained winds above 50 km h\(^{-1}\) were recorded at all 5 stations between kms 453 and 459 (including ECCC Rock River). Gale-force winds did not occur at km 450, the border, or km 4 which was inoperative at the time (Fig. 3.8). Prevailing winds were easterly or slightly northeasterly depending on the station. The highest mean wind speed of 70 km h\(^{-1}\) was recorded at 1 PM YST at Rock River on 9 March. The highest maximum wind speed of 96 km h\(^{-1}\) was recorded at YT km 453 between 12 PM and 1 PM YST. The Dempster Highway was closed between Eagle Plains and Fort McPherson until overnight between 12 and 13 March while the highway crews cleared the road.

Traveling north from Eagle Plains, influences from the wind and recent windstorm became apparent well before reaching Hurricane Alley. Near km 418, isolated flagged trees and some trees leaning with the direction of prevailing winds were observed (Fig. 3.4). Ripples and dunes in the snow surface showed evidence of blowing and drifting snow (Fig 3.9). At km 440, a large snow drift approximately 1.5 m deep and 200 m long had blocked the road (Fig. 2.7). Further snow drifts also occurred within Hurricane Alley near kms 452 and 461 with windrows on the sides of the road. On the morning of the 13\(^{th}\), winds were generally < 10 km h\(^{-1}\) within Hurricane Alley. The prevailing direction was northeasterly. In line with results from Humphries (2020), the snow throughout much of Hurricane Alley was shallow and dense with grasses from tussocks poking through the layer of snow (Fig. 3.6). The exceptions to this were surrounding the snow fences (which have since been removed; Fig. 3.6) and further south near km 450 where the ridge is farther from the road.
Figure 3.9. Snowpack near km 450 in Hurricane Alley. The new weather station is visible in the centre of the image. Only taller shrubs are poking out of the top of the deep snowpack. Ripples and drifts are visible in the snowpack demonstrating the effects of wind action. Photograph taken in March 2022 facing southwest.
and weaker winds result in deeper and less dense snow (Fig. 3.9).

In contrast to the mainly calm conditions within Hurricane Alley, the winds were stronger at the border (km 465) on 13 March. Average wind speeds were between 25 and 35 km h\(^{-1}\) with maximum speeds closer to 40 km h\(^{-1}\) and from a prevailing southwesterly direction. These moderate winds represent the opposing situation to a few days prior when strong easterlies were encountered within Hurricane Alley. The wind was strong enough to cause blowing snow (Fig. 3.10). Much of the border station including the antennas had been covered in snow and ice, and there was some build-up on the anemometer itself (Fig. 3.11). Further downslope near km 4, the winds still appeared to be westerly or southwesterly, though not as strong as at the border. The exact speed and direction could not be verified, because the anemometer had been damaged previously (Fig. 3.8).

### 3.5 Data sources

As described in Section 3.4.2, the seven new meteorological stations in the Hurricane Alley area are among the main wind data sources for this project (Table 3.4). The data recorded at each of these stations is fed into the Campbell Cloud via satellite connection. The Campbell Cloud is used by the Government of Yukon to track weather, ground, and road conditions in near-real time throughout the territory. Wind speed and direction at the Hurricane Alley stations can be observed and downloaded from this source.

Another major source of data for this thesis is the ECCC Rock River meteorological station. Wind speed and direction data (among other weather data) are available from ECCC’s historical data record (ECCC 2023f) (Table 3.4). At most ECCC stations, including Rock River, wind is measured at a height of 10 m in a location where the ground
Figure 3.10. Blowing snow from southwesterly winds descending down the ridge in the Northwest Territories. Photograph taken in March 2022 facing south by C.R. Burn.
Figure 3.11. The new weather station at the territorial border (km 465) displaying substantial buildup of snow and ice. Less accumulation has occurred on the anemometer (top right) compared to other elements of the station including the antennas (top centre). Note that the antenna was replaced in July 2022 in an attempt to minimize the build-up of snow and ice in winter. Photograph taken in March 2022 facing southwest.
surface is level and far from any obstacles which may obstruct wind flow (ECCC 2023e). Standard type U2A anemometers are used (ECCC 2020a). ECCC provides data on hourly wind speed and direction, and daily maximum wind gusts. Wind speed data are provided in km h\(^{-1}\) as the average during the final one-, two-, or ten-minute period in each hour (Table 3.4; ECCC 2020a; 2021; and 2023e). Wind directions are provided to the nearest ten degrees as the average during the final two-minute period in each hour (ECCC 2023e). The daily maximum wind gust and associated direction are provided if the gust exceeds 30 km h\(^{-1}\). Wind gust durations commonly last between 3 and 5 seconds (ECCC 2023e). For Rock River, the hourly wind record spans July 2006 to present with mostly continuous data.

Additional ECCC data used within this thesis are publicly available surface analysis charts (ECCC 2023a). These analysis charts are published four times daily at 00, 06, 12, and 18 UTC and are used to represent the state of the atmosphere including pressure systems and gradients. Of interest to this thesis are the preliminary surface analysis charts covering all of Canada and the complete surface analysis charts covering much of the Northern Hemisphere. Archived analysis charts for North America are available since January 1990 from the National Oceanic and Atmospheric Administration and National Weather Service Weather Prediction Center (NOAA/NWS 2022). Upper atmosphere data were also used in limited capacity for this thesis. These included 500 hPa analysis charts published twice daily at 00 and 12 UTC by the University of Wyoming (2023). Additionally, NOAA’s Physical Sciences Laboratory (2023) provides daily mean composite data for a variety of weather variables. These data were used to describe upper air wind speeds and jet stream positioning.
In addition to the wind data from the new Hurricane Alley stations and ECCC Rock River, some wind data are also available from the nearby TC stations at kms 421 (Fig. 3.12a), and 8.5 (Fig. 3.12b); and the North Vittrekwa NorthwesTel (Fig. 3.13) station near the territorial border (Table 3.4). The TC stations were installed between 2013 and 2014 as part of the NTAI and have been recording data since February 2014 (Idrees et al. 2015). Unlike the new stations installed in the Hurricane Alley region, only some of the NTAI stations have their data transmitted via satellite. Otherwise, recorded data are instead stored locally and downloaded during periodic site visits. The NTAI stations record hourly wind speed and direction data with an RM Young 0510AP-10-L sensor at a height of 3 m. At the NorthwesTel North Vittrekwa site, some hourly wind speed and direction data are available from August 2012 until August 2013 for speed and until May 2015 for direction. The height of wind recordings at North Vittrekwa is unclear, although wind speed data were likely erroneous and not considered for the analysis (Section 4.3.3).

3.6. Data analysis

3.6.1. Wind records

The primary data analysed within this thesis are hourly wind data from several meteorological stations (Section 3.5). For each station, these data were organized on a monthly basis and various metrics were determined including monthly mean wind speeds and total hours of gale- and storm-force winds. For calculations of overall means at the stations with longer records, ECCC’s “3 and 5 rule” (ECCC 2020a) was followed. The “3 and 5 rule” states that for metrics which are averages (e.g., mean monthly wind speed), monthly values should be excluded if more than three consecutive or five total days are missing. For hourly data, this would correspond to more than 72 consecutive or 120 total
Figure 3.12. NTA1 weather stations at (a) km 421 (photograph taken facing south in June 2019) and (b) km 8.5 (photograph taken in March 2022 facing east by C.R. Burn).
Figure 3.13. NorthwesTel North Vittrekwa (background) and km 465 (foreground) near the Yukon-Northwest Territories border. North Vittrekwa is located approximately 400 m north-northwest of km 465. Photograph taken in March 2022 facing north by C.R. Burn.
missing hours. For metrics which are totals (e.g., total hours of gale-force winds), ECCC guidelines suggest that monthly values should be excluded from calculations if any data are missing. However, for the purposes of this thesis, the “3 and 5 rule” was still followed for such metrics to improve data completeness, and because many months in the records had a very small number of missing hours. Monthly data which did not meet the “3 and 5 rule” were still presented in the results and identified as such.

During the data organization phase of this project, certain adjustments were taken to improve data quality. For the ECCC Rock River data, one such adjustment needed to be made for calm winds. When winds are calm at ECCC stations, the direction value either appears as ‘0’ or a blank cell. Wind direction values of 0 were removed so as not to be erroneously associated with northerly winds which are instead represented with a value of 36 (in tens of °). For the seven new stations with data available on the Campbell Cloud, attention had to be given to missing hourly data. When downloading these data as .csv files, any hours with missing data were skipped over, so blank cells were added during processing to improve ease of analysis. Some instances of prolonged periods of apparent calm conditions were also removed from the data records and subsequent analysis. This was mainly a concern at the new stations and occasionally the NTAI stations. Because these periods sometimes lasted for several days or a week or longer, they were interpreted as the anemometer propellor freezing up rather than actual periods of calm conditions. For example, during a two-week period during 13-27 January 2023, no mean or maximum wind speeds above 0 km h\(^{-1}\) were recorded at km 465. Comparisons with the other nearby stations (including Rock River) were also used to determine if conditions were calm.
3.6.2 Wind roses

Wind roses were constructed for many of the stations with speed classes as outlined in Table 1.1 (ECCC 2017; 2021; Humphries et al. 2019): calm (0-5 km h\(^{-1}\)), breeze (6-49 km h\(^{-1}\)), gale (50-88 km h\(^{-1}\)), and storm (>88 km h\(^{-1}\)). Wind direction was separated into 12 classes: north (N; 345-15°), north-northeast (NNE; 15-45°), east-northeast (ENE; 45-75°), east (E; 75-105°), east-southeast (ESE; 105-135°), south-southeast (SSE; 135-165°), south (S; 165-195°), south-southwest (SSW; 195-225°), west-southwest (WSW; 225-255°), west (W; 255-285°), west-northwest (WNW; 285-315°), and north-northwest (N; 315-345°). This division was made in part because wind direction at ECCC Rock River has 36 possible values (between 1 and 36, given to the nearest ten degrees) resulting in 3 values in each class. Using the four cardinal (north, east, south, and west) and four ordinal directions (northeast, southeast, southwest, and northwest) would result in an uneven number of values (4 or 5) in each of these eight classes. At other stations wind direction was given to the nearest degree or tenth of a degree and simply assigned to one of the 12 classes.

3.6.3 Windstorm classification

One element of the analysis was the identification of ‘windstorms’ or ‘high wind events’ at several of the stations. For the purposes of the analysis, a windstorm is described as a time period where gale-force winds or greater (≥50 km h\(^{-1}\)) occurred for at least four consecutive or six total hours. The beginning of the windstorm occurred in the hour when the wind speed first reached at least 50 km h\(^{-1}\). The end of the windstorm was identified as the hour when the wind speed was last at least 50 km h\(^{-1}\) before decreasing to calm conditions (0-5 km h\(^{-1}\)). That is, a windstorm ended when the wind speed declined from
gale force (or greater) to calm conditions later on. If the wind speed declined below 50 km h\textsuperscript{-1} but did not reach calm conditions and instead returned to gale force conditions later on, then the windstorm had not ended. Windstorm identification was completed for ECCC Rock River, the seven new stations in the Hurricane Alley region, and NTAI kms 421 and 8.5. Windstorm duration, separation between windstorms, maximum wind speed, and total hours of gale-force winds or greater were among the metrics identified for each event. The anemometer height differed among stations, so windstorms would have been undercounted at the stations where wind is recorded at 3 rather than 10 m as a result of the surface frictional effects (Section 2.4).

3.6.4 Relations between stations

Wind speeds among stations were compared using least-square linear regressions (Rock River and YT km 457 only) and Pearson correlation coefficients (Pearson’s $R$; Rock River and all seven new stations), both determined using Microsoft Excel. Rock River and YT km 457 were compared to understand the relation between wind speed at different anemometer heights (Section 4.2.3), while relations between all stations in the Hurricane Alley were compared to assess spatial variability (Section 4.4.2). In both cases, relations were determined for all wind speed data, and gale-force winds or greater only. When considering gale-force winds or greater, correlations were calculated twice for each station pair: once for the hours in which gale-force winds or greater were recorded at one station, and once for when the same was true at the other station.
3.6.5 Synoptic weather conditions

Relations between synoptic weather systems and high wind events were considered based on the windstorms identified earlier in the analysis (Section 3.6.3) and analysis charts available from ECCC. This analysis was mainly limited to the operational period of the seven new weather stations (Dec. 2021-Mar. 2023) and was largely focused on identifying common synoptic weather patterns among the windstorms. Three windstorms were selected for further analysis: an easterly event in the Yukon (Jan. 2022), a westerly event in the Northwest Territories (Jan. 2023), and an extreme easterly event in the Yukon (Feb. 2014). Wind characteristics, additional weather metrics, and specific synoptic conditions were considered in more detail for these case studies.

3.7 Other data quality considerations

Across the entire ECCC Rock River record, approximately 6-7% of hourly data were missing with most of the months that failed the “3 and 5 rule” in the earlier half of the record before February 2014 (Table 3.5). Since February 2014, data quality has improved except for a prolonged period of missing data between March and August 2021. At the other stations, data quality was varied. At NorthwesTel North Vittrekwa, at least some of the wind speed data was erroneous, and wind speed was thus not analysed. Save for a prolonged period of missing data between September 2018 and July 2019, km 8.5 had fewer data issues than km 421. At km 421, missing data was not a concern through the first half of the record when data was stored on a logger and periodically downloaded. However, more recently when the data was transmitted via satellite to the Campbell Cloud, missing data became more common. During the overlap of the two data sources in 2017 and 2018,
Table 3.5. Total hours of missing data in the ECCC Rock River wind record. Values in red also failed the “3 and 5” rule, while cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
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<th>Jun</th>
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<td>-</td>
<td>-</td>
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<td>105</td>
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<td>2008</td>
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<td>144</td>
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<td>13</td>
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<td>2023</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>
more data was missing on the Campbell Cloud than the logger, suggesting that problems with satellite connectivity were responsible. This is also a concern at the seven new stations where the satellite antennas were prone to freezing and not transmitting data (even if it was recorded) (Table 3.6). The antennas were replaced in July 2022 with more ice-resistant models. There was less missing data during winter 2022-23, likely also helped by proactive ice clearing by highway maintenance crews (C. Brais, pers. comm. 2023). Substantial amounts of data were still missing at kms 453 and 465, although this would be expected considering that km 453 is located far off the road, and km 465 appears prone to ice build-up (Table 3.6). Substantial ice build-up may have also jammed the anemometers themselves on occasion, as is evidenced by prolonged periods of apparently calm winds (Section 3.6.1). Wind speeds were missing between late January and late July 2022 at km 4 due to damage sustained to the anemometer (Fig. 3.8).

Wind speed measurements at the new stations were inaccurate through to early December 2021 due to a programming error, so data during this period were not considered in the analyses. As noted in Section 3.6.1, the wind direction may be assigned a value of ‘0’ for calm conditions at ECCC stations, which is not the same as a northerly wind – assigned a value of ‘36.’ One oddity associated with this is that wind direction values of 0 appear to be associated with wind speeds of 1 km h⁻¹, while actual calm conditions (0 km h⁻¹) are not assigned a specific direction value. This is likely a result of wind speed and direction being recorded over slightly different time periods (ECCC 2020a; 2021; and 2023e). Calm conditions which are not associated with a direction cannot be plotted on wind roses. This applies to approximately 7% of hourly data recorded at Rock River. Most of these data were actual calm conditions with wind speeds of 0 km h⁻¹ (6.38%, Table 1.1).
Table 3.6. Total hours of missing data in the wind records of the seven new stations. Values in red also failed the “3 and 5” rule.

<table>
<thead>
<tr>
<th>Month</th>
<th>YT km 450</th>
<th>YT km 453</th>
<th>YT km 454</th>
<th>YT km 457</th>
<th>YT km 459</th>
<th>YT km 465</th>
<th>NT km 4</th>
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<td>378</td>
<td>392</td>
<td>397</td>
<td>471</td>
<td>470</td>
<td>512</td>
<td>291</td>
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<tr>
<td>Jan-22</td>
<td>72</td>
<td>402</td>
<td>311</td>
<td>244</td>
<td>127</td>
<td>643</td>
<td>200</td>
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<tr>
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<td>1</td>
<td>0</td>
<td>0</td>
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<td>672</td>
</tr>
<tr>
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<td>1</td>
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<td>0</td>
<td>176</td>
<td>744</td>
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<tr>
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<td>1</td>
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<td>1</td>
<td>10</td>
<td>1</td>
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<td>3</td>
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<tr>
<td>Jan-23</td>
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<td>668</td>
<td>4</td>
<td>9</td>
<td>6</td>
<td>347</td>
<td>9</td>
</tr>
<tr>
<td>Feb-23</td>
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<td>104</td>
<td>61</td>
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<td>47</td>
<td>43</td>
</tr>
<tr>
<td>Mar-23</td>
<td>4</td>
<td>237</td>
<td>4</td>
<td>35</td>
<td>1</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>
with the remainder being associated with direction values of 0 even if there was a slight wind. At the other stations, all calm measurements were associated with a direction value and could be plotted under the ‘calm’ class on wind roses.

At all stations except for Rock River northerly winds are relatively rare, or rather too rare. This is likely a consequence of the method of wind direction averaging at the stations. In the simplest manner, wind directions of 359 and 1° should average together to 360° or due north, but arithmetically average to 180° and instead appear as a southerly wind. This would also be the case if about half of measurements were east of 0° and west of 360°. Alternatively, if three quarters of the measurements were east of 0° or west of 360°, then the respective directions may appear to be approximately easterly or westerly. The consequence of this averaging method is that northerly winds are virtually absent at most stations with winds from other directions overrepresented. Without access to the original raw data and an abundance of analysis time, it is impossible to identify which winds should have been northerlies and therefore correct for such an issue. Thus, when wind roses are presented within this thesis, it is important to consider that northerly winds are underrepresented, and most other directions are somewhat overrepresented. Based on the more accurate Rock River wind direction data, this might apply to somewhere around 9% of the data.

As of March 2020, Yukon no longer observes time changes and is permanently on Pacific Daylight Time (PDT) or Yukon Standard Time (YST; UTC -7) rather than the previous Pacific Standard and Daylight Times (UTC -8). Interestingly, the difference between UTC and LST at Rock River (and potentially other Yukon ECCC stations) is still UTC -8, and thus during the analysis, the Rock River record had to be adjusted to line up
with the new stations. Data from the Campbell Cloud defaults to the user time zone, so the 2020 time change was not a concern.

**3.8 Summary**

The Hurricane Alley region is located within a section of Richardson Mountains where the mountain range narrows, and strong winds are encountered. Regional wind speeds are not particularly strong in the historic record, although interest in the local winds in Hurricane Alley has grown since the installation of ECCC Rock River. Additional nearby weather stations have been installed by Transport Canada, NorthwesTel, and the Government of Yukon and their contractors. Prevailing wind direction along the Dempster Highway is influenced by the ridge in Hurricane Alley: easterly to the west of the ridge in the Yukon and westerly to the east of the ridge in the Northwest Territories. Historic wind records and additional meteorological data have been studied to describe the wind regime of the region with results presented in Chapter 4.
Chapter 4: RESULTS

4.1 Introduction

In this chapter, the strong winds affecting Hurricane Alley and the surrounding region are discussed in detail. Consideration is first given to the wind conditions throughout the record at ECCC Rock River (Fig. 1.3a). A brief discussion of wind conditions at other nearby meteorological stations then follows. Next, the wind conditions recorded at the seven new weather stations positioned throughout Hurricane Alley are discussed. Finally, connections between synoptic conditions and high wind events are identified before three case studies are presented to illustrate these relations.

4.2 ECCC Rock River

4.2.1 Wind characteristics

In the nearly 17 years with 147,000 hours of wind data from ECCC Rock River for July 2006 to March 2023, wind speed and direction were recorded during 93.2 and 92.4% of hours, respectively (Table 3.5). Figure 4.1a displays the mean monthly wind speeds, while Appendix Table A1 presents these data over the entire record. Of these data, eight years were used to calculate mean statistics, as they did not have any months which failed ECCC’s “3 and 5” rule (ECCC 2020a). Over these eight years the mean wind speed was 18.2 km h\(^{-1}\) with a range between 17.0 (2022) and 19.7 km h\(^{-1}\) (2019). On a monthly basis, mean wind speeds tended to be lower in the winter months than in late spring and early summer. May and June have had the highest mean wind speeds of 23.7 and 22.8 km h\(^{-1}\), respectively; while February’s mean wind speed, 13.1 km h\(^{-1}\), was the lowest of any month.
Figure 4.1. Mean monthly (a) wind speeds and (b) hours of gale- and storm-force winds recorded at ECCC Rock River at a height of 10 m (Jul. 2006-Mar. 2023). Only months with complete data are used in the calculation for means (see Tables A1 through A3).
Figure 4.1b displays the mean monthly hours of gale- and storm-force winds (Table 1.1) in the Rock River record. Individual monthly values can be found in Tables A2 and A3. Of the eight years with complete data, an annual mean of 776 hours of gale-force winds have occurred with a range between 616 hours (2022) and 958 hours (2019) (Table A2). Cumulatively, this is equivalent to just over a month of gales annually. On a monthly basis, the total hours of gale-force winds tended to be lowest in the summer. A mean of 13 hours of gale-force winds have occurred in July, compared to between 78 and 84 hours in the spring months and October. For storm-force winds (Table A3) in years with complete data, the annual mean has been 60 hours with a range of between 40 (2017) and 83 (2016) hours. However, more storm-force winds were recorded in 2014 (134 hours) and 2008 (84 hours) which both contain months with incomplete data. Monthly distributions were more variable than for gales: storm-force winds have not been recorded in the summer, have been very rare in May and September, and have been most common in November, December, and January (means between 10 and 17 hours).

Wind roses for each season are presented in Fig. 4.2. Calm winds (Table 1.1) are underrepresented on these plots because these winds are not assigned a direction at ECCC stations, so they cannot be plotted on a wind rose (Section 3.7). This applies to 10.9, 6.2, 1.8, and 8.7% of hours in winter, spring, summer, and autumn, respectively. Gale- and storm-force winds at Rock River were almost exclusively easterly or east-northeasterly (Fig. 4.2). Prevailing winds were easterly in each season, although there was variability between seasons, with winter winds being most variable.

Table 4.1 summarizes the proportion of wind classes on seasonal and annual bases. Breezes have been the predominant wind category with strong winds of gale force or higher
Figure 4.2. Wind roses for ECCC Rock River for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON). Hourly wind data from July 2006 to March 2023. Calm, breeze, gale, and storm and hurricane winds are respectively represented by dark blue, light blue, orange, and red colours.
Table 4.1. Percentage of each wind class by season and overall for the ECCC Rock River wind record (July 2006-March 2023). Note that the seasonal and annual sums do not always add to 100% due to rounding errors.

<table>
<thead>
<tr>
<th>Wind Class</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
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<tbody>
<tr>
<td>Calm</td>
<td>44.7</td>
<td>29.5</td>
<td>17.1</td>
<td>35.3</td>
<td>31.8</td>
</tr>
<tr>
<td>Breeze</td>
<td>45.3</td>
<td>59.2</td>
<td>78.5</td>
<td>54.4</td>
<td>59.2</td>
</tr>
<tr>
<td>Gale</td>
<td>8.5</td>
<td>10.7</td>
<td>4.4</td>
<td>9.4</td>
<td>8.2</td>
</tr>
<tr>
<td>Storm</td>
<td>1.6</td>
<td>0.6</td>
<td>0.0</td>
<td>0.8</td>
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</table>
occurring 9% of the time, overall. Winds of at least 50 km h$^{-1}$ occurred about 10 or 11% of the time in winter, spring, and autumn but only 4.4% of the time in summer. Even though the highest winds typically occurred in winter (Section 4.2.2), calm conditions were most common in the same season. Table A4 summarizes the directions of gale- and storm-force winds. For both of these wind classes, easterly or east-northeasterly winds made up at least 95% of occurrences, with due east winds (75-105°) being just over 60% for both classes. The remainder of gale- and storm-force winds were mostly east-northeasterlies (45-75°), north-northeasterlies (15-45°) or east-southeasterlies (105-135°). Only about 0.5% of all gale-force winds were westerlies (225-315°).

4.2.2 Windstorm characteristics

A total of 672 high wind events were identified in the nearly 17 years of hourly wind data from ECCC Rock River between July 2006 and March 2023 (Fig. 4.3). This value is not exhaustive of all high wind events as it represents those where gale-force winds or greater ($\geq$50 km h$^{-1}$) occurred for at least four consecutive or six total hours (Section 3.6.3). This selection predominantly represents the strong easterly events occurring to the west of the ridge in Yukon. Strong westerly events which occurred to the east of the ridge in the Northwest Territories are discussed in Section 4.4. Prolonged periods of missing data in the record have likely led to an underestimation of the total number of events (Table 3.5). In years with complete data, there has been a mean of 39 windstorms per year, though the number of events has varied between 57 in 2015-16 and 29 in 2016-17 (Table A5). The number of high wind events was relatively low in summer but more evenly distributed through the other seasons (Fig. 4.3).
Figure 4.3. Distribution of high wind events by season in the ECCC Rock River wind record (Jul. 2006-Mar. 2023).
The distribution of windstorm durations is presented in Fig. 4.4. This duration is from the time when wind speeds first increased to gale force until the time which they last decreased below gale force during a specific event (Section 3.6.3). For at least 354 events (52.7%), the wind speed periodically dropped below gale force, but increased later without calm conditions being established; for 31 events (4.6 %), missing hourly data prevented this determination. For the remaining 285 events (42.4%), the wind speed was sustained at gale force or above for the entire event. The distribution in Fig. 4.4 is right-skewed with shorter events of at most 15 hours in length occurring with a similar frequency to those longer than 15 hours. The number of events of at most 5 hours in length is artificially reduced because events with 1-3 hours of gale-force winds or greater were not considered. Events most commonly lasted between 6 and 10 hours, with a mode of 9 hours (Table 4.2). The median and mean event durations were 16 and 20.9 hours, respectively. Nearly three quarters of the events (498 in total) were up to 1 day long with 268 of those lasting fewer than 12 hours. Just 7.7% of the events (52 in total) lasted longer than 2 days.

Figure 4.5 similarly displays the distribution of separation times between events. In some cases (45 events), this time could not be determined accurately due to large data gaps. In other cases (27 events), the exact start or end of an event could not be determined due to isolated missing hourly data. The former events were removed from the analysis, while the latter events were not. The distribution of the 626 separation periods is right-skewed with events generally occurring closer together than farther apart. Events most commonly occurred between 1 and 2 days after the preceding windstorm, although on an hourly basis, the mode was 67 hours (2.79 days) (Table 4.2). The median separation between events was 4.25 days or 102 hours. The mean separation was 7.40 days or 178 hours with 64.9% of
Figure 4.4. Distribution of windstorm durations in the hourly ECCC Rock River wind record (July 2006-March 2023).
Table 4.2. Summary of windstorm metrics by season for ECCC Rock River (July 2006-March 2023).

<table>
<thead>
<tr>
<th>Metric</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
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<td><strong>Duration (h)</strong></td>
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<td></td>
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<tr>
<td>Median</td>
<td>15</td>
<td>17</td>
<td>12</td>
<td>15</td>
<td>16</td>
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<td>22.83</td>
<td>20.96</td>
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<td>19.25</td>
<td>13</td>
<td>16</td>
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<tr>
<td><strong>Separation (d)</strong></td>
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<td>3.54</td>
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<td>4.25</td>
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<td>5.97</td>
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<td>2.79</td>
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<td>22</td>
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<tr>
<td><strong>Hours of At Least Gale (n, (\geq50) km h(^{-1}))</strong></td>
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<td>Median</td>
<td>13</td>
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<td>10</td>
<td>13</td>
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</tr>
<tr>
<td>Mean</td>
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</tbody>
</table>
Figure 4.5. Distribution of separations between windstorms in the hourly ECCC Rock River wind record (July 2006-March 2023).
the events (406 in total) occurring within a week of the preceding windstorm. The mean separation of just over a week is representative of approximately 40 windstorms each year.

The distribution of maximum wind speed in each event is presented in Fig. 4.6. The data are right-skewed with lower maximum wind speeds being more common. The maximum wind speed was most commonly between 61 and 65 km h\(^{-1}\) with the specific mode being 63 km h\(^{-1}\). (Table 4.2). The median and mean maximum speeds were 73 and 75.2 km h\(^{-1}\), respectively. Notably, the maximum speed only reached storm force (≥89 km h\(^{-1}\)) in 20.8% (140 in total) of the events, and hurricane force (≥119 km h\(^{-1}\)) in less than 1% of events (4 in total). Tables A6 and A7 respectively summarize the numbers of gale- and storm-force winds by event. The four events where hurricane-force winds were recorded occurred in Nov. 2008 (1 hour), Jan. 2010 (4 hours), Feb. 2014 (18 hours), and Dec. 2015 (1 hour).

Figure 4.7 displays the distribution of hours of gale-force winds or greater (≥50 km h\(^{-1}\)) by event. This plot is similar to Fig. 4.4 which displays the duration of events, because the wind speed was often – though not always – at least 50 km h\(^{-1}\) for the majority of the event. Accordingly, the underlying statistics are quite similar: between 6 and 10 hours of gale-force winds or greater have been most common. The specific mode, median, and mean are 8, 13, and 17.4 hours, respectively (Table 4.2).

A summary of the windstorm metrics by season is presented in Table 4.2. Mean event durations were similar across all seasons with the winter mean of 18.6 hours being slightly lower than in the other seasons (21.0-22.8 hours). When considering median durations, summer events were shorter (12 hours) than in other seasons (15-17 hours). Based on the interquartile ranges (IQR), event durations were more variable in spring and
Figure 4.6 Distribution of maximum wind speed in windstorms identified in the ECCC Rock River hourly wind record (July 2006-March 2023).
Figure 4.7. Distribution of hours of at least gale-force winds in windstorms identified in the ECCC Rock River hourly wind record (July 2006-March 2023). This plot appears visually similar to Fig. 4.4, because for many of the events, the wind did not drop below gale-force during the event (i.e., event duration and hours of gales are equal during those windstorms).
summer and less variable in autumn and winter. Metrics for separation between events were similar in autumn, winter, and spring. Conversely, summer events were separated by longer and more variable time frames. Maximum event wind speeds were higher and more variable in winter (mean of 81.8 km h\(^{-1}\), IQR of 26 km h\(^{-1}\)), and lower and less variable in summer (mean of 61 km h\(^{-1}\), IQR of 10 km h\(^{-1}\)). Total hours of gale-force winds or stronger were similar across all seasons, although the mode for summer events (4 hours) was quite short, whereas the mode for autumn events (12 hours) was longer.

4.2.3 Relation between ECCC Rock River and YT km 457

The new weather station at km 457 and ECCC Rock River are separated by just 225 metres and 15 metres of elevation and have very similar wind characteristics (see Section 4.4.1). Differences in recorded wind speeds between the two stations likely resulted mainly from the difference in height of the anemometer above the surface: 10 m at Rock River and 3 m at km 457. To quantify this, least square linear regressions were developed on a monthly basis to compare wind speeds at Rock River with km 457 (Table A8). Across the nearly 11,000 hours of overlapping data between the two stations, the regression equation was:

\[ U_{457} = 0.84U_{RR} + 0.48 \]

where \(U_{457}\) and \(U_{RR}\) are the mean hourly wind speeds at km 457 and ECCC Rock River. The coefficient of determination \((R^2)\) for eq. 4.1 was 0.97. These values suggest that wind speeds at km 457 were consistently lower than at Rock River, but there was a very high correlation between the two stations. From this equation, wind speeds of the gale, storm, and hurricane force thresholds (50, 89, and 119 km h\(^{-1}\)) at Rock River would be 42.7, 75.6, and 100.9 km h\(^{-1}\) near the surface at km 457. The y-intercept of 0.48 is likely insignificant.
since winds at Rock River are only given to the nearest unit and the starting threshold at YT km 457 means that calm or near-calm winds may not be accurately recorded (Table 3.3). On a monthly basis, the range in regression coefficient values was 0.77 (August 2022) to 0.89 (November 2022). All $R^2$ values were at least 0.94 with the lowest value occurring in March 2022. Considering only the overlapping hours where gale-force winds or higher occurred at Rock River (897 hours), the regression equation was:

$$[4.2] \quad U_{457} = 0.82U_{RR} + 1.80$$

The $R^2$ value for eq. 4.2 was 0.90. Compared to the entire dataset, these coefficients indicate that at higher wind speeds at Rock River, wind speeds at km 457 were reduced more than in the overall record due to friction at ground level, and the correlation was also slightly lower.

### 4.3 Other weather stations

#### 4.3.1 NTAI YT km 421

Data from Transport Canada’s meteorological station at km 421 (Fig. 1.1b; Fig. 3.12a) are summarized by Humphries et al. (2019) for February 2014 to July 2018. The data from this station are available from February 2014 to present (Table A9) with data since February 2017 also available from the Campbell Cloud. The data record on the Campbell Cloud contained more missing values than data directly downloaded from a datalogger at the site, likely due to interrupted satellite connectivity. The wind regime at km 421 was similar to ECCC Rock River, though mean speeds were lower due to the lower anemometer height (Figs 4.1a, 4.8a; Tables A1, A9). Namely, wind speeds were generally highest in late spring and early summer: the April, May, and June means were respectively 15.2, 16.5 and 14.8 km h$^{-1}$. Wind speeds were generally lower in winter months: the means for November
Figure 4.8. Mean monthly (a) wind speeds and (b) hours of gale-force winds recorded at the two NTAI stations at a height of 3 m. Data from YT km 421 for Feb. 2014 – Mar. 2023 and from NT km 8.5 for Feb. 2014 – Jul. 2022. Only months with complete data are used in the calculation for means (see Tables A9 through A12).
through February were all below 10 km h\(^{-1}\) with February’s mean of 7.6 km h\(^{-1}\) being the lowest of any month. The overall mean wind speed of 11.8 km h\(^{-1}\) was very similar to the mean value of 3.2 m s\(^{-1}\) (11.5 km h\(^{-1}\)) presented by Humphries et al. (2019). Mean monthly wind speeds were on average around 60% greater at Rock River relative to km 457, likely in large part due to the greater anemometer height at the former. Fewer hours of high winds have been recorded at km 421 compared to Rock River (Figs 4.1a and 4.8b; Tables A2, A3, A10). A mean of 81 hours of gale-force winds occurred each year at km 421 (Table A10). This is around nine times lower than at Rock River (Section 4.2.1), again likely due to the difference in anemometer heights. Storm- or hurricane-force winds have not (yet) been recorded at km 421.

A total of 67 easterly high wind events were identified in the record: 28 in spring, 19 in autumn, 16 in winter, and just three during the summer months. Table 4.3 summarizes the metrics of these windstorms. Of the 67 events, 61 were also captured at Rock River. For the six which were not captured, three occurred during data outages. However, a total of 371 high wind events occurred at Rock River during the same time period, again demonstrating the effects differing anemometer heights have on local wind characteristics. Windstorms at km 421 had a median duration of 9 hours, with 7 of those hours being gale-force winds, and were separated by about a month (median of 31.20 days). The mean maximum wind speed during the events was 61.54 km h\(^{-1}\). A wind rose for the data (Fig. 4.9a) demonstrates that prevailing easterlies (75-105°) occurred about 34% of the time with the gale-force winds also almost exclusively either easterlies or east-northeasterlies. This result is similar to Rock River (Fig. 4.9b) which is also located west of Richardson Mountains.
Table 4.3. Summary of windstorm metrics for the 61 high wind events captured at NTAI km 421 (Feb. 2014-Mar. 2023).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Median</th>
<th>Mean</th>
<th>Mode</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (h)</td>
<td>9</td>
<td>10.75</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Separation (d)</td>
<td>31.20</td>
<td>51.73</td>
<td>-</td>
<td>60.29</td>
</tr>
<tr>
<td>Max Wind Speed (km h⁻¹)</td>
<td>59.54</td>
<td>61.54</td>
<td>56.41</td>
<td>10.37</td>
</tr>
<tr>
<td>Hours of at Least Gale (n, ≥50 km h⁻¹)</td>
<td>7</td>
<td>8.69</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 4.9. Wind roses for (a) NTAI km 421 (Feb. 2014-Jul. 2021), (b) ECCC Rock River (Feb. 2014-Jul. 2021), (c) NTAI km 8.5 (Feb. 2014-Jul. 2021), and (d) NorthwesTel North Vittrekwa (Aug. 2012-May 2015, wind direction only). Calm, breeze, gale, and storm and hurricane winds are respectively represented by dark blue, light blue, orange, and red colours. Wind data are recorded at heights of 3 m at the NTAI stations and 10 m at Rock River. Northerly winds are underrepresented at all stations except Rock River (see Section 3.7).
4.3.2 NTAI NT km 8.5

Data for another of Transport Canada’s meteorological stations, at km 8.5 (Figs 1.1b and c; Fig. 3.12b), was discussed by both Humphries et al. (2019; Feb. 2014-Sep. 2018) and Kokelj et al. (2022; Mar. 2014-Jul. 2021). Data from February 2014 through August 2022 is presented here. Mean monthly wind speeds at NT km 8.5 were less variable throughout the year and generally lower when compared to km 421 (Fig. 4.8a; Tables A9, A11) – perhaps a consequence of being located further away from the border ridge. In years with complete data (2017, 2020, and 2021), the overall mean wind speed was 8.4 km h\(^{-1}\) which is less than at NTAI km 421. This value is also very similar to the means of 2.3 (Humphries et al. 2019) and 2.2 m s\(^{-1}\) (Kokelj et al. 2022) – or about 7.9 and 8.3 km h\(^{-1}\) – presented in the literature. In the three years of the record with mostly complete data, a mean of 28 hours of gale-force winds was recorded (Fig. 4.8b; Table A12). Most of these gales occurred between November and March and were rare between May and September. As with km 421, storm-force and hurricane-force winds were not present in the record. A total of 23 westerly high wind events were identified in the record (Table A13). Of these 23 events, only two were also recorded as strong westerly events at ECCC Rock River. However, as with km 421, the total number of events recorded at Rock River (346) over the same time period was much greater due to the difference in anemometer heights and specific location. Due to the positioning of km 8.5 to the east of the border ridge in the Northwest Territories, prevailing winds were either west-southwesterly (225-255°) or westerly (255-285°) (Fig. 4.9c). Together, these two directions accounted for around 40% of all observations. The gale-force winds occurred exclusively from these prevailing directions, including during the 23 high wind events identified in the record.
4.3.3 NorthwesTel North Vittrekwa

Telecommunications company NorthwesTel has several repeater stations along the north Dempster Highway including North Vittrekwa near the territorial border in Wright Pass, approximately 400 m north-northeast of the new weather station at YT km 465 (Fig. 3.13). Wind speed and direction were briefly recorded at an unknown height at North Vittrekwa starting in August 2012 with speed data ending in August 2013 and direction data ending in May 2015. However, recorded wind speeds are inconsistent with data from the other nearby stations and probably erroneous. Thus, the discussion here is limited to direction. To illustrate this, over the period of wind speed record at North Vittrekwa, 999 hours of gale-force winds, 95 hours of storm-force winds, and 29 hours of hurricane-force winds were recorded. At ECCC Rock River, these respective totals over the same period were 560, 32, and 0 hours. A wind rose for North Vittrekwa is presented in Fig. 4.9d. In contrast with either of the NTAI stations and ECCC Rock River, the wind record at North Vittrekwa exhibited bidirectionality aligned with Wright Pass. East-northeasterly (45-75°) winds accounted for about 32% of observations, while westerly (255-285°) and west-southwesterly winds (225-255°) together also accounted for around 35% of observations.

4.4 Hurricane Alley weather stations

4.4.1 Wind characteristics

The seven new meteorological stations in the Hurricane Alley area were installed in early November 2021 with the following sections addressing the data records between early December 2021 and the end of March 2023. These new stations were assigned to four separate regions: the edge of Hurricane Alley (km 450; Fig. 3.9), within Hurricane Alley
proper (kms 453, 454, 457, and 459; Fig. 1.3b), the border pass (km 465; Fig. 3.11), and east of the border ridge (km 4; Fig. 3.8). The four stations within Hurricane Alley itself experience similar wind conditions, so km 457 has been selected as a representative station.

4.4.1.1 Wind speed

Mean monthly wind speeds at kms 450, 457, 465, and 4 have been plotted in Fig. 4.10 with a summary of all stations presented in Table A14. In general, mean wind speeds increased northward in Hurricane Alley from km 453 to km 459, though all four of the new stations in this region experienced similar wind regimes. The monthly means at km 457 were similar to Rock River (Table A14), but about 10-15% lower due to the difference in anemometer heights (Section 4.2.3). Compared to km 421 (Section 4.3.1) where the anemometer is also at a height of 3 m, mean monthly wind speeds were approximately 35-40% greater at km 457 (Tables A9, A14). Similarly, though missing data were a concern, mean monthly wind speeds were greater at km 4 when compared with km 8.5 in overlapping months (Section 4.3.2; Tables A11 and A14). Wind speeds were noticeably lower at km 450 compared to all other stations, with mean monthly wind speeds of 5-10 km h\(^{-1}\). Mean wind speeds at the other stations were similar throughout spring and summer of 2022, though less so in autumn and winter. For example, in November 2022, mean wind speeds were much higher at kms 465 (21.6 km h\(^{-1}\)) and 4 (26.0 km h\(^{-1}\)) compared to kms 457 (7.5 km h\(^{-1}\)) and 459 (9.3 km h\(^{-1}\)). Conversely, during January 2023, mean wind speeds were higher on the Yukon side (Fig. 4.10; Table A14). Missing data at km 465 almost certainly led to over-estimation of mean wind speed there in the early months of the record.
Figure 4.10. Mean monthly wind speeds for a selection of stations in the Hurricane Alley area (Dec. 2021-Mar. 2023). Missing data has likely led to overestimates of wind speeds at km 465 between December 2021 and March 2022 (Table A14), so these months are not presented here. Similarly, no wind speed data are available from km 4 between late January 2022 and late July 2022 due to sensor damage, so the months of February 2022 through July 2022 are not displayed.
Total monthly hours of mean gale-force winds are plotted in Fig. 4.11 and summarized in Table A15. Notably, gale-force winds were only recorded during one hour at km 450. Gale-force winds were much more common within Hurricane Alley itself with total monthly hours again increasing northwards as with wind speeds, although monthly totals were generally higher at km 453 than km 454, possibly due to the proximity of the ridge at the former station. The number of gales recorded at km 457 was similar to – but lower than – ECCC Rock River, especially in late spring and early summer. The difference is likely due to anemometer heights at the two stations. Differences between kms 457 and 4 were especially noticeable in late autumn 2022 and winter 2022-23. For example, during November 2022, 136 hours of gales were recorded at km 4, but only 6 at km 457. Gale-force winds were also more common at km 4 in December 2022. The reverse occurred in January and February 2023 with higher totals at the Yukon stations than km 4. Storm-force winds (Table A15) were relatively rare at the new stations. Between December 2021 and March 2023, storm-force winds have been recorded for 5 or fewer hours at all of the new stations and have not yet been recorded at kms 450, 465, and 4. From December 2021 to March 2023 for all stations, highest mean wind speed of 94.4 km h\(^{-1}\) was recorded at km 453 (Table 4.4). This is noticeably lower than the highest mean wind speed of 111 km h\(^{-1}\) recorded at a height of 10 m at Rock River.

When considering maximum hourly wind speeds, total hours of high wind increased overall (Table A16), and northwards within Hurricane Alley. Gale-force winds were recorded for 99 total hours at km 450, though storm-force winds were still absent from the record, and also quite rare at km 465 (9 hours total). Storm-force winds were much more common at the other five stations relative to mean wind speeds. Despite having
Figure 4.11. Total monthly hours of gale-force winds for a selection of stations in the Hurricane Alley area. Table A15 provides a summary of these data. As with Fig. 4.10, values for km 4 between February and July 2022 are not presented due to missing data from late January to late July 2022. Monthly values for December 2021 through March 2022 at km 465 are also missing large amounts of data and the values presented in this plot are likely underestimates.
Table 4.4. Greatest wind speeds recorded at each station in the Hurricane Alley area (Dec. 2021-Mar. 2023) and the date and time (YST) of occurrence. Year is not specified as all recordings occurred during the calendar year of 2022. Maximum hourly wind speeds are not recorded at ECCC Rock River.

<table>
<thead>
<tr>
<th>YT km</th>
<th>YT km</th>
<th>YT km</th>
<th>Rock River</th>
<th>YT km</th>
<th>YT km</th>
<th>YT km</th>
<th>NT km</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>453</td>
<td>454</td>
<td>457</td>
<td>459</td>
<td>465</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55.8</td>
<td>94.4</td>
<td>89.8</td>
<td>111</td>
<td>91.4</td>
<td>91.6</td>
<td>85.1</td>
<td>82.4</td>
</tr>
<tr>
<td>8 PM</td>
<td>11 AM</td>
<td>6 PM</td>
<td>7 PM</td>
<td>11 AM</td>
<td>8 AM</td>
<td>4 AM</td>
<td>1 AM</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<tr>
<td>80.0</td>
<td>135.9</td>
<td>128.5</td>
<td>-</td>
<td>112.5</td>
<td>111.0</td>
<td>104.7</td>
<td>132.0</td>
</tr>
<tr>
<td>10 PM</td>
<td>7 AM</td>
<td>12 AM</td>
<td>-</td>
<td>5 AM</td>
<td>5 AM</td>
<td>5 AM</td>
<td>1 PM</td>
</tr>
</tbody>
</table>
several months of missing wind speed data, km 4 recorded 167 hours of storm-force winds – the most of any station. Storm-force winds were also recorded during all months on record at km 4. This is in contrast to the other stations where storm-force winds were not recorded in the summer months. Of the stations within Hurricane Alley, km 459 recorded the most hours of gale (1,808), while km 457 recorded the most hours of storm-force winds (117). Hurricane-force maximum winds were recorded during 2 hours at km 453, 1 hour at km 454, and 6 hours at km 4. The greatest maximum wind speed recorded at any station was 135.9 km h$^{-1}$ at km 453 (Table 4.4).

4.4.1.2. Wind direction

Wind roses for December 2021 through March 2023 for the seven new stations and ECCC Rock River are displayed in Figs 4.12 and 4.13. Unlike wind speed, there is less concern over differences of wind directions between the anemometer heights of 3 and 10 m. As discussed in Section 3.7, northerly winds are under-represented at each of the new stations with winds from other directions likely over-represented. The wind roses for the five stations within Hurricane Alley itself (kms 453 through 459 and ECCC Rock River; Figs 4.12, 4.13b) were fairly similar. Easterly winds (75-105°) prevailed at all five stations, occurring between 16% (km 453) and 28% (km 454) of the time. East-northeasterly winds (45-75°) were also common and occurred more than 10% of the time at kms 453, 454, and 459. For all five stations, the strongest winds originated from these prevailing directions. At km 450 (Fig. 4.13a), winds were noticeably calmer than the other stations with gale-force winds being rare. The prevailing wind direction was east-southeasterly (105-135°) with just under 25% of hourly winds blowing from this direction. The wind rose for km
Figure 4.12. Wind roses for (a) km 453, (b) km 454, (c) km 459, and (d) ECCC Rock River. Hourly wind data from December 2021 to March 2023. Calm, breeze, gale, and storm and hurricane winds are respectively represented by dark blue, light blue, orange, and red colours.
Figure 4.13. Wind roses for (a) km 450, (b) km 457, (c) km 465, and (d) km 4. Hourly wind data from December 2021 to March 2023. Calm, breeze, and gale winds are respectively represented by dark blue, light blue, and orange colours.
465 (Fig. 4.13c) is similar to that of North Vittrekwa (Fig. 4.9d), namely prevailing winds are bidirectional and aligned with the orientation of Wright Pass. East-northeasterly (45-75°) winds and west-southwesterly (225-255°) winds together occurred about 60% of the time. The wind speed data from km 465 suggested that calm winds were uncommon, with breezes being the most frequent wind class. Gale-force winds occurred from both prevailing directions. At km 4 (Fig. 4.13d), prevailing winds were predominantly westerlies (255-285°), which occurred about 26% of the time. West-northwesterly and west-southwesterly winds (285-315°, 225-255°) together accounted for an additional 25% of the record at this station.

4.4.2 Relations between stations

A correlation matrix for mean hourly wind speeds for all eight stations in the Hurricane Alley area is presented in Table 4.5. Correlation coefficients (R) were consistently high among the five stations within Hurricane Alley (kms 453 through 459 and ECCC Rock River) even when considering that wind speeds were recorded at a lower height at the new stations compared to Rock River. The lowest correlation among these stations was 0.82 (kms 453 and 459), while the greatest was 0.99 (Rock River and km 457). Correlations between km 450 and the five stations further into Hurricane Alley were lower and all slightly greater than 0.5, because wind conditions at km 450 were much calmer than the other stations (Sections 4.4.1; 4.4.3). Correlations between km 465 and all other stations were similarly around 0.5 (range of 0.43-0.55), because the bidirectional nature of the winds at Wright Pass (Fig. 4.13c) meant that both the easterlies and westerlies were recorded at km 465. For km 4, correlations were consistently close to zero except with km 465 (R = 0.55) indicating that wind conditions on opposite sides of the ridge were unrelated.
Table 4.5. Correlation matrix for mean hourly wind speeds in the Hurricane Alley area (Dec. 2021-Mar. 2023). The upper diagonal displays the Pearson correlation coefficients ($R$), and the lower diagonal gives $n$ for each station pair. $P < 0.05$ for all pairs except kms 450 and 4.

<table>
<thead>
<tr>
<th>Station</th>
<th>YT km 450</th>
<th>YT km 453</th>
<th>YT km 454</th>
<th>Rock River</th>
<th>YT km 457</th>
<th>YT km 459</th>
<th>YT km 465</th>
<th>NT km 4</th>
</tr>
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<tbody>
<tr>
<td>YT km 450</td>
<td>X</td>
<td>0.54</td>
<td>0.54</td>
<td>0.52</td>
<td>0.51</td>
<td>0.51</td>
<td>0.43</td>
<td>0.02</td>
</tr>
<tr>
<td>YT km 453</td>
<td>9,045</td>
<td>X</td>
<td>0.91</td>
<td>0.88</td>
<td>0.88</td>
<td>0.82</td>
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<tr>
<td>YT km 454</td>
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<td>8,669</td>
<td>X</td>
<td>0.89</td>
<td>0.88</td>
<td>0.86</td>
<td>0.47</td>
<td>-0.06</td>
</tr>
<tr>
<td>Rock River</td>
<td>11,094</td>
<td>9,017</td>
<td>10,420</td>
<td>X</td>
<td>0.99</td>
<td>0.87</td>
<td>0.49</td>
<td>-0.04</td>
</tr>
<tr>
<td>YT km 457</td>
<td>10,780</td>
<td>8,927</td>
<td>10,301</td>
<td>10,742</td>
<td>X</td>
<td>0.88</td>
<td>0.50</td>
<td>-0.03</td>
</tr>
<tr>
<td>YT km 459</td>
<td>10,931</td>
<td>8,959</td>
<td>10,378</td>
<td>10,929</td>
<td>10,771</td>
<td>X</td>
<td>0.50</td>
<td>-0.07</td>
</tr>
<tr>
<td>YT km 465</td>
<td>9,015</td>
<td>7,294</td>
<td>8,603</td>
<td>8,974</td>
<td>8,947</td>
<td>9,009</td>
<td>X</td>
<td>0.55</td>
</tr>
<tr>
<td>NT km 4</td>
<td>6,687</td>
<td>4,722</td>
<td>6,105</td>
<td>6,840</td>
<td>6,468</td>
<td>6,635</td>
<td>5,726</td>
<td>X</td>
</tr>
</tbody>
</table>
Correlations for when each station recorded gale-force winds or greater are similarly presented in Table A17. In general, the correlation coefficients were reduced relative to the entire dataset. However, correlations were still fairly high among the five stations within Hurricane Alley with $R$-values being between 0.44 and 0.95 (kms 459 and 454, and Rock River and km 457). Correlations could not be constructed for gale-force winds at km 450, because only one such hour occurred in the record. When wind speeds were gale-force at km 465, correlations were reduced in comparison with the entire record, likely because both strong easterly and westerly winds may occur at this location. When high winds occurred at km 4, correlation coefficients were close to zero and generally negative, demonstrating the differing wind conditions on opposite sides of the ridge. P-values were also high for all correlation pairs including km 4 suggesting that there was no statistically-significant relation between high winds at km 4 and winds at the other stations. The correlation coefficient between kms 4 and 465 was also quite low at a value of 0.080.

### 4.4.3 Windstorm characteristics

During the period of record for the seven new weather stations (Dec. 2021-Mar. 2023), 50 high wind events were identified in the ECCC Rock River hourly wind record. At all seven of the new stations, the number of events on record was lower than at Rock River, mainly due to the difference in anemometer heights, but also partially due to specific station locations and missing data. Missing data likely led to an undercount of events at kms 453, 465, and 4 (see Fig. 4.11; Table 3.6). In many cases, the events identified in the Rock River wind record could still be identified at the other stations as increases in mean wind speed and/or high maximum wind speeds, even if they did not meet the threshold to be labelled
as a windstorm at those stations. Of the 18 events recorded at km 465, five were easterly events that were also recorded on the Yukon side. All 20 of the events recorded at km 4 were westerlies that were not recorded on the Yukon side.

The metrics of the windstorms identified above are summarized by station in Table 4.6. Different events are captured depending on the station location: easterly in the Yukon, westerly in the Northwest Territories (km 4), and both easterly and westerly near Wright Pass (km 465). Median event durations were similar across all stations within Hurricane Alley itself (15-16 hours), while kms 465 and 4 had slightly longer median durations (18.5, 21 hours). Mean durations were around 20 hours, except for km 4 (29 hours). At the new stations, the separation between events was shortest at km 459 (median of 5.9 days). Median event separations were longer towards the southern end of Hurricane Alley (9-10 days) and at km 4 (8.7 days). Maximum event wind speeds were comparable across all stations, though lowest at km 459 (median of 61.5 km h\(^{-1}\)) and highest at km 453 (median of 71.4 km h\(^{-1}\)). All stations had very similar total hours of gale-force winds or greater with medians of between 14 and 16 hours, though km 454 was slightly lower at 12 hours.

The windstorm metrics outlined in Table 4.6 are similar across many of the stations. However, this was not the case for the station to record gale-force winds first during windstorms (Table 4.7). Of the 50 total events identified in the mean hourly wind speed record between December 2021 and March 2023, Rock River was the first or one of the first stations (during many of the events multiple stations recorded a wind speed of at least 50 km h\(^{-1}\) during the same hour) in 45 of them. This is unsurprising given that the anemometer height at Rock River meant that high winds were more likely to be recorded. Kms 459 and 457 were the first or among the first stations during 16 and 7 of the events.
Table 4.6. Summary of metrics for individual windstorms recorded in the Hurricane Alley area for December 2021 through March 2023. No events were recorded at km 450 during this timespan. Modes are not given for some metrics as no values occurred more than once.

<table>
<thead>
<tr>
<th>Metric</th>
<th>YT km 453</th>
<th>YT km 454</th>
<th>Rock River</th>
<th>YT km 457</th>
<th>YT km 459</th>
<th>YT km 465</th>
<th>NT km 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Events</td>
<td>20</td>
<td>25</td>
<td>50</td>
<td>33</td>
<td>37</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Duration (h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>15</td>
<td>15</td>
<td>16.5</td>
<td>16</td>
<td>16</td>
<td>18.5</td>
<td>21.5</td>
</tr>
<tr>
<td>Mean</td>
<td>23.90</td>
<td>17.92</td>
<td>20.84</td>
<td>20.39</td>
<td>22.76</td>
<td>21.83</td>
<td>28.90</td>
</tr>
<tr>
<td>Mode</td>
<td>11</td>
<td>15</td>
<td>9</td>
<td>13</td>
<td>16</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>IQR</td>
<td>18.75</td>
<td>9</td>
<td>11.75</td>
<td>9</td>
<td>11</td>
<td>12.25</td>
<td>31</td>
</tr>
<tr>
<td>Separation (d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>10.08</td>
<td>9.19</td>
<td>5.33</td>
<td>6.9</td>
<td>5.5</td>
<td>18.96</td>
<td>8.71</td>
</tr>
<tr>
<td>Mean</td>
<td>24.07</td>
<td>19.11</td>
<td>8.89</td>
<td>14.06</td>
<td>12.31</td>
<td>26.58</td>
<td>23.31</td>
</tr>
<tr>
<td>Mode</td>
<td>-</td>
<td>9.46</td>
<td>0.96</td>
<td>2.08</td>
<td>1.92</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IQR</td>
<td>25.08</td>
<td>12.56</td>
<td>8.33</td>
<td>12.57</td>
<td>8.75</td>
<td>21.38</td>
<td>20.38</td>
</tr>
<tr>
<td>Max Wind Speed (km h⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>71.45</td>
<td>67.10</td>
<td>72.5</td>
<td>67.40</td>
<td>61.50</td>
<td>62.35</td>
<td>70.60</td>
</tr>
<tr>
<td>Mean</td>
<td>70.69</td>
<td>68.14</td>
<td>76.00</td>
<td>69.02</td>
<td>66.03</td>
<td>64.99</td>
<td>69.67</td>
</tr>
<tr>
<td>Mode</td>
<td>-</td>
<td>84.8</td>
<td>-</td>
<td>81</td>
<td>-</td>
<td>56.1</td>
<td>-</td>
</tr>
<tr>
<td>IQR</td>
<td>15.12</td>
<td>14</td>
<td>18</td>
<td>18.2</td>
<td>14.3</td>
<td>14.65</td>
<td>18.48</td>
</tr>
<tr>
<td>Hours of at least Gale (n, ≥50 km h⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Median</td>
<td>14.5</td>
<td>12</td>
<td>15</td>
<td>14</td>
<td>15</td>
<td>15</td>
<td>16</td>
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<tr>
<td>Mean</td>
<td>15.95</td>
<td>13.56</td>
<td>17.42</td>
<td>14.79</td>
<td>17.35</td>
<td>15.89</td>
<td>18.00</td>
</tr>
<tr>
<td>Mode</td>
<td>18</td>
<td>13</td>
<td>15</td>
<td>17</td>
<td>10</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>IQR</td>
<td>7.25</td>
<td>6</td>
<td>11</td>
<td>9</td>
<td>11</td>
<td>8</td>
<td>16.5</td>
</tr>
</tbody>
</table>
Table 4.7. Number of events in which each station was the first or among the first to record gale-force winds (Dec. 2021-Mar. 2023) for a total of 50 events identified in the mean wind speed records and 61 events in the maximum wind speed records. These events are all easterly windstorms which occurred on the Yukon side of the ridge. The sum of the totals exceeds these number of events, because for many of the events multiple stations initially recorded gale-force winds during the same hour.

<table>
<thead>
<tr>
<th>YT km</th>
<th>YT km</th>
<th>YT km</th>
<th>Rock River</th>
<th>YT km</th>
<th>YT km</th>
<th>YT km</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>453</td>
<td>454</td>
<td>457</td>
<td>459</td>
<td>465</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean Wind Speed (including Rock River)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>45</td>
<td>7</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean Wind Speed (excluding Rock River)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6</td>
<td>4</td>
<td>-</td>
<td>31</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum Wind Speed (excluding Rock River)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>19</td>
<td>-</td>
<td>28</td>
<td>43</td>
<td>1</td>
</tr>
</tbody>
</table>
Excluding Rock River, these values increased to 35 and 31 events. When considering maximum wind speeds (Fig. 4.14; Table 4.7) across 61 events, kms 459 (43 events) and 457 (28 events) were again the first or among the first stations to reach gale force. The maximum wind speed at km 454 was also often among the first to reach gale force. During the strong easterly events, the approximate order of stations reaching gale-force winds was km 459, km 457, km 454, and km 453. Kms 465 and 450 did not always record gale-force wind gusts, but if they did, the border station often recorded them slightly earlier. For westerly windstorms, km 4 recorded gale-force winds ahead of or at the same time as km 465 in about 90% of events, while gale-force winds at km 465 were recorded ahead of or at the same time as km 4 in about 25% of events.

4.5 Synoptic characteristics

In the following sections, consideration is given to the synoptic weather patterns associated with high wind events which occur in the Yukon (easterlies) and Northwest Territories (westerlies). ECCC synoptic weather charts were analyzed for the windstorms which occurred during the operation of the new weather stations in the Hurricane Alley area (Dec. 2021-Mar. 2023) to identify common patterns in synoptic-scale pressure systems. During this time, there were approximately 52 easterly events and 25 westerly events identified in the records. The remainder of Section 4.5 focuses on briefly summarizing general synoptic conditions in these easterly and westerly events. In the following section (Section 4.6), three windstorms are considered in more detail: an easterly event in the Yukon, a westerly event in the Northwest Territories, and an extreme easterly event in the Yukon.
Figure 4.14. Number of events in which each station was the first or among the first to record gale-force wind gusts (Dec. 2021-Mar. 2023) (see Table 4.7).
4.5.1 Yukon windstorms

Considering Table 4.2 and the discussion from Section 4.2.2, windstorm characteristics at ECCC Rock River were often fairly similar across autumn, winter, and spring when compared with summer. The same is true of synoptic weather patterns which exhibited similar characteristics, especially from about mid-autumn to mid-spring. Commonly, the strong easterlies were associated with low pressure extratropical cyclones moving northerly, northeasterly, or easterly into the Gulf of Alaska (Fig. 4.15a). These low-pressure systems often deepened and slowed as they reached the Gulf of Alaska, sometimes even stalling within the Gulf (Fig. 4.15b). Regions of high pressure and anticyclones were located over the western Arctic at a variety of locations: the Beaufort Sea, the North Slope of Yukon and Alaska, the Mackenzie River Valley, and the Canadian Arctic Archipelago. The specific positioning of these high-pressure regions and the cyclone in the Gulf of Alaska resulted in a north-south or northeast-southwest pressure gradient and easterly gradient winds in the Hurricane Alley area. Between these events, high-pressure conditions often prevailed over the Yukon (Fig. 4.16) as suggested by Wahl et al. (1987; Fig. 2.1a). In contrast with the synoptic conditions commonly associated with autumn, winter, and spring windstorms, high wind events in summer did not appear to be associated with any common synoptic patterns. Pressure patterns were much more variable and weaker than in winter, and larger synoptic pressure systems appeared less common (Fig. 4.17).

4.5.2 Northwest Territories windstorms

While strong winter easterly events were often associated with low pressure to the south and high pressure to the north, the opposite appeared to be the case for westerly events.
Figure 4.15. Surface analysis charts for (a) 18 UTC on 18 March 2023, and (b) 00 UTC on 31 October 2022. Both weather patterns are associated with easterly windstorms with extratropical cyclones in the Gulf of Alaska and high-pressure regions further north or northeast. The red star indicates the location of Hurricane Alley. These figures are reproductions of analysis charts available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
Figure 4.16. Surface analysis chart for 18 UTC on 1 February 2022. Anticyclonic conditions are dominant across Yukon with a strong pressure gradient across southwestern Yukon and lower pressure in the Gulf of Alaska (similar to Fig. 2.1a from Wahl et al. 1987). The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>. 
Figure 4.17. Surface analysis chart for 00 UTC on 23 August 2022 during a summer easterly event. An anticyclone is situated over the Beaufort Sea while weak low-pressure centres and a stationary front are present across central Yukon and Alaska. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
The westerly windstorms were associated with regions of high pressure over southern Yukon (or further south) and low pressure situated to the north (Fig. 4.18a) at a variety of locations: along the North Slope of Alaska and Yukon, the Mackenzie Delta, the Mackenzie Valley, and Canadian Arctic Archipelago. During some windstorms, extratropical cyclones moved north across the Bering Sea or extreme eastern Russia and into the Beaufort Sea (Fig. 4.18b). In either case, pressure gradients were typically oriented approximately south-north in the Hurricane Alley area with westerly gradient winds. As with the easterly events, summer westerly events did not appear to have any common or strong synoptic patterns (Fig. 4.19).

4.6 Case studies

In the following sections, three high wind events that occurred in the Hurricane Alley region are discussed with an emphasis on wind characteristics at each station and synoptic weather conditions. The first two are representative of the typical easterly or westerly events which can be observed on the Yukon and Northwest Territories sides of the ridge, respectively. The third event is an extreme easterly event in which 18 hours of hurricane-force winds were recorded at Rock River. The potential mechanisms responsible for these three events are considered in the discussion (Section 5.5.2).

4.6.1 Yukon event

A high wind event representative of a typical easterly event occurred between 27 and 28 January 2022 (Fig. 4.20a; Table A18). The threshold for an event was met at ECCC Rock River and kms 453, 454, 457, and 459. At NTAI km 421 at least one hour of gale-force
Figure 4.18. Surface analysis charts for (a) 00 UTC on 6 January 2022, and (b) 06 UTC on 24 February 2023. Both patterns are associated with westerly windstorms with high-pressure regions over southern Yukon or Northern British Columbia and low pressure to the north or northeast. The red star indicates the location of Hurricane Alley. These figures are reproductions of analysis charts available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
Figure 4.19. Surface analysis chart for 18 UTC on 6 August 2022 during a summer westerly event. A line of low-pressure centres is oriented north-northwest to south-southeast in the Mackenzie Valley region. Regions of high pressure are situated further south and southwest including an anticyclone in the Pacific Ocean. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
Figure 4.20. (a) Wind speeds at ECCC Rock River (10 m) and kms 450, 457, and 465 (3 m) during an easterly windstorm in Hurricane Alley that occurred between 27 and 28 January 2022. Data starts at 12 AM YST (7 AM UTC) on 27 January. The red line indicates the gale force threshold of 50 km h\(^{-1}\). The wind speeds at kms 453, 454, and 459 follow a similar pattern to km 457 (Table A18). (b) Temperatures at ECCC Rock River and NT km 4 during the windstorm.
wind was recorded, though missing data prevented any further assessment. Wind speeds on the other side of the ridge at km 4 were calm or weak breezes, before the anemometer was damaged around midday on the 27th. Further downslope at km 8.5, winds were also calm or weak breezes and broadly northeasterlies during the event. Mean wind speeds initially reached gale force at a height of 3 m at kms 457 and 459, followed by 454, and 453 (Rock River preceded these stations due to the higher anemometer height). For maximum wind speeds, the order was kms 454, 457, 459, and 453. The windstorm metrics at each station are presented in Table 4.8. The windstorm lasted 28 hours at a height of 10 m (ECCC Rock River) and as many as 27 hours at a height of 3 m (kms 457 and 459). The greatest wind speed of 81 km h\(^{-1}\) was recorded at Rock River in hours 27 and 28 (2 and 3 AM YST on 28 January). For maximum hourly wind speeds, the event duration was longest at km 454 (40 hours). The greatest maximum wind speed of 112.5 km h\(^{-1}\) was recorded at km 453 in hour 25 (12 AM YST on 28 January). Characteristics common to many of the windstorms on record are rapid intensification and decline of wind speed just prior to and after the event. The rapid decline in wind speed at the end of this event is evident in Fig. 4.20a where the wind speeds recorded at Rock River and km 457 respectively decline from 59 to 13 km h\(^{-1}\) and 53.3 to 11.3 km h\(^{-1}\) over the course of one hour. The rapid intensification is not as obvious as other windstorms (Sections 4.6.2 and 4.6.3), because there is an initial peak of wind speed just prior to the start of the event. However, after this initial weaker peak, the wind speed at Rock River increased from 13 to 57 km h\(^{-1}\) over the course of two hours, while the wind speed at km 457 increased from 8.5 to 53.7 km h\(^{-1}\) over the course of three hours.
Table 4.8. Windstorm metrics by station during an easterly windstorm in Hurricane Alley that occurred between 27 and 28 January 2022. Maximum hourly wind speeds are not reported at Rock River. The threshold for an event was not met at either km 450 or km 465.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Wind Speed</th>
<th>Max Wind Speed</th>
<th>Max Speed (km h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duration</td>
<td>Hours of Gale</td>
<td>Max Speed</td>
</tr>
<tr>
<td>YT km 450</td>
<td>-</td>
<td>-</td>
<td>20.8</td>
</tr>
<tr>
<td>YT km 453</td>
<td>19</td>
<td>19</td>
<td>72.2</td>
</tr>
<tr>
<td>YT km 454</td>
<td>19</td>
<td>19</td>
<td>67.1</td>
</tr>
<tr>
<td>YT km 457</td>
<td>27</td>
<td>25</td>
<td>69.6</td>
</tr>
<tr>
<td>Rock River</td>
<td>28</td>
<td>28</td>
<td>81</td>
</tr>
<tr>
<td>YT km 459</td>
<td>27</td>
<td>25</td>
<td>66.8</td>
</tr>
<tr>
<td>YT km 465</td>
<td>-</td>
<td>-</td>
<td>45.1</td>
</tr>
</tbody>
</table>
Wind directions at ECCC Rock River and kms 453, 454, 457, and 459 were easterly or east-northeasterly throughout the course of the event (Table A18). At Rock River, and kms 457 and 459 the wind direction was around 80°. Further south at kms 454 and 453, the wind direction was slightly more northerly, with directions closer to 70°. Even though mean wind speeds did not exceed 50 km h\(^{-1}\) at km 465, east-northeasterly winds were recorded. Wind direction was variable at km 450 throughout the event. Wind direction data from both kms 4 and 8.5 indicated that winds on the east side of the ridge were southeast prior to, northeast during, and northwest following the event. Wind directions associated with maximum hourly wind speeds were still broadly easterly or east-northeasterly (between about 45-105°) at kms 453, 454, 457, and 459. In the two hours where the maximum wind speed reached gale force at km 465, the direction was also east-northeasterly (values of 55 and 50°). During the four hours when maximum wind speeds were gale force at km 450, the direction was northerly between 0 and 24° in three of the hours.

Other weather metrics recorded at ECCC Rock River during this event are presented in Table A19. The temperature steadily declined prior to and during the first half of the event from around -18 to -26 °C (Fig. 4.20b). For the remainder of the event and following the event, the temperature was mostly steady around -26 °C except for the hours near the end of the event where it briefly increased to near -24 °C. Temperatures at km 4 on the opposite side of the ridge followed a similar pattern but were slightly cooler over the course of the event (Fig. 4.20b). Wind chill at Rock River became very severe during the event, declining to a minimum of -47 °C during the event before increasing closer to -30 °C after the event. Station pressure declined during the event from around 93.5 prior to
the event to 92.5 kPa. A minimum pressure of 92.41 kPa was recorded in hour 33 (8 AM YST on 28 January). After the event, pressure increased again to near 93.0 kPa, though did decline again on the following day.

Analysis of ECCC synoptic charts preceding, during, and following the event indicated that dominant anti-cyclonic conditions over the western Arctic shifted north as an extratropical cyclone moved north and northeast into the Gulf of Alaska (Fig. 4.21). This cyclone stalled and weakened in the Gulf of Alaska before eventually moving southwest along the Pacific Coast. Anticyclonic conditions and high pressures were re-established in the western Arctic following this. During the event, the extratropical cyclone in the Gulf of Alaska and high pressure along the Beaufort Sea coast produced a north-south pressure gradient which was especially strong across central Yukon and Alaska. Gradient winds would have been easterly in the Hurricane Alley area during the event.

Considering upper atmosphere conditions at a level of 500 hPa during the event, the extratropical cyclone visible in Fig. 4.21 was identifiable as an upper air low with a trough extending north-south across Alaska (Fig. 4.22). A ridge of high pressure extended south-north across much of western North America – including along the Yukon-Northwest Territories border – during the event. In line with the pressure patterns visible in Fig. 4.22, a ridge in the jet stream was also visible across western North America (Fig. 4.23). The jet stream strength over the western Arctic during the event was stronger than the days preceding and following the event. Over the Hurricane Alley area, jet stream speeds were around 54-72 km h\(^{-1}\) (15-20 m s\(^{-1}\)) from the west or west-southwest.
Figure 4.21. Surface analysis chart for 12 UTC (5 AM YST) on 28 January 2022. The extratropical cyclone in the Gulf of Alaska and high-pressure region along the North Slope have produced a strong north-south pressure gradient near Hurricane Alley. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
Figure 4.22. Upper air (500 hPa) analysis chart for 12 UTC (5 AM YST) on 28 January 2022. A trough and low pressure are located over central Alaska and the Gulf of Alaska with higher pressure and a ridge over western North America. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from the University of Wyoming (2023) at <https://weather.uwyo.edu/index.shtml>. 
Figure 4.23. Upper air (500 hPa) composite mean vector wind speeds (m s\(^{-1}\)) for 27 through 28 January 2022. The average jet stream positioning on these days can be identified as the areas of higher wind speeds. The red star indicates the location of Hurricane Alley. Image provided by the NOAA Physical Sciences Laboratory (2023), Boulder Colorado from their website at <https://psl.noaa.gov/>.
4.6.2 Northwest Territories event

High winds representative of a typical westerly event occurred between 28 and 29 January 2023 (Fig. 4.24a; Table A20). Due to poor data quality at km 465 and damage sustained to the anemometer at km 4 in early January 2022, a representative event where data from NTAI km 8.5 were also available could not be selected. The event lasted 19 hours at km 4 and 10 hours at km 465 with 19 and 9 of those hours respectively being gale force. The greatest mean wind speeds on record were 79.2 km h$^{-1}$ at km 4 and 63.9 km h$^{-1}$ at km 465. Winds exceeded gale force at km 4 one hour prior to km 465. Winds were greater at km 465 than km 4 both before and after the event, though greater at km 4 during the event (Fig. 4.24a). The rapid intensification and decline of wind speed surrounding this event are evident at km 4 (Fig. 4.24a). Considering maximum hourly wind speeds, the event lasted 21 hours at km 4, and 14 hours at km 465. The greatest maximum wind speeds were 108.2 and 84.0 km h$^{-1}$ at the two stations, respectively. Wind direction was westerly (or slightly northwesterly) throughout the event. Wind conditions on the opposite side of the ridge in the Yukon during this event ranged between calm winds and moderate breezes, at most reaching around 30 km h$^{-1}$. Wind directions were variable with westerly and northwesterly winds common at many of the stations.

Hourly temperatures at km 4 and additional weather metrics from ECCC Rock River during this event are provided in Fig. 4.24b and Table A21. Due to the high variability in local weather conditions, the Rock River data are probably not representative of conditions on the Northwest Territories side of the ridge but are presented as this is the closest weather station with more detailed data. Hourly temperatures at both stations were both close to -21 °C to begin but become uncoupled as the event developed. Temperatures
Figure 4.24. (a) Wind speeds at kms 465 and 4 during a westerly windstorm in the Northwest Territories that occurred between 28 and 29 January 2023. Data starts at 12 AM YST (7 AM UTC) on 28 January. The red line indicates the gale force threshold of 50 km h\(^{-1}\). (b) Temperatures at NT km 4 and Rock River during the windstorm.
at km 4 (Fig. 4.24b) increased from near -21 to -9.4 °C prior to and in the first few hours of the event. During the event, the temperature briefly declined to a minimum of -17.3 °C before increasing to around -13 °C at the end of the event. After the strong wind dissipated, the temperature fluctuated between -13 and -10 °C. At Rock River, temperatures were cooler and stayed mostly steady around -20 °C on 28 January but increased throughout the 29th such that temperatures at the two stations were once again similar. Wind chill at Rock River was variable, but warmer values occurred earlier in the event before becoming colder closer to the middle of the event and warming after the event. Station pressure generally declined over the course of the two days from 95.4 to 93.5 kPa but stayed fairly steady around 94 kPa throughout much of the event.

The ECCC synoptic charts preceding, during, and following the event indicated high pressure across much of the western Arctic (Gulf of Alaska, northern Yukon, and the Beaufort Sea) prior to the event. During the event, the high-pressure region over northern Yukon moved south along the Yukon-Northwest Territories border and was replaced by a low-pressure centre (Fig. 4.25). This resulted in a strong south-north pressure gradient and westerly gradient winds in the Hurricane Alley area. Following this event, the pressure centres equilibrated, and relatively high-pressure conditions were re-established.

The upper atmosphere (500 hPa) analysis charts during the event indicated high pressure across the western Arctic with a ridge in the Pacific Ocean extending from the south (Fig. 4.26), similar to the surface high pressure conditions across much of the region (Fig. 4.25). This high-pressure ridge was also present when considering the jet stream position (Fig. 4.27). Upper air wind speeds were weak along the ridge axis (<36 km h⁻¹; < 10 m s⁻¹) in the North Pacific Ocean, but stronger along the jet stream over the western
Figure 4.25. Surface analysis chart for 00 UTC on 29 January 2023 (5 PM YST on 28 January). The high-pressure region over south-central Yukon and extratropical cyclone along the Beaufort Sea Coast have produced a south-north pressure gradient that is particularly strong across central and northern Yukon. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from ECCC (2023a) at <https://www.weather.gc.ca/analysis/index_e.html>.
Figure 4.26. Upper air (500 hPa) analysis chart for 00 UTC on 29 January 2023 (5 PM YST on 28 January). A ridge and high pressure are located over the western Arctic and further south. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from the University of Wyoming (2023) at <https://weather.uwyo.edu/index.shtml>. 
Figure 4.27. Upper air (500 hPa) composite mean vector wind speeds (m s\(^{-1}\)) for 28 through 29 January 2023. The average jet stream positioning on these days can be identified as the areas of higher wind speeds. The red star indicates the location of Hurricane Alley. Image provided by the NOAA Physical Sciences Laboratory (2023), Boulder Colorado from their website at <https://psl.noaa.gov/>.
Arctic. Over the Hurricane Alley area, upper-level wind speeds were around 90 km h\(^{-1}\) (25 m s\(^{-1}\)) from the west or northwest. As with the Yukon event (section 4.6.1), the jet stream wind speeds were stronger during the event relative to the preceding and following days.

4.6.3 Extreme Yukon event

The ECCC Rock River wind record includes 24 hours of hurricane-force winds (\(\geq 119\) km h\(^{-1}\)), 18 of which occurred during a windstorm between 15 and 16 February 2014. Weather metrics recorded at Rock River during this event are listed in Table A22 with wind speed and direction presented in Fig. 4.28a. The event lasted for 33 hours with gale-force winds or greater recorded in all but one hour. In addition to the 18 hours of hurricane-force winds, there were 9 hours of storm-force winds (89-118 km h\(^{-1}\)) and 5 hours of gale-force winds (50-88 km h\(^{-1}\)). Hurricane-force winds were sustained for 17 consecutive hours. The maximum sustained wind speed of 137 km h\(^{-1}\) was recorded during hour 23 (10 PM on 15 February). Rapid intensification and decline in wind speed were apparent in the event (Fig. 4.28a) with the wind speed increasing from 7 to 82 km h\(^{-1}\) in one hour at the beginning. At the end of the event, the wind speed decreased from 65 to 16 km h\(^{-1}\) in one hour. The direction of the wind was slightly north of east and sustained around 80° throughout the event. Winds were light and westerly or southwesterly before and after the event.

Considering the additional weather metrics at ECCC Rock River (Fig. 4.28b, Table A22), the temperature was steady around -32 °C before the event but increased in association with the onset of the high winds to -27.4 °C. For the remainder of the event and after the high winds dissipated, the temperature was variable in the range of -31 to -27 °C. Wind chills were already around -40 °C prior to the event, but dropped to -58 during the
Figure 4.28. (a) Wind speed (black line) and direction (grey line) at ECCC Rock River during an easterly windstorm in Hurricane Alley that occurred between 15 and 16 February 2014. Data starts at 12 AM PST (8 AM UTC) on 15 February. The red, blue, and orange lines respectively indicate the gale- (50 km h\(^{-1}\)), storm- (89 km h\(^{-1}\)), and hurricane-force (119 km h\(^{-1}\)) wind speed thresholds. (b) Temperatures at ECCC Rock River during the event.
strongest winds, before increasing to the low -30s after the event. Pressure declined by over 2 kPa from 91.3 kPa preceding the event to 89.1 kPa late in the event. After the event, the pressure rose again towards 91 kPa.

The NOAA and NWS surface analysis charts revealed similar synoptic conditions in the days preceding, during, and following the windstorm (Fig. 4.29). A deep extratropical cyclone stalled in the Gulf of Alaska and anticyclones were dominant over the Beaufort Sea. These pressure systems created a north-south pressure gradient. During the event, high-pressure centres also developed over the Mackenzie River Valley with the resultant pressure gradient oriented northeast to southwest. Gradient winds would have been easterly or southeasterly in the Hurricane Alley region. Because of the similar synoptic conditions, high winds were also recorded at Rock River on 11 through 13 February.

The upper air (500 hPa) analysis charts (Fig. 4.30) clearly displayed the extratropical cyclone from Fig. 4.29 as a region of low pressure over the Gulf of Alaska and southwest Alaska. A trough extended southeast into the Pacific Ocean and a high-pressure ridge extended northwest across western North America. The jet stream was well-developed during the windstorm and meandered across the contiguous United States (Fig. 4.31). A weaker offshoot of the main jet stream was located over the Arctic with the highest wind speeds across southeastern Alaska and southwestern Yukon. In the Hurricane Alley area, the zonal wind speed gradient was high with upper-level wind speeds near 36-72 km h\(^{-1}\) (10-20 m s\(^{-1}\)) from the south. This offshoot weakened in the days following the event. Prior to the windstorm, the meanders in the main jet stream were more pronounced.
Figure 4.29. Surface analysis chart for 00 UTC on 16 February 2014 (4 PM PST on 15 February). An extratropical cyclone in the Gulf of Alaska and a high-pressure ridge situated over the Mackenzie River Valley have created a strong northeast-southwest pressure gradient across the Yukon. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from the National Oceanic and Atmospheric Administration and National Weather Service (2022) at <https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php>. 
Figure 4.30. Upper air (500 hPa) analysis chart for 00 UTC on 16 February 2014 (4 PM PST on 15 February). Low pressure is centred over the Alaska Gulf Coast and Gulf of Alaska while a ridge is trending south-southeast to north-northwest across western North America. The red star indicates the location of Hurricane Alley. This figure is a reproduction of an analysis chart available from the University of Wyoming (2023) at <https://weather.uwyo.edu/index.shtml>.
Figure 4.31. Upper air (500 hPa) composite mean vector wind speeds (m s\(^{-1}\)) for 15 through 16 February 2014. The average jet stream positioning on these days can be identified as the areas of higher wind speeds. The red star indicates the location of Hurricane Alley. Image provided by the NOAA Physical Sciences Laboratory (2023), Boulder Colorado from their website at <https://psl.noaa.gov/>.
4.7 Summary

The key results based on analysis of wind data at several stations in the Hurricane Alley area were presented within this chapter. Over the nearly 17 years of data, the mean annual wind speed at Rock River was 18.2 km h$^{-1}$. A total of 672 high wind events were identified in the record with roughly equal frequency in autumn, winter, and spring, but low frequency in summer. In large part due to lower anemometer heights, mean wind speeds were lower and high wind event thresholds were met less often at all other weather stations. Prevailing and high winds were easterly to the west of the ridge in the Yukon and westerly to the east of the ridge in the Northwest Territories. Near the border pass, winds were common from both directions. Subsequently, wind speeds were highly correlated among the Yukon stations. Wind speeds at the border station (km 465) exhibited moderate correlations with stations on both sides of the ridge. Strong easterly winds in the Yukon appeared to be associated with extratropical cyclones in the Gulf of Alaska and high pressure further north and northeast. Strong westerly winds in the Northwest Territories appeared to be associated with high pressure conditions over southern Yukon and low pressure to the north.
Chapter 5: DISCUSSION

5.1 Introduction

The wind characteristics at different stations in the Hurricane Alley area were described in Chapter 4. This chapter contains discussion of those results focusing on the four main objectives of this thesis. These objectives relate to: (1) the key properties and trends of winds at ECCC Rock River; (2) the influence of synoptic weather patterns on the creation of high winds; (3) an assessment of the spatial variation of the winds including the prevailing mechanism of the high winds; and (4) an evaluation of the positioning of the new weather stations. The chapter begins with a summary of key results.

5.2 Summary of wind conditions

5.2.1 Regional winds

The wind regime within and surrounding the Hurricane Alley area is highly localized. Compared to other nearby ECCC stations at Fort McPherson, NT, and Old Crow, YT, much higher wind speeds have been recorded at Rock River. During the 1981-2010 climate normal (ECCC 2023c), the highest hourly wind speeds recorded at Fort McPherson and Old Crow were 56 and 74 km h\(^{-1}\), respectively (Table 3.2). These values have been exceeded many times each year at Rock River, where the mean maximum wind speed of the 672 high wind events was 75.2 km h\(^{-1}\) (Table 4.2). A maximum wind speed of 56 km h\(^{-1}\) was met or exceeded in 645, or 96\%, of these events, while a maximum wind speed of 74 km h\(^{-1}\) was reached or exceeded in 333, or just under half, of these events. The high winds were exclusively easterly at Rock River (Fig. 4.2; Section 4.2).
The localized nature of the winds in Hurricane Alley is evident in comparison with the NTAI weather stations at kms 421 and 8.5. The mean annual wind speed at Rock River of 18.2 km h\(^{-1}\) was greater than at these other stations: 11.2 km h\(^{-1}\) at km 421 and 8.4 km h\(^{-1}\) at km 8.5. At least some of this difference is attributable to the greater anemometer height at Rock River, though mean monthly wind speeds at km 457 were still noticeably greater (about 35-40%) than at km 421. Similarly, in the limited overlapping months, wind speeds were greater at km 4 than further downslope at km 8.5. Easterly winds prevailed at both Rock River and km 421 (Fig. 4.9). Mean monthly wind speeds followed a similar trend throughout the year (Figs 4.1a, 4.8a), namely higher in late spring and early summer (April-June) and lower in winter (December-February).

Winds at km 8.5 to the east of the border ridge were predominantly westerly or southwesterly (Fig. 4.9c) with the strongest winds originating from these directions. Mean monthly wind speeds were less variable at km 8.5 than at km 421 on the west side of the ridge (Fig. 4.8a) with the highest and lowest monthly means of 10.2 and 5.8 km h\(^{-1}\) occurring during February and April. Notably, February had the lowest monthly mean wind speeds on the Yukon side, but the highest on the Northwest Territories side of the border ridge. High winds were much more common within Hurricane Alley than at either km 421 or km 8.5 (Tables A10, A12, A15). Over the period of record, there have been at least 67 easterly windstorms recorded at km 421 (Feb. 2014 – Mar. 2023), and 23 westerly windstorms recorded at km 8.5 (Feb. 2014 – Jul. 2022). Comparatively, there have already been up to 37 easterly events (km 459) and 20 westerly events (km 4) recorded at the new stations over a much shorter record (Dec. 2021 – Mar. 2023). High wind events have been recorded more often at Rock River due to the greater anemometer height. Unlike the
stations on either side of the ridge, winds in the border pass at North Vittrekwa and km 465 were bidirectional with westerly or west-southwesterly winds occurring with similar frequency as east-northeasterly winds.

5.2.2 Local winds
As described in Section 4.4.1, the seven new stations within Hurricane Alley can be divided into four categories: the edge of Hurricane Alley (km 450), within Hurricane Alley proper (kms 453, 454, 457, 459), the border pass (km 465), and east of the border ridge (km 4) (Fig. 5.1). The wind conditions at the stations within Hurricane Alley were similar with average monthly wind speeds generally increasing northwards from km 453 to km 459 (Table A14). Within Hurricane Alley, easterly winds prevailed at the four new stations and Rock River (Fig. 5.1), with the strongest winds also being easterlies or northeasterlies (Figs 4.12, 4.13b). At km 450, winds were generally calmer and predominantly east-southeasterly (Fig. 4.13a, Fig. 5.1). Within the border pass at km 465, winds were bidirectional and either west-southwesterly or east-northeasterly (Fig. 4.13c, Fig. 5.1) with high winds originating from both directions. To the east of the ridge at km 4, the winds were predominantly westerly (Fig. 4.13d, Fig. 5.1).

Wind speeds at km 450 were relatively low (Table A14), with only one hour of gale-force wind recorded between December 2021 and March 2023. Mean monthly wind speeds were greater at km 421 (Table A9) than km 450 during every month of the record except for February 2023, perhaps because the break in slope and ridge are much closer to km 421 (1.1 and 1.6 km) than km 450 (5.0 and 6.5 km) (Table 3.1). Monthly mean wind speeds (Fig. 4.10) and hours of high winds (Fig. 4.11) at kms 465 and 4 differed greatly
Figure 5.1. Map of the Hurricane Alley area with wind roses (direction only) superimposed over the locations of weather stations. Note that the wind rose for ECCC Rock River has been displaced to the west to avoid overlapping with km 457. Wind data from December 2021-March 2023 for all stations except for NTAI km 8.5 (Feb. 2014-Jul. 2021).
from the stations on the west side of the ridge. For example, in November 2022, westerly events were more common and the monthly mean wind speeds and total hours of gale were greater at kms 465 (21.6 km h\(^{-1}\), 18 hours) and 4 (26.0 km h\(^{-1}\), 136 hours) than km 457 (7.1 km h\(^{-1}\), 6 hours). In January 2023, easterly events were more common, and these respective values were 9.1 km h\(^{-1}\) and 9 hours, 6.2 km h\(^{-1}\) and 24 hours, and 11.3 km h\(^{-1}\) and 53 hours.

5.3 Observations at ECCC Rock River

5.3.1 Key results and trends

Key results of the analysis of the ECCC Rock River wind record were presented in Section 4.1 and summarized in a regional context in Section 5.2. The overall mean wind speed was 18.2 km h\(^{-1}\) with monthly variation between 13.1 km h\(^{-1}\) (February) and 23.7 km h\(^{-1}\) (May). A total of 672 high wind events were identified in the record with just 11.9% (80) of those events occurring in the summer months and the remaining 88.1% (592) distributed roughly evenly between the other three seasons. This is not surprising as many mountainous areas in the mid-latitude and polar regions experience reduced downslope wind activity in the summer months, including along the Cordillera of western North America (Guzman-Morales and Gershunov 2019; Abatzoglou et al. 2020). This seasonal pattern is also evident when considering individual hours of high winds: gale-force winds or greater were recorded during just 4.4% of hours in summer, but between 10.1 and 11.3% of the time in the other seasons (Table 4.1; see also Fig. 4.1b).

Mean seasonal wind speeds at Rock River were 14.8 (winter), 19.9 (spring), 19.5 (summer), and 17.4 km h\(^{-1}\) (autumn) (Table 4.1). Despite having less than half of the hours of high winds as the other seasons, the mean wind speed in summer was the second highest
and just behind the spring value. This is likely a consequence of breezes (6-49 km h\(^{-1}\)) being most common and calm winds (0-5 km h\(^{-1}\)) being least common in summer, while the opposite was true during winter. In summer, 17.1% and 78.5% of the wind record were calm winds and breezes, respectively (Table 4.1). For winter, these respective values were 44.7 and 45.3%. In winter, high pressure is dominant over Yukon (Wahl et al. 1987; Fig. 2.1a), and thus the Rock River winter wind record has a high frequency of calm conditions (McIlveen 1986; Ross 2013). The high winds in winter are associated with extratropical cyclones which periodically move into the Gulf of Alaska as part of the Aleutian Low (Wahl et al. 1987). In summer, low-pressure systems are more common over Yukon (Wahl et al. 1987; Fig. 2.1c), bringing more turbulent weather including stronger winds (Ross 2013; Stull 2017). Convection is stronger in the summer months when the daily cycle of insolation is more pronounced (Stull 2017), and moderate winds develop each day. This pattern has been observed in other areas which experience downslope winds such as the Wright Valley in Antarctica (McKendry and Lewthwaite 1990), where in the summer months, calm conditions were relatively rare, and the diurnal cycles of winds were clearly evident, while in the winter months, calm conditions and gales were both frequent.

In an analysis of wind characteristics in the Hurricane Alley area, Humphries et al. (2019) briefly assessed whether the monthly hours of high wind at Rock River had changed over time. They did not detect any such adjustment in the frequency of gale- and storm-force winds. A similar plot to Fig. 4 in Humphries et al. (2019) is presented in Fig. 5.2 with data until March 2023. The data are plotted as percentage of high winds (gale-force or greater) by month. As with the suggestion from Humphries et al. (2019), Fig. 5.2 does not show any change in the frequency of high winds. The least squares linear regression slope
Figure 5.2. Frequency (%) of hours of gale-force winds or stronger by month over the ECCC Rock River wind record (July 2006-March 2023; black line). The 12-month running mean (blue line) and linear trendline (red dashed line) are also plotted. Months where more than half of the hourly data were missing are not included on this plot. The running mean was ended in early 2021 to avoid the large data gap during that year.
is -0.00012 % month\(^{-1}\) (or -0.0014 % year\(^{-1}\)) with a coefficient of determination \((R^2)\) of 0.0013. A plot of mean monthly wind speeds (Fig. 5.3) similarly displays no meaningful change in monthly wind speeds. The least squares linear regression is -0.00022 km h\(^{-1}\) month\(^{-1}\) (or -0.0026 km h\(^{-1}\) year\(^{-1}\)) with a coefficient of determination \((R^2)\) of 0.0065. While neither dataset demonstrated a meaningful trend over time, both Figs 5.2 and 5.3 indicate monthly variability in high winds and wind speeds. The 12-month running means do display interannual variability, although there do not appear to be any longer-term trends.

**5.3.2 Effect of anemometer height**

Wind speeds were characteristically higher, and windstorms were more frequent at Rock River relative to km 457 (and other stations). This was likely an effect of the anemometers being located at different heights above the surface: 10 m at Rock River and 3 m at the other stations. The horizontal separation (225 m) and difference in elevations (15 m) between the two stations may have played a small role as well. A logarithmic wind profile develops close to the ground surface due to frictional effects (Patton et al. 2007; Barry 2008; Stull 2017; Fig. 2.2) (see also Section 2.4). This means that anemometers closer to the ground surface (e.g., km 457) would record lower wind speeds than at greater heights (e.g., Rock River). Additionally, as wind speeds increase, so too does wind shear and the absolute difference in wind speeds at different heights (Fig. 2.2; Wang and Emmerich 2010; Stull 2017). Individual monthly least squares linear regressions between Rock River and km 457 (Table A8) suggested that the largest difference in wind speeds between the two stations was in summer. The regression coefficients during the summer months of June, July, and August averaged 0.79, while for all other months averaged 0.86. This is
Figure 5.3. Mean wind speed by month over the ECCC Rock River wind record (July 2006-March 2023; black line). The 12-month running mean (blue line) and linear trendline (red dashed line) are also plotted. Months where more than half of the hourly data were missing are not included on this plot. The running mean was ended in early 2021 to avoid the large data gap during that year.
possibly because the somewhat higher mean wind speeds in summer were associated with more wind shear and thus a greater difference in wind speeds between the two stations. Additionally, the reduced friction from snowcover during the winter months could result in winds being slowed down less near the surface at km 457 (Fig. 5.4; Bañuelos-Ruedas et al. 2010). At gale-force wind speeds or greater, both the regression coefficient (m = 0.82) and coefficient of determination ($R^2 = 0.90$) were slightly lower than for all wind speeds (m = 0.84, $R^2 = 0.97$). This is possibly a consequence of friction and drag forces increasing at higher fluid speeds (Giambattista et al. 2016; Stull 2017). Thus, at higher wind speeds, both frictional effects and the wind speed difference between the anemometers are greater.

The effect of snow depths likely also played a role on wind speeds recorded at each station. In winter, snow is redistributed by high winds and deposited in areas where the wind is slower, or some obstacle is present (Whiteman 2000). Within Hurricane Alley, snowpacks are quite shallow due to redistribution from the high winds (Appendix 2; Humphries 2020). Average March snow depths in 2019 in Hurricane Alley were 30 cm. In comparison, snow depths at kms 421 and 8.5 in March 2015 were 1.0 and 1.2 m, respectively (Idrees et al. 2015; Stockton et al. 2019). While snowpacks reduce the roughness length of a surface (Section 2.4), they also raise the effective ground surface height (Fig. 5.4), and therefore wind speeds will be lower since the anemometers are closer to the surface. This is likely part of the reason why wind speeds were lower at kms 421 and 8.5 (and km 450) compared the stations within Hurricane Alley (Fig. 1.3). However, the deeper snowpacks and increased snow deposition themselves imply lower wind speeds relative to Hurricane Alley where snowpacks are shallow due to the high winds (Fig. 1.3).
Figure 5.4. Photographs of the NTAI weather station at km 421 during (a) summer (July 2021 looking southeast) and (b) winter (March 2022 looking northeast). The snowcover during winter makes the surface much smoother than in summer when the vegetation is exposed and also raises the effective surface height.
5.4 Effect of synoptic weather conditions

Downslope winds like those observed in the Hurricane Alley region are a product of the interactions between regional synoptic-scale weather systems and more local topography (Barry 2008, Stull 2017, Abatzoglou et al. 2020). In Section 4.5, strong winds on opposite sides of the ridge in Hurricane Alley were shown to be associated with differing synoptic-scale systems. Strong easterly events on the Yukon side of the ridge appeared to commonly develop when the pressure gradient was oriented approximately north to south with easterly gradient winds (Fig. 4.15). Cyclonic (counterclockwise) flow around low-pressure systems and anticyclonic (clockwise) flow around the high-pressure systems would both result in easterly gradient winds in the Hurricane Alley vicinity. This pattern is visible in the mean sea-level pressure maps for Yukon presented by Wahl et al. (1987; Fig. 2.1a). Alternatively, strong westerly winds on the Northwest Territories side of the ridge often developed in association with south-north pressure gradients and westerly gradient winds, caused by high-pressure regions over southern Yukon or northern British Columbia and low-pressure regions further north (Fig. 4.18). Cyclonic flow around the low-pressure systems to the north and anticyclonic flow around the high-pressure systems to the south would both result in westerly gradient winds in Hurricane Alley.

The three case studies discussed in Section 4.6 followed the patterns described above. The two easterly events (Sections 4.6.1 and 4.6.3) were associated with extratropical cyclones in the Gulf of Alaska and high pressure further north. The westerly event (Section 4.6.2) was associated with an anticyclone over southeast Yukon and a low-pressure system along the Beaufort Sea coast. Both easterly events were associated with an upper air trough extending south into the Pacific Ocean and an upper air ridge extending north across
western North America (Figs 4.22, 4.30). During the westerly event, a high-pressure ridge instead extended northwards over the Pacific Ocean while a trough extended southwards across central North America (Fig. 4.26).

Relative to the positions of meanders in the jet stream, surface high-pressure regions are typically located to the east of ridges, while surface low-pressure regions are located to the east of troughs (Whiteman 2000; Stull 2017). This is because anticyclonic flow around surface high-pressure centres transfers warmer tropical air northwards resulting in deeper isobaric surfaces, creating high pressure and a ridge at altitude. Conversely, cyclonic flow around surface low-pressure regions transfers cold Arctic air equatorward resulting in shallower isobaric surfaces, creating low pressure and a trough at altitude. From the easterly case study (Section 4.6.1), the extratropical cyclone was centred near the Katmai Peninsula (Fig. 4.21) with the jet stream trough extending southwesterly into the Pacific Ocean just to the west of this cyclone (Fig. 4.22). High pressure was centred along the Montana-Idaho border (Fig. 4.21) just to the east of the ridge axis over western North America (Fig. 4.22). A similar setup was identifiable in the extreme easterly event (Section 4.6.3): the extratropical cyclone centred over the Katmai Peninsula (Fig. 4.29) just to the east of the jet stream trough axis (Fig. 4.30), and the high-pressure region centred over the Mackenzie Valley (Fig. 4.29) just to the east of the ridge axis.

The general northeasterly track of extratropical cyclones through the Gulf of Alaska associated with many easterly windstorms is also consistent with typical Northern Hemisphere cyclone tracks due to steering from the jet stream (Stull 2017). For the westerly event (Section 4.6.2), an anticyclone was centred over southwest Yukon and southeast Northwest Territories (Fig. 4.25), east of the ridge axis extending northwards across central
Alaska (Fig. 4.26). There was no obvious trough associated with the low-pressure centre along the Beaufort Sea coast visible in the upper air data (Fig. 4.26). However, the surface analysis chart did display a short-wave trough extending just south of this localized pressure centre. Short-wave troughs (or ridges) are smaller perturbations superimposed upon the larger troughs and ridges making up Rossby waves (Whiteman 2000). The upper atmospheric conditions in association with high wind events represent an area of potential future research.

Synoptic weather patterns were less obvious during instances of high winds in the summer months, likely because high winds were influenced by local convection (Stull 2017). The mean winter surface pressure pattern presented by Wahl et al. (1987; Fig. 2.1a) was possibly responsible for the trends in monthly mean wind speeds on opposite sides of the ridge. Winter wind speeds at km 8.5 were higher than in the other seasons, but lower at Rock River and km 421. In winter, high pressure dominant over central Yukon is associated with strong westerly winds on the Northwest Territories side of the ridge. Monthly mean wind speeds were strongest in late spring and early summer (April through June) at the Yukon stations, for the high pressure shifted further north (Fig. 2.1b). Wahl et al. (1987) also noted that southeasterly flow associated with the spring pressure pattern is responsible for April and May being the windiest months at many interior Yukon stations (e.g., Dawson).
5.5 Effect of Richardson Mountains

5.5.1 Spatial variability of winds

As has been previously described in earlier sections of this thesis and by Humphries et al. (2019), the ridge in the Hurricane Alley area controls local wind characteristics. This ridge makes up one of the narrower sections of Richardson Mountains and forms part of the Yukon-Northwest Territories border. Analysis of wind data from the seven new stations within the Hurricane Alley area showed that the stations on the Yukon side of the ridge (kms 450, 453, 454, 457, 459) experienced prevailing easterly winds, the station on the Northwest Territories side of the ridge (km 4) experienced prevailing westerly winds, and the station within Wright Pass near the territorial border (km 465) commonly experienced winds from both directions (Fig. 5.1). These prevailing directions were aligned close to perpendicular with the north-south trending ridge. Winds at km 453 were slightly more northeasterly than other stations within Hurricane Alley, and the ridge there is aligned more northwesterly-southwesterly (Fig. 5.1). Similarly, prevailing winds at km 8.5 were more southwesterly than westerly. At km 450, prevailing winds were east-southeasterly, although this station is located much further away from the ridge and possibly was also affected by the wider block of Richardson Mountains south of Hurricane Alley (Fig. 1.1b). Further south at km 421, prevailing winds were also easterly, perpendicular to this wider block of Richardson Mountains (Fig. 1.1b).

In addition to differing wind directions on either side of the ridge, there was also spatial variability in the wind speeds recorded at each station. Wind speeds were much lower at km 450 than any of the other new stations (Fig. 4.10; Table A14). In some cases, wind speeds at km 453 were higher than at 454. Otherwise, wind speeds within Hurricane
Alley tended to increase northwards (Table A14) with high winds becoming more frequent as well (Tables A15, A16). Mean monthly wind speeds at km 4 were comparable to the stations within Hurricane Alley (Fig. 4.10; Table A14), although individual monthly values varied depending on whether westerly or easterly events were more common (Section 5.2.2). Of the seven new stations, mean monthly wind speeds were commonly highest at km 465 (Fig. 4.10; Table A14), although hours of high winds were typically less than stations on either side of the ridge (Tables A15, A16) even when considering missing data. This is potentially because km 465 is positioned within Wright Pass where the elevation is slightly lower than the surrounding ridge. The higher relief to the north and south would block winds from reaching the other stations while local ‘gap winds’ could develop within the pass itself (Whiteman 2000; Stull 2017). However, because winds accelerate as they move downslope, other stations record a greater total of hours with high wind. Cao and Fovell (2016) identified similar characteristics for the Santa Ana Winds in California where wind speeds were greater just downslope of the ridge than at the ridge itself. As the surface winds continue further downslope, they slow down as the slope levels out or a hydraulic jump occurs (Section 2.4.2).

Considering the metadata presented in Table 3.1, one possible explanation for increasing wind speeds northwards through Hurricane Alley is the proximity of the station to the ridge. Km 459 was located about 2.4 km from the ridge, while the stations further south were closer to 3 km from the ridge. Similarly, km 450 is located much further from the ridge (6.5 km) than the other stations and thus recorded relatively weaker winds. The same is true to the east of the ridge: much stronger winds were recorded at km 4 relative to km 8.5. The spatial trend of increasing wind speeds within Hurricane Alley remained the
same for gale-force, but not storm-force winds. Of the stations at kms 453, 454, 457, and 459, km 459 recorded the most hours where maximum winds were gale-force (1,808), but the least storm-force maximum winds (73). The proximity of km 459 to the ridge likely resulted in the greater frequency of gales, while the lower frequency of storm-force winds was potentially due to the shorter downslope distance for acceleration of these winds. This result suggests an area of future research where the wind speed characteristics with distance from the ridge are considered. In addition to distance from the ridge, mountain width also seemed to play a role on wind speeds at the NTAI stations where Richardson Mountains are wider (Fig. 1.1b). Wind speeds were lower at these stations compared to the stations closer to the narrow ridge within Hurricane Alley. The elevation difference between station locations and the ridgetop was similar for all stations (between about 4-500 m) and did not appear to play a major role in wind conditions.

Irrespective of the variations in wind speed discussed above, trends (or a lack thereof) in relations of wind speed among the stations were apparent (Section 4.4.2; Table 4.5). For stations within Hurricane Alley itself (kms 453, 454, 457, 459, and Rock River), correlation coefficients ($R$) were all at least 0.82 for each station pair, indicating high consistency of wind speeds within Hurricane Alley. Comparing these stations with km 450, correlation coefficients were only moderate ($R = 0.51-0.54$). There was little correlation between km 4 and all other stations ($R \leq 0.07$). The only exception to this was the relation between kms 4 and 465 where a moderate correlation coefficient of 0.55 was calculated. Relations between km 465 and the other Yukon stations were also moderate with correlation coefficients in the range of 0.43-0.54. These relations again illustrate the impact which the ridge has on local wind conditions. There is virtually no relation between stations
on the Yukon and Northwest Territories sides of the ridge, but there are strong relations among the stations within Hurricane Alley. Additionally, the wind characteristics at the border pass are moderately related to wind conditions on both sides of the ridge. These moderate correlations between km 465 and stations on either side of the ridge are likely a result of both easterlies and westerlies being common in the border pass, but only one direction to either side of the ridge. Isolating for only broadly easterly (45-135°) or westerly (225-315°) winds does increase the correlation coefficients, but only slightly. Considering only the hours when easterly winds occurred at both Rock River and km 465, the correlation coefficient increased from 0.49 to 0.67. For westerly winds at both km 4 and km 465, the correlation coefficient only increased marginally from 0.55 to 0.57. These correlation coefficients were still only moderate, possibly as a result of two main factors related to wind speed: 1) mean wind speeds were commonly higher at km 465 than other stations (Table A14), and 2) the greater downslope distances at other stations meant that winds accelerated more so high winds were more common. Both of these factors meant that correlations were still only moderate with km 465, even when isolating for common wind directions.

5.5.2 Mechanism responsible for downslope winds

In their modelling of high wind events in the Hurricane Alley area, Ribberink et al. (2020) suggested that the foehn mechanism was commonly responsible for the windstorms. Results obtained within this thesis corroborate this. Foehn winds are associated with the damming of cold, statically-stable air layers behind a topographic feature and overriding air layers spilling over the topography and accelerating downslope (Section 2.5.1; Barry
Foehn winds are typically associated with increases in temperature and decreases in humidity due to adiabatic warming (Speirs et al. 2010; Schwarz et al. 2020). Such winds will also be associated with relatively calm conditions on one side of the ridge and high winds on the other. This was the case during most high wind events recorded at the stations in the Hurricane Alley area. For example, of the 23 high wind events recorded at km 8.5 east of the ridge, just two could be identified in the record at Rock River west of the ridge (Table A13). When considering data from Rock River and the new stations (excluding km 450; Table 4.6), between 20 and 50 strong easterly events were recorded at the stations west of the ridge in Yukon. None of these events were recorded at km 4, and five were recorded at km 465. Conversely, 20 strong westerly events were recorded at km 4. None of these events were recorded at the stations west of the ridge, although 13 of them were recorded at km 465.

Based on temperature data, two of the three case studies presented in Section 4.6, appear to have been foehn events. Warming was observed during the intensification of winds in the case studies for both the westerly event and extreme easterly event (Sections 4.6.2 and 4.6.3; Figs 4.24, 4.28). During the westerly event, the temperature increased 4.8 °C in three hours at the start of the event (Fig. 4.24b); during the extreme easterly event, the temperature increased 3.3 °C in four hours at the start of the event (Fig. 4.28b). Additionally, during the westerly event, temperatures at km 4 were consistently higher than at Rock River indicating warming as the air passed over the ridge and accelerated downslope (Fig. 4.24b).

Conversely, for the case study of the easterly event (Section 4.6.1), the temperature generally decreased even as the wind speed increased (Fig. 4.20). As with the westerly
event, conditions were slightly warmer on the windy side of the ridge suggesting adiabatic warming. Cooling during this event may have been caused by the bora mechanism, although the foehn mechanism cannot be ruled out. Wind speeds on the Northwest Territories side of the ridge were not particularly strong as would be expected during a bora (Stull 2017). It is also possible that the cooling during the event might have been due to regional temperature patterns. The mountain ranges of northern Yukon generally block cold Arctic air from entering much of the territory (Wahl et al. 1987), while the flatter Mackenzie Delta and Peel Plateau in the Northwest Territories are much more susceptible to Arctic air intrusions and therefore are cooler than the Yukon – as observed in some of the case studies analyzed by Ribberink et al. (2020). Thus, intrusions of this relatively cooler air might lead to declines in temperature associated with the high winds, even if a foehn mechanism is responsible. Future analysis of both local and regional temperature patterns in additional case studies could help to clarify this. The local temperature patterns on opposite sides of the ridge evident from the first two case studies (Sections 4.6.1 and 4.6.2) would also imply local pressure gradients that help drive the winds from one side of the ridge to the other (e.g., Speirs et al. 2010; Cao and Fovell 2016).

Humidity measurements at Rock River during the two easterly events only indicated slightly dryer conditions in association with the high winds (Tables A19, A22), while erroneous data from km 4 meant that a determination could not be made for the westerly event. Furthermore, the humidity measurements at both of these stations are relative humidity which also depends on temperature and may not be indicative of absolute humidity (Whiteman 2000; Stull 2017). Still, large declines in relative humidity have been observed in association with some foehn events (e.g., Speirs et al. 2010; Chow et al. 2013).
In addition to demonstrating the spatial variability in wind characteristics on opposite sides of the ridge, the wind speed relations presented in Section 4.4.2 also suggest that the strong wind events are associated with the foehn mechanism. Considering only the hours when high winds were recorded (Table A17), all relations declined relative to the entire datasets. However, the relations still suggested that strong winds at certain stations are associated with strong winds at other locations. For the stations within Hurricane Alley proper (kms 453, 454, 457, 459, and Rock River), correlation coefficients for strong winds had a range of 0.44-0.95 indicating moderate to strong relations. In other words, strong winds at one of these stations were sometimes or often recorded at the same time as strong winds at the other stations. The reason for the weaker relations relative to the entire dataset is potentially because high winds and high wind events were variable between specific stations. For example, the total number of high wind events recorded among these stations varied between 20 and 50 (Table 4.6) with many only recorded at some of the stations. When considering the relations between these stations and km 465, the correlation coefficients were between 0.38 and 0.51 indicating that strong winds within Hurricane Alley were sometimes associated with strong winds at Wright Pass. The correlations between the stations within Hurricane Alley and at km 4 were all close to zero indicating almost no relation between strong winds on opposite sides of the ridge. The analysis did not indicate much of a relation between strong winds at kms 4 and 465 ($R = 0.08$) and vice versa ($R = 0.09$). Considering that 13 of the 18 high wind events identified in the record at km 465 were westerly events which were also recorded at km 4, this result is unexpected. Isolating for only strong westerly winds at both stations (as in Section 5.5.1) resulted in similarly low correlations. One possible explanation for this discrepancy is that the greater
downslopes distance from the ridge at km 4 resulted in stronger and longer-duration high winds (e.g., Fig. 4.24a) reducing the correlation between the two stations. The more frequent high winds at km 4 relative to km 465 (Tables A15, A16) – especially considering the amount of missing data at km 4 and some of these high winds at km 465 being easterlies – are potential indicators of this. Otherwise, the relations indicated that high winds on one side of the ridge share almost no relation with high winds on the other side of the ridge, suggesting that a foehn mechanism was responsible.

The rapid intensification of wind speeds during many windstorms, including the three case studies (Figs 4.20a, 4.24a, 4.28a), also suggests operation of the foehn mechanism. For example, during the extreme easterly event (Section 4.6.3), the wind speed increased from 7 to 82 km h\(^{-1}\) in the first hour of the windstorm (Fig. 4.28a). The rapid intensification of wind speed on one side of the ridge is consistent with the foehn mechanism and hydraulic flow (Durran 1986; Whiteman 2000; Chow et al. 2013). When air is accumulating on the upwind side of the ridge, winds would be relatively calm downwind, but as soon as air spills over the ridgetop, it will accelerate downslope and result in a sudden increase in wind speed. The dissipation phase of the high wind events was also rapid, though not as sudden as the intensification phase (see Figs 4.20a, 4.24a, 4.28a). This may have been due to more gradual synoptic adjustments leading to changes in wind direction and less air damming behind the ridge.

While the foehn mechanism appears to be responsible for many of the strong winds in the Hurricane Alley region, it is not the only mechanism responsible for strong downslope winds in general (Sections 2.5, 2.6). Katabatic winds would not be responsible for strong downslope winds in the Hurricane Alley area due to the short downslope
distances. Strong katabatic winds are associated slopes sometimes hundreds of km in length such as along the North Slope or the ice sheets of Antarctic and Greenland (Wahl et al. 1987; Mackay and Burn 2005; Speirs et al. 2010; Stull 2017; Abatzoglou et al. 2020).

Unlike katabatic winds, strong winds in the Hurricane Alley area could potentially also form by the bora mechanism. The bora mechanism is associated with a deep layer of cold air accelerating over a topographic feature and down the lee slope as described by the Bernoulli effect (Barry 2008; Stull 2017). They would be associated with moderately strong winds on one side of the ridge and high winds on the other with similar directionality (Stull 2017; Fig. 2.6b). The bora mechanism was potentially responsible for the event featured in the first case study (Section 4.6.1), and the two westerly events recorded at both Rock River and km 8.5 (Table A13). However, many other high wind events in the analysis featured directional strong winds on one side of the ridge and relatively weak winds on the other side with variable directionality. If boras were common in the Hurricane Alley area, then the relations for strong winds discussed in Section 4.4.2 should have been greater on opposite sides of the ridge, and high wind events that occurred on both sides of the ridge should have been more common. Ribberink et al. (2020) suggested windstorms may occasionally form from the transfer of momentum from low-level jet streams downward by mountain waves. The westerly wind event in March 2020 which was recorded at both Rock River and km 8.5 was an example of this mechanism. It is possible that this mechanism may have been responsible for some of the other high wind events in the analysis, though a more detailed assessment of upper atmosphere conditions would be required. A low-level jet may not necessarily be measured at surface weather stations and could appear similar to a foehn (or bora) otherwise.
5.6 Positioning of new weather stations

The rationale behind individual site selection of the seven new weather stations was provided in Section 3.4.1. The site selection was based on eyewitness reports of wind conditions and some limited previous research. However, the Hurricane Alley region is not the only section of the Eagle Plains maintenance division of the Dempster Highway in which winds affect highway operations. Some of the new stations may therefore be moved to other sections of the road. The following discussion will briefly outline the importance (or redundancy) of the new stations. These stations can be separated into four groups based on their positioning: the edge of Hurricane Alley (km 450), the border pass (km 465), east of the ridge (km 4), and within Hurricane Alley proper (kms 453, 454, 457, and 459). Rock River can also be associated with the latter category due to its positioning near km 457.

Winds were highly-correlated among the four new stations within Hurricane Alley (kms 453, 454, 457, and 459) and Rock River (Table 4.5) with correlation coefficients for all winds among the station pairs being 0.82 or greater. Given that the wind characteristics at these four stations were closely related to those of Rock River, all are redundant to a certain extent and could potentially be relocated in future. However, it would still be prudent to leave at least one of these four stations at its current location as a backup in case of data outages at Rock River (Table 3.5), and also to compare wind speeds at the different anemometer heights. Additionally, the new stations report maximum hourly wind speeds, while Rock River does not. In the opinion of the author, if only one of these four stations is to remain in place, it should probably be km 459 or 457. Km 459 has recorded the highest mean wind speeds (Table A14), most hours of high winds (Tables A15 and A16), and most windstorms (Table 4.6) of the four stations. Additionally, km 459 was the station where
wind gusts most frequently first reached gale force during high wind events (Fig. 4.14). Km 457 is the closest station to Rock River and therefore most suited to cover any data gaps and compare the different anemometer heights, and also had slightly higher correlations with the other three stations than km 459. Km 454 is located in a suitable location, although did not exhibit these advantages to the same extent.

In contrast with Ribberink et al. (2020), the discussion of which station initially recorded high winds (Section 4.4.3) in this thesis suggested that km 453 was rarely the first or among the first station to record high winds. This is possibly because the threshold of gale force was used in this analysis, while Ribberink et al. (2020) were instead considering any initial increase in wind speeds. However, the other suggestions advanced by Ribberink et al. (2020) do appear to have been supported by the results in this thesis. The median (71.4 km h\(^{-1}\)) and mean (70.7 km h\(^{-1}\)) maximum wind speeds during the windstorms recorded at km 453 were slightly greater than those recorded at stations further north in Hurricane Alley (Table 4.6). Furthermore, the mean event duration of around 24 hours at km 453 was greatest of the four new stations within Hurricane Alley, although the metrics for hours of gale-force winds or greater were not substantially different. Despite this discussion, one major disadvantage of km 453 is its positioning far away from the road. While the replacement of satellite components and clearing of ice and snow by highway crews appears to have reduced missing data at the other stations, the same could not be said for km 453. Between November 2022 and March 2023, km 453 had nearly 1,700 hours of missing data, while the other three stations had at most 136 hours of missing data (Table 3.6). Additionally, with 20 total events recorded between December 2021 and March 2023 (Table 4.6), km 453 recorded fewer events than the other stations (although some were
likely missed due to the data quality issues). The record from km 465 was unique in the collection with prevailing winds being bidirectional (Fig. 5.1). Both easterly and westerly events were recorded here. Ice and snow accumulation on the equipment was more severe than at the other stations (Fig. 3.11), resulting in more missing data (Table 3.6), but replacement of the satellite communications equipment improved data collection in winter 2022/23.

Km 4 is also an important location to collect data as prevailing winds are westerly in contrast to the stations on the Yukon side of the ridge. Km 4 more commonly recorded high winds than the NTAI station at km 8.5. However, the specific positioning of the station at km 4 is problematic and it should be relocated across the road to avoid damage during highway maintenance operations. The current position is right next to where snow is cleared after windstorms – disturbed snow from this clearing is visible in the lower right corner of Fig. 3.8. The anemometer is believed to have been accidentally damaged during snow clearing after a windstorm in January 2022.

Mean wind speeds (Table A14), and hours of high winds (Tables A15, A16) were relatively low at km 450. Only one hour of gale-force wind was recorded at this station between December 2021 and March 2023. It may be appropriate to relocate this station to another region of concern.

5.7 Summary

Within this chapter, key results from Chapter 4 have been related to the four key objectives outlined in Section 1.5. No long-term trends have been identified in the wind record of Rock River. Summer wind conditions are characteristically different from the other
seasons, likely due to the influence of active convection. High wind events were less frequent in the summer months. The ridge to the east of Hurricane Alley acts as a division between wind characteristics with prevailing easterlies on the Yukon side and prevailing westerlies on the Northwest Territories side. There is evidence that the high wind events commonly develop as a result of the foehn mechanism. These windstorms generally occur in association with regional synoptic weather systems, although the ridge again acts as a boundary. The westerly winds are associated with south-north pressure gradients and westerly gradient winds, while the easterly events are associated with north-south pressure gradients and easterly gradient winds. The seven new stations installed in the Hurricane Alley region display spatial variability in wind characteristics, but also consistency and redundancy depending on the station. Thus, in future, some of these stations may be relocated to other sections of the north Dempster Highway to study winds at those locations.
Chapter 6: SUMMARY AND CONCLUSIONS

6.1 Summary

This thesis investigated the characteristics and occurrence of high wind events along a section of the north Dempster Highway known as Hurricane Alley near the Yukon-Northwest Territories border. Historic wind records were analyzed to summarize baseline wind characteristics for a number of regional weather stations: ECCC Rock River, NTAI kms 421 and 8.5, and NorthwesTel North Vittrekwa. Seven additional weather stations were installed in late autumn 2021 to increase data coverage and allow for a more spatially-detailed assessment of wind characteristics. In addition to assessing the characteristics of the winds and high wind events, synoptic weather charts were analyzed to identify common weather patterns associated with the high wind events. Together, these results were used to identify the likely mechanism responsible for the high winds and evaluate the positioning of the new weather stations.

6.2 Conclusions

The following conclusions were identified based on the analysis of wind records and synoptic weather charts in the Hurricane Alley region of the north Dempster Highway:

1) The territorial boundary ridge acts as both a physical barrier for winds and division between wind characteristics. To the west of the ridge in the Yukon, prevailing winds are easterlies; to the east in the Northwest Territories, prevailing winds are westerlies; and at the border pass, prevailing winds are from both directions. In each case, the strongest winds are almost exclusively
associated with these prevailing directions. The strongest winds are highly localized and stations further from the ridge (kms 450, 8.5) experience lower wind speeds.

2) No long-term trends in mean monthly wind speeds or annual hours of high wind were identified in the Rock River record. However, there was some interannual variability and strong seasonal variability. Of the 672 high wind events identified in the record, 28.7% occurred in autumn, 30.8% in winter, 28.6% in spring, and just 11.9% in summer. High winds were more frequent in the winter months, but mean wind speeds appear to be higher in late spring and early summer.

3) The median windstorm duration at Rock River was 16 hours with 13 of those hours being gale-force winds or greater. On a seasonal basis, event duration and hours of high winds were similar across winter, spring, and autumn, but reduced during summer. Similar median totals were identified in the records at kms 453, 454, 457, and 459. Additionally, the intensification and decline in wind speeds at the start and end of events occurred rapidly, with changes from calm winds to gale-force or greater (or vice versa) occurring over as little time as one hour.

4) Wind speeds were higher at the stations in the Hurricane Alley area than at other regional stations (e.g., kms 421, 8.5). At Rock River, gale-force winds or greater occurred during at least 10% of hours in winter, spring, and autumn, but only 4.4% of hours in summer. Conversely, calm winds were least common in the summer months and mean monthly wind speeds were highest in late spring and early summer. Storm-force winds were most common in the months of
November through January with at least 10 hours being recorded on average during each month.

5) High wind events are associated with differing synoptic weather patterns depending on the direction. Easterly wind events were associated with low-pressure extratropical cyclones in the Gulf of Alaska and high-pressure regions to the north, resulting in a north-south pressure gradient and easterly gradient winds in the Hurricane Alley area. Westerly wind events were associated with high-pressure regions over southern Yukon or northern British Columbia and low-pressure systems to the north, resulting in a south-north pressure gradient and westerly gradient winds in the Hurricane Alley area. These patterns were most prevalent outside of summer when high winds were more likely associated with local convection.

6) The high wind events appeared to be commonly caused by the foehn mechanism, but boras or low-level jets may have contributed to some events.

7) The seven new stations allowed for a more spatially detailed measurement of winds but also resulted in redundancy. The stations may be relocated in future but at least three should be kept close to their current positions: at km 4, km 465, and at least one within Hurricane Alley (km 459 or 457).

6.3 Future research

The research within this thesis has focused mainly on describing wind and windstorm characteristics in the Hurricane Alley area and linking these to regional weather systems. However, many avenues for future research related to the winds or similar study areas
remain. The winds of Hurricane Alley emphasize the fact that high winds may be spatially localized. This should be considered during the route selection phase of road development in mountains, especially in isolated areas. With respect to Hurricane Alley, there have already been discussions of better integrating the monitoring network of the new stations and publicly available road condition information. Additionally, to better forecast the occurrence of high winds, synoptic weather charts could be monitored for patterns associated with the development of high winds. Development and use of a forecast model with higher resolution than those used by ECCC – as suggested by Ribberink et al. (2020) – would predict wind speeds more accurately.

As only briefly considered within this thesis, further research on the high winds might focus on analyzing upper-atmosphere conditions, and additional weather metrics (as in the case studies). This could help to clarify the degree to which specific events are caused by difference mechanisms (foehns, boras, low-level jets). Additional consideration of temperature patterns during the high wind events may also assist this analysis. There is also the opportunity for future research to assess the specific effects of wind characteristics on snowpack properties and road operations, and how this changes under different wind regimes. For instance, there have been suggestions that moderately high winds result in longer road closures due to increased snow drifting on the road surface, and an increased time to clear the road (C. Brais, pers. comm. 2022; e.g., Fig. 2.7). However, during strong winds, the snow may be blown over the road surface and not drift within the windrows. Furthermore, the option to move some of the new weather stations out of Hurricane Alley (or install additional stations) could allow for the assessment of wind properties near other locations of concern along the Dempster Highway. In particular, relocation of weather
stations to km 444, where persistent snow drifting may block the road, and to km 406, near the southernmost point of the road parallel to the Richardson Mountains, may be of interest to the Eagle Plains maintenance division highway crew. Future research may also consider the effect which specific station positioning relative to the ridge has on local wind characteristics. This is especially true when considering the low correlation between wind conditions at km 465 and km 4, despite strong westerly winds occurring at both.
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Appendix 1: WIND BASICS

A1.1 Wind

A1.1.1 Atmospheric forces

Atmospheric motion of the air – or wind – is driven by the pressure gradient force and acted on by gravity, friction, Coriolis, centripetal, and advection forces (McIlveen 1986; Ross 2013; Stull 2017). Of these forces, only the pressure gradient force can initiate wind, while all other forces act to modify the air motion, either by changing its speed or direction. From Newton’s second law of motion, acceleration, $a$ (m s$^{-2}$), occurs when a force, $F$ (N), operates on a body of some mass, $m$ (kg): $F = ma$ (McIlveen 1986). In practice, there will always be some force(s) acting on an air mass outside of a vacuum, but when forces are small, winds approximately follow Newton’s first law of motion: in the absence of forces, objects will continue their initial form of motion. Air masses experiencing only small forces will result in largely calm conditions or steady winds.

Most of the forces acting to drive winds are considered to act horizontally (Stull 2017). The pressure gradient force, which initiates winds, is due to a difference in atmospheric pressure over horizontal distance (McIlveen 1986; Ross 2013; Stull 2017). Pressure differentials at the Earth’s surface are caused by differential insolation due to factors such as latitude, season, landcover, and slope. In regions that receive more (less) solar energy, surface air masses are warmer (cooler) and are less (more) dense resulting in rising (sinking) air and low (high) pressure at the surface. The pressure gradient force then drives air from regions of high pressure towards regions of low pressure, producing wind.
The Coriolis force is an apparent deflection of air masses due to the rotation of the Earth (McIlveen 1986; Ross 2013; Stull 2017). The Coriolis force is zero at the equator and increases towards the poles and with wind speed. It acts perpendicularly to the motion of an air parcel, deflecting winds to the right in the Northern Hemisphere (Appendix Fig. A1).

Objects travelling in a circular motion at a constant speed continuously change direction (Ross 2013; Giambattista et al. 2016). In order for an object to travel in circular motion where its direction is constantly changing, there must be an acceleration towards the centre of rotation. This acceleration results from a net imbalance of forces which is referred to as the centripetal acceleration or centripetal force (Fig. A1). In the atmosphere, the centripetal force points inwards to pressure centres, i.e., the centres of rotation, and arises from the imbalance of the pressure gradient and Coriolis forces (Section A1.2 describes gradient winds associated with the centripetal force). The related centrifugal force is an apparent force arising from inertia that is felt by objects traversing a circular path which points outwards and opposite to the centripetal force (Stull 2017).

Friction (or drag) resists motion (McIlveen 1986; Ross 2013; Stull 2017). Near the surface, drag increases due to the effects of obstacles such as variable topography, vegetation, and infrastructure. This results in wind shear from deceleration of air near the surface relative to layers higher in the atmosphere (Section 2.4). In addition, air masses and winds are also influenced by gravity. The effect of gravity in relation to downslope winds is described in Section 2.5. Finally, advection, though not a true force, may cause wind speed changes at a specific location. An air parcel with variable winds moving or advecting will result in changing wind speeds as the air parcel moves over the location (Stull 2017).
Figure A1. Production of centripetal acceleration and gradient winds around low- (a, b, c) and high-pressure (d, e, f) centres after Figs 11.10 and 11.11 from Ross (2013). CF, PGF, and CA respectively represent the Coriolis force, the pressure gradient force, and the resulting centripetal acceleration. In (a) and (d), the wind is initially geostrophic, but as it moves around the pressure centre, the pressure gradient force works to either decrease or increase the wind speed, so the Coriolis force subsequently decreases or increases in (b) and (e), resulting in a net centripetal acceleration in (c) and (f). Note that the forces in (c) and (f) have been exaggerated relative to the preceding figures. See text for further discussion.
A1.1.2 Winds

The forces described in the previous section combine in different configurations to produce several broad categories of horizontal winds. The geostrophic wind is an idealized wind which arises from the interaction and balancing of the pressure gradient and Coriolis forces (McIlveen 1986; Ross 2013; Stull 2017). When lines of constant pressure, *isobars*, are relatively straight, the pressure gradient force will create wind blowing from regions of high pressure to regions of low pressure (Ross 2013). Initially the flow will be perpendicular to the isobars, but the Coriolis force deflects the wind to the right (in the Northern Hemisphere) such that as the air accelerates, the Coriolis force will also increase, deflecting the wind until the forces balance and the wind travels parallel to the isobars. In the Northern Hemisphere, geostrophic winds blow with the low-pressure region to the left of their direction of travel (Ross 2013; Stull 2017). Near-geostrophic winds may occur close to the Earth’s surface, but true geostrophic winds are found higher in the atmosphere where the surficial effects of friction are negligible (McIlveen 1986; Ross 2013; Stull 2017).

The atmospheric boundary layer is the lowest layer of the atmosphere, between 0.3 and 3 km above the surface, where frictional effects are encountered and turbulence and thermal heating result in a well-mixed layer (Ross 2013; Stull 2017). When frictional forces are added to the interaction between the pressure gradient and Coriolis forces, the resulting wind (atmospheric boundary layer wind) is slightly slower than the geostrophic wind, so the atmospheric boundary layer wind crosses the isobars at a low angle towards the low-pressure region.
As previously noted, a centripetal force is also introduced into the force balance with the pressure gradient and Coriolis forces when isobars curve around pressure centres (Ross 2013; Stull 2017). This results in the gradient wind above the atmospheric boundary layer (Fig. A1). Gradient winds circle cyclonically (counterclockwise) around low-pressure centres and anticyclonically (clockwise) around high-pressure centres in the Northern Hemisphere. Around low-pressure centres, when flow is initially geostrophic and linear, the pressure gradient force pointing towards the pressure centre will act to oppose this linear motion (because the pressure gradient itself is curved) slowing the wind down (Fig. A1a). The Coriolis force is reduced at a lower wind speed (Fig. A1b), causing net centripetal acceleration (Fig. A1c) towards the low and counterclockwise flow in the Northern Hemisphere (Ross 2013). Around high-pressure centres, the pressure gradient force points away from the pressure centre and works to increase the wind speed (Fig. A1d). Thus, the Coriolis force must increase (Fig. A1e) and, aloft, net centripetal acceleration (Fig. A1f) is towards the high leading to clockwise flow in the Northern Hemisphere. Near the surface where friction is present, an atmospheric boundary layer gradient wind will be produced, with the wind crossing the isobars towards the lower pressure (Ross 2013; Stull 2017). This results in winds spiralling cyclonically (counterclockwise) inwards and converging towards low-pressure centres and spiralling anticyclonically (clockwise) and diverging away from high-pressure centres.

A1.1.3 General circulation

Differences in insolation received at the surface drive not only local pressure differentials, but also larger global pressure patterns or the general circulation. The general circulation
is driven by global heat transfer, since receipt of shortwave solar radiation is more concentrated closer to the equator than at the poles (Ross 2013; Stull 2017). To prevent the temperature in the tropics from continuously rising and the poles from continuously falling, heat is transferred poleward from near the equator. Momentum is also transferred poleward (Ross 2013). In the rotating Earth system, angular momentum must be conserved otherwise winds would alter the angular velocity of the Earth. The planet’s rotation is west to east, so with easterly winds momentum is transferred from the Earth to atmosphere, while the opposite is true for westerlies. Within the atmosphere, momentum is transferred from the easterlies near the equator and poles to the westerlies of the mid-latitudes.

The transfers of energy and momentum around the planet result in the average pressure and wind patterns making up the general circulation (Fig. A2). Air near high-pressure bands at latitudes of 30° (the subtropical highs) travels poleward and is deflected by the Coriolis force to produce westerlies in the mid-latitudes. The mid-latitudes are also home to transient pressure systems, so winds are only westerlies in aggregate and may be highly variable (Ross 2013; Stull 2017). Near the poles, surface heating is minimal and high-pressure regions (polar highs) develop with cold, dry, and mainly calm conditions (Fig. A2). Winds travel southwards from the polar highs and are deflected by the Coriolis force to create the polar easterlies. In subpolar regions, near latitudes of 60°, are bands of low pressure known as the subpolar lows. Three cells of circulation are developed in each hemisphere: the Hadley cell (tropics), the Ferrel cell (midlatitudes), and the Polar cell (poles). Air arriving at the subpolar lows rises and diverges, traveling north (south) aloft, descending at the polar (subtropical) highs, and together creating the Polar (Ferrel) cell with winds near the surface. The general circulation and cells are weaker in the summer
**Figure A2.** Simplified general circulation near the Earth’s surface. PC, FC, and HC respectively represent the Polar, Ferrel, and Hadley cells in each hemisphere. Fig. 11.3a from Stull (2017) redistributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. Major cells added to original.
hemisphere than in the winter hemisphere due to reduction of the zonal temperature gradient.

Upper-level jet streams of high-speed westerlies develop near the boundaries of the cells and are stronger in the winter hemisphere. Jet streams are high-altitude regions of high-speed westerly winds situated near the tropopause and which greatly influence surface weather patterns (Ross 2013; Stull 2017). The tropopause is the boundary between the troposphere and stratosphere at an altitude between 18 km in the tropics and 8 km near the poles. The polar jet stream is variable in position being situated between latitudes of 40 and 60°. It ranges from 150-500 km in width with average wind speeds of 160 km h⁻¹, though wind speeds may reach as high as 400 km h⁻¹ in faster jet streaks. Meanders in the polar jet stream known as Rossby waves greatly influence the movement of surface weather systems.

The discussion in the preceding sections has established the basis for the development of major wind types through the interactions among several atmospheric forces, as well as the relevant global wind patterns. Hurricane Alley is located in the polar region just north of the Arctic Circle and should be affected by the band of subpolar lows and polar easterlies. However, it is close enough to the midlatitudes such that the transient pressure systems should also impact the area bringing atmospheric boundary layer gradient winds with them. An overview of cyclones and anticyclones, and air masses are presented in the following section, with relevant pressure systems to Hurricane Alley discussed in Chapter 2.
A1.2 Weather system basics

A1.2.1 Cyclones and anticyclones

While the general circulation model provides a useful planetary scale view, regional pressure and wind conditions are more complex with smaller pressure systems. High-pressure centres are regions where pressure is at a relative maximum. An anticyclone develops when a circular flow occurs around these centres (Stull 2017). High-pressure centres on the surface are also associated with high pressure aloft which leads to subsidence of air and divergence at the surface. Anticyclones are commonly associated with fair weather: clear skies, light winds, occasional light precipitation, and extreme temperatures (very hot in the summer and very cold in the winter) (McIlveen 1986; Ross 2013).

Surface highs at larger synoptic scales develop by three main mechanisms: general circulation (Section A1.3), monsoons, and transient Rossby Waves (Stull 2017). Monsoonal circulation represents the hemispheric-scale flow from oceans to continents in summer and continents to oceans in winter, although this effect is weaker outside of the tropics (McIlveen 1986, Ross 2013; Stull 2017). Anticyclones develop over the cooler ocean (continent) in summer (winter) resulting in moist maritime (dry continental) air masses flowing over land and rainy (dry) conditions. With respect to transient Rossby waves, anticyclones develop in the midlatitudes to the east of ridges where the Rossby waves meander poleward and divergence occurs.

Low-pressure centres are regions where pressure is at a relative minimum due to surface heating causing warm, rising air (Ross 2013). A cyclone develops when circular, converging flow occurs around these centres via the atmospheric boundary layer gradient wind (section A1.2) (Stull 2017). In contrast to anticyclones, cyclones are associated with
turbulent weather: cloudy conditions, strong winds, and heavy precipitation. Extratropical or mid-latitude cyclones commonly develop at the Polar front where the cold Polar easterlies and warmer mid-latitude westerlies meet. The development (cyclogenesis) and dissipation (cyclolysis) of mid-latitude cyclones largely build on the early 20th Century Polar front theory (Fig. A3) (Atkinson 1981; McIlveen 1986; Ross 2013; Stull 2017). Extratropical cyclones typically exist for between a few days and a week.

A1.2.2 Air masses

Air masses are widespread, relatively homogenous regions of air on the order of 1,000 km wide occupying the lower atmosphere (Wahl et al. 1987; Ross 2013; Stull 2017). That is, the temperature, moisture, stability, cloudiness, and other characteristics are similar throughout an air mass. They form when air remains stationary over a surface long enough for it to obtain characteristics similar to the underlying surface. Air masses are labelled with a two (or sometimes three) letter abbreviation to describe their characteristics. The first letter is either ‘c’ or ‘m’ which identifies whether the air mass formed over land (continental) or water (maritime). Continental air masses are dry, while maritime air masses are moist. The second letter represents the origin and temperature of the air: T for tropical (warm), P for polar (cold), A for Arctic (very cold). For example, cold and dry cP air masses may form over northern North America, and cool and moist mP air masses may develop over the Bering Sea and Gulf of Alaska.
Figure A3. Stages of Northern Hemisphere extratropical cyclone development. Cyclogenesis occurs as follows: a horizontal ‘kink’ or wave develops at a stationary front due to divergence aloft (a), the divergence aloft results in rising air and a surface low with cyclonic winds and warm and cold fronts (b), further strengthening as the warm front displaces the colder air (c). Cycolysis occurs as follows: near peak cyclone intensity, an occluded front develops as the cold front catches up to the warm front (d); the cyclone weakens (e); and dissipates as the front and low pressure become disconnected (f). Fig. 13.3 from Stull (2017) redistributed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
Appendix 2: SITE CONDITIONS

A2.1 Transport Canada (TC) stations

The TC weather stations installed as part of the NTAI at kms 421 (Fig. A4) and 8.5 (Fig. A5) are of interest to this project. Both stations are at elevations high enough to be within the alpine tundra. Km 421 is located on the western slope of Richardson Mountains in the Glacier Creek area, 30 km south of Hurricane Alley and 15 km north of the Arctic Circle (Fig. 1.1b; Idrees et al. 2015). Km 8.5 is located on the eastern slope of Richardson Mountains near the territorial border, just downslope of areas that experience the strongest winds. Mosses and lichens are the dominant vegetation types at each site with some dwarf birch shrubs near km 8.5 (Idrees et al. 2015; Stockton et al. 2019; Kokelj et al. 2022).

Snow depths measured in mid-March 2015 were 1.0 and 1.2 m at kms 421 and 8.5, respectively (Idrees et al. 2015; Stockton et al. 2019).

A2.2 Hurricane Alley stations

A total of nine weather stations within the Hurricane Alley area were studied within this thesis: ECCC Rock River, NorthwesTel North Vittrekwa, and the seven new stations installed by TEB and Northern Avcom Ltd. Due to the high winds encountered at most of these sites and their close proximities, site conditions are relatively similar. Vegetation on middle and upper slopes of Richardson Mountains is shrub and heath tundra, with sedge tussocks on the lower slopes (Smith et al. 2004, p. 105). Near km 452, vegetation is tussock sedge (Humphries 2020). Near km 456, tussock sedge is less common with lichen, tall grasses, and shrubs covering the ground. Vegetation heights at these two locations were on average between 7-12 cm in June 2019. Areas with stronger (weaker) winter winds result
Figure A4. The TC weather station at YT km 421. Photograph taken in March 2022 facing northeast.
Figure A5. The TC weather station at NT km 8.5. Photograph taken in March 2022 facing northwest.
in a shallower (deeper) and denser (less dense) snowcover (Humphries 2020). In March 2019, the snowpack in undisturbed tundra near km 456 had average depths and densities of 30 cm and 0.23 g cm$^{-3}$. Comparatively, near km 452 where the winds are weaker, these values were 90 cm and 0.34 g cm$^{-3}$.

During the March 2022 field site visit, the snowpack was shallow and dense enough to walk directly to most stations without snowshoes. This was not the case at km 450 where snowpacks were deeper and less dense (similar to kms 421 and 8.5). Km 453 and North Vittrekwa were not visited due to their distance from the road, but the snowpack properties were likely similar to kms 454 and 465. Images of the stations at kms 450, 454, 457, Rock River, 459, 465, and 4 are presented in Figs A6 through A12. In addition to the deeper and lighter snowpack near km 450, taller shrubs were visible poking out of the snowpack, and isolated trees were present nearby (Fig. A6). A denser stand of trees is also located east of this station (outside the left frame in Fig. A6). At km 454, the snowpack was noticeably shallower and denser, and low shrubs and tall grasses were visible, especially upslope of the station (Fig. A7). Near km 457 and Rock River, the snowpack was even shallower with vegetation easily visible and some nearly bare patches over rockier ground (Figs A8, A9). At km 459, conditions were similar to km 454, although shrubs were absent (Fig. A10). Near the territorial border, snowpacks appeared slightly deeper and no vegetation was visible (Fig. A11). The station components had a significant buildup of snow and ice (Fig. 3.11). At km 4, the snowpack was again shallow with visible vegetation both upslope and downslope of the station (the latter visible in the right background of Fig. A12). However, the snowpack in the immediate vicinity of km 4 is disturbed since this is where highway crews plow the snow off the road.
Figure A6. The new weather station at YT km 450. Photograph taken in March 2022 facing south.
Figure A7. The new weather station at YT km 454. Photograph taken in March 2022 facing northeast.
Figure A8. The new weather station at YT km 457. Photograph taken in March 2022 facing southwest.
Figure A9. ECCC Rock River. Photograph taken in March 2022 facing southwest.
Figure A10. The new weather station at YT km 459. Photograph taken in March 2022 facing northeast.
Figure A11. The new weather station at YT km 465. Photograph taken in March 2022 facing west.
Figure A12. The new weather station at NT km 4. Photograph taken in March 2022 facing northeast.
### Appendix 3: DATA TABLES

**Table A1.** Mean wind speed (km h\(^{-1}\)) by month in the ECCC Rock River wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Blank cells are missing all hourly data, while cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

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Table A2. Total number of hours of gale-force winds (50-88 km h\(^{-1}\)) in the ECCC Rock River wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Values in bold are months with no missing hourly data. Blank cells are missing all hourly data, while cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

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Mean 66.8 42.7 81.6 77.9 83.8 49.9 12.7 32.3 53.4 78.6 70.6 67.9 776.2
Table A3. Following Table A2 but for storm-force winds (89-118 km h⁻¹).

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Table A5. Total number of high wind events by season and year in the ECCC Rock River wind record. For this table years run from June to May. Values in red contain months where the “3 and 5” rule is not met, and the number of events is potentially undercounted.

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Table A6. Frequency of hours of gale-force winds (50-88 km h\(^{-1}\)) in high wind events identified in the ECCC Rock River wind record (July 2006-March 2023).

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<th>Cumulative Frequency (%)</th>
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Table A7. Following Table A6, but for storm-force winds (89-118 km h\(^{-1}\)).

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Table A8. Monthly least square linear regressions between hourly wind speeds at ECCC Rock River and km 457.

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Table A9. Mean wind speed (km h$^{-1}$) by month in the NTAI km 421 wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

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Table A10. Total number of hours of gale-force winds (50-88 km h\(^{-1}\)) in the NTAI km 421 wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Values in bold are months with no missing hourly data. Cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

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Table A11. Mean wind speed (km h\(^{-1}\)) by month in the NTAI km 8.5 wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Blank cells are missing all hourly data, while cells marked with “-” are not included in the record (either preceding its beginning or not yet available).

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Table A12. Total number of hours of gale-force winds (50-88 km h\(^{-1}\)) in the NTAI km 8.5 wind record. Values in red fail the “3 and 5” rule and are not used in calculations of the monthly means. Values in bold are months with no missing hourly data. Blank cells are missing all hourly data, while cells marked with “-” are not included in the record (either preceding its beginning or occurring after the analysis took place).

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Table A13. High wind events and their characteristics identified in the NTAI km 8.5 wind record (Feb. 2014-Aug. 2022). Values in red identify sections of the record where wind speed data was potentially erroneous, and events were missed. A significant period of missing data occurred between September 2018 and June 2019. Only two of these events were also captured at ECCC Rock River (in April 2018 and March 2020).

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Table A14. Mean monthly wind speeds (km h\(^{-1}\)) at the seven new meteorological stations in the Hurricane Alley area and ECCC Rock River. Values in red fail the “3 and 5” rule. No wind speed data is available for the months of February through June 2022 at km 4 due to sensor damage.

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Table A15. Total monthly hours of gale-force mean winds at the seven new meteorological stations in the Hurricane Alley area and ECCC Rock River. If storm-force winds are present in the record, they are recorded in brackets next to the total hours of gales. Values in red fail the “3 and 5” rule, while values in bold contain no missing hourly data. No wind speed data is available for the months of February through June 2022 at km 4 due to sensor damage.

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Table A16. Total monthly hours of gale- and storm-force maximum winds at the seven new meteorological stations in the Hurricane Alley area. If storm-force winds are present in the record, they are recorded in brackets next to the total hours of gales. Values in red fail the “3 and 5” rule, while values in bold contain no missing hourly data. No wind speed data is available for the months of February through June 2022 at km 4 due to sensor damage.

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Table A17. Correlation metrics for station pairs in the Hurricane Alley area when mean wind speeds are gale force or greater (Dec. 2021-Mar. 2023). Km 450 has been omitted from this table as only one hour of gale-force wind was recorded there. Columns represent the independent variable when gale-force winds are recorded at that station, while rows represent the dependent variable when gale-force winds are recorded at the independent station.

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Table A18. Wind speed (km h⁻¹) and direction (°) metrics for an easterly event that occurred between 27 and 28 January 2022. Gale-force wind speeds or greater and associated direction are shown in bold. Maximum wind speeds and directions are not provided for ECCC Rock River.

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Table A20. Wind speed (km h\(^{-1}\)) and direction (\(^{\circ}\)) metrics for a westerly event that occurred between 28 and 29 January 2023. Gale-force wind speeds or greater and associated direction are shown in bold.

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Table A22. ECCC Rock River weather metrics during a strong easterly event occurring between 15 and 16 February 2014. Gale-force wind speeds or greater and associated direction are shown in bold. Some hourly pressure data is missing.

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