# A Micrometeorological Study of an Abrupt Treeline on Pike's Peak

A Thesis

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Bachelor of Arts

By

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## Introduction

High-altitude treelines are a global phenomenon. Treelines are either an abrupt line or a broad ecotone that trees are unable to grow above. The factors that determine various treelines are still debated. Körner (1998) came to the conclusion that treeline is determined by growing season air temperatures, known as the growth limitation hypothesis. Soil temperatures were used as a proxy for air temperatures. At 30 treelines, growing season mean temperatures ranged between 5 and 8°C (Körner and Paulsen 2004). Trees did not grow above the elevation where this range of mean soil temperatures occured. However, many view this conclusion as over-simplified. Grace et al. (2002) argues that it is not clear what the main process that limits growth is globally, citing other possible limiting factors such as nutrient-availability, seed-viability, seed dispersal, and grazing animals. Sky exposure is another possible limiting factor; micro-site facilitation in high stress environments like treeline can enable tree growth by limiting sky exposure (Germino and Smith 1999, Germino et al. 2002, Maher and Germino 2006). Proximity to neighbors is beneficial above treeline and detrimental below (Harsch and Bader 2011). Other factors that may limit treeline are snow depth (Holtmeier and Broll 1992, 2010, 2012), human influence, topography-induced extreme wind (Körner 2007), snow avalanche, debris flows (Alftine and Malanson 2004), geology, geomorphology, turf exfoliation (Butler et al. 2007), and treeline form (Harsch and Bader 2009, 2011).

As a result of climate change, regional warming is causing many treelines to increase in elevation worldwide (Harsch et al. 2009). However, not all treelines are advancing. Harsch et al. (2009) connected the probability of a treeline to advance with the spatial pattern of the trees at treeline. Diffuse treelines were found to be much more likely to advance than abrupt, krummholz, and island treelines. Only 25% of abrupt treelines are advancing (Harsch and Bader 2009). There is a general consensus that diffuse treelines are growth limited (Harsch and Bader 2011). There is less agreement on the mechanism limiting abrupt treelines, unless there has been a disturbance. Harsch and Bader (2011) propose that seedling mortality is the limiting factor at abrupt treelines, not dieback nor growth limitation. Abrupt treelines were more likely to advance if they experienced winter warming, not yearly mean warming or summer warming (Harsch et al. 2009). Harsch and Bader (2011) propose that the mechanism that causes seedling mortality above abrupt treelines is permafrost or wind.

The high elevation of treelines in the Rocky Mountains is subject to intense solar radiation during the day and extreme radiative cooling at night due to a weak greenhouse gas effect (Oke 1987). During the day, the ground is warmed by this intense solar radiation, which leads to strong radiative heating of the air above the ground. At night, the exposed ground rapidly loses heat to the sky and dramatically cools the air above the ground, resulting in strong nightly temperature inversions. Temperatures below 5°C can inhibit tree growth (Grace et al. 2002). Opening of buds and germination of seeds only occurs at and above 6°C (Grace et al. 2002). The combination of intense solar radiation during the day and radiative cooling at night can lead to low temperature photoinhibition of photosynthesis, reducing tree growth even when temperatures are warm during the day (Germino and Smith 1999, Germino et al. 2002).

Our study transect is an abrupt treeline that has slowly increased in elevation since the early 1900's (Neumeyer 2016). The abrupt treeline in our study site may be advancing as a result of timberline acting as a shelterbelt, ameliorating the conditions for seedling establishment. Shelterbelts are used in agriculture to benefit crops in the eddy created on the leeward side of a shelterbelt (Kort 1988). Shelterbelts can reduce wind which can decrease crop damage, decrease erosion, increase retention of snow, and increase daytime temperatures (Kort 1988). Air flow at treeline is a mechanism that has not yet been researched in-depth. How air flow impacts the microclimate at treeline is a necessary component to understanding the dynamics of the advancing abrupt treeline in our study site. An eddy forming uphill of treeline would drastically impact temperature and vapor pressure in the forest-tundra ecotone, which could offer an explanation for the increasing elevation of the abrupt treeline. The aim of this study was to determine if an eddy exists on the leeward side of timberline, and if an eddy exists, determine if the eddy structures the microclimate at treeline.

## Methods

### *Location:*

The research transect encompassed the forest-tundra ecotone on a North-West (NW) facing slope at treeline on the western slope of Pike's Peak in Pike National Forest between 3500 and 3550 meters above sea level (Figure 1). The angle of slope was about 28° (Figure 2). The study transect was approximately 100

**Figure 1 – Satellite image of the location of the study transect on the western slope of Pike's Peak in Pike National Forest, west of Colorado Springs (Google Earth 2011).**

by 30 meters (Figure 3). The transect was composed of Engelmann spruce. There was no shrub belt; the treeline transitioned directly from forest to tundra. The tundra above was composed of uniformly vegetated decomposing Pike’s Peak Granite.

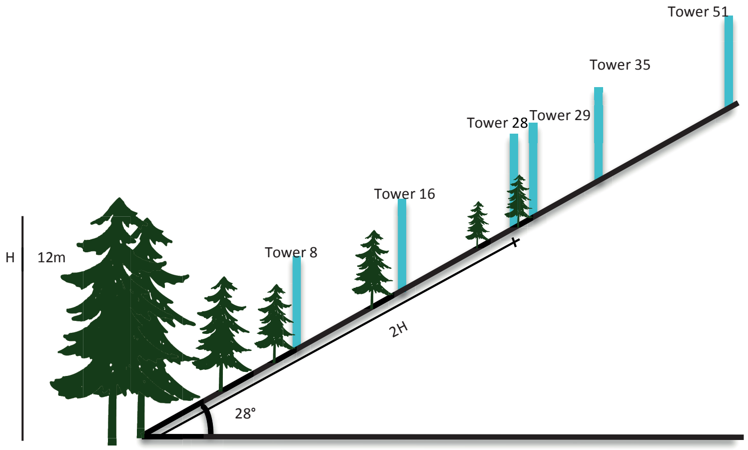
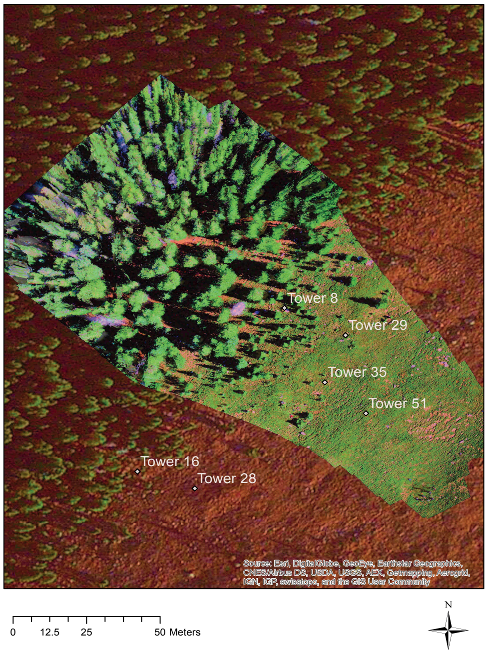


**Figure 2 – Cross-section of the study site, including the six tower locations. They are named by their distance in meters from treeline.**

***Remote sensing:***

An orthophoto was created of the study area from images taken from DJI’s S1000, an 8-propeller drone. The photos were taken by a Canon Powershot SX260 HS. The intervelometer was programmed to take a photo every 3 seconds. The drone flew at a constant elevation, which translates to 20 meters above the highest site and 70 meters above the lowest site due to the slope of the study site. The photos were then stitched together using a photoscan software, Agisoft (Figure 3).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

**Figure 3 – Aerial view of the study site, including the six tower locations. They are named by their distance in meters from treeline. Agisoft was used to stitch together photographs taken from DJI’s S1000 drone.**

### *Snow data:*

In mid-June we recorded the outlines of the remaining snow patches with Trimble's GeoExplorer 6000 Series global positioning system (GPS). We used Trimble's Pathfinder Office to correct the data of the location of the snow patches, using the nearest base station. The snow patches were superimposed onto the orthophoto of the study area using ArcMap 10.3.1.

### *Tree form data:*

The trees in the treeline ecotone were observed to see if they exhibited signs of ice crystal blasting caused by high-speed winter winds. A Trimble GPS was used to mark one line of the lowest asymmetrical, wind-affected trees and another line to mark the highest symmetrical, unaffected trees. These lines were mapped onto the orthophoto of the study area using ArcMap.

At and above the line of wind-affected trees, the trees were further analyzed to determine the predominant winter wind direction based on the side of the tree showing the most missing needles and abrasion caused by ice-blasting. The wind direction at each tree was also mapped onto the orthophoto using ArcMap.

### *Wind Direction:*

Onset's Wind Direction Smart Sensor and HOBO Data Loggers were used to record the wind direction at 6 meters above the ground every 10 seconds at each tower for about 2-day intervals from mid-June until the end of August. The towers are shown in Figure 3.

We divided the wind directions into 20° ranges (e.g. [0°-20°), [20°-40°), [40°-60°), etc.) to determine the predominant wind direction. We combined the 30-minute averages of all the wind direction data from six towers at 8, 16, 28, 29, 35, and 51 meters from the old growth trees, respectively (hereafter referred to as Tower 8, Tower 16, Tower 28, Tower 29, Tower 35, and Tower 51). Additionally we used the *openair* package in R to further analyze the wind data. These six towers recorded wind direction at 6 meters, wind speed at multiple heights, relative humidity at multiple heights, and temperature at multiple heights for at least two days each at six locations in the treeline ecotone.

### ***Wind Speed:***

The wind speed profile was measured at multiple locations in the ecotone between the forest and the tundra using Onset's Wind Speed Smart Sensors and HOBO Data Loggers at 0.1, 0.5, 1.5, 2.6, 3.7, 6, and 9 meters off the ground at each tower location.

Tower 8 and Tower 16 were in the lowest, most forested portion of the ecotone (Figure 3). Tower 28 and Tower 29 were in the middle of the ecotone, where it becomes almost completely unforested except for a few seedlings (Figure 3). Tower 35 and Tower 51 were in the tundra above the treeline (Figure 3).

The 9-meter anemometer was essential for further analysis because it was unaffected by the trees and could be used as a representation of the ambient air speed. We used the 9-meter wind velocity at each tower to normalize the data from all the lower anemometers. We divided the wind speed by the ambient wind speed, which yields a value greater than 1 if greater than the ambient wind speed, equal to 1 if equivalent to the ambient wind speed, and less than 1 if less than the ambient wind speed. This allowed us to compare the data between towers. The highest anemometer on Tower 16, 28, and 35 was 6 meters off the ground so we used the values at 3.7 and 6 meters to create a logarithmic trendline to estimate the value at 9 meters, which was then used to normalize the data.

### ***Temperature and vapor pressure data:***

Temperature and relative humidity were also measured at each tower at 0.1, 0.5, 1.5, 2.6, 3.7, 6, and 9 meters above the ground using Onset's Temperature and Relative Humidity Sensor with Radiation Shields and HOBO Data Loggers. The relative humidity and temperature data was used to calculate the vapor pressure at every time interval at each tower. Temperature and vapor pressure were also normalized to the 9-meter sensor. The highest sensor on Towers 16 and 28 was 6 meters off the ground so a logarithmic curve was also used to estimate the temperature and relative humidity at 9 meters.

### ***Spline interpolation of the data:***

Spline interpolation was used in ArcMap 10.3.1 to estimate the values in between the towers based on the normalized profiles for wind speed, temperature and vapor pressure at each tower and their distances from the 12- to 14-meter old growth trees. Spline interpolation is good for estimating surfaces that vary smoothly such as wind speed, temperature, and vapor pressure (Childs 2004).

## Results

### *Wind Direction and Tree Form*

The treeline ecotone transitions abruptly from forest to tundra and is perpendicular to the slope. The old growth trees transition to saplings and seedlings and then to alpine tundra within 30 meters (Figure 4). The trees closest to timberline did not display signs of wind abrasion and had symmetrical branches. With increasing elevation the trees became more affected by wind and less symmetrical. The timberline created a distinct line from the lowest asymmetrical trees (Figure 4). The distance from timberline to the asymmetrical trees was approximately 30 meters, which is two times the height of the old growth trees that stand at 12-14 meters tall (Figure 2).

In mid-June some snow patches remained in the forest-tundra ecotone. The snow patches were almost exclusively between the asymmetrical line and the timberline (Figure 4). The predominant

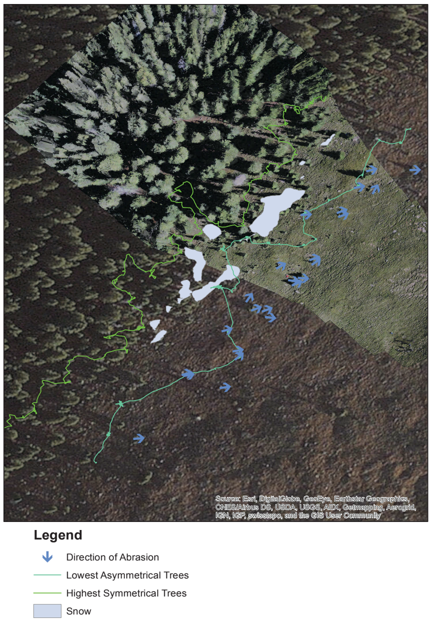


**Figure 4 – Direction of wind abrasion arrows (blue), lowest asymmetrical trees line (cyan), timberline (green), mid-June snow patches overlaid on orthophoto of the study area (white).**

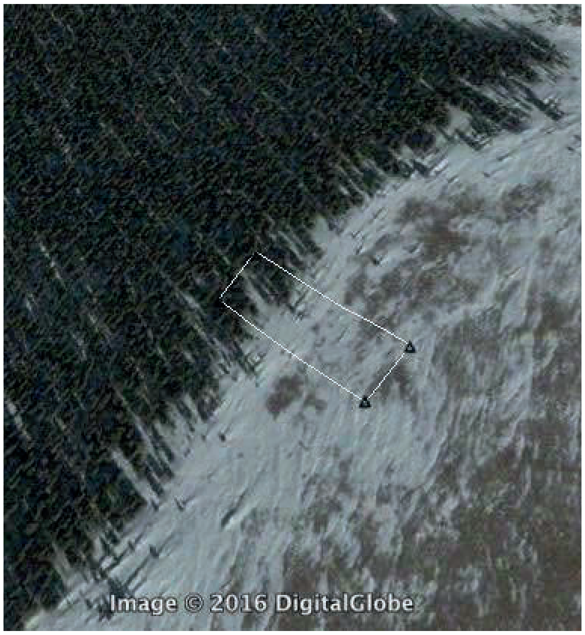


**Figure 5 – The study transect shown on a Google Earth image of the study transect with snow accumulation (Google Earth).**

abrasion-causing winds appeared to be winds parallel to treeline and winds slightly skewed uphill based on the asymmetry of the trees at and above 2H (Figure 4). Snowdrifts visible in a Google Earth image from 2006 show accumulation on the leeward side of trees in the treeline ecotone reflecting the same predominant wind direction as the wind abrasion patterns on the asymmetrical trees (Figure 5).

The average wind direction during the summer was very similar to the wind direction during the winter based on the abrasion patterns, and snow drifts. The predominant wind direction throughout the 10-week sampling period was between 180° and 240° (Figure 6). The wind direction was within this range 59% of the time: 19% was parallel to treeline (180- 200°), 23% was skewed uphill between 200° and 220°, and 17% was skewed uphill between 220° and 240° (Table 1). The wind direction is parallel more often at night than it is during the day. Although winds came from 90-180° less frequently, the winds the came within 90-180° had much higher wind speeds (Figures 6).

| Wind Direction | Frequency | Relative Frequency |
|---|---|---|
| 0-20 | 19 | 0.02 |
| 20-40 | 23 | 0.03 |
| 40-60 | 46 | 0.05 |
| 60-80 | 15 | 0.02 |
| 80-100 | 8 | 0.01 |
| 100-120 | 14 | 0.02 |
| 120-140 | 17 | 0.02 |
| 140-160 | 26 | 0.03 |
| **160-180** | **76** | **0.09** |
| **180-200** | **164** | **0.19** |
| **200-220** | **198** | **0.23** |
| **220-240** | **146** | **0.17** |
| **240-260** | **57** | **0.07** |
| 260-280 | 13 | 0.02 |
| 280-300 | 5 | 0.01 |
| 300-320 | 7 | 0.01 |
| 320-340 | 4 | 0.00 |
| 340-360 | 6 | 0.01 |
| Total | 844 | 1.00 |

**Table 1 – Frequency and relative frequency of wind directions during the 10-week study period.**

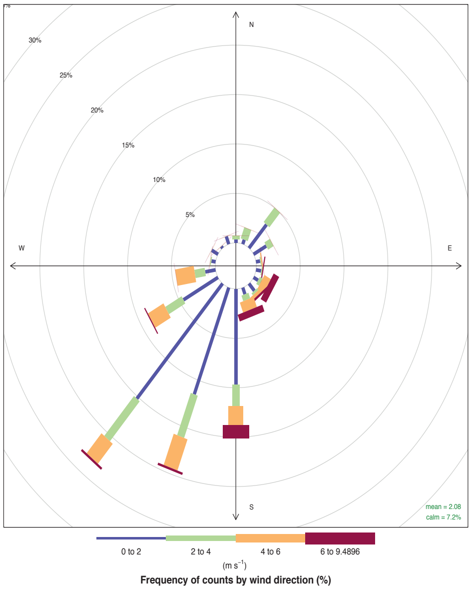


**Figure 6 – Wind rose made using openair package in R showing percent wind direction and wind speed.**

***Wind Profiles:***

The wind profiles measured at varying distances from timberline appear to be dependent on wind direction. The spline interpolations of the wind speed profiles also show distinct stories based on wind direction (Figure 7). When the wind flows parallel to treeline, the 0.70 isovel that represents 70% of the ambient wind speed decreases exponentially as the distance from old growth forest increases (Figure 8). The isovel drops smoothly from 7.5 meters at Tower 8 to 1.0 meter at Tower 51. A power function fits the 70% isovel best ($R^2$=0.96), but is theoretically inaccurate; as the distance from old growth approaches zero, the height of the isovel would approach infinity. An exponential function still fits the data well ($R^2$=0.88) and makes theoretical sense, but underestimates the height of the 70% isovel at

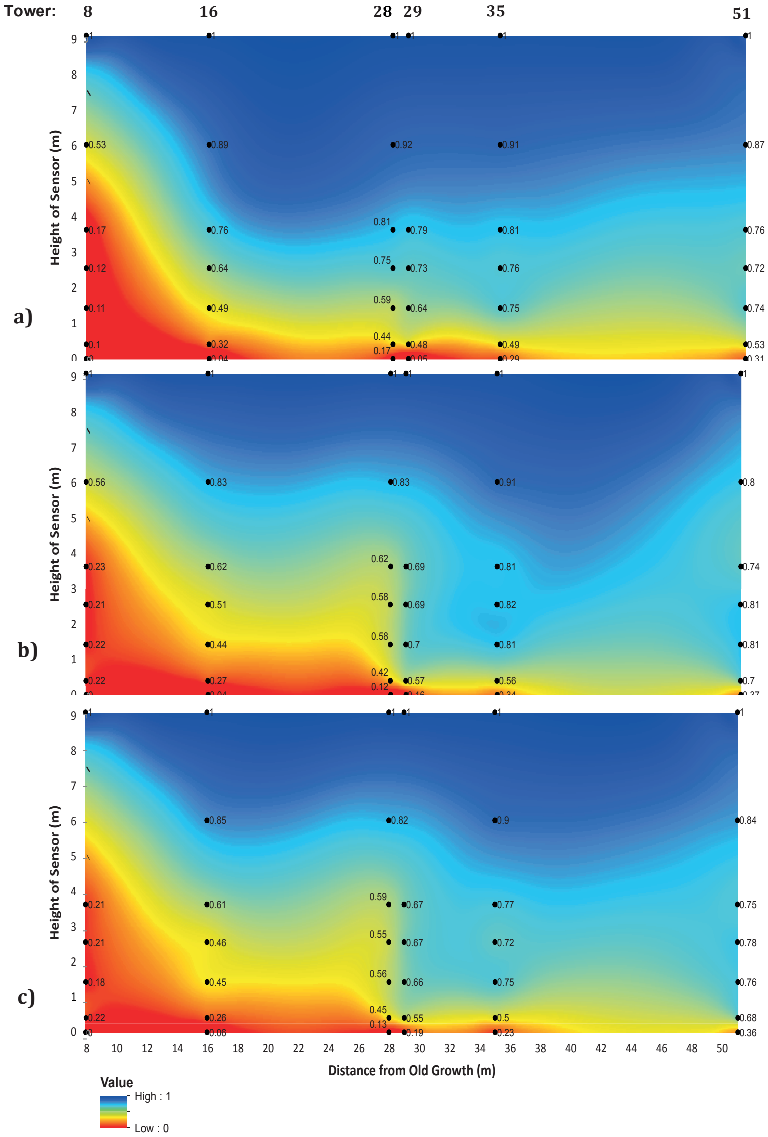


**Figure 7 – Spline interpolations made using ArcMap 10.3.1 based on normalized wind speed profiles at the 6 tower locations based on 7 anemometers at 0.1, 0.5, 1.5, 2.6, 3.7, 6.0, and 9.0 meters above the ground, respectively: a) spline interpolation with wind was flowing cross-slope, parallel to treeline (180-200°), b) spline interpolation with wind flow skewed uphill (200-220°), c) spline interpolation with wind flow skewed slightly more uphill (220-240°). The black lines represent the 70% and 30% isovels.**

Tower 8 (Figure 8a). The 70% isovel stacks neatly over the 30% isovel when the wind flow is parallel to treeline. The 30% isovel also decreases exponentially with distance from old growth. A power function fits the data with an $R^2$ value of 0.94, and an exponential function fits the data with an $R^2$ value of 0.86 (Figure 8a).

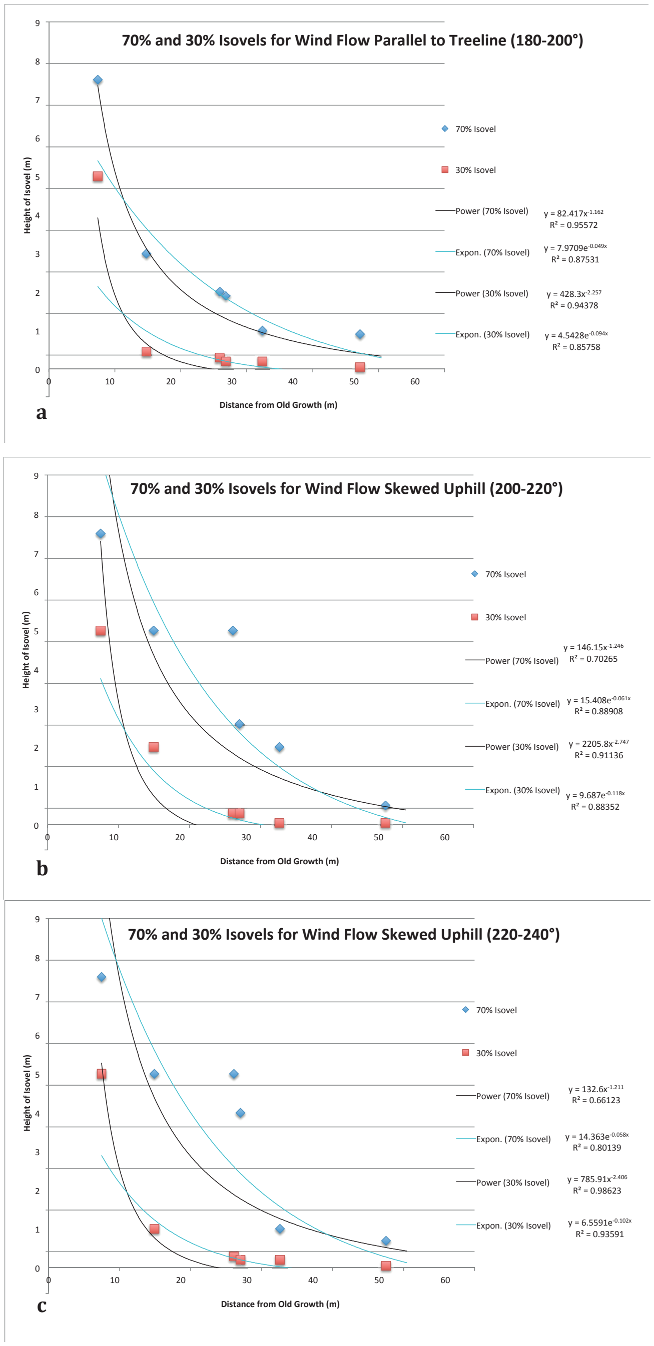


**Figure 8 – The 70% and 30% of ambient wind speed isovels plotted against distance from the old growth trees: a) 70% and 30% isovels during parallel flow (180-200°), b) 70% and 30% isovels during slightly upslope winds (200-220°), c) 70% and 30% isovels during slightly more upslope winds (220-240°).**

The 70% isovel behaves much less smoothly when the wind flow is skewed uphill. The isovel remains level between 16 and 28 meters from the old growth, and then sharply decreases after 2H (Figure 8a and 8b). Power functions fit the 70% isovels well for 200-220° ($R^2$ = 0.70) and 220-240° flow ($R^2$ = 0.66), however exponential functions fit the isovels better ($R^2$ = 0.89 and $R^2$ = 0.80, respectively). For both the power and exponential functions there is one outlier for 200-220° flow and two outliers for the 220-240° flow that are higher off the ground than the trendlines predict. The 30% isovel remains smooth when the wind flow is skewed uphill for both 200-220° flow and 220-240° flow (Figure 8b). For 200-220° flow both the power and exponential functions had an $R^2$ value greater than 0.88. For 220-240° flow both the power and exponential functions had an $R^2$ value greater than 0.94 (Figure 8c).

Tower 8, which is surrounded by the largest trees, displays a wind profile characteristic of forested flow (Oke 1987). The wind speed slows dramatically from above the canopy at 9.0 meters to below the canopy at 6.0 meters. For all profiles from 180-240°, the 70% isovel is between 6.0 and 9.0 meters, the 30% isovel is between 3.7 and 6 meters, and the 0.1 meter anemometer slows to zero (Figure 7).

Tower 16 is in between the elevation of the old growth trees and the elevation of the asymmetrical trees. There is a layer of highly protected air near the ground, but the layer is about 4 times shallower than at Tower 8. The profiles at Tower 16 are more dependent on wind direction than the wind profiles at Tower 8. For parallel flow the 70% isovel is between 2.6 and 3.7 meters and the 30% isovel is between 0.1 and 0.5 meters (Figure 8a). Whereas for 200-240° askew flow, the 70% isovel is much higher, between 3.7 and 6.0 meters, and the 30% isovel is also higher, between 0.5 and 1.5 meters (Figure 8b and 8c). The 70% and 30% isovels both increase, which reflects slower wind speeds higher off the ground during askew flow than during parallel flow.

Tower 28 and Tower 29 are at the transition point from timberline to asymmetrical trees. Their wind profiles also exhibit dependence on wind direction. For parallel flow, the 70% isovel is between 1.5 and 2.6 meters and the 30% isovel is between 0.1 and 0.5 meters (Figure 8a). For 200-240° askew flow, the 70% isovel is much higher, between 3.7 and 6.0 meters, and the 30% isovel is the same, between 0.1

and 0.5 meters (Figure 7b and 7c). The 70% isovels were higher above the ground for slightly skewed flow than for parallel flow.

The wind profiles of Tower 35 and Tower 51, which are both in the unforested tundra, are nearly identical for both parallel and skewed flow. The wind speeds near the ground are much closer to the ambient wind speed than at any of the other towers. The 70% isovel is between 0.5 and 1.5 meters and the 30% isovel is between 0 and 0.1 meters for 180-240° flows (Figure 7).

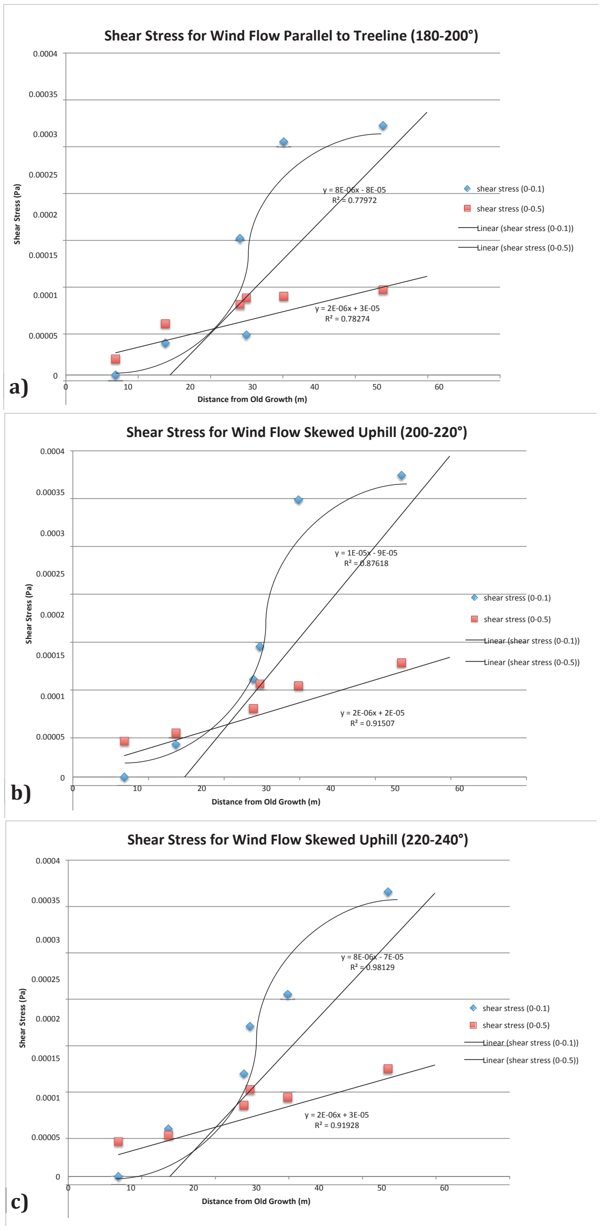


**Figure 9 – The shear stress between the ground and 0.1 meters and the ground and 0.5 meters plotted against distance from the old growth trees: a) shear stress during parallel flow (180-200°), b) shear stress isovels during slightly upslope winds (200-220°), c) shear stress during slightly more upslope winds (220-240°).**

For all wind directions between 180 and 240° shear stress between 0 and 0.1 meters and between 0 and 0.5 meters increases as the distance from old growth increases (Figure 9). The shear between the ground (assumed to be 0 $ms^{-1}$) and 0.1 meters seems to fit a logistic curve, crossing a threshold at the transition point to unforested tundra. The increasing shear stress that begins above 2H at the transition to tundra is also evident in the Google Earth image that shows snow accumulating within 2H of the old growth, but mostly scoured away above 2H (Figure 5). The shear between the ground and 0.5 meters has a more linear relationship with distance from timberline.

The shear stress between 0.1 and 1.5 meters still shows a positive relationship with distance from old growth (Figure 10), however the relationship is not nearly as strong a correlation as was shown between 0 and 0.1 meters and the 0 and 0.5 meters. During all three wind direction intervals the shear stress is the lowest 8 meters from timberline because all of the air was much slower than the ambient air temperature under 3.7 meters. Between 16 and 35 meters from timberline the shear stress generally increased with distance from timberline. The biggest outlier during all 3 intervals, other than the expected Tower 8 value, was the shear stress at Tower 51. The value at Tower 51 is less than the linear trendline predicts because there is not a great difference between the wind speeds at 1.5 meters and the wind speeds at 0.1 meters because they are both similar to the ambient wind speed.

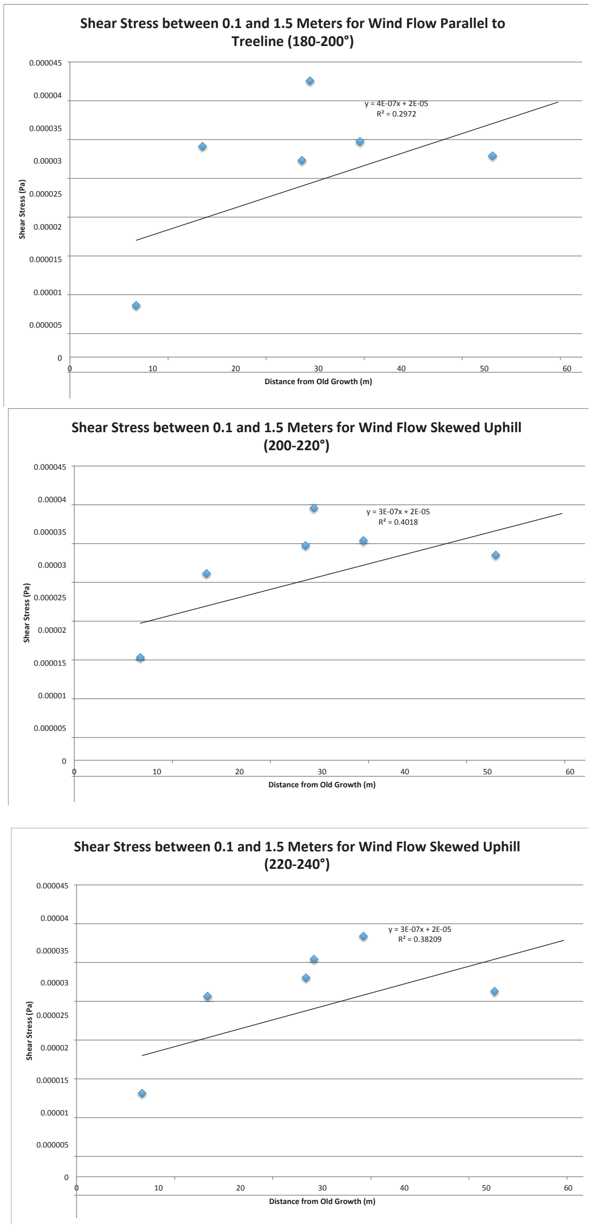


**Figure 10 – The shear stress between 0.1 meters and 1.5 meters plotted against distance from the old growth trees: a) shear stress during parallel flow (180-200°), b) shear stress isovels during slightly upslope winds (200-220°), c) shear stress during slightly more upslope winds (220-240°).**

### *Temperature:*

The nighttime (3:00-6:00) temperature data during parallel flow had distinct profiles from the profiles during skewed flow. During parallel wind flow the profiles in the transition from forest to tundra were fairly uniform (Figure 11a). There was a strong inversion at each of the six towers. The inversion is the strongest at 8 meters from the old growth because the sensor nearest the ground has the greatest difference from the ambient air temperature than at any of the other towers. 28 and 29 meters from the old growth had the weakest inversions because the lowest sensor is most similar to the ambient air temperature.

There was not enough data to create a spline interpolation of daytime temperature during parallel flow because the wind direction was

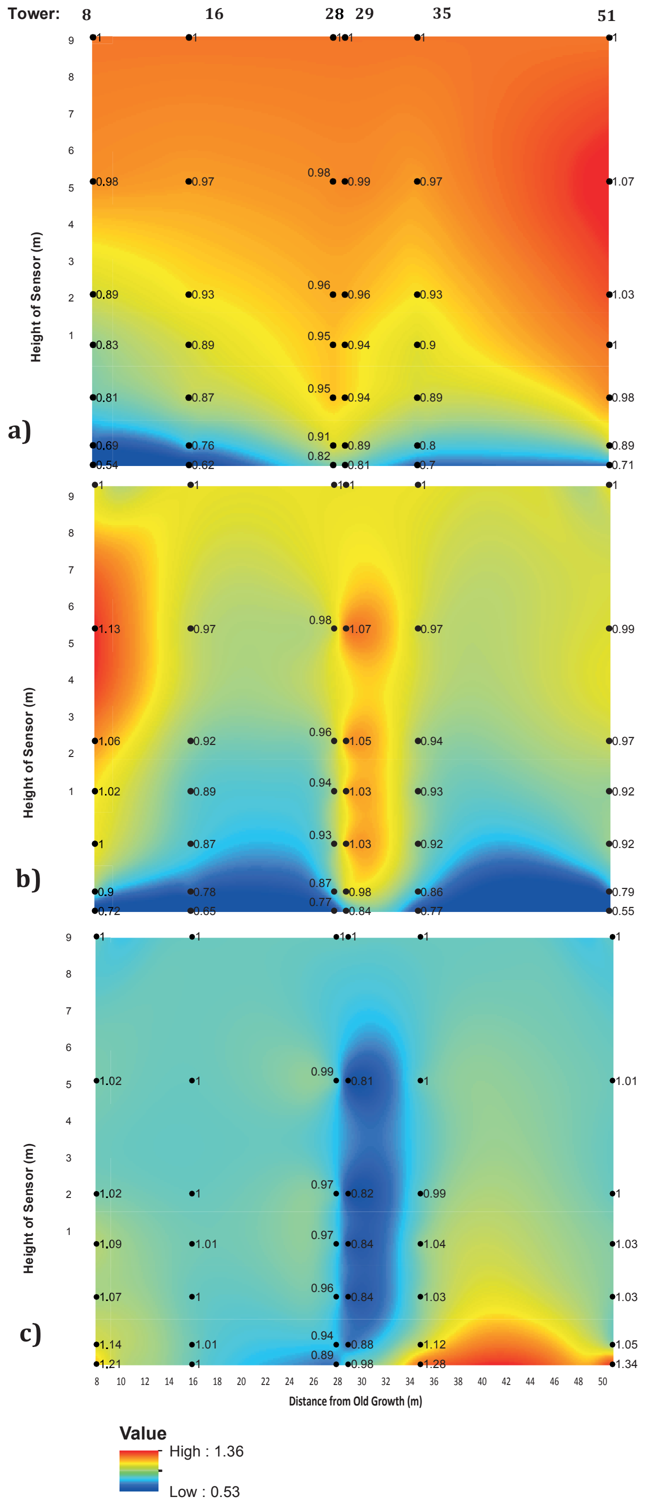


**Figure 11 – Spline interpolations made using ArcMap 10.3.1 based on normalized temperature profiles at the 6 tower locations based on 7 temperature sensors at 0.1, 0.5, 1.5, 2.6, 3.7, 6.0, and 9.0 meters above the ground, respectively: a) spline interpolation of night temperature with wind was flowing cross-slope, parallel to treeline (180-200°), b) spline interpolation of night temperature with wind flow skewed uphill (200-220°), c) spline interpolation of day temperature with wind flow skewed slightly more uphill (220-220°).**

not parallel to treeline as often during the day as it was during the night.

The nighttime temperature profiles during uphill skewed (200-220°) flow were clearly distinct from the nighttime temperature profiles during parallel flow (Figure 11b). The 0.1-meter sensor was always colder than all of the higher sensors, reflecting a temperature inversion. However, the profiles across the towers were by no means uniform. The most striking difference between parallel and askew flow is the warm pockets of air visible above 0.5 meters at Tower 8 and Tower 29. At Tower 8, the ambient air temperature was colder than the 2.6-, 3.7-, and 6.0-meter air temperatures (Figure 11b); this temperature profile is characteristic of a closed canopy system. This temperature regime is also visible in an infrared image taken before dawn at the study site (Figure 12). The forest is much warmer than the treeless tundra. Tower 16 and Tower 28 had a clearly visible inversion. Tower 29 had a profile not dissimilar to Tower 8; the 1.5-, 2.6-, 3.7-, and 6.0-meter air temperatures were warmer than the ambient air temperature (Figure 11b). Tower 35 and Tower 51 also had a clearly visible inversion (Figure 11b).

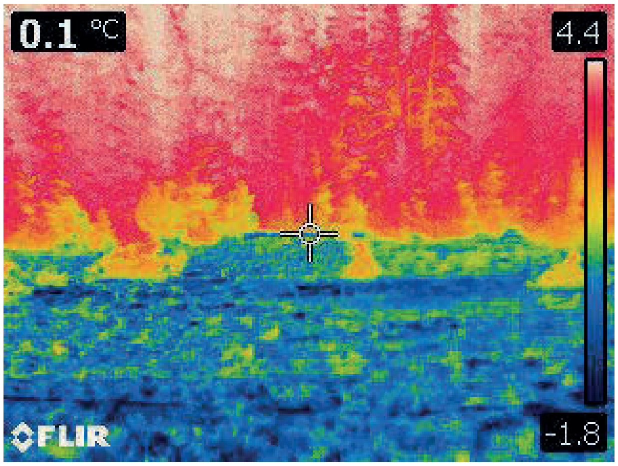


**Figure 12 – Infrared image taken looking downhill at the abrupt treeline taken before dawn in late August. The forest is much warmer than tundra.**

The daytime (9:00-12:00) temperature profiles during skewed flow were also not uniform across the treeline ecotone (Figure 11c). The spline interpolation was almost opposite of the nighttime askew flow spline interpolation other than the pocket of cold air between 0.1 and 0.5 meters at Tower 29. Towers 8, 35, and 51 exhibited normal daytime profiles; the temperature decreased with height above the ground (Figure 11c). Tower 16 was a very similar temperature from 0.1 to 9.0 meters (Figure 11c). Tower 29 was almost completely opposite of the nighttime temperature profile at the same tower, with air temperatures colder than the ambient air between 0.5 and 9.0 meters (Figure 11c).

***Vapor Pressure:***

The vapor pressure data is difficult to interpret without further data collection. All spline interpolations show high vapor pressures near the ground at Tower 8 and Tower 16 during parallel and skew flow at night and day (Figure 13). Tower 28, during parallel and skewed flow at night and day, has much lower vapor pressure than the ambient vapor pressure from 0.1 to 3.7 meters. Tower 29 has much higher vapor pressures between 0.1 to 3.7 or 6.0 meters compared to ambient vapor pressure. During 220-240° flow, the pocket of air with very low vapor pressures expands (Figure 13c).

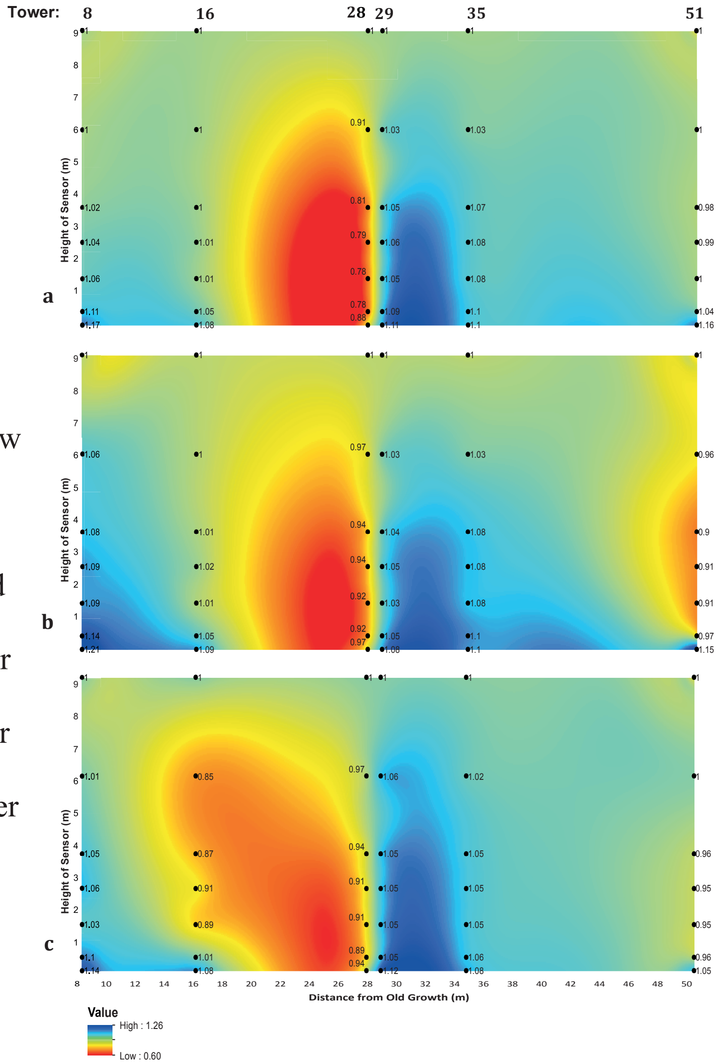


**Figure 13 – Spline interpolations made using ArcMap 10.3.1 based on normalized vapor pressure profiles at the 6 tower locations based on 7 relative humidity sensors at 0.1, 0.5, 1.5, 2.6, 3.7, 6.0, and 9.0 meters above the ground, respectively: a) spline interpolation with wind was flowing cross-slope, parallel to treeline (180-200°), b) spline interpolation with wind flow skewed uphill (200-220°), c) spline interpolation with wind flow skewed slightly more uphill (220-240°).**

## Discussion:

### *Wind*

Askew flow and parallel flow create distinct climatic features from one another. The wind came from 200-240° (slightly skewed uphill) 40% of the time during the study period. The wind flow was parallel to treeline 19% of the time. During parallel flow, slowed wind speeds were present near the old growth trees and near the ground (Figure 14). During askew flow there was a significantly larger pocket of slowed air extending over 2 meters above the ground and towards the tundra (Figure 15). The wind speed spline interpolations clearly show a larger area of slowed air during askew flow than during parallel flow (Figure 7). This larger pocket of slowed air may be an indication of the formation of an eddy on the leeward side of the old growth trees during askew wind flow. Eddies can be created on the leeward side of shelterbelts (Oke 1987), and the timberline may act as a shelterbelt. Eddies form immediately downwind of a barrier where a low-pressure zone forms, which draws air into a semi-stationary lee eddy (Oke 1987).

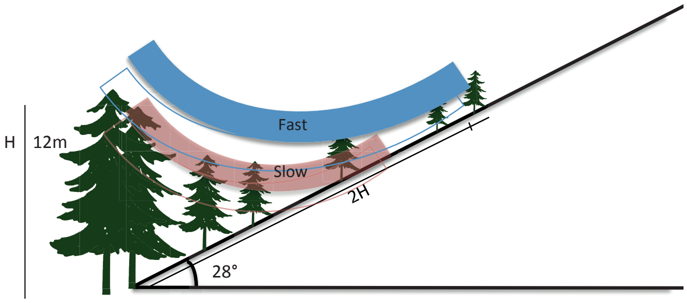


**Figure 14 – Schematic of wind flow during parallel flow.**

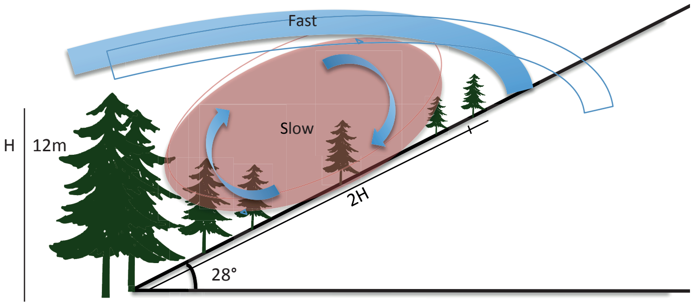


**Figure 15 – Schematic of wind flow during askew flow.**

A decrease in eddy size with decreasing obliquity of flow is another characteristic of modelled shelterbelt dynamics (Wang and Takle 1995). As the angle of the wind flow becomes more oblique, the sheltered area is reduced until it is near non-existent with parallel flow, except for friction from the shelterbelt itself (Oke 1987). Our data show an even bigger pocket of reduced wind speeds on the leeward side of timberline during more askew (220-240°) flow, than in slightly less askew (200-220°) flow (Figure 7b and 7c).

Our data also show reduced winds near timberline as a result of friction from the shelterbelt during parallel flow (Figure 7a). During parallel flow the 70% isovel decreases smoothly from timberline to the tundra. The isovel at each tower fits closely with both a power function ($y = \frac{a}{x^{1.2}}$) and a decreasing exponential function, which reflects slowed wind speeds only caused by the roughness of the forest. In askew flow the 70% isovel does not decrease smoothly from timberline to tundra, as the isovel remains relatively constant in height from timberline to 2H before decreasing dramatically upslope of 2H. When the askew wind profile is fitted with either a power or exponential function, there is one outlier around 2H during 200-220° wind where the height of the isovel is greater than expected, and two outliers around 2H during the more askew 220-240° flow (Figure 8). All of the outliers are higher off the ground than the power or exponential functions predict, which is reflection of slower wind speed higher above the ground than predicted during askew flow. This dynamic may reflect the presence of a semi-stationary eddy between timberline and 2H.

The quick recovery of wind speed during askew flow is another indication of an eddy. During askew flow the wind exhibits a quick recovery above 2H, similar to Oke's (1987) description of wind regaining speed quickly after a large wind speed reduction in the lee of a high-density shelterbelt because the ambient air speed is quickly drawn in (Oke 1987). Even though the treeline is not a high-density shelterbelt it may act as one; there is mostly likely not any through-flow as the forest extends over 500 meters downwind, which presents a significant resistance to flow. In askew flow wind speed recovers so quickly above 2H that it is equally fast near the ground as it for parallel flow, which has adjusted to the tundra for about 250 meters.

2H coincides with the elevation of the lowest asymmetrical trees and the transition to unforested tundra. The transition may be explained by an increase in shear stress. The shear stress between the ground and 0.1 meters increases abruptly around 2H during all flow from 180-240° (Figure 9). Upslope of 2H, the tundra had fairly normal wind profiles with high wind speeds and high shear near the ground. For parallel flow the wind had adjusted to the tundra for 250 meters, also creating high shear near the ground. In comparison to the forest, the tundra is aerodynamically smoother. This smoothness creates much less resistance to flow, bringing high wind speeds close to the ground. During parallel flow (180-200°), 51 meters uphill of timberline, the wind speed was approximately 50% of the ambient wind speed 0.5 meters off the ground 30% of ambient wind speed and 0.1 meters off the ground. For askew flow (200-240°) it was 70% at 0.5 meters and 40% at 0.1 meters.

Above treeline in the unforested tundra, the wind profile near the ground is only controlled by topography (Holtmeier & Broll 2010). During askew flow the wind flows from a rough to smooth surface, causing acceleration over the smooth surface (Oke 1987). This increases the shear near the ground.

High wind speeds have many effects on temperature distribution at treeline. Increased wind speeds create a cooler climate during the day, and a warmer climate at night. Wind decreases air temperature during the day through mixing of the cold free atmosphere with lower layers of air, inhibiting adjustment to the warm ground (Holtmeier and Broll 2010). At night wind increases temperatures through mixing with higher layers, which at night are much warmer than the ground, preventing adjustment to the cold ground. At night, reduced wind speeds decrease temperatures through decreased convective warming, which decreases leaf temperature (Germino et al. 2002). At night during parallel flow it was warmer at and above 2H compared to below most likely due to convective warming as a result of the higher wind speeds (Figure 11a).

During askew flow we would expect air to have a long residence time within the semi-stationary eddy, allowing it to adjust to the ground, and very short residence time in the band of fast air above the eddy, which should bring air adjusted to the forest below and ambient air into the treeline ecotone (Figure 16). At night during askew flow data from Tower 29, which is around 2H where wind speeds begin to recover, show increased winds speeds and increased temperatures between 0.5 and 6.0 meters above the ground, which could be caused by the increased mixing and short residence time (Figure 11b).

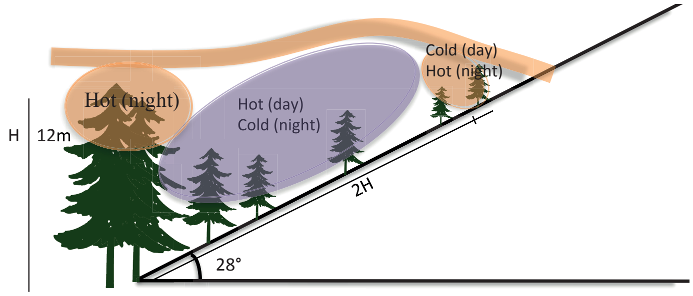


**Figure 16 – Schematic of temperature during askew flow. During parallel flow, the purple bubble would decrease in height.**

Contrary to the pattern expected, it is warm at Tower 8 near the old growth, where wind speeds are very low (Figure 11b). Slow wind speeds should allow for adjustment to cold ground, but can be explained by warming from the closed canopy forest. Based on night-time IR photographs (Figure 12), the canopies of the old growth forest provide significant heat storage, capable of sensible heating of the adjacent air. This mitigates the effects of radiative cooling from the ground. The warm stream at 2H in night askew flow could be influenced from the warmer canopy air, as the air could be transported from the forest below.

During daytime askew flow, Tower 29 at 2H reflects convection occurring as well, but during the day the mixing decreases temperatures because the free atmosphere is cooler than the air heated by radiation from the ground. The wind speeds increase and the temperature decreases compared to surrounding towers (Figure 11c). By this logic it makes sense that between timberline and 2H is warmer than the cool bubble at 2H, because there are slower winds speeds and less mixing. The cool stream at 2H in day askew flow could also be influenced from the cooler canopy air, as the air could be transported from the forest. The temperatures near the ground in the tundra might be much warmer during the day than the rest of the spline interpolation due to completely non-existent shading that would exist to some degree below 2H.

### ***The impacts of an eddy at treeline***

We established that there is most likely an eddy in the lee of timberline during askew flow as evidenced by the increasing size (both length and height) of the slow air bubble from parallel to askew flow. This increased size of the slow air bubble creates sheltered conditions downwind of the shelterbelt. Shelterbelts are known to ameliorate agricultural health because eddies can create beneficial climatic conditions through decreased wind speeds (Kort 1988). However, the eddy created in our study site may not create a better environment for tree growth.

Too much protection from the wind has been shown to negatively impact emergent Engelmann Spruce. Survivorship of Engelmann Spruce emergents was 20%

lower if the microsite feature, such as a rock, log, or tree island, was upwind of the emergent (Germino et al. 2002). As long as the cuticle is not damaged wind reduces water loss by maintaining leaf temperatures below freezing and reducing the temperature and vapor pressure gradients between leaf and air, reducing transpiration (Marchand 1996). Without wind, convection would decrease making the needles closer to ground temperature than to air temperature (Germino et al. 2002). Needle temperatures could overheat during the day or drop below productive temperatures at night, causing decreased survival rates for Engelmann Spruce germinants on the leeward side of structures.

Too little protection can also negatively impact tree establishment. It is possible that extreme wind alone could inhibit tree growth. Körner (2007) notes that topography-induced extreme wind speed can prevent tree growth. The uppermost trees are only present in sheltered micro-sites and are suppressed or not present at windswept convexities (Holtmeier and Broll 2012). The tundra could be treeless due to over-exposure to wind. Wind exposure may inhibit tree growth, before temperature inhibits tree growth (Holtmeier and Broll 2012). Trees at an adjacent diffuse treeline are able to grow about 100 meters higher in elevation, which may support wind being the limiting factor at our field site.

The abrupt treeline's eddy in the study site may inhibit tree establishment when ambient wind speeds are slow, but may benefit tree establishment when ambient wind speeds are extremely fast. Tree establishment requires moderate wind flow, somewhere between an over-protected eddy and an over-exposed slope. This non-linearity would appear to create a microclimate between the eddy and the tundra that is beneficial to seedling establishment.

### *Snow*

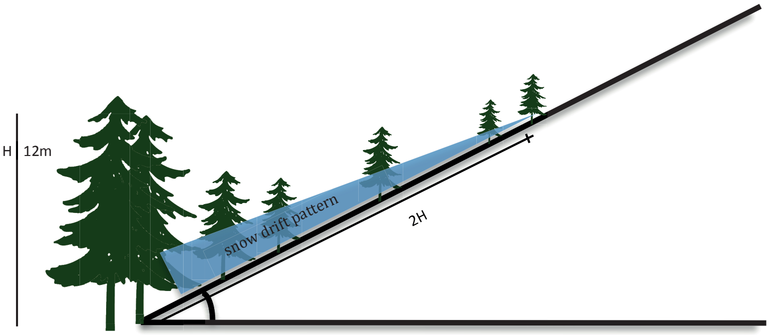


**Figure 17 – Schematic of the snow distribution uphill of timberline.**

Wind deposits snow in the eddy in the lee of the old growth trees, and wind removes snow above 2H at the study transect (Figure 5, Figure 17). It is well established that wind removes snow from wind-exposed surfaces (Hiemstra 2002; Holtmeier and Broll 2010). Prevailing winter winds come from the same general direction every year in the study area based on wind-abrasion patterns on asymmetrical trees. In places where winds come from the same direction every winter, snowdrifts occur in the same place every year (Barbour and Billings 2000). Similar environments will therefore be created every year (Hiemstra 2002). The deepest drifts form on the leeward side of trees (Hiemstra 2002) and in the sheltered zone, which is observed between timberline and 2H in the Google Earth image. Deep drifts last longer into the summer (Hiemstra 2006), which is why the only snow remaining in mid-June was between timberline and 2H. Snow that accumulates on the leeward side of trees protects the trees from both low air temperatures and abrading winds (Cairns 2001).

Snow can have both harmful and beneficial impacts on young trees. Snow fungi can negatively impact growth of seedlings and saplings, and big snowdrifts can shorten growing season (Holtmeier and Broll 2012). However, snow can also greatly benefit emergent seedlings. Snow protects plants from frost, abrasion, and winter dessication

(Holtmeier and Broll 1992, 2012). Germination might be most likely in moist microsites such as those with late-lying snow (Malanson et al. 2007). Too much and too little snow can harm seedling establishment; tree establishment is most successful with a moderate amount of snow.  This creates another nonlinearity at treeline, which indicates an area between the eddy and the tundra with a beneficial amount of snow to protect seedlings from wind without inhibiting growth.

The nonlinear impacts of wind snow create similar spatially distributed feedbacks, which should cause increased seedling establishment between the eddy and 2H. However, this pattern is not clearly evident in the study transect. There must be a factor, such as sky exposure, making this seemingly optimal microclimate inhospitable.

### *Exposure to open sky*

In the Rocky Mountains, unclouded skies create frost at night and intense solar radiation during the day at high elevations (Maher & Germino 2006). Seedling mortality is more likely caused when a seedling does not have open sky protection provided by neighboring plant cover, than from competition with a neighboring plant (Maher & Germino 2006). If there is no cover, frost is more likely at night and high solar radiation is more likely during the day; the combination of these two factors make low-temperature photoinhibition of photosynthesis more likely (Germino and Smith 1999). Even partial cover from a neighboring plant allows less long-wave radiation to escape to the atmosphere. In Germino and Smith's (1999) field experiment spruce seedlings were predominantly found between 40-80% sky exposure, and few were found at microsites with greater than 80%. Microsite facilitation may be vital for initial seed germination and successful seedling establishment in treeline ecotones (Smith et al. 2003). There are usually positive relationships of conifer seedlings and neighboring plants (Maher & Germino 2006). Seedlings were most often present in grass cover, or in close proximity to rocks or woody debris, greater than 2 cm above the ground (Germino et al. 2002). Survival of germinants in microsites with grass cover was twice that in microsites without vegetative cover, which was twice the survival rate in microsites with grass surrounding but not covering the emergent (Germino et al. 2002). Smith et al. (2003) describes a positive feedback cycle in which increased seedling establishment creates more microsite facilitation, leading to greater seedling and sapling establishment. However, if increased seedling establishment creates a substantial eddy, it may inhibit new tree establishment downwind as a result of limited convection.

Our study transect encompasses a range of sky exposure. There is limited exposure near timberline, and exposure increases slowly until 2H. At 2H open sky exposure abruptly shifts to 100% in most places, probably making at and above 2H much less hospitable. This could be the limiting factor inhibiting tree establishment in the presumably optimal microclimate between the eddy and 2H created by the spatially nonlinear feedbacks of wind and snow.

### ***Seed dispersal***

Seed dispersal is most likely not a limiting factor at the study site because the wind often comes from the forest below, allowing for transportation of winged Engelmann Spruce seeds. Moen et al. (2008) found ample seedfall above treeline of winged Birch seeds. Winged seeds are dispersed by wind and are dependent on proximity and location of seed sources and predominant wind direction (Malanson et al 2007). Larsson (2003) saw snowdrifts working as good seed traps. However, places that collect seeds, such as snowdrifts and eddies, may be in short supply above 2H. So even if seed dispersal is not an issue they are less likely to be caught in a seed trap above 2H because snowdrifts are less frequent. Additionally, there could be more seedfall in the eddy due to decreased wind velocity. Decreased wind speed would decrease the ability to transport seeds, increasing seed deposition. It is important to note however that seed viability at high altitude should be considered. Tranquillini (1979) cites various studies that found that production of viable seeds at high elevation fails except in exceptionally warm years.

## Conclusion

At abrupt treelines there is a sharp transition from fully grown trees to no trees, which according to Harsch and Bader (2011) points to seedling mortality being the most important factor limiting treeline advancement, not growth limitation nor dieback. However, there were not dead seedlings present in the study transect, so germinant mortality or an earlier stage must be the limiting factor.

Our study site is one of the few abrupt treelines that is advancing with recent regional warming. Tree establishment above 2H must be inhibited by too high of wind speeds creating high shear and near non-existent snow cover during the winter. The area between timberline and 2H has been slowly filling in with seedlings since the early 1900’s. The trees in this section do not grow into krummholz form. If a seedling can be established it grows into a fully-grown symmetrical tree. It is difficult, but not impossible for seedlings to become established in this zone. Tree establishment is most likely dependent on very specific microsites within this area that have moderate wind flow, moderate snow cover in the winter, and 40-80% open sky exposure. However, the microclimate between the eddy and 2H that typically has moderate wind flow and moderate snow cover, tends to have more open sky exposure than Engelmann spruce can tolerate. The net effect of wind, snow, and sky exposure enable the treeline to slowly advance uphill.

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