UNLOCKING AN ABRUPT TREE LINE: A SYNTHESIS OF MICROMETEOROLOGY AND VEGETATIVE RESPONSE

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Abstract

The advancement of global tree lines in response to climate change has raised questions among researchers about tree recruitment at elevations beyond tree line. This study aims to help understand this process by examining the progression of an abrupt tree line of engelmann spruce on the western slope of Pikes Peak, in Colorado Springs, Colorado. Methodology for this study includes drone photography, GIS mapping, dendrochronology, tree growth measurements, and soil moisture measurements. The results of our examination suggest that the three main mechanisms controlling advancement at our tree line include a leeward eddy when upslope winds interact with the tree line like a shelterbelt, a spiral eddy when winds are parallel to tree line, and cold air damming of katabatic winds against the tree line at night. Our examination of the vegetative response of trees at our tree line suggests that the most healthy recruitment is occurring on the southern edge of our transect and at the upper extent of the area expected to be protected by the tree line. We have found that trees and limbs that exist within the cold air dam at tree line have experienced decreased growth compared to trees outside of this layer of cold air.

Introduction

In the face of climate change, tree line ecotones have become a popular research focus across the world. We look at a tree line as the transition zone between the upper alpine and lower tundra life zones, the elevation where harsh living conditions limit tree establishment from advancing upslope. While there are a variety of mechanisms that may or may not allow trees to establish themselves beyond tree limit, average temperature during the growing season is widely considered the most important factor (Harsch, 2011). Körner and Paulsen's, *A World-wide Study of High Altitude Treeline Temperatures*, recorded seasonal mean ground temperatures of tree lines to be between 5 and 8˚C. This range is quite narrow based on our understanding that the minimum temperature for tissue of growth in plants is 5˚C (Körner, 2008). The onset of global warming leads us to question whether increased temperatures will unlock global tree lines and allow them to advance to a higher elevation limit. A study by Melanie Harsch, from the University of Washington, determined that in a data set of 166 tree lines worldwide, 52% had advanced since 1900 and only 1% observed tree line recession, the remaining 47% were static (Harsch, 2009). The rate of tree line advancement may serve as an interesting gauge of climate change for the future.

To fully understand the process of tree line advancement Harsch has identified four globally recurrent spatial forms that tree lines take; diffuse, abrupt, island, and krummholz.

> "1. Diffuse, characterized by a gradual decrease in height of single-stemmed trees along the treeline ecotone. Tree density also tends to decrease along the treeline ecotone. 2. Abrupt, characterized by a continuous forest >3 m tall directly bordering low alpine vegetation. Tree height as well as density thus changes rapidly. Trees may be present above the continuous forest but their presence is infrequent. 3. Island, characterized by clumped patches or linear strips ('fingers') of krummholz or trees above the continuous forest limit. 4. Krummholz, characterized by severely stunted or deformed multi-stemmed trees. The krummholz growth form can occur in clumped patches above the upright forest, in which case we class the treeline as an island treeline, or it can occur as a dispersed or contiguous band above the upright forest, in which case we class the treeline as a 'krummholz treeline'. The characteristics of krummholz treelines also apply to krummholz-island treelines, whereas other features of island treelines are more specific to this form only (Harsch, 2009)."

These growth forms have been observed on mountains across the world and one tree line form is usually not specific to a single mountain or mountain range. While no two mountains hold identical environmental conditions, identifying recruitment patterns and processes within each tree line form will help us make sense of how these ecotones are adapting to a changing climate.

In order to understand the progression of different tree line forms we must study the micrometeorological factors that play into tree line construction.

As mentioned before, average temperature during the growing season plays a key role in tree establishment, however other factors such as wind play important roles in shaping trees as well as tree line structure. While temperature directly affects tree growth, it also controls surface air flow during the day and night. We must understand the day and nighttime temperature regimes to grasp the complex micrometeorology of a tree line..

The influence of sunlight is what determines a thermal regime. During the day the sun warms the surface of the earth, making it warmer as you get closer to the ground setting up an upward flux of sensible heat.. At night, in the absence of sunlight, a temperature inversion sets in, where it is colder at heights closer to the surface because the surface cools through radiation. This sets up a downward flux of sensible heat.

As mentioned before, these differences in temperature regime affect surface air flow on a mountain. During the night, in the absence of insolation, heat from the surface radiates out, creating a temperature inversion, which causes cold, dense air along the surface to flow down slope, in what we call katabatic winds. During the morning parcels of air along the surface are warmed by the sun's rays, as well as radiation from the ground, causing air to become more buoyant, allowing it to rise. As it rises it encounters the inversion "lid" that does not allow it to move further in the vertical direction. Instead it flows upslope beneath the "lid", creating what is commonly referred to as anabatic winds (Tyson, 1968).

The ground serves as an energy storage for the sun, radiating during the day, and into the night, until the surface becomes colder than the air above it. This makes temperature extremes during the day and deficits during the night, most extreme along the surface, where tree establishment is taking place. These diurnal mountain winds are present throughout the year, however their signature is most extreme during the summer, when day and night temperature differences are greatest (Tyson, 1968). The complexity of these flows is taken to a new level when coming in contact with an obstruction, such as an abrupt tree line.

It is expected that anabatic and katabatic winds will respond differently when coming in contact with an abrupt tree line due to orientation of the wind coming in contact with continuous closed canopy forest down slope of tundra. When confronted with an abrupt tree line, the response of anabatic (upslope) winds coming over top of the tree line may be conceptualized as a shelterbelt system. Upslope winds can also occur at night, creating a similar shelter effect. However katabatic nighttime air drainage on the surface interacting with the abrupt tree line is suspected to result in cold air damming. I take the shelterbelt as the closest well studied analogous system to the tree line. While to my knowledge no previous published studies have analyzed the wind flow over a tree line, there is a wealth of information about the interaction of a shelterbelt and a tree line.

When air flows over the shelterbelt, the shelterbelt accelerates wind speeds over the obstruction and decelerates horizontal wind speeds on either side of the obstruction, creating turbulence. As an air mass approaches an obstruction, the high pressure build up on the wind-ward side causes the air to slow down and be displaced upwards (Oke, 2002). The convergence of air being pushed over the shelterbelt accelerates the parcel to re-establish the laminar flow. In TK Oke’s, *Boundary Layer Climates*, this area is referred to as the

“Displacement Zone (Figure 1). The downward acceleration creates turbulence, forming a leeward eddy, a jet of accelerated air, and can create an upper eddy, (Figure 2). Following the barrier, the compacted air mass diverges and decelerates in the upper eddy, and the flow is returned to its original laminar structure. The leeward eddy, which is located in Oke’s “Cavity” in Figure 1, holds well mixed air and often serves as a protected area for crops --- and by analogy for mid sized trees at the tree line. Oke uses the height of the barrier (h) as a unit to measure the area affected by the shelterbelt. Oke’s finding is that “the barrier is seen to affect flow to at least 3h above the surface, and to the same distance in front of the barrier (Figure 1 (Figure 7.6b BLC, Oke 2002)). The distance of influence downwind of the barrier depends upon the density of the barrier, defined as the ratio of the open area of the barrier as viewed normal to its axis, to its total vertical area, expressed as a percentage. (i.e. a totally impermeable barrier has the maximum density of 100%). The distance of downwind influence is usually judged in terms of the percentage reduction of horizontal wind speed compared to the upwind (open) value at the same height (Oke, 2002).” This protected area typically extends 5-10h downwind of the barrier.

Applying the concept of a shelterbelt to a tree line allows us to compare the distance of influence at the surface to recruitment patterns. This may reveal clues to how a tree line is advancing upslope. Before we can consider these connections it is important to consider the fact that Oke’s shelterbelt system is idealized over a level surface, with a uniformly porous barrier, and perpendicular airflow. While the system at an abrupt tree line is far from this idealization, these concepts certainly do apply, and must be adapted to the abrupt tree line system to develop a picture of the processes at play. Discrepancies that are likely to adjust our understanding may include the heterogeneous porosity of a tree line, skewed incidence angle of flows in contact with the barrier, and the slope of the mountain. In addition, the tree line is not a barrier that disrupts flow on otherwise homogeneous surface. It is rather a zone where two surfaces of different height and aerodynamic surface roughness meet.

The heterogeneous porosity of any natural shelterbelt is certain to affect the uniformity of turbulence across each segment of the barrier. Idealizing the thought process used in understanding how air flow will be affected by the barrier is a necessary for conceptualizing air flow at tree line. An important thing to consider when examining the porosity of the barrier is that decreased porosity results in increased streamline curvature (Wang et al, 1995) leading to a better defined leeward eddy, that is smaller in horizontal extent, and larger in vertical extent.. A familiarity of facts such as this help us visualize airflow and infer how it might affect micrometeorological factors such as air mixing in the areas protected by the barrier.

Another discrepancy between Oke's shelterbelt system and the shelterbelt effect of an abrupt tree line is the fact that upslope air flow at tree line will not always come perpendicular to the barrier, Wang and Tackle have found that "with increasing incidence angle, horizontal ranges of both wind speed reduction zones decreases, and horizontal range of the leeward zone decreases faster than that of the wind-ward zone. However, height of the leeward wind speed reduction zone increases with increasing incidence angle (Wang et al, 1995)." Varied wind direction is inevitable in a natural system such as a tree line, the resulting skewed incidence angles will constantly adjust the extent of the area affected by the barrier. Winds that come at more parallel angles to tree line will create additional eddy systems that are certain to influence the recruitment of trees and advancement of tree line. Skewed incidence angle combined with sloped interactions with the tree line create an even more warped shelter effect. We expect that after upslope flows are pushed over the tree line, the sloped mountain surface will limit the extent of eddies, forcing them to return to a laminar flow more rapidly.

It is important that we try to understand the extent of influence from large eddies because not only do they induce mixing, but also provide protection from ice blasting during the winter. Ice blasting sands down the bark of trees forcing them into atypical growth forms such as krummholz. While asymmetrical trees may affect their resiliency, they also provide clues to wind patterns. Exposing these patterns help us make sense of the microclimate at tree line during the day and at night.

During the night it is expected that the gravity driven flow of dense air near the ground winds will respond differently when encountering a tree line than upslope flows over the shelterbelt, especially when the upslope flow coexists with the near the ground density/gravity driven drainage. Once the temperature inversion sets in, and surface air becomes cold and dense in the tundra, it will flow down slope and dam up in front of the obstruction. This will create a layer of cold air along the surface that is deepest along the shelterbelt. If the shelter effect is present beyond the tree line it will likely enhance the effect of cold air damming, by trapping air and increasing residence time. Colder conditions along the surface are likely to retard tree growth within this layer.

The multitude of factors that contribute to tree development and the vast complexity of tree line micrometeorology pose a challenging task at understanding how and why global tree lines are advancing. This study aims to answer some of these questions looking particularly at the micrometeorological dynamics and spatial structure of an abrupt tree line on the western slope of Pikes Peak, in Colorado Springs, Colorado. We hypothesize that the three main mechanisms that drive the advancement of this abrupt tree line are a spiral eddy caused by parallel flow, a leeward eddy caused by flow over the tree line, and cold air damming at night. We believe that these mechanisms affect surface conditions such as temperature, and wind, which ultimately shape a tree line.

Methodology

The methodology behind this study aims to help understand the processes contributing to the advancement of an abrupt tree line from the response of the trees to the microclimate. Data for this study were collected at an abrupt tree line on the western slope of Pike's Peak, Colorado. Our research site (Figure 3) consisted of a marked off rectangular transect measuring 30m by 100m. The location of the transect was chosen based off of the uniformity of the abrupt tree line, which we felt provided a reasonable proxy for abrupt tree lines in general. The transect spans from the upper montane life zone of an Engelmann spruce forest, into the tundra life zone. We divide our transect into the Old Growth Forest, the Eddy zone, and the Tundra by collecting observational data to delineate the tallest trees in the old growth forest, and asymmetrical trees in the tundra. We created an old growth tree line, by walking the length of the transect between the tallest trees at their uppermost elevation using the line feature on a Trimble GPS unit. We used the same feature and tactic to delineate where trees become asymmetrical upslope of the old growth tree line. These lines give us an idea of the upslope area protected by the tree line, denoting the eddy zone from the old growth forest and the tundra (Figure 3). We then walked the asymmetrical tree line, taking GPS data points of each asymmetrical tree and recording the direction of asymmetrical branches using a compass. We plugged the direction of asymmetry into the attribute table of these data points and altered the symbology of each point to direct an arrow in the direction of asymmetry. After marking off our area of interest and denoting its subsections, we began to take inventory of the trees.

We tagged and numbered each tree in the transect and collected GPS data points at their location. We then used increment borers to extract cores to the pith of each tree and measured the height of extraction. Trees that were too small to core were aged manually by counting the annual growth scars on the bark. The cores were transported to a lab at Colorado College, where dendrochronology was performed.

Our dendrochronology process included preparing the cores for ring counting, counting rings, accounting for height of measurement, and calculating tree age. To prepare each core, we mounted them to wooden frames, and sanded them to 600 grid. We then counted tree rings under a microscope using Velmex Linear Bench, and Measure 12x softwares. After determining the number and width (to nearest 0.001mm) of rings on each core we plugged our values into an equation that accounted for the number of rings versus height of measurement, which was created using trees previously uprooted and aged on Pike's Peak. Manual aging for trees too small to core also used this equation to account for the height of measurement. After subtracting the number of rings by the year of extraction (2015) we had determined tree age for all of the trees in our transect.

After determining the age of each tree, and uploading our GPS data into ArcMap, we entered the ages of each tree into the attribute table and used the symbology feature to develop an age map. To add variation to our map and expose tree growth throughout the area of interest we took several measurements of trees at the tree line.

Our growth measurements included growth increment, height, and bud status. We used meter sticks to measure the length of the leading shoot of each tree as well as the height of smaller trees. Larger trees required us to mark off a large extendable paint stick at one meter increments and attach a meter stick to the top, then use binoculars to record the height and growth increment to the centimeter. After collecting the height and growth increment of each tree we calculated growth residuals so we could compare tree growth across the transect, accounting for tree height. Residuals were calculated by first graphing height versus growth increment on excel. After creating the graph, we inserted a linear trend line and used its equation to calculate predicted growth for all trees. We then subtracted growth increment by predicted growth to calculate growth residual. Growth residual was added to the attribute table of our existing map in ArcMap to create growth residual maps which we separated into trees shorter than one meter, and trees taller than one meter.

Our final physical observation of vegetation was of budding progress during the summer season's budding event. This data collection consisted of taking GPS data using a Trimble GPS at trees on the edge of the old growth forest and in the tundra and then quantifying bud growth from 0-5 in the upper third and lower third of the tree. Recordings of 0 meant a tree had not yet started budding, and recordings of 5 represented significant bud growth. Again, this data was used in conjunction with our other maps to expose tree growth in our transect.

Other observational data was collected to delineate the remaining snow at tree line in June. This data was collected by using the polygon feature on a Trimble GPS. We exported all GPS data into ArcMap to create maps of our observations. Later in the season, after the snow had melted, we created a soil moisture transect in our area of interest using moisture probes buried 6 cm below the surface. We collected GPS data the location of each probe and added the recorded values to the attribute table of the points on ArcMap. Other forms of data collection at our research site aimed to create detailed base layers for the maps used in this study

We implemented an eight propeller drone (DJI S1000) attached with a visible light camera (VIS), a near infrared camera (NIR), and an infrared camera (IR) to map our area of interest. In order to map our transect to the desired resolution we knew we would have to fly low and then stitch multiple photos together. To create photos with the proper amount of overlap for stitching we set intervalometers on each camera to take photos every second and flew over a path with several turns that went beyond the extent of our transect.

The images were then stitched together using Agisoft to align like pixels, create a mesh, and finally a dense cloud. This created 3D models of our area of interest in VIS, NIR, and IR. We then georeferenced the models by applying GPS data of identifiable objects in our transect to their approximate location in the model. The georeferenced models were then exported as orthophotos or a digital elevation models (DEM). DEM’s provide a digital 3D skeleton of an area or object. Orthophotos act as a skin which can be draped over a DEM, to create a high resolution, 3D model of an area. The pixel values in an orthophoto can then be manipulated to expose interesting wavelengths of light. We created orthophotos in VIS, NIR, and IR, however only the NIR and VIS orthophotos were used in this study. Our models were then imported to ArcMap, to add base layer imagery for our existing data and to conduct pixel analysis.

Our VIS orthophoto, provided a high resolution base map for our transect. We used this orthophoto as a base layer for several maps used in this study. In ArcMap we altered the color bands of pixels in our NIR orthophoto to expose NIR reflectance of vegetation and create a

Difference Vegetative Index (DVI). We defined the DVI as infrared minus blue. Healthy vegetation reflects large amounts of NIR light, which makes DVI a useful tool for exposing plant stress. In this study, our DVI image was used as a base layer for maps exposing tree growth.

At the end of our data collection season we attempted to fly our drone at night and take photos using our IR camera to expose the nighttime thermal regime at tree line. This data would have been very useful to help explain cold air damming at tree line, however our drone suffered damage while being transported up the mountain. Upon takeoff, we immediately lost control of the device and watched it fly out of reach of our telemetry. Despite the adversity, we were able to collect nighttime IR photos of our transect using a different IR camera. Fortunately, these photos were able to capture the effect we were looking for.

Results and Discussion

Tree Line Advancement

Our findings are indicative of a dynamic abrupt tree line, advancing upwards into the tundra. This pattern is easily distinguished through the age map found in Figure 4. The tree line was mostly static until the 1900's, when a couple trees started advancing out of the old growth forest, and into the eddy zone. Initially, recruitment occurred on the southern edge of the transect and along the edge of the old growth forest. The establishment of these trees was followed by mass recruitment and an increase in tree density within the eddy zone starting in the 1950's. Meredith Parish's study, "*A Micrometeorological Study of an Abrupt Treeline on Pike's Peak"*, looked at this abrupt tree line from a micrometeorological standpoint using deployable weather stations. A 6m wind vane recorded the highest frequency of winds coming from the southwest, at about 200°, when 360/0° is pointed directly north (Figure 5). This prevailing wind will contact tree line at a skewed angle, more parallel than perpendicular to tree line. Based on the prevailing wind it seems likely that the 1900-1950 entry into the eddy zone created tiny shelterbelts, allowing further recruitment to ensue behind these pioneer trees. This pattern is evident on the age map (Figure 4), where three trees from 1900-1950 lead lines of younger recruitment. The small shelterbelts created by these trees shield saplings from ice blasting in the winter and create a warmer microclimate that provides conditions suitable for establishment. The effect of these tiny shelterbelts is illustrated in Figure 6, a Google Earth image of our research site. This image displays how trees on the southern edge of the transect are blocking snow from trees behind them. Another interesting thing to note is the location of recruitment in the tundra since 1950 (Figure 4). It appears that once again, trees are starting to establish themselves on the southern edge of the transect. It will be interesting to see if recruitment in the tundra creates shelterbelts and fills out in a similar manner to what occurred in the eddy throughout the 1900's. This pattern may suggest an important spatial control on recruitment at tree line. It has certainly created an interesting tree density dynamic throughout the transect. We calculated tree density by dividing the number of trees in each section of the transect by the area of that section. In the tundra we find the lowest tree density, .026 trees/m^2. In the eddy we find the highest tree density, .257 trees/m^2. And in the old growth forest we find a middle tree density value of .14 trees/m^2. As you go up in elevation, it is expected that once you pass tree limit, tree density will drop significantly due to the harsh conditions of the tundra. Here we have noticed an increase in tree density from the old growth forest into the eddy. This spatial structure undoubtedly creates the most effective strategy for recruitment in the eddy, however the mechanisms at play are less inherent from a micrometeorological standpoint.

With prevailing winds coming from approximately the same angle during the day and at night, we have divided the flow into X and Y components that create two overlapping eddy systems along the tree line. This breakdown of the prevailing wind creates a cartoon that helps us conceptualize the complex wind patterns that help shape tree line. Since the prevailing wind is more parallel to tree line than perpendicular, we believe that the X component has a higher magnitude than the Y component. We refer to the X component (parallel to tree line) as the spiral eddy and the the Y component (perpendicular to tree line) as the leeward eddy. Each system provides an influential layer of protection for plants in the eddy zone throughout the day, however at night they may actually be harmful. The nighttime regime is the most vulnerable time for a tree’s resiliency. This study has identified the spiral eddy system, the leeward eddy system, and the nighttime regime as the main controls for the advancement of this abrupt tree line.

Spiral Eddy System

The X component of the prevailing winds creates the spiral eddy system, which depending on the direction of wind, may be present during the day and at night. It is primarily a function of horizontal winds encountering the rough edge of the old growth forest. The increased friction along the old growth forest creates shear stress, which decreases horizontal wind speeds as you get closer to the tree line. The gradient of high wind speeds in the tundra and low wind speeds along the old growth forest creates momentum flux, capping the slower moving air within the eddy zone into potentially stationary eddies illustrated in Figure 7. The stationary eddies carve out the asymmetrical tree line that we use to distinguish the upper extent of the eddy zone. Circumstantial evidence for this is in the directionality of the asymmetry in the trees on the asymmetric tree line (Figure 8). The air, snow, and ice coming in contact with these trees is capped by the momentum flux of the tundra, bending towards the tree line. This effect carves out limbs and inside edges of trees, and then traps air parcels in the eddy zone. The air funneling and decrease in speed contributes to snow deposition in the eddy zone. In early June all remaining snow from the winter was concentrated in this area (Figure 8). These findings further illustrate how air is channeled into the eddy and trapped there. We expect that once air enters the eddy zone, it mixes with other trapped parcels creating stable temperature profiles that are warmer during the day and colder at night. This thermal control will support tree growth during the day, and retard tree growth at night.

Leeward Eddy System

The Y component of the prevailing wind creates the leeward eddy system which is apparent during the day and at night when winds flow upslope. This concept is based on the effect of a shelterbelt, where laminar wind encounters a barrier head on and is compacted, then accelerated downwards. Once the air squeezes past the barrier it then expands and slows back down. This system creates a leeward eddy, a jet, and a top eddy (Figure 2). The jet layer is fired between the top eddy and the leeward eddy like a baseball pitching machine. The higher wind speeds in the jet create a steep gradient sending momentum flux downward and capping the leeward eddy. We understand the horizontal extent of the leeward eddy at our abrupt tree line to be about two times the vertical height of the shelterbelt based on the porosity of the tree line and the mountain slope angle which interacts with the flow. Much like the spiral eddy, the lid effect of the leeward eddy increases residence time of air parcels and provides ice blasting protection for trees in front of the tree line. We based our original understanding of the microclimate at tree line on this system, however the skewed wind profile makes it a little more complicated. As wind becomes more and more oblique against a barrier, its protected zone is proportionately limited (Oke, 2002). This suggests that the protected zone created by the leeward eddy is smaller than we originally expected and that the recruitment in the eddy zone is primarily controlled by the spiral eddy.

Regardless of the dominant flow, the complementary nature of these wind patterns must add to each process at play. One example of a process influenced by both eddy systems is snow deposition. We understand that the leeward eddy deposits snow in the eddy zone similar to the spiral eddy. The sudden deceleration that occurs after the wind is fired over the tree line captures snow and drops it just beyond the tree line (Figure 8). The results of the soil core experiment support this observation. Figure 9 is a map of soil moisture throughout the transect. Our findings show the greatest soil moisture in the center and on the upper edge of the eddy zone, this is where we expect to find the greatest amount of snow deposition. Low values were found along the edge of the old growth forest and in the tundra. We expect to find low moisture along the edge of the old growth forest due to a high demand for water in that area. The tundra's dry soil is likely to be a function of limited snow deposition and blasting from the jet. Meredith Parish's study identifies that wind profiles from the tundra (Figure 10) show a kink of fast moving air at 2m. The jet carries accelerated air over the tree line, triggering increased evaporation in the tundra, just beyond the eddy zone.

Daytime Regime of the Tree Line

The daytime regime is largely controlled by the amount of sunshine on tree line. In the presence of insolation, the expected thermal profile will have warmer temperatures close to the ground and cooler temperatures as you move off the ground. The warmth of the day creates less dense air parcels which allow winds to move at higher speeds. Increased wind speeds create steeper gradients and more shear stress along the tree line. Steeper wind speed gradients increase the amount of momentum flux, promoting longer residency of air parcels within the eddy zone. These factors promote mixing within the protected layer, making it warmer during the day. The warmth and protection of eddy zone improves living conditions for trees in that area. The sunlight allows photosynthesis and respiration to occur in trees, which are both necessary for tree establishment.

Nighttime Regime

At night, in the absence of insolation, radiative cooling results in temperature inversion, causing the air to be colder as you get closer to the ground. This inversion allows cold dense air to flow down slope from the tundra, towards the eddy and the old growth forest. We have identified this phenomenon as a primary control for the successful establishment of trees at tree line. While prevailing nighttime winds 6m above the ground encounter tree line from the southwest, we suspect that measurements closer to the ground would reveal down slope directionality due to katabatic winds. Once the nighttime regime sets in and cold air has made its way down to the eddy zone, it is dammed up against the old growth forest, creating a thermal internal boundary layer (TIBL) which we expect to be about 1m tall along the old growth tree line. Thermal imagery taken at tree line during the night exposes this cold air damming (Figure 11). Here the coldest measurements were recorded along the edge of the old growth forest, directly where we expect the cold air damming to occur. This photo was taken at the end of the growing season, when nighttime temperatures inside and outside the cold air dam are too cold for tissue growth. We expect that an image taken earlier in the season would reveal a cold air dam with unfavorable growth conditions surrounded by more favorable growth conditions outside the TIBL. Trees stuck within this TIBL will not be able to grow at night until their leader is able to poke through into warmer layers. The katabatic flows in conjunction with prevailing winds from the southwest, will allow the spiral eddy and the leeward eddy systems to interact with the cold air dammed against the old growth forest. The protection provided by the eddy systems support the establishment of the cold air dam by increasing residence time of parcels within the eddy zone. The combination of these wind patterns is expected to halt tree respiration at night.

Vegetative Response

Our understanding of the spiral eddy, the leeward eddy, and the nighttime regime are largely backed by the vegetative response of tree line. Drone imagery taken at the transect allowed us to create a Difference Vegetative Index (DVI) (Base layer of Figures 12 and 13), which helps us understand the plant stress dynamic. High DVI values (98-180) correspond to dense vegetation, medium DVI values (16-98) correspond to sparse vegetation and low DVI values (-67-16) correspond to rocks and dry soil. The DVI image illustrates the high values for trees in the eddy zone and the tundra, with lower values for trees in the old growth forest. This pattern was unexpected due to the harsh environmental conditions in eddy zone and tundra. The highest DVI values of trees were found on the southern edge of tundra in the transect. The age map (Figure 4) also suggested successful recruitment on the southern edge of the transect, however it is still unclear why that is a good place for tree establishment. The cold air pooling along the old growth forest explains the low DVI values in that area, and an increase in values as you move to the upward extent of the eddy, where the pooling is less present. These findings are consistent with growth interval data.

After measuring leader growth of each tree in the transect, our measurements were used to calculate residuals. Our residual values measure how much more or how much less the tree grew than what was expected based on their height. Following the calculation, we separated the values into trees less than 1m and trees greater than 1m and then mapped them (Figure 12 and Figure 13). Separating trees based on their height was meant to distinguish whether or not they were being affected by cold air damming. We found that trees taller than 1m (Figure 13) grew best along the upper edge of the eddy zone, and worst along the old growth forest where the cold air damming is most prominent. Most of the trees shorter than 1m underperformed in the eddy zone and particularly low residual values were noted along the old growth forest (Figure 12). Again, we expect the decline in performance along the old growth forest to be a result of cold air damming at night.

To complement our growth interval data and further understand the effect and extent of cold air damming at tree line, we measured the progress of buds during the budding event of the summer. This event marks a new year of growth for trees on Pikes Peak, and the progress of each tree at this critical moment adds insight to a tree's ability to grow in this rough environment. We separated our measurements by height, comparing buds in the lower and upper third of trees, and then mapped them to illustrate the effect of cold air damming. Figure 14 illustrates low buds in the transect. We measured progress qualitatively on a scale from 0 to 4. Values of zero meant the buds were completely closed, and open progress was measured from 1 to 4. We found that low buds were not as developed throughout the transect. In the center of the eddy zone many of the buds had not yet opened. This finding is particularly interesting when juxtaposed against the top bud measurements (Figure 15). Again, we collected qualitative measurements where values of zero mean closed buds and values greater than one represent the progress of buds. The top buds performed much better throughout the eddy. Surprisingly, we found that trees along the old growth forest had posted the most bud develop. This finding suggests that along the old growth forest buds were more developed at the top of trees than at the bottom. This difference in budding progress exhibits how cold air damming effects trees regardless of their height. Any limbs within the cold air TIBL are subject to harsher growth conditions at night, which means that they have far less time to grow each day. This makes it hard for trees to be shorter than the height of the cold air TIBL. While these trees still enjoy warmer temperatures during the day, their location is not ideal until they surpass TIBL. Trees that exceed the TIBL will be warm enough to grow upwards during the day and at night. We expect the depth of the TIBL to decrease as you move away from the old growth forest.

Based on our analysis of the vegetative response of trees at tree line, successful recruitment will most likely occur at the upper extent of the eddy. We attribute this finding to a shallower cold air dam TIBL at night, and day time protection from the spiral and leeward eddies. This finding complements the results of Meredith Parish's study, which isolated this area to contain the most promising growth conditions based on temperature data recorded using weather towers (Figure 16). The spline illustrates temperatures at varied distances from the tree line under three different sets of conditions. Figure 16a displays the nighttime temperature regime when winds are mostly parallel to the tree line, we associate these winds with a pronounced spiral eddy. At night we expect to find a temperature inversion at the surface. The signature of cold air damming and temperature inversion spans the surface until you are about 28m uphill from the old growth forest. At the upper extent of the eddy zone there is a column of warm air that descends over the leeward eddy.. The vegetative analysis of our research found this area to provide the most habitable growth conditions and the warmer temperatures suggested by the spline data support this finding. Following the upper extent of the eddy zone, temperatures in the tundra hold the expected temperature inversion. Figure 16b shows the nighttime temperature regime when winds are more perpendicular to the tree line. We see a similar pattern at play with a temperature inversion on either side of the warm upper eddy zone, however the increase of temperature with height in the inverted areas is more gradual and temperatures are slightly higher in the warm air column. With strong winds moving upslope we expect there to be a more distinct leeward eddy which will support mixing throughout the parcel within the eddy, but decreased mixing of the eddy air and air outside of it. Decreased mixing of outside warmer air in conjunction with the increased mixing of the colder air inside of the eddy offers a reasonable rationale for colder temperatures spreading to greater heights from the surface. Figure 16c shows spline data for the daytime temperature regime with winds flowing slightly skewed to tree line with a large uphill component. During the day we expect the surface to be warm, radiating heat upwards. This expectation holds true aside from the upper extent of the eddy, which reveals a column of cold air. The spline then shows a warm spot beyond the eddy zone. It is interesting how the upper eddy zone is holds colder air during the day and warmer air at night. We suspect that warmer temperatures in the upper eddy zone at night are more important to tree growth because they allows trees to maintain temperatures warm enough for respiration. The mechanisms accounting for these opposing diurnal temperature patterns are unclear, but are certain to affect establishment in that area. Another interesting observation from the spline data is the height of the cold air TIBL at night. Our study has found that trees taller than 1m are more successful than trees shorter than 1m in the eddy zone. The agreement of vegetative observations and micrometeorological data help confirm insights about the mechanisms of this abrupt tree line. While our efforts have answered a lot of questions, they have raised many others.

This study has highlighted the importance of cold air damming at tree line, and future research might aim to dive deeper into this mechanism using improved experimental design. One suggestion would be to collect wind direction data at the surface, as well as 6m above the ground to compare surface and aloft flows. This method would capture katabatic flows and allow us to further understand the residency of cold air damming. Another promising method would be to observe the nighttime thermal regime by stitching together photos taken with an IR camera after a drone flight.

Figures

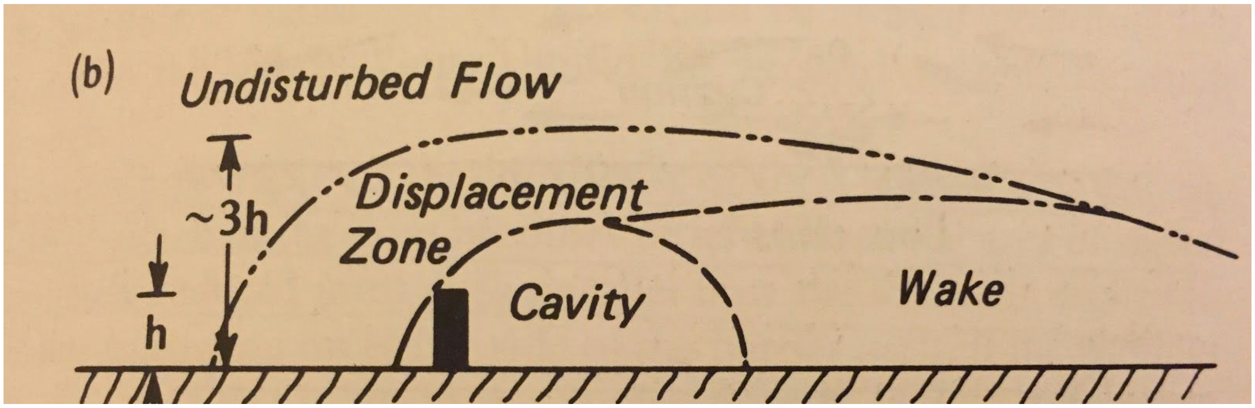


Figure 1. Model of laminar flow interacting with a shelterbelt barrier, producing a displacement zone, a cavity, and a wake. (TK Oke, Boundary Layer Climates, Figure7.6b BLC)

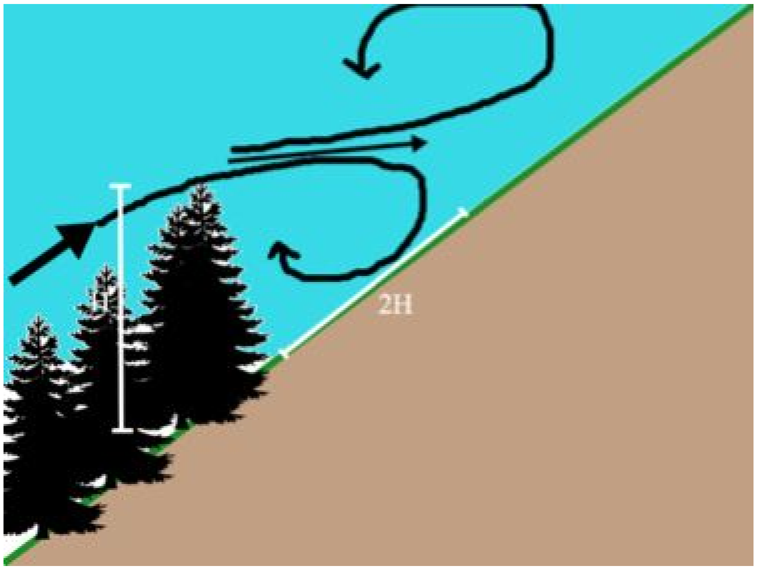


Figure 2. Leeward Eddy Diagram created using Microsoft Office. The leeward eddy system is our 'cartoon' understanding of upslope flow coming over the abrupt tree line. From top to bottom the black arrows represent the upper eddy, the jet, and the leeward eddy. We predict the horizontal extent of the leeward eddy to be approximately two times the height of the tree line.

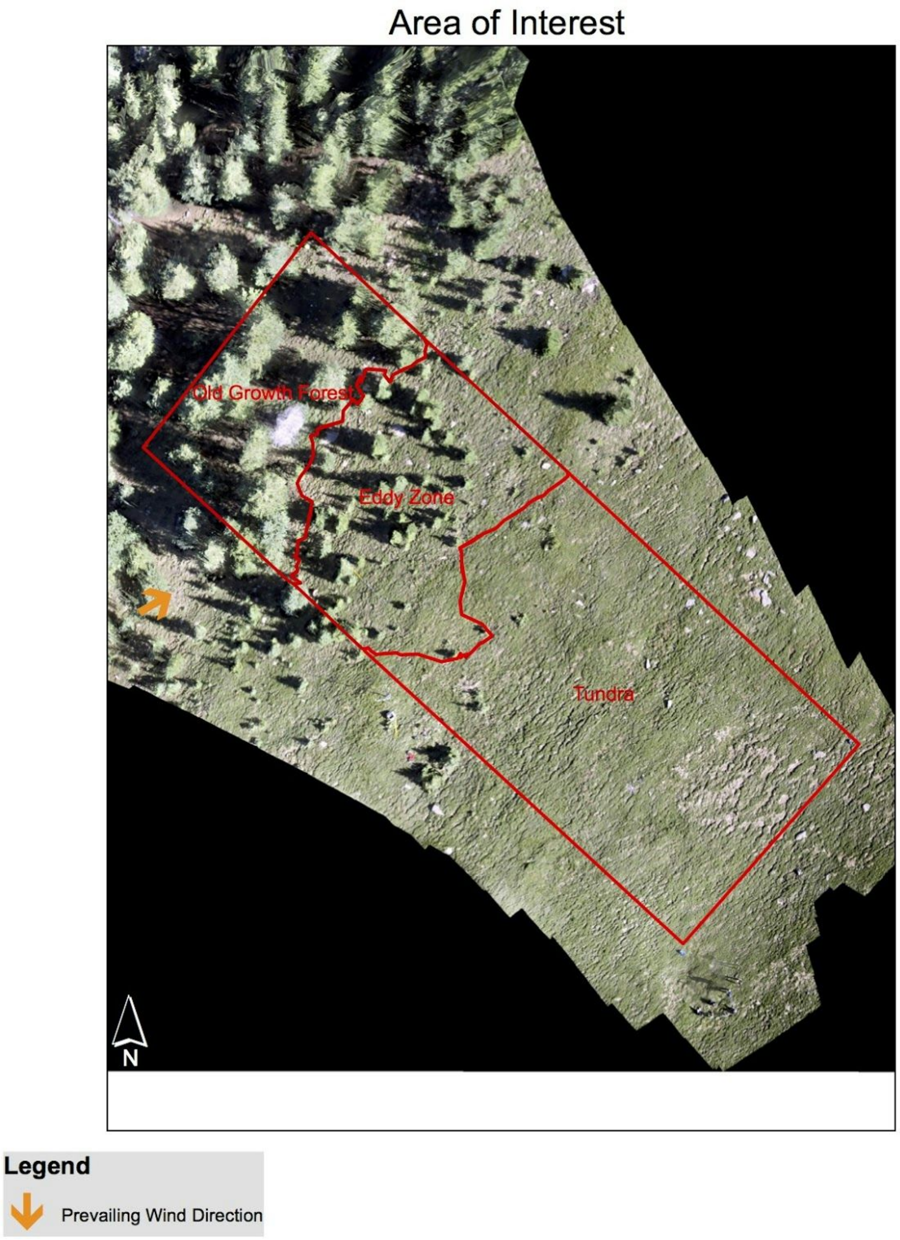


Figure 3. Area of Interest Map made on ArcMap. Our area of interest is on the eastern facing slope of Pike's Peak, Colorado Springs, Colorado. We sectioned off our transect into the Old Growth Forest, the Eddy Zone, and the Tundra. The line denoting the boundary between the Old Growth Forest and the Eddy zone connects the tallest trees at tree line. The line denoting the Eddy Zone from the Tundra connects the lowest elevation of asymmetrical trees. The orange arrow represents the prevailing wind direction.

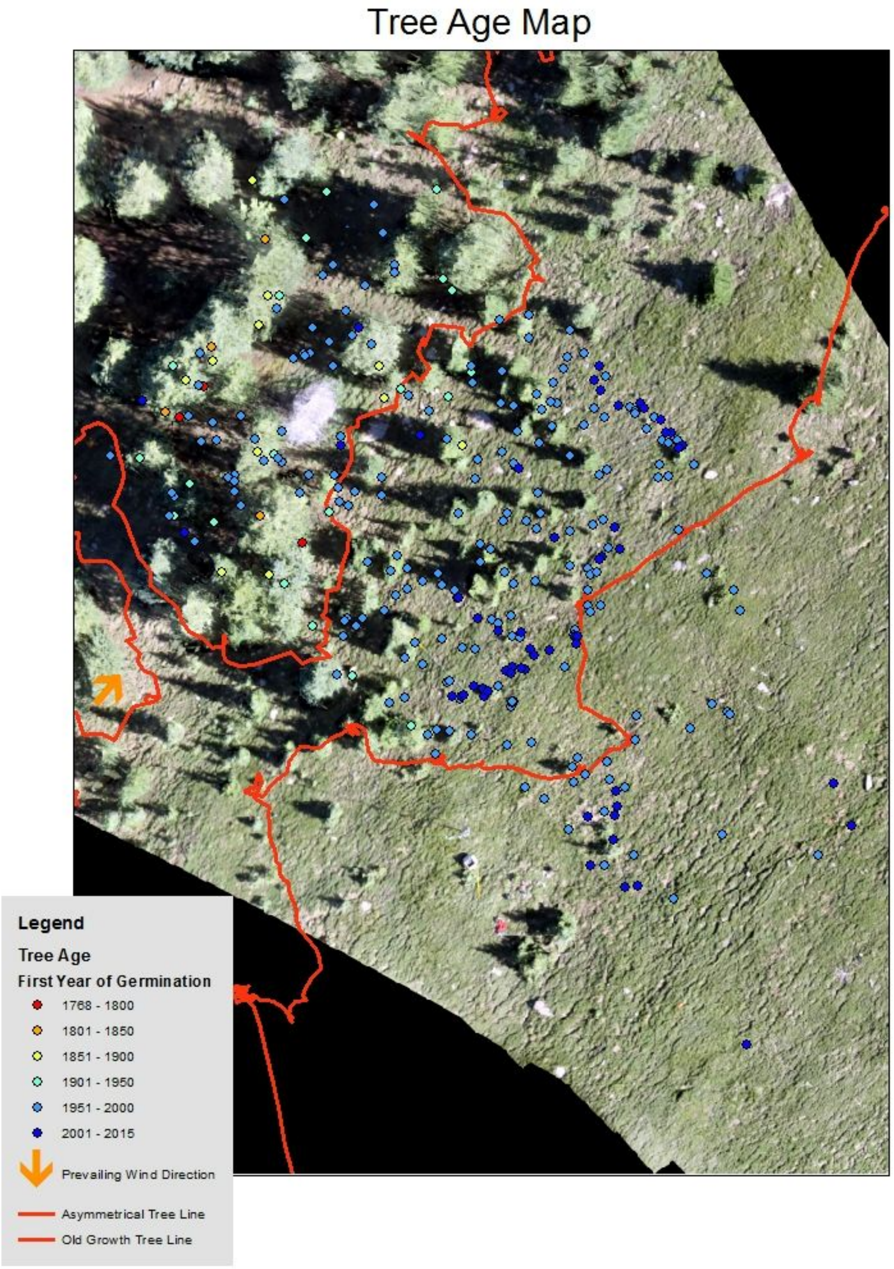


Figure 4. The Tree Age Map denotes the first year of germination of each tree using the symbology feature on ArcMap. The oldest trees in our transect are generally located in the Old Growth forest, and younger trees are found as you move upslope, which suggests that the tree line is advancing. On the bottom (southern) edge of the transect, lines of recruitment from 1951-2000 and 2001-2015 have formed behind pioneer trees from 1901-1950.

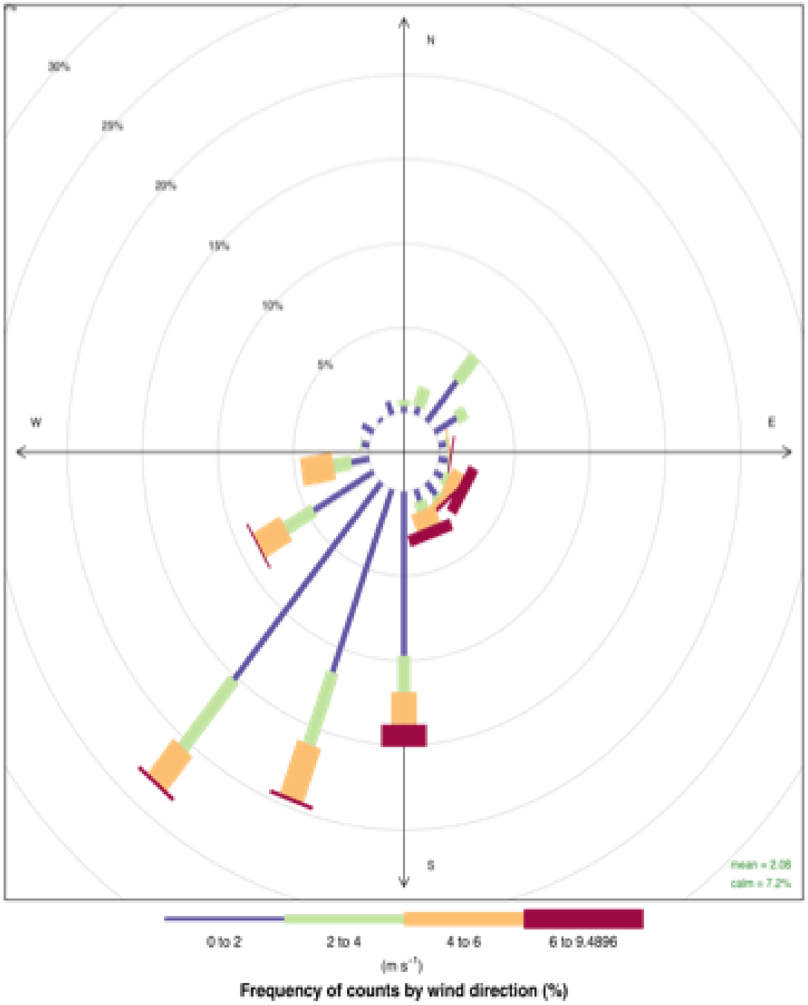


Figure 5. Wind Rose diagram from Meredith Parish's "A Micrometeorological Study of an Abrupt Treeline on Pike's Peak". The Wind Rose displays the frequency of wind direction measured by 6m wind vane from several meteorological towers arranged in the transect during the summer of 2015. Winds that measured 0˚/360˚ went from south to north. Each value on the diagram accounts for 20˚, with the most frequent winds coming between 200˚ and 220˚. The color and shape of the bar denote the wind speed in m s^{-1}.

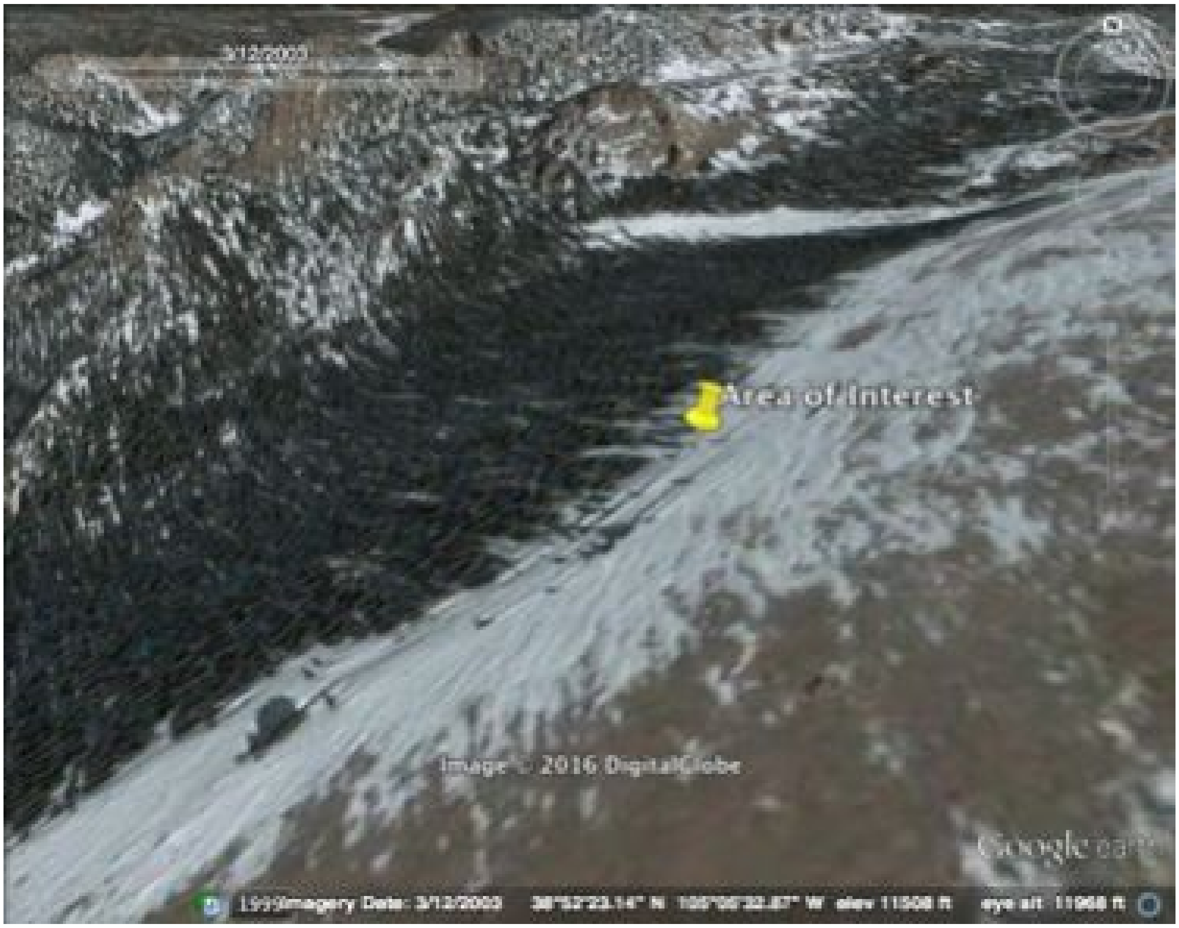


Figure 6. Snow Drift at Area of Interest taken from Google Earth. This image denotes the location of our transect from Google Earth and exposes how trees affect snow drift during the winter. Protection from ice blasting has allowed for recruitment to occur behind the miniature shelterbelt trees.

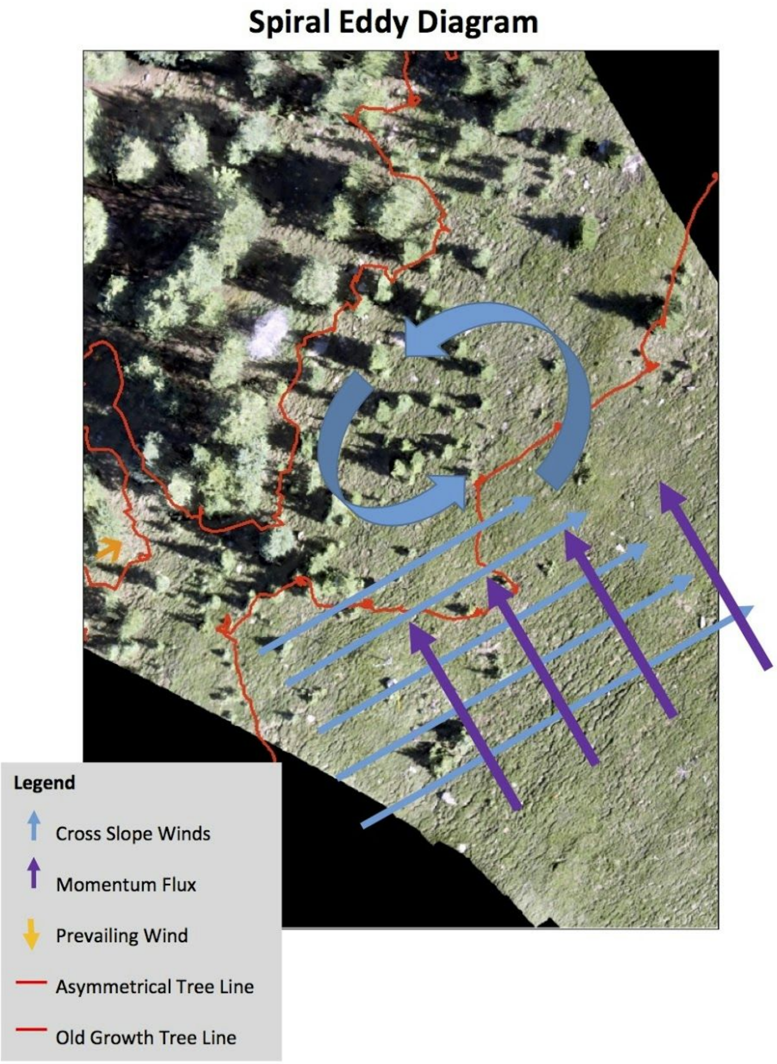


Figure 7. Spiral Eddy Diagram created using ArcMap and Microsoft Office. The Spiral Eddy is our 'cartoon' understanding how cross slope winds interact with the tree line. The blue arrows represent cross slope winds which increase in magnitude as you move upslope. Momentum flux is created by the wind speed gradient, capping air parcels against the tree line, where cross slope winds are slowest.

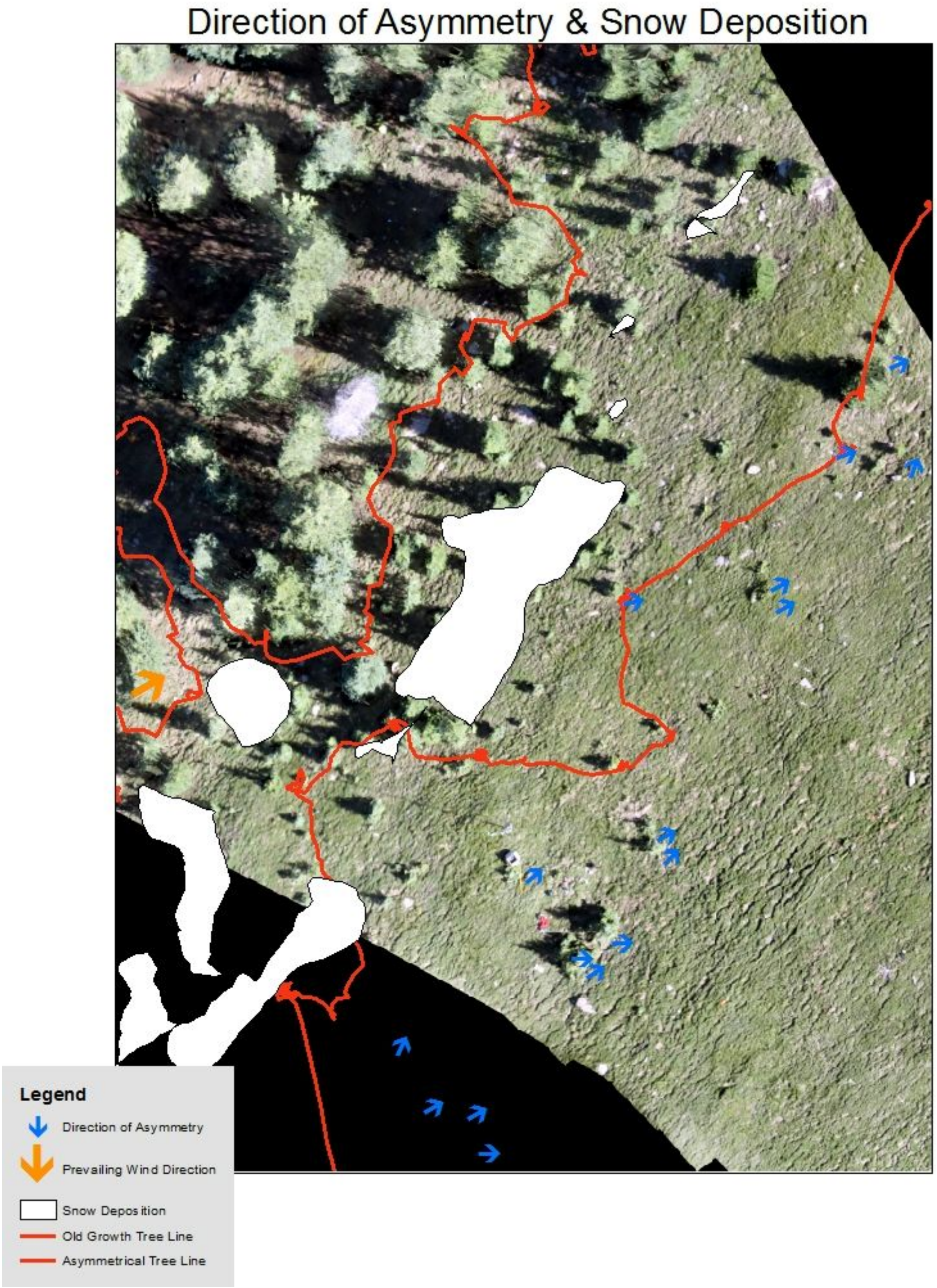


Figure 8. Direction of Asymmetry and Location of Snow Deposition map created using ArcMap. The blue arrows denote the direction of limb asymmetry on trees in the tundra. The presence of limbs on the downwind side of trees suggests that prevailing winds are funneled towards the tree line. In the process, snow is deposited in the eddy zone, which can be seen in the white polygons. We expect the leeward eddy to also be responsible for much of the snow deposition.

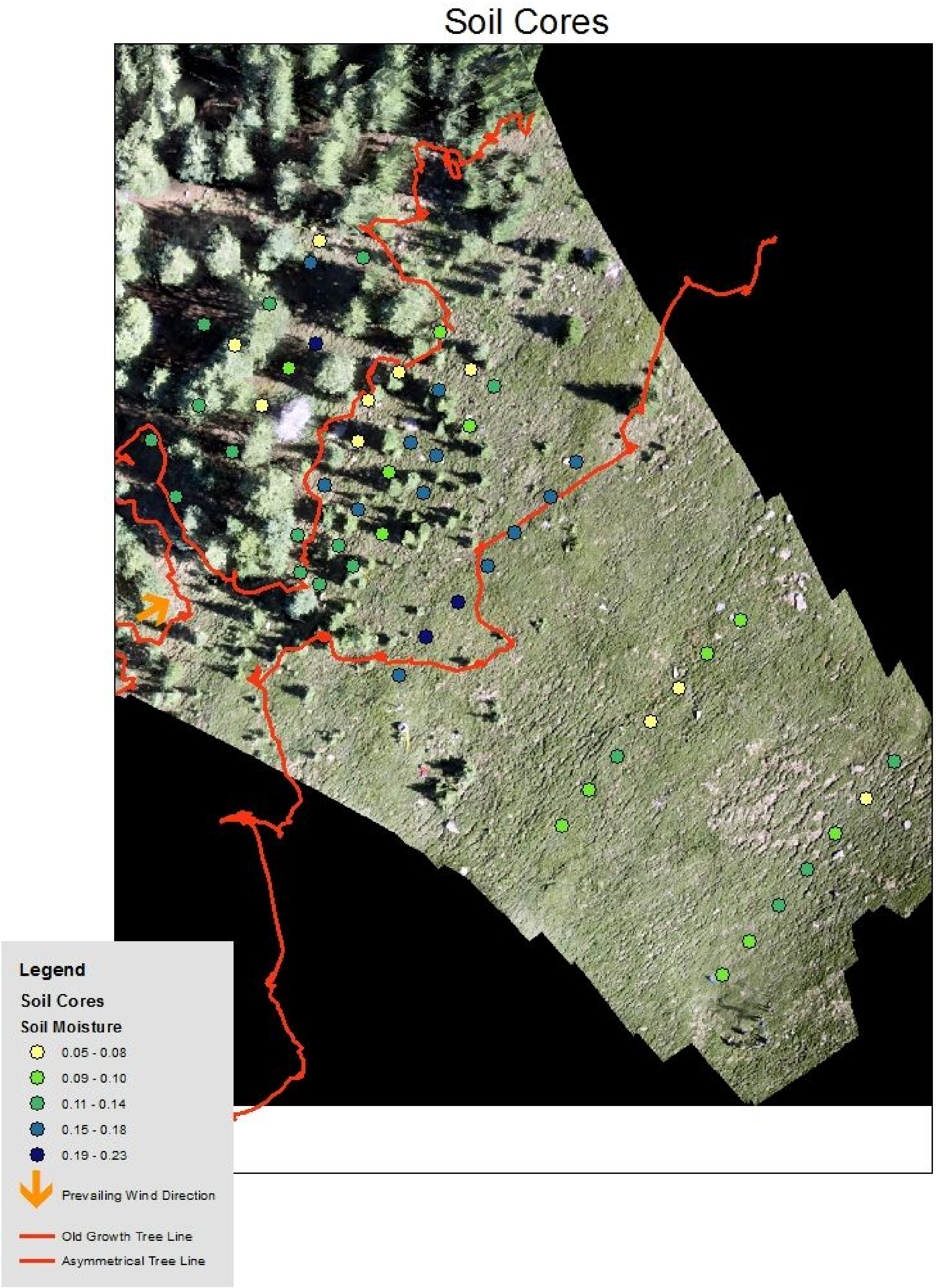


Figure 9. Soil Core Map made on ArcMap. The soil moisture transect reveals the highest moisture in the eddy zone, particularly at its upper limit. High values were also found in the old growth forest. Low moisture was found in the tundra.

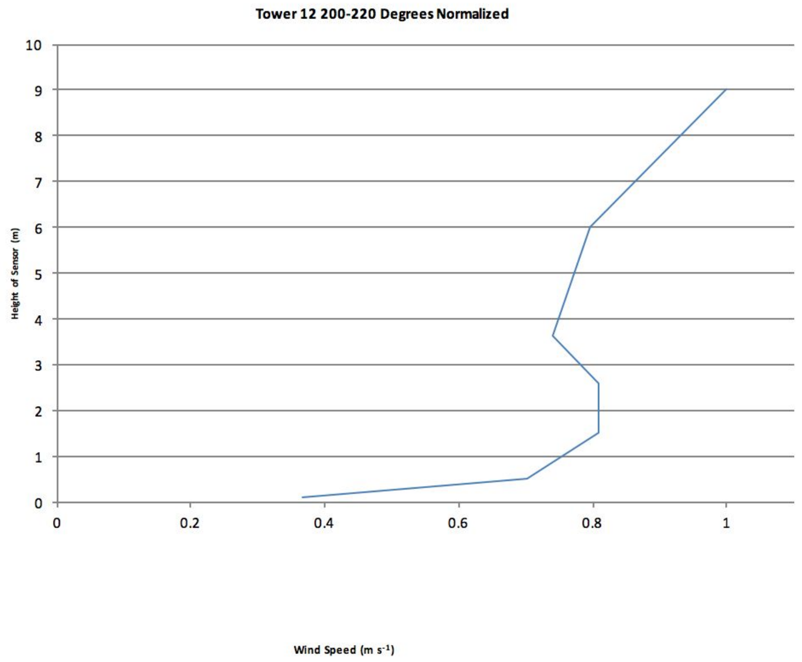


Figure 10. Normalized wind speed profile measured in the tundra from Meredith Parish's "A Micrometeorological Study of an Abrupt Treeline on Pike's Peak" (Parish, 2016). This wind speed profile exposes a jet layer at 2m. Normalized to the ambient wind speed measured at the 9m anemometer averaged wind speed profile

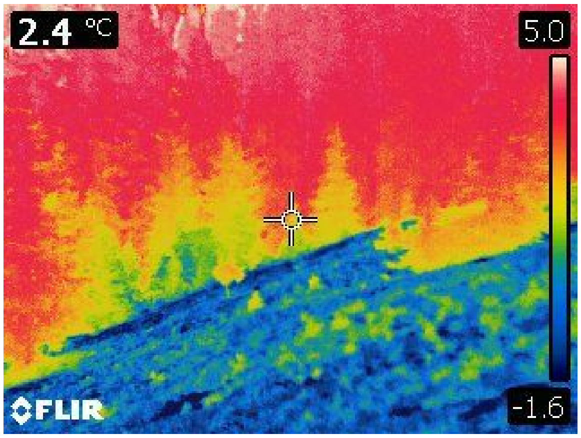
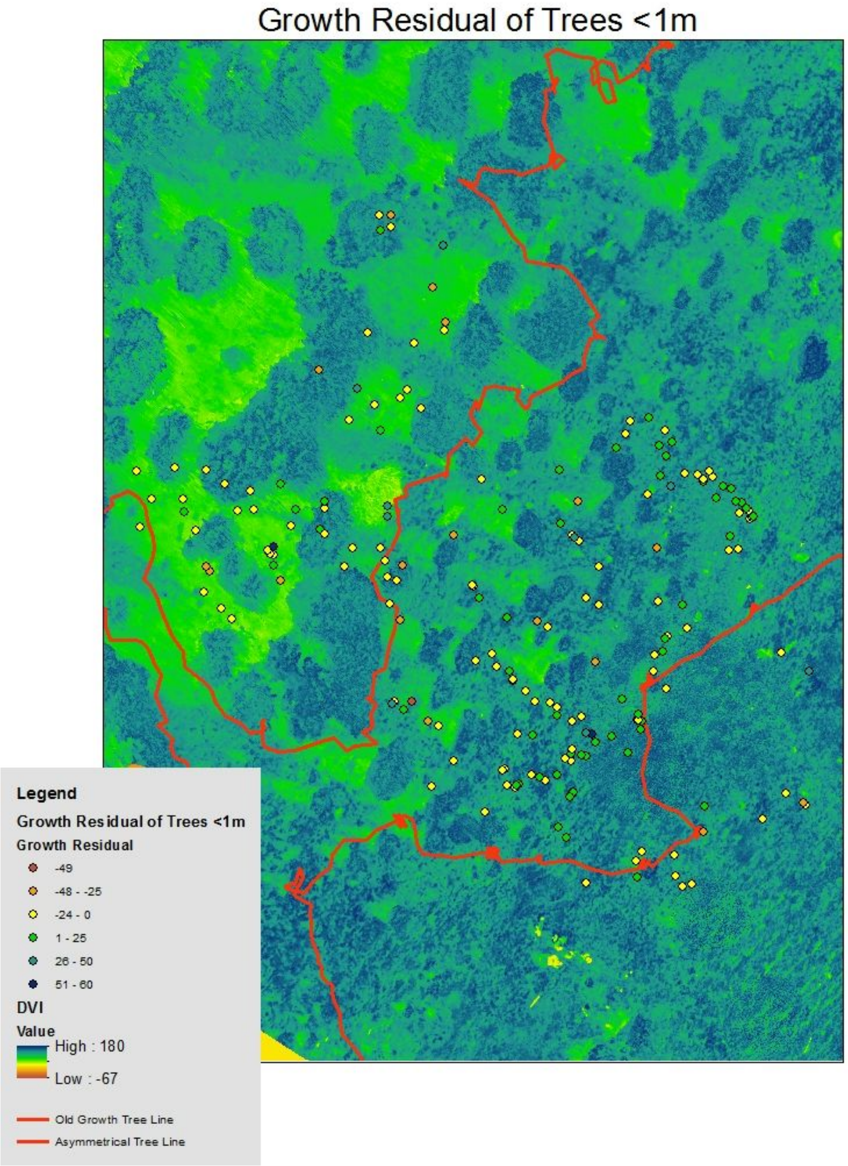


Figure 11. Infrared image of tree line taken at night using a FLIR E6 infrared camera. This image was taken looking downwards at the abrupt tree line from the tundra. It reveals cold air damming along the tree line, where temperatures drop as low as -1.6˚C.



Growth Residual of Trees <1m

Figure 12. Growth Residual for trees shorter than 1m with a DVI base layer created on ArcMap. High DVI values (98-180) correspond to dense vegetation, medium DVI values (16-98) correspond to sparse vegetation and low DVI values (-67-16) correspond to rocks and dry soil. The map symbology represents the annual growth residuals according to tree height for trees shorter than 1m. The highest residuals values are generally located in the upper extent of the eddy zone.

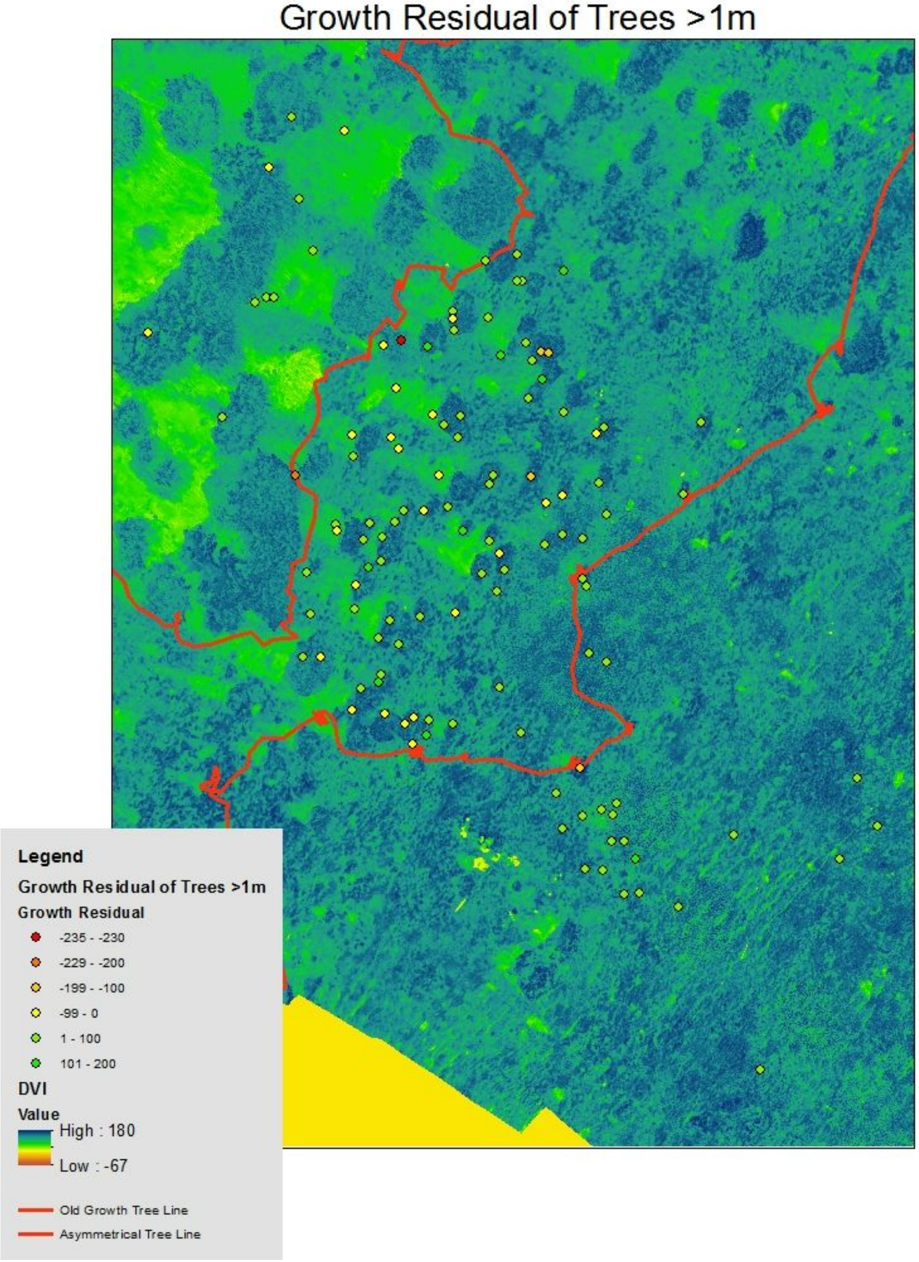


Figure 13. Growth residual for trees taller than 1m with a DVI base layer created on ArcMap. High DVI values (98-180) correspond to dense vegetation, medium DVI values (16-98) correspond to sparse vegetation and low DVI values (-67-16) correspond to rocks and dry soil. The map symbology represents the annual growth residuals according to tree height for trees taller than 1m. Taller trees generally posted higher residual values. The highest values were recorded in tundra, followed by the upper extent of the eddy.

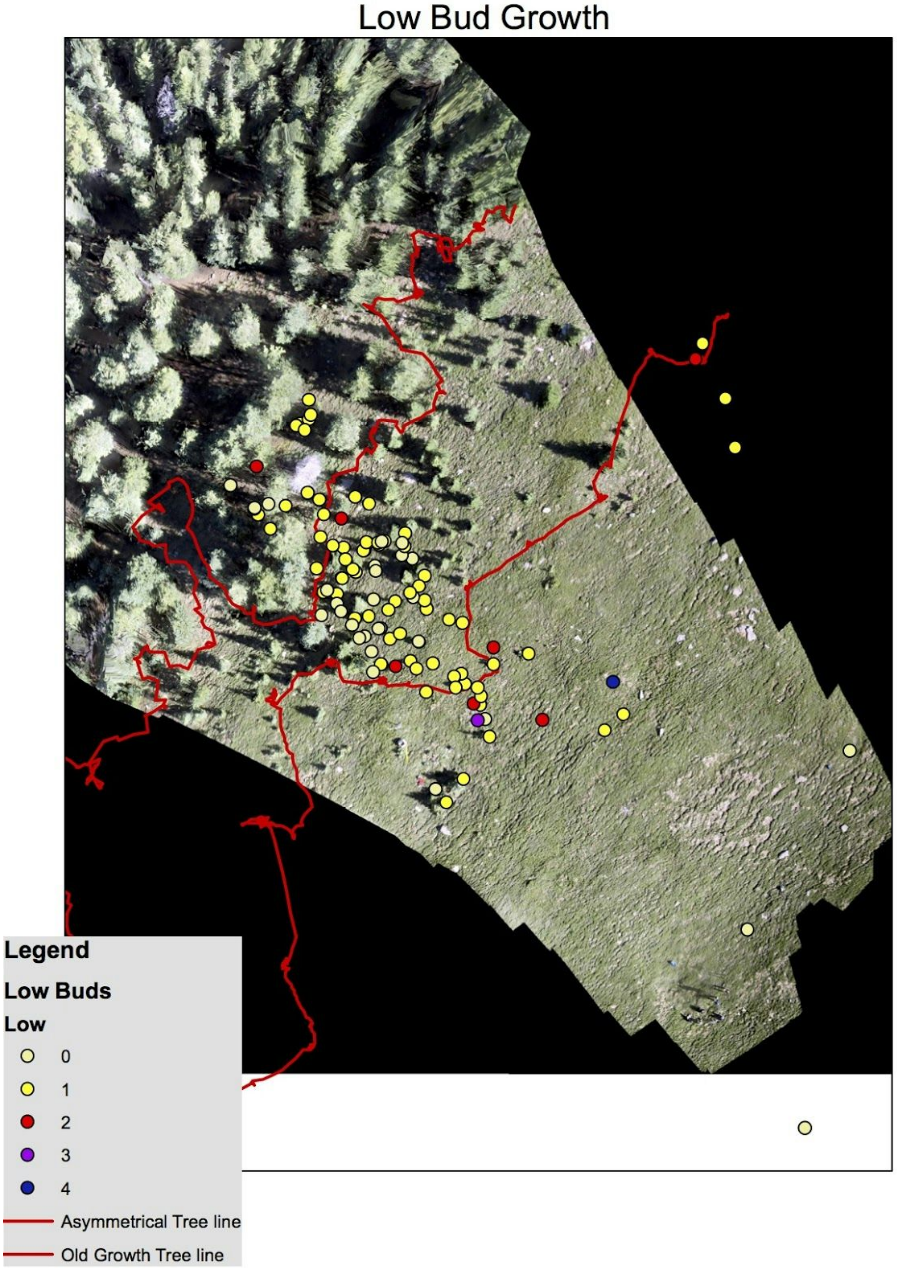


Figure 14. Early summer low bud development map created on ArcMap. The map symbology displays bud development of the lower third of trees. Lower buds show minimal development compared to top buds (Figure 15). Closed bud values are centralized in the center of the eddy zone.

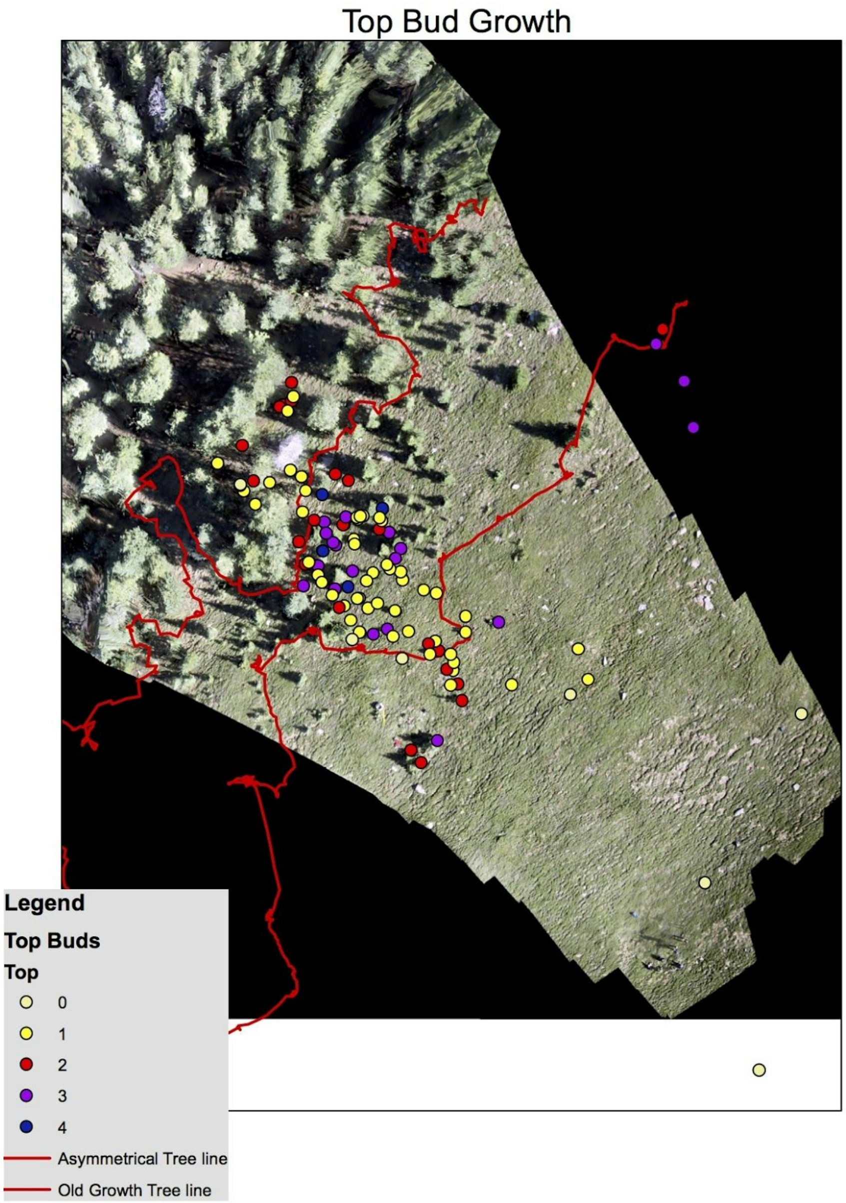


Figure 15. Early summer top bud development map created on ArcMap. The map symbology displays bud development of the upper third of trees. Top buds show increased development compared to lows buds (Figure 14). The most significant development is centralized along the old growth forest.

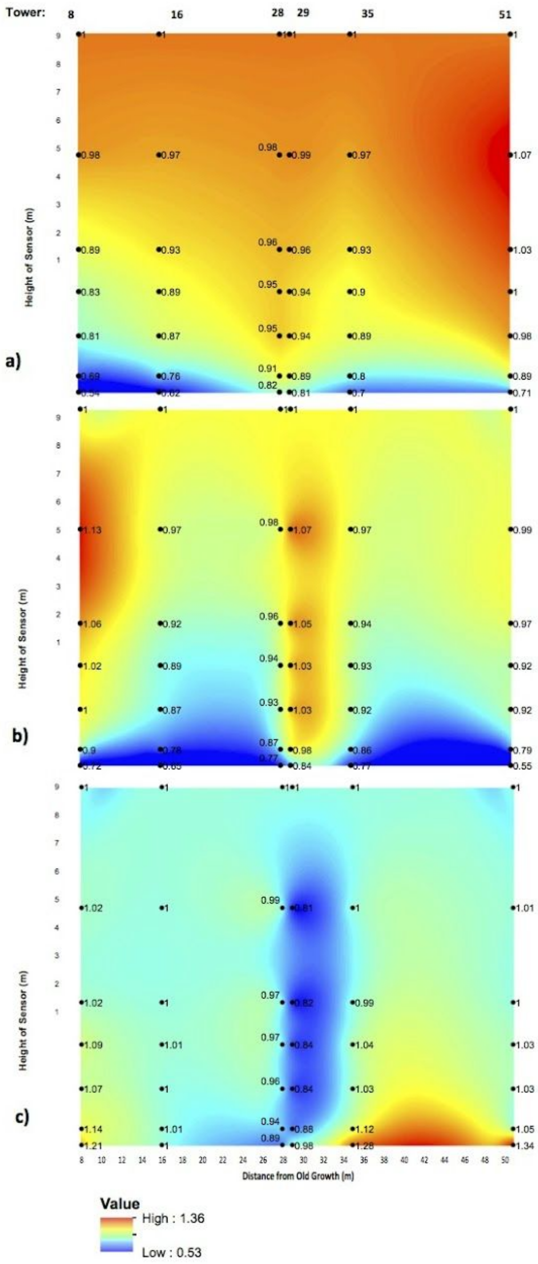


Figure 16. Spline Temperature Interpolations from Meredith Parish's "A Micrometeorological Study of an Abrupt Treeline on Pike's Peak" (Parish, 2016). a) The nighttime temperature regime when winds are mostly parallel to the tree line, we associate these winds with a pronounced spiral eddy. b) The nighttime temperature regime when winds are skewed to tree line. c) The daytime temperature regime when winds are skewed to tree line.

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