# TREELINE MICROMETEOROLOGY AND HOW IT IS AFFECTED BY AIRFLOW ON PIKES PEAK

A THESIS

Presented to

The Faculty of the Department of Environmental Science
The Colorado College

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Arts

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May 2017

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## ABSTRACT

We aimed to find what kinds of microclimates were created by an abrupt treeline and relate those microclimates to the spatial structure of the treeline itself. We specifically wanted to understand how airflow is directly related to air temperature upslope of treeline.

To do this, we took data from an abrupt treeline on Pike's Peak in the Front Range of the Colorado Rocky Mountain Range. Our data was taken in September of 2016, which is representative of the tail-end of the growing season for trees. The wind speed and direction appeared to have a strong relationship with the air temperature, as the daytime uphill anabatic airflow created eddy zones of slow-moving air that were able to warm up from sensible heat dissipated at the ground surface., The nighttime downhill katabatic winds accumulated pockets of slow-moving cold air.

This study helped us understand that sheltering with respect to treelines is not the result of single and independent trees, but rather the result of the entire treeline as complete three-dimensional structure. This is important because the effects of sheltering at treeline will vary from location to location based on the shape of the entire spatial structure of the ecotone.

# INTRODUCTION

Treelines are climatically constrained ecosystems, which means that they are good indicators for the effects of climate change (Grace et al., 2002). Most treelines worldwide share a common limiting temperature, based on root-zone temperatures. With increasing global temperatures at higher elevations, we should see an upslope advance of alpine treelines.The literature suggests that different treeline forms advance at different rates and are more/less responsive to warming because of different constraints. Specifically, diffuse treelines are the most responsive to climate change (Harsch et al., 2009). However, this is not the case for abrupt treelines, which move at a very slow rate compared to their diffuse counterparts (Pike's Peak Project). Abrupt treelines are ecotones that have a distinct spatial structure. As elevation increases, the trees come to a nearly immediate stop, as opposed to diffuse treelines where trees reduce in frequency and stature more gradually as elevation increases.

One of the most influential variables that determines where new seedlings can establish is temperature (Holtmeier and Broll, 2010). Tree physiology suggests that seedlings physically cannot photosynthesize below a certain temperature (typically 0 degrees centigrade), which means that they likely die off if conditions are too cold (Grace et al, 2002). If the the seedlings get too cold, they are not able to grow fast enough to replace tissue damaged by wind and detrimental organisms such as pathogenic fungi. The growing threshold temperature is 4 degrees centigrade (Grace et al, 2002). Temperature itself can be influenced by a number of factors: wind speed, snowpack, and shading to name a few (Malanson, 2011 and references within).

We can divide temperature into two categories: winter temperature, and growing season temperature. From a theoretical standpoint winter temperatures should not matter because trees are dormant during the winter, and should withstand the low temperatures. Furthermore, seedling death is more likely the result of warm winter temperatures because of desiccation. In winter, the roots of trees are underground and do not have access to liquid water. Warm air temperatures surrounding the needles cause an increase in evaporation, which depletes the seedling of its water storage for the winter (Marchand, 2014). In practice, winter warming seems to be important for treeline advancement. Harsch and colleagues found that treelines of all forms responded positively to warmer winters (Harsch et al., 2009). This is paradoxical because the mechanics of winter desiccation suggest that trees should respond negatively to winter warming. Some possible explanations for this paradox could be that warmer winters lead to longer growing seasons, or warmer winters lead to more snow because warm air can hold more moisture.

Snow is complicated in that it can be both beneficial and harmful to seedlings. Too much snow can lead to fungus, because the late spring melt produces too much moisture. And a lack of sufficient snowpack can lead to excessive sky exposure and not enough protection from snow blasting (Holtmeier and Broll, 2010). Furthermore, snow provides the moisture that seedlings need to photosynthesize, which also plays into the importance of snow.

However, there is still much confusion as to which season is more influential to treeline advancement. Some ecologists theorize that growth depends on the ability to use carbohydrates, which is temperature limited, so summer should be more important. And furthermore, as seedlings grow taller and thicker, they can provide more shelter for other seedlings to establish, leading to the advancement of treeline (Korner, 2004). Winter temperatures cannot help the seedlings produce as much biomass as the warm summer temperatures do.

However, these views of treeline assume that trees are independent of each other and temperature influences each tree in the exact same way, which is not the case. Trees can modify climates, especially on the micro-scale, which means that the treeline needs to be thought of as a whole system, rather than individual trees. Current models of treeline structure do not include mechanisms of tree interactions (Malanson, 2011). They simply assume that being next to another tree is beneficial, but fail to include a realistic view of sheltering. Unique microclimates can be created based on the shape of the whole treeline, and this can lead to less sensitivity to climatic factors such as environmental temperature. Treelines can shelter from the wind, reduce open sky exposure, increase snow accumulation (Germino, 2002). So, the treeline pattern entirely depends upon the spatial structure of the shelter available at each treeline, and thus will differ greatly from site to site (Resler et al., 2005). It is interesting to note that landscape-scale treeline scientists believe that heat deficiency is the limiting factor on high elevation tree-growth, not magnitude of cold (Malanson, 2011). But still, more than just temperature needs to be considered on such a 3-dimensional model of a complex ecotone.

Looking at treeline as a three dimensional system, we can see that unique spatial structures are created as a direct result of treelines and the positive feedbacks that occur within the system as a whole. A positive feedback is a pattern such that trees help other trees grow by providing shelter, or a lack of trees contributes to the decline of trees because of a lack of shelter. Positive feedbacks occur often within plant communities that alter their environment to favor themselves (Bader et al., 2007). The nature of positive feedbacks contributes to the the abruptness of treelines because they sharpen boundaries (Wilson and Agnew, 1992).

It is also important to consider other factors that can influence spatial structure of treelines. As mentioned before, snowpack can play a great role in seedling survival. If there is too much snowpack, the seedlings can be harmed by a certain species of snow fungus that flourishes in deep snow. If there is too little snowpack, then seedlings can be wind-blasted or damaged by too much exposure to harmful sunrays. In fact, most studies in the treeline community have been examining how wind influences snowpack in the winter, and how deep slabs of snow are deposited directly behind abrupt treelines because of eddy structures (Holtmeier and Broll, 2010). This makes a lot of sense, but possibly does not explain the whole process. Sheltering may also be significant in the summer. This is why we are looking specifically at the growing season and trying to find any patterns that exist between wind/temperature/seedling establishment.

### *PHYSICS* (adapted from Oke, 1987):

So why is the air warm or cold right next to the treeline? It all has to do with the different types of heat absorbed and released by the ground. As the sun shines during the daytime, the ground absorbs shortwave radiation. In addition, the ground absorbs longwave radiation from the air. The heat gets dissipated in four different ways: 1. Radiated into space. 2. Absorbed by the ground. 3. Evaporation of water. 4. Carried away by the air above the ground. If the pathways that carry heat away are effective, then the temperature will be low. If they are ineffective, temperature will be higher.

At night, the ground gets cold as the longwave radiation is released from the ground and back into the atmosphere, different sources of heat try to replace the lost radiation, but cannot keep up with the rate at which the ground is losing heat. These sources are the same as mentioned above: radiation from other objects and the sky, ground heat, condensation of water, and heat transferred through warm air. The more heat that these pathways can provide, the warmer the ground temperature will be. The more heat that can be drawn away from the surface means the lower the ground temperature will be. So with this knowledge, we know that during the day the ground is warm and during the night the ground is cold.

### *Mountain Winds*

It is also important to look at wind patterns to see when and why certain airflow structures are created or destroyed at treeline. We can see general patterns with mountain winds. Closely related to the temperature patterns, winds are determined by how warm or cold the air is. Anabatic, or uphill winds, are created mostly during the day, when the ground is warmed through shortwave radiation and consequently the air column is warmed directly above the ground. So the air on top of the mountain slope gets warmed, becomes a zone of lower pressure, and pulls up the valley air through convection. This effect creates the anabatic winds we see during the daytime.

At night, the opposite effect happens, where the air cools dramatically. As it cools, it becomes extremely dense and slides down the mountain, as the air on top of the mountain is denser than the air below it. These downslope katabatic winds are the general trend we see at nighttime.

So why are wind patterns important to us as we examine spatial dynamics at treeline? Because they can determine the favorable or unfavorable microclimates that seedlings interact with. The anabatic winds are crucial to the creation of eddy structures directly behind the abrupt treeline. An eddy structure occurs when a fluid moves across two different types of surfaces: rough and smooth. In this case we are looking at air moving over trees and over tundra. As the anabatic wind moves over the rough surface of the trees, friction is slowing it down layer by layer until it reaches the tundra. At the tundra, the air dramatically speeds up as there are less trees (friction) to slow it down. When the air speeds up at the tundra, a lower pressure zone is created and as a result, lift and drag pull some of the air back towards treeline, creating an eddy. The eddy structure can act as a microclimate, and the fast moving air above the eddy prevents the mixing between atmospheric air and the air inside the eddy. This lack of mixing allows the air to eddy air to heat up, creating a warm air pocket during the day.

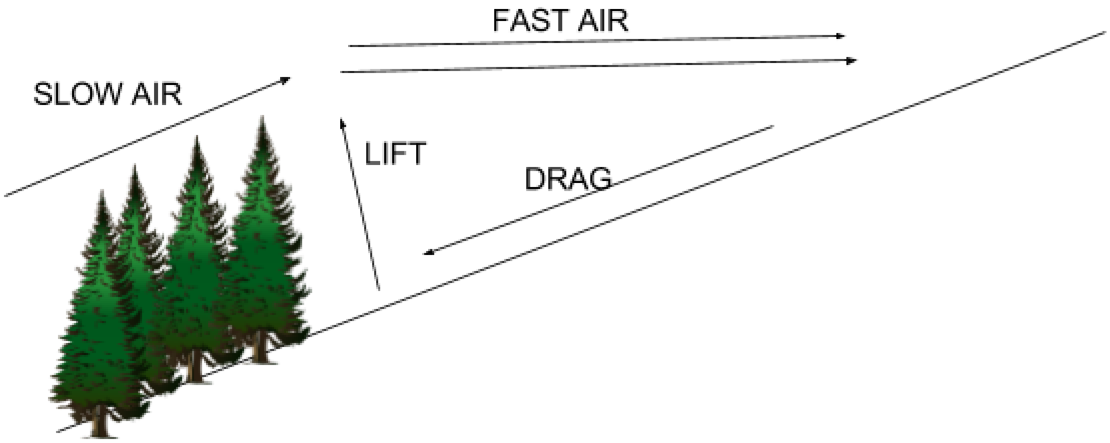

Figure 1: How an eddy is created from daytime anabatic winds.

On the contrary, at night when the air is sliding down the hillside, the treeline can act as a dam blocking the downhill flow and building up an extremely cold pocket of air. We predict that this is part of the reason why abrupt treelines remain abrupt, because there is an extremely cold and unfavorable microclimate directly above the treeline during the night, making it difficult for seedlings to establish.

# HYPOTHESIS

In this study, we look at both the daytime and the nighttime wind and temperature regimes from the zone directly above treeline extending into the tundra. We are investigating how temperature is directly correlated to wind speed, and how that might influence where new seedlings establish. In the case of an uphill wind, an eddy should be created behind the treeline. This is a spatial structure that needs to be considered when looking at airflow patterns, as it can create temperatures that might constrain or benefit seedlings. During the day, the increased residence time of air within the eddy structure should create a warm pocket, which should benefit seedling growth and survival. During the night, the cold air is dammed up against the treeline, creating a cold pocket that should be detrimental to seedling growth. The daytime warm zone and the nighttime cold zone may not line up spatially, and this could influence the future pattern of treeline establishment. If they did lineup, it is possible that they would cancel each other out, and result in no treeline movement at all. Furthermore, when the air flows parallel to the treeline, there is less of an eddy structure, which means that the sheltered zone is essentially non-existent. When the wind blows downhill (mostly during the nighttime regime), a pool of cold air gets dammed up against the abrupt treeline, most likely creating an unfavorable spot for seedlings to establish.

# METHODS

## Field Site:

Figure 2: An aerial view of our field site.

Our site is located on the back side of Pike's Peak at about 3,520 meters above sea level. The site is northwest facing and composed primarily of Engelmann Spruce with an absence of shrubs.

Within our study site, we chose an area of interest that we thought was representative of an abrupt treeline. This means a very straight continuous line of old growth trees with not many holes or gaps. At this site, we set up a transect for the wind speeds and temperature we wanted to analyze with respect to sheltering. We estimated the sheltered zone by looking at the small seedlings that existed beyond the treeline, and determining which ones were protected from the wind-blasting that occurs during the winter. We found that the sheltered zone ended at about ~70 meters. With this in mind, we wanted to include all of the sheltered zone plus a portion of tundra to study.

So we chose eight different stations to examine the air columns that extended 8 meters directly upwards. The stations were placed every 15 meters, starting right beyond treeline. This gave us a representative cross section of the area of interest.

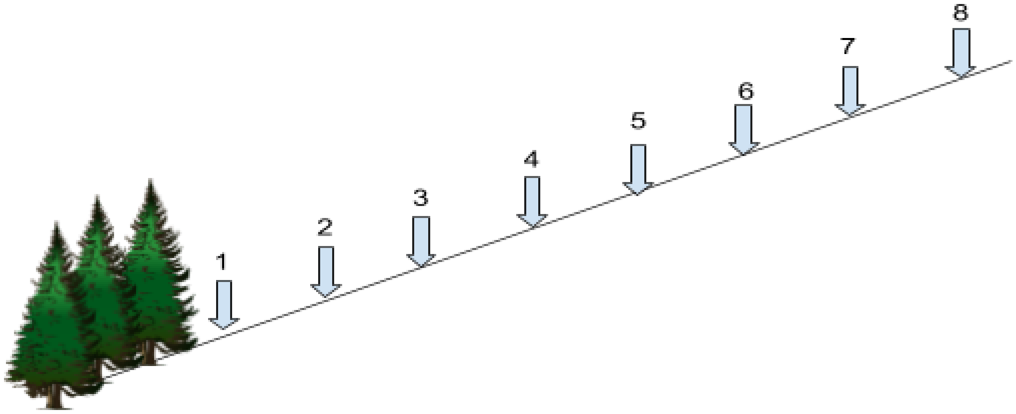

Figure 3: The layout of our weather tower stations in relation to treeline and tundra.

After picking our site, and setting up our stations, we proceeded by building weather towers. To construct the weather tower, we fastened a wind anemometer, a weather vane, and a thermometer to 6 different heights on a long metal pole. The heights were: 0.5 meters, 1 meter, 2 meters, 4 meters, 6 meters, and 8 meters. We then programmed this tower to log 1 minute averages at each of the 8 sites.

However, because this tower was always moving, we needed to make a control tower to log the ambient conditions in order to normalize the data we collected from the moveable tower. This tower was constructed on a 2 meter pole with just one set of instruments fastened to the top. We then placed this tower about 50 meters uphill of station 8, to ensure that we were collecting accurate tundra data.

Next, we needed to determine what our time stays should be for the tall tower at each station. We decided on two different approaches: 1. Short 30 minute intervals at each station over the course of one morning (nighttime regime) and one afternoon (daytime regime). 2. Long overnight stays that collected data at one station for over 24 hours. When analyzing data, this would allow us to consider both 1-minute averages (with the short stays), and 30-minute averages (long stays) to see if the wind speed and temperature were more closely correlated for a certain time interval.

Associated with this study was another study on seedling establishment and growth at the same treeline area.

## RESULTS

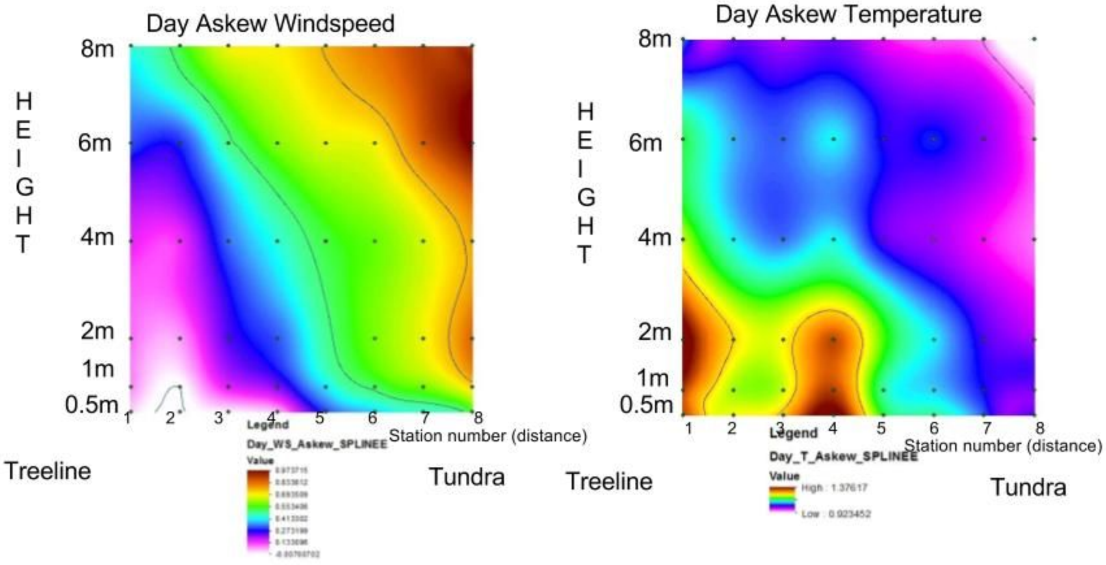

Figure 4: Daytime airflow askew to the treeline. Windspeed and air temperature normalized to ambient airflow and temperature measured in the high tundra.

It is important to look at the figures in the context of sheltering. As mentioned in the introduction, sheltering is the mechanism that can be attributed to the entire treeline as a three-dimensional structure. It occurs when the daytime anabatic wind blows uphill and an eddy structure is created uphill of the treeline. The lack of mixing allows the eddy air to warm up and possibly create a favorable microclimate for seedling establishment. With this in mind, we can see patterns start to emerge from the figures. Looking at figure 4, daytime askew flows, the most common flow during the day, we can see a clearly defined area of slow moving air, or a sheltered zone. This sheltered zone, which we consider to be air movement less than 25% of the ambient wind, extends to between stations 4 and 5, which is the same elevation where we started to see the wind-blasted trees. So, we can conclude that the upper edge of the eddy is created at the site where the fast wind hits the tundra like we expected. The pool of slow moving air also extends upward to about 6 meters, which is interesting because the trees that created the shelter are about 15 meters tall, so the top edge of the sheltered zone is quite a bit lower than the height of the treeline. This characteristic of the sheltered zone was unexpected because we expect the sheltered zone to be the same height as the obstacle that is creating it (Wang and Tackle, 1997). This is likely because the treetops in the top of the treeline is a very permeable structure that cannot uniformly block all of the air like the bottom of the trees, so the eddy is formed lower than the top of the barrier. The shape of the sheltered zone has a flat top and a steep drop off. The flat top of the sheltered zone is well above the saplings and seedlings that are present in the area, which are about 2-3 meters tall. Angle of the hillside could also play a role in the height of the sheltered zone. If the slope of the hillside is significant, like our ~25 degree slope, and the wind does not flow parallel to the ground, then the interaction between angle of the wind and angle of the hillside will create a shorter sheltered zone.

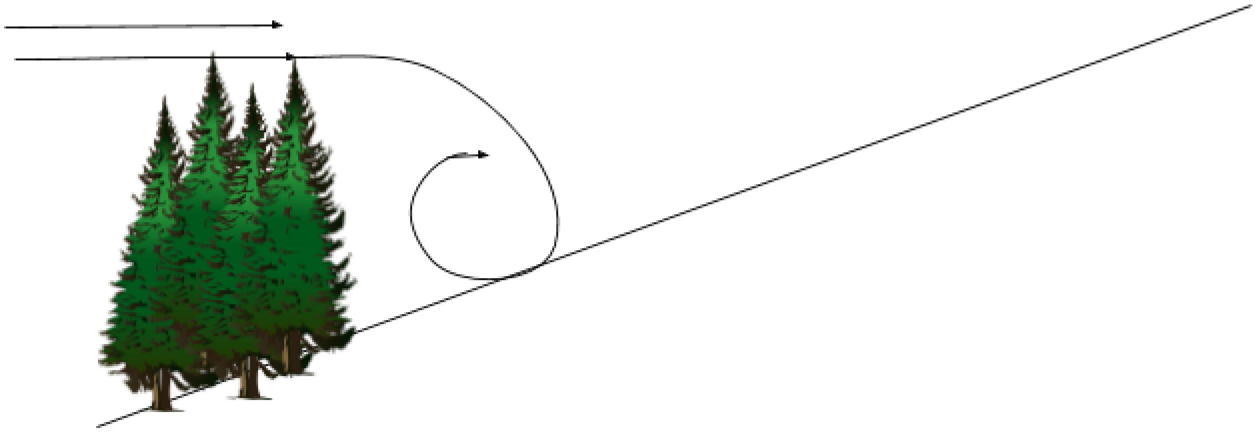

Figure 5: An example of how a shorter sheltered zone would be created as a result of a steep hillside.

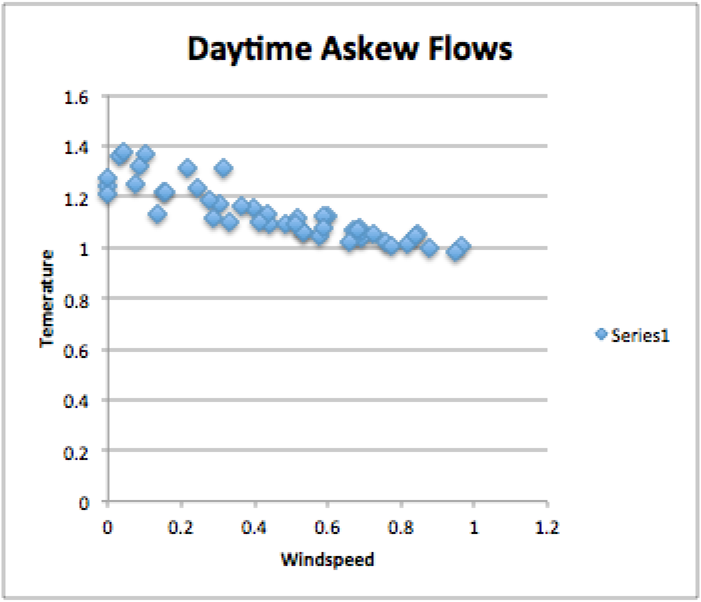

Figure 6: The relationship between normalized temperature and windspeed during askew uphill flows. Increasing wind speed decreases temperature.

We can also see a correlation between the wind speed gradient and the temperature gradient in figure 6. There is a strong negative relationship (R 2=0.7698, N=47, p<0.005) during daytime askew flows--as windspeed increases, temperature decreases. The relationship signifies that temperature is strongly impacted by wind speed --- 77% of variation in temperature is explained by wind speed alone. This indicates that the sheltering has strong impact on temperature, as expected by the theory. Sheltering increases residence time of the air parcel, decreases sensible heat flow out of the parcel and thus allows it to heat up.

Considering details of Figure 4, one thing that we did not expect in the temperature map was the unusual cold pocket right in between stations 2 and 3 in the sheltered zone. This could be explained by a few mechanisms. One possibility is the presence of a complex eddy structure. We expected a large simple eddy as the air flows over the trees, but in reality, multiple eddies could exist because of the unique direction of the askew flows. The wind could begin to make a large simple eddy, but as it interacts with different obstacles (especially as it does flow askew rather than perpendicular to the treeline), it could create smaller residual eddies. Perhaps a smaller and more complex eddy structure was created at station 4, where the air remains unmixed with the atmosphere and no eddy was created at stations 2 and 3 so the air was able to be mixed with the colder atmospheric air. Alternatively, this cold pocket could also potentially be explained by evapotranspiration. Because more moisture might exist between 2 and 3 based on sapling presence, the ground could essentially “sweat” off a significant portion of its heat. As the wind blows, more and more heat is taken away from the ground and transferred into the atmosphere. The last possibility we should consider for the cold zone between stations 2 and 3 is the possibility of shading by the saplings. An artifact could be in play, because the sensor from the thermometer could falsely be reporting the air temperature based on the artificial cooling of the outer shell of the instrument however, this should primarily impact the lowest thermometers on the tower.

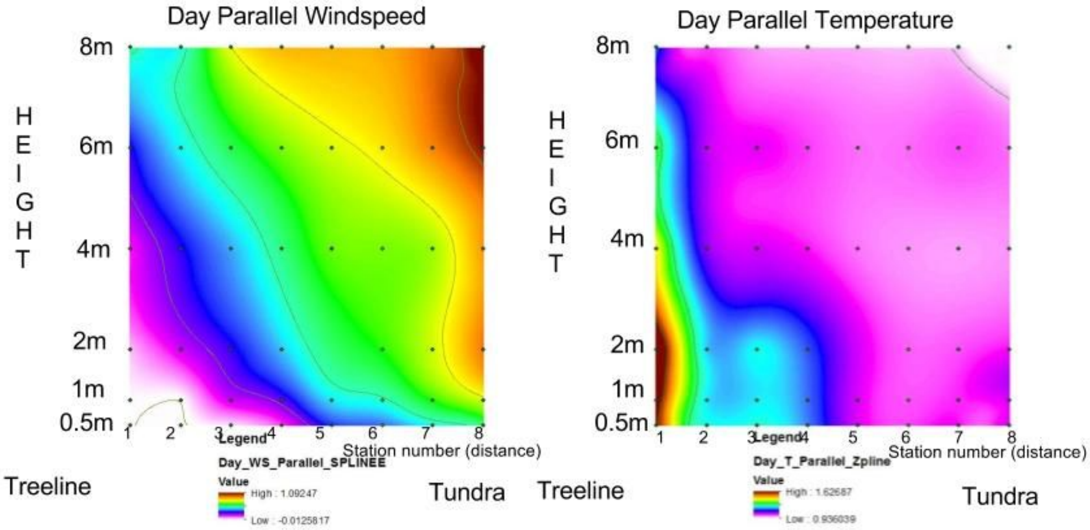

Figure 7: Daytime airflow parallel to the treeline. Windspeed and air temperature normalized to ambient airflow and temperature measured in the high tundra.

As we can see from the daytime parallel flows (figure 7), the sheltered zone is much smaller than with askew flows. The 25% isoval only extends to about station 4, there is no flat top to the sheltered zone like we observed with askew flows. The sheltered zone is about 5 meters tall at station 1, 2 meters tall at station 2, 1 meter tall at station 3, 0.5 meters tall at station 4, and essentially non-existent at station 5. The height of the isoval decreases exponentially with distance away from the treeline,($R^2=0.831$, $N=5$,$p=0.031$). The reason why the air slows down right next to treeline is most likely due to friction with the treeline itself. The layers of air closer to the treeline slow down each adjacent layer of air further away from the treeline. If we look at the isovel locations of parallel vs. askew flows, we can see that the parallel 50% isovel shifted downhill by about 15 meters.

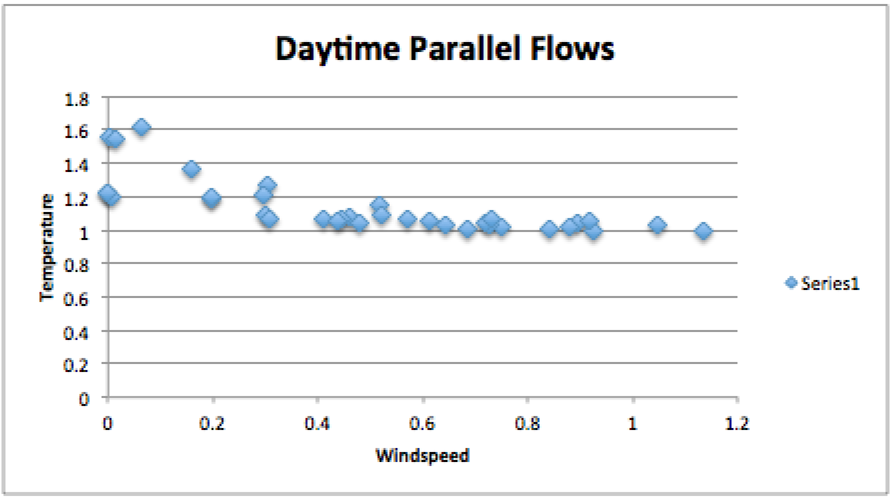

Figure 8: The relationship between normalized temperature and windspeed during parallel flows. Increasing windspeed decreases temperature.

The relationship between windspeed and temperature once again is very strong (R^2=0.574, n=47, p<0.0005), which is what we expected. Interestingly, the relationship is weaker than with askew flows, and windspeeds above 40% of ambient flows, do not appear to have any impact on temperature. Perhaps the weaker relationship is the result of the near absence of the sheltered zone i.e. there are fewer points for which velocity is 40% ambient. Comparing the windspeed and temperature interpolations in Figures 5 and 7, it is clear that the zone of high temperatures is much smaller during parallel flows because the sheltered zone is also smaller. With parallel flows, the warm zone is restricted to station 1, directly adjacent to treeline. Thus, when parallel winds blow, there is less of a favorable growing zone, so seedlings should prefer when winds blow askew or uphill.

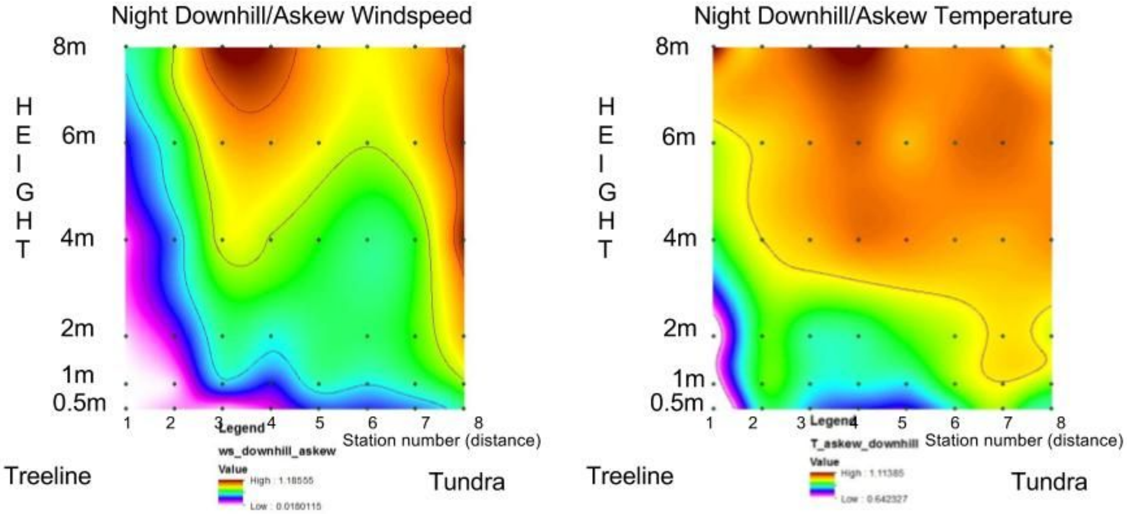

Figure 9: Nighttime airflow downhill and askew to the treeline. Windspeed and air temperature normalized to ambient airflow and temperature measured in the high tundra.

Figure 9 shows us the nighttime trends. The nighttime downhill/askew, most common flow at night, wind speed map shows that the low wind speeds are restricted to the area right next to treeline and closer to the ground (0.5m) at zones 3 and 4. This is how we expected the wind speeds to look, because of the damming effect of the treeline. The air slides quickly downhill over the smooth tundra, but as it meets up with the dense old growth trees it cannot pass through easily, so it becomes slow moving, almost stagnant. Even though there are holes in the treeline, the air still gets dammed up because the trees present more friction than the tundra and the parcels of blocked air slow down more parcels of sliding air. This effect can be seen in figure 8, as the fastest moving air climbs up and over the stagnant pocket right next to treeline.

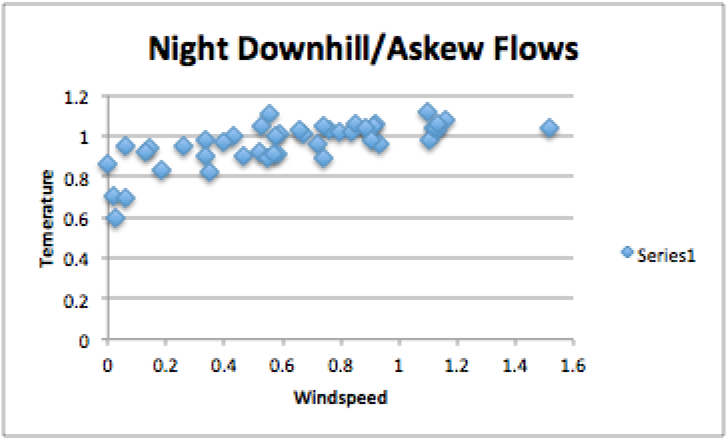

Figure 10: The relationship between normalized temperature and windspeed during downhill/askew flows at nighttime. Increasing wind speed increases temperature.

A relationship exists between windspeed and temperature at night, but is in the opposite direction during the daytime (r^2=0.504, n=47, p<0.0005). As windspeed increases at night, the temperature tends to get warmer, not colder. The coldest section of air exists adjacent to treeline and directly above the surface of the tundra. This is because at night surfaces cool due to radiation of infrared waves into space, and the layer of air directly above them supplies them with heat. This results in strong inversions near the ground. At the treeline, the slow moving air does not mix with the warmer atmospheric air, making it an extremely cold and unfavorable zone for seedlings. However, the coldest air sits only about 0.5 meters above the tundra, which is a relatively thin layer compared to the warm layer of air during the day time. This means that once seedlings grow to a certain height (above 0.5m), they could push out of the cold zone and reach the warmer air during the nighttime. We predicted that the cold zone would be a bit bigger than it actually is, because of the influence of bolster eddies, or eddies that are created when air flows directly into an obstacle and flows backwards onto itself.

In figure 9, the unusual warm zone at station 2 could be the result of radiation from existing trees. At station 2, there are saplings that are about 1-3 meters tall, and at night these saplings radiate heat into the air around them. The infrared radiation from saplings was clearly visible in thermal photographs taken before sunrise  We are still confused by the extremely cold pocket of air right next to the treeline (station 1), because if trees radiate heat at night, then this area should be receiving most of the heat from the old growth trees. But there is a battle between the incredibly cold air that gets dammed up against the dense forest and the radiation from the forest itself.

The cold spot adjacent to treeline at night (station 1) makes sense in context of our research done on seedling establishment. In this zone at our field site, there are no establishing trees, just barren tundra, which is likely the result of the extremely cold temperatures at night.

There is a second cold spot located at stations 3-5, which overlaps almost exactly with the warm temperatures during the day. Seedling growth seems to respond to accumulated heat (Intro of roadmap paper), so therefore it is not clear whether the nighttime cooling will outweigh the daytime warming. It is feasible that the daytime warming will outweigh the nighttime cooling with respect to accumulation of heat. This appears to be so because there is a belt of healthy established seedlings that exists right at station 4 (Lani Chang, 2017). So the two extremes during the daytime regime and during the nighttime regime seem to play a crucial role in determining the spatial structure of the treeline, but they are only understood when considering the treeline as a whole.

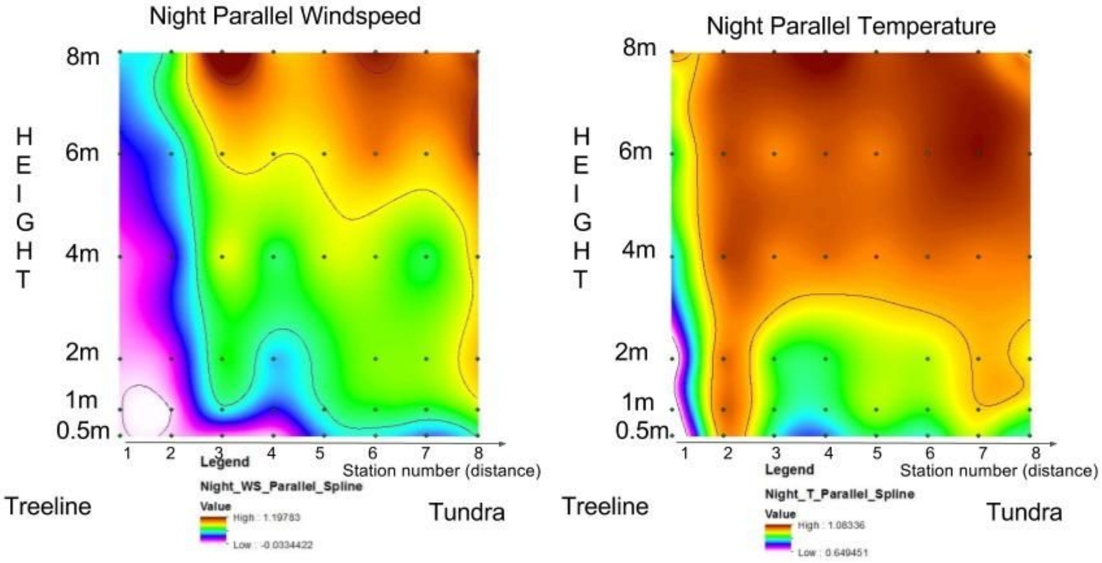

Figure 11: Nighttime airflow parallel to the treeline. Windspeed and air temperature normalized to ambient airflow and temperature measured in the high tundra.

Figure 11 shows us the results of the parallel wind flows at nighttime. Here, we see there is a larger volume of slow moving air than in the downhill flows. The slow moving air here is the result of friction with the treeline, this is similar to the daytime parallel flows, as the air moves across the treeline, it is slowed down by the rough surfaces. The slow zone exists up to 6m high at station 1, up to 4 meters high at station 2, and it drops down to about 0.5m at stations 3 and 4. It is interesting to see that there is a bubble of slow moving air right above station 4, which manifests itself in a blue hump. This is likely the result of a terrain issue--because the parallel flow is defined as plus or minus 10 degrees of parallel, then slightly askew flows could interact with the abnormalities of the abrupt treeline and create eddies beyond the treeline.

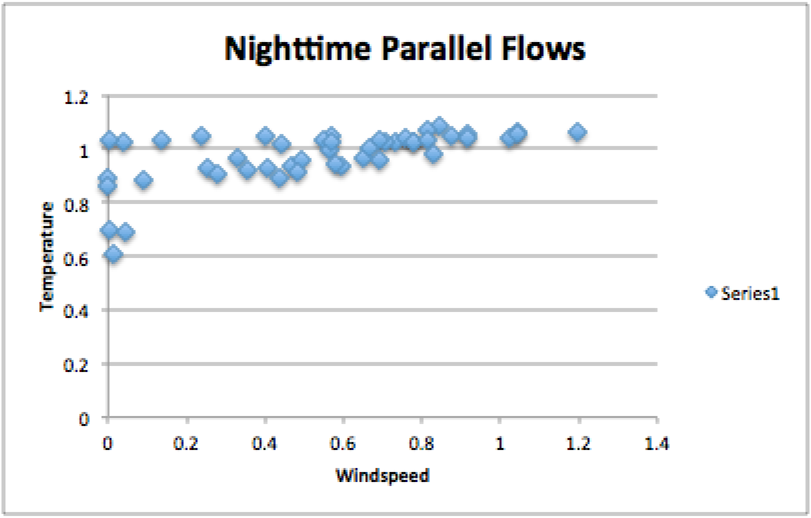

Figure 12: The relationship between normalized temperature and windspeed during parallel flows at nighttime. Increasing wind speed increases temperature.

As we can see from figure 12, there is a positive relationship between windspeed and temperature for parallel flows at night ($r^2=0.421$, $n=47$, $p<0.0005$), however, not as strong of a relationship for low wind speeds. So when parallel wind speeds are lower than 40% of ambient winds, temperature can decrease dramatically, but does not decrease dramatically in all instances. The relationship at low wind speeds appears to be more variable than for other wind flow regimes.

Considering the interpolated temperature and wind speed (Figure 12), similar to the downhill/askew flows at night, there is a cold air pocket adjacent to treeline during the parallel flows at night. However, one difference that we see is an extremely warm zone at station 2, almost as warm as the atmospheric air above the sheltered zone. This once again could be attributed to the radiation from saplings, but this time the air is moving parallel to treeline and remaining in that warm row of air. Overall, there is good evidence that windspeed and temperature are directly related, like we expected. However, there are other influences in play that could disturb and change the shape of the simple sheltered zone that we predicted.

## CONCLUSION

With this study, we were trying to determine what kind of microclimate spatial structures are created by an abrupt treeline--not just focusing on airflow interactions with one tree, but rather with the treeline as a whole. How do our findings contrast with the existing literature?

We were successful in finding a strong relationship between windspeed and temperature, and how these two variables interact to create a clear microclimate. This microclimate had a distinct spatial structure, which took the form a sheltered zone during the day time, and a cold unprotected zone at night. The sheltered zone is created from airflow over treeline, which forms complex eddy structures that trap air in certain areas and prevent mixing with atmospheric air.

The length of the sheltered zone behind an obstacle typically extends to 10 times the height the obstacle (Oke, 1987), but our sheltered zone only exists about 4-5 times the height of the trees, which is about 60-75 meters upslope. This may be because the treeline at our field site is on a steep slope (~25 degrees). The relatively short sheltered zone could potentially be a reason why this abrupt treeline is moving so slowly, and also why abrupt treelines tend to establish on steeper slopes (personal communication Miro, regarding treelines on Pikes Peak). Diffuse treelines tend to establish on more shallow slopes on Pikes Peak, most likely because the sheltered zone can be a lot bigger. But, with that said, diffuse treelines also do not have the kind of well-defined spatial structure that abrupt treelines have, and thus may not have as structured stationary eddies.

As expected, there was a clearly defined warm zone within the eddy structure. Overall, this is consistent with our theory of how airflow around eddies can prevent mixing with atmospheric air. However, certain details are inconsistent with our hypotheses. It is still difficult to draw a conclusion as to why station 4 is so warm, while stations 2 and 3 are much colder during the day. The wind patterns make sense, but the temperature patterns do not always make clear sense.

During the nighttime, there was a cold zone as we expected. This cold zone is likely attributed to the damming of cold air against treeline. The cold spot at night is congruent with the findings of Akhalkatsi et al. 2006, which explains that forest canopies can trap and accumulate cold air, which in turn prevents convective mixing with other warmer air. This thermal difference makes it difficult for certain zones to warm up at night. Station 2 is confusing during the night because it is a warm column of air in the zone where we expected all the air to be cold. Once again, it is difficult to make a concrete conclusion about why station 2 is so much warmer than its neighboring stations 1 and 3, because there are so many complex mechanisms in play.

Comparing my results to the results of seedling distribution and growth at our field site (Chang, 2017), one thing we can conclude is that seedlings very much prefer the warm daytime temperatures of station 4 and will continue to establish and grow until perhaps they establish a new treeline themselves. It also seems like warm growing temperatures are the limiting factor in the context of seedling establishment, because even though station 4 gets very cold at night, it gets very warm during the day. And the seedlings thrive in the warm daytime temperatures even though they are exposed to the polar opposite at night.

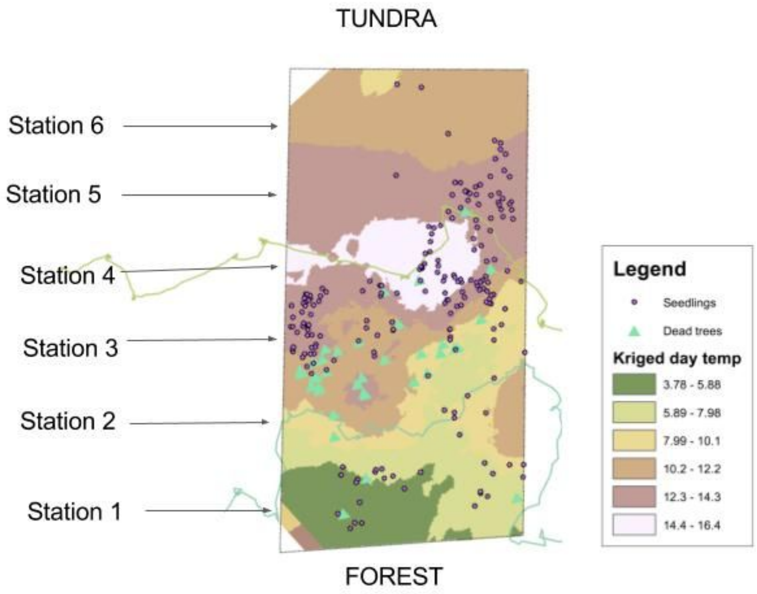

Figure 13: From Chang, 2017. Maps out the locations of established seedlings and dead trees in our field site, and includes locations of stations 1-6. Station 7 and 8 are in the high tundra (not represented in the figure).

Figure 13 (from Lani Chang, my senior thesis partner who studied seedling establishment) shows that there is a clearly defined spatial pattern to where seedlings tend to establish and also where they tend to face mortality. Around station 4 is a strong establishment zone. The line of alive seedlings is almost exactly parallel to treeline, which shows that the existing old growth treeline must have some relationship to where they establish. It also coincides with the warm zone at station 4 that we found on our temperature maps of the sheltered zone. Furthermore, the majority of dead seedlings are found at station 3, where the daytime temperatures are not as warm, which reinforces our theory that warm daytime temperatures are crucial to seedling growth and survival. There are also warm daytime temperatures at station 1, but nighttime temperatures may outweigh daytime temperatures at this station because there are no seedlings are present. We would expect to see seedlings here, based on the importance of warm daytime temperatures, but the extremely cold temperatures at night may likely become a limiting factor because they are so much colder than any other station at night.

Our findings contrast with generally accepted theories of positive interactions at treeline. Firstly, in the modeling of treeline George Malanson and colleagues (Malanson et al. 2011) assumed that sheltering is an additive process that is independent of the three-dimensional structure of the treeline. When modeling positive interactions at treeline using cellular automata the authors assumed that sites immediately adjacent to existing trees were of highest quality for seedling establishment. This disregarded the spatial structure of the treeline. We found that the type of sheltering present at treeline is highly dependent on the three-dimensional structure and the interaction of this structure with airflow direction--rather than assuming that there is sheltering present wherever a single tree is present. We further found that sites immediately adjacent to mature trees may not be as suitable for establishment compared to sites that are somewhat further away, but not too far --- all due to the nature of the airflow and it’s interaction with the surface energy balance. Making the spatial relationship between seedling establishment and presence of mature trees much more complex than previously thought.

In addition, literature suggests that winter temperatures are key to dynamics of abrupt treelines (Harsch, 2009). Harsch found that warm winter temperatures are associated with advancement of treelines, and developed a theoretical framework that placed winter temperatures and processes (such as snowpack) as the only significant factors in treeline advancement. Others have adopted Harsch’s framework and helped the framework to become more or less standard for treeline dynamics, even though it has not been thoroughly tested  However, we found that growing season temperatures can also play an important role in how abrupt treelines are organized and where new seedlings are able to establish.

Furthermore, our study proves that sheltering still has important impacts beyond distribution of snow--which is in contrast with Renard et al. 2015. This paper claims that shelter zones are important because they create sufficient snowpack, which is crucial to the survival seedlings. Sheltering can create favorable zones in the growing season as well. There are many different sheltering effects that can result from an abrupt treeline. For example, the reduced wind within the sheltered zone can reduce evapotranspiration rates --- this can increase photosynthesis as the seedlings can keep their stomata open for the majority of the daylight hours. In addition the increased daytime temperatures in the summer can allow the seedlings to have a longer growing season (Resler et al, 2005). There is also the effect of shading in the summer, which may be beneficial because it reduces excessive solar radiation (Holtmeier, 2003).

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