MICROCLIMATOLOGICAL FEEDBACKS AT TREELINE:
IS TREELINE STRUCTURE MODIFYING THE LOCAL MICROCLIMATE?

A THESIS

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ABSTRACT

Recent study of altitudinal treeline advance has revealed that increasing seasonal temperatures only partly explain the processes that influence treeline structure and elevation. Microsite modifications, induced by the structure of the treeline, may in fact play a large role in regulating the microclimate, creating more favorable conditions for further seedling establishment and recruitment near the treeline. To explore these modifications, previous research on Pikes Peak has compared heating dynamics within a treeline microclimate to the microclimate of an adjacent rockslide at an identical elevation. Observations indicated that the treeline heats up faster and to a higher maximum temperature than the rockslide nearly every day of the study period (Johnson, 2011). Potential mechanisms for this differential heating were explored, however only the sheltering potential of the trees to reduce winds proved worthy of further investigation (Anderson, 2012). To expand upon these findings, this study aims to verify the presence of differential heating between treeline and rockslide, investigate the role of sheltering to reduce heat loss within treeline, and explore to what extent this sheltering could extend beyond the treeline's leading edge. First, this study found that temperatures within the treeline were on average ~7C warmer than the rockslide from 15cm above the ground to 10cm deep within the soil, a critical habitat for seedling establishment (Körner, 1998). Furthermore, this study reveals that the magnitude of differential heating increases throughout the growing season, exhibiting larger differences later in the season. These findings indicate that, despite decreasing solar input late in the season, the treeline has a higher capacity to retain heat than the rockslide and prolongs favorable growing conditions later into the summer months. To investigate how sheltering may play a role in holding heat within the treeline, the zero-plane displacement was calculated for the treeline, rockslide, and upper tundra. Results indicate that treeline form shelters a boundary layer of warm air close to the ground that could enable increased heat storage within the treeline's soil. Furthermore, this sheltering effect extends beyond the treeline's leading edge and modifies the tundra microclimate by reducing wind effects in lee of the treeline. This mechanism of sheltering could create a positive feedback loop in which microclimatological modifications, induced by the trees presence, allow for continual growth beyond the forest boundary.

INTRODUCTION

Overview

Treeline Dynamics

Alpine treelines, commonly constrained to a thermal boundary, are advancing in response to warmer temperatures (Körner, 1998; Körner and Paulsen, 2004). Worldwide, treelines exit within a narrow range of mean growing season temperatures (Körner and Paulsen, 2004), suggesting that low-temperature constraints, such as low temperature growth limitation, determines the position of treeline (Harsch, 2011). If low-temperature growth limitation is the primary constraint on alpine tree growth and seedling establishment, increased advance of treeline could be a strong indicator of climate change (Smith, 2009).

While treeline advance is certainly linked to rising temperature, the mechanisms in which treelines advance and the factors influencing these mechanisms are more complex. A global study of treeline advance found that only 52% of worldwide treelines had advanced since the beginning of the 20th century (Harsch, 2009), suggesting that there are specific factors that affect the likelihood for treelines to advance. One such factor, treeline form, seemed to be indicative of advancement. The form of an alpine treeline can be abrupt, diffuse, exhibit island-like stands, or feature stunted krummholz (Harsch, 2011). Findings on the impact of treeline form on advancement revealed that 80% of diffuse treelines had advanced over the last 100 years, whereas only 22% of abrupt or krummholz treelines had exhibited advance (Harsch, 2009). The relationship between treeline form and likelihood of advance, suggests that the structure of treeline plays a unique role in effecting the mechanisms of advancement. However, the processes by which treeline form influences advancement remain unclear.

In order to explore possible mechanisms for treeline advance, it is important to first understand the mechanisms that constrain treelines to a specific thermal or altitudinal limit. Treelines are found around the world, and generally exist when low temperature prevents tree growth from occurring above a specific thermal boundary. Two main ways in which low temperatures limit treeline formation are growth limitation (the ability to develop new biomass) and seedling mortality (Harsch, 2011).

Opinions vary concerning which of these mechanisms plays the greatest role in constraining treeline, and how they differ according to treeline type. However, recent research suggests that there is a minimum temperature that permits production of new cells and development of functional tissue in trees and that treelines are constrained by their growing season temperatures (Körner, 1998). The 'growth-limitation hypothesis' is especially observed in diffuse treelines, where tree height and annual growth rates decrease with elevation and colder temperatures. Advancement of diffuse treelines has been closely linked to increases in local growing season temperatures, reinforcing the plausibility of growth-limitation as a constraint on treeline position (Harsch, 2011). Growing season temperatures, therefore, appear to be the main driver for most alpine and arctic treelines (Harsch, 2011).

The second factor that contributes to low temperature limitation of treeline is seedling establishment and survivorship. The factors leading to seedling mortality are less temperature dependent and are instead linked to other climatic stressors, such as winter dessication, water stress, and high sky exposure (Germino, 2002). As such, the degree to which seedling mortality controls treeline will change very little with increased growing season temperatures. On the other hand, the role of temperature driven growth-limitation on treelines would be significantly affected by future warming. Evidence of diffuse treelines advancing in response to increased seasonal temperatures could be the best supporting argument of growth-limitation (Harsch, 2011). By achieving a better understanding of the factors catering to treeline advance, the mechanisms that limit treelines will become clearer.

Diffuse treelines, which exhibit low temperature growth-limitation, are advancing more than any other treeline type, but how is the diffuse treeline form influencing this response? Are treelines diffuse because they are advancing? Or, are treelines advancing because they are diffuse? Recent studies suggest that positive feedbacks associated with diffuse treeline structure may be initiating increased treeline advance. As trees become established above the timberline, their presence modifies the local environment by reducing winds and therefore improving microsite conditions on their leeward side (Resler, 2006). The beneficial effects of sheltering include locally moderating temperatures, providing protection from severe weather and harsh winds, improving soil conditions, and acting as a seed trap (Resler, 2006). These effects are evidenced by increased seedling survivorship adjacent to micro-topographical features and have been referenced as a possible mechanism for treeline migration (Resler, 2006). Furthermore, previous researchers have investigated the potential for trees within a diffuse treeline to create localized warming within the treeline microclimate. Differential heating created within a diffuse treeline could be the result of microclimate modifications attributed to the trees and their spatial distribution (Germino, 2002).

Previous Research on Pikes Peak

Ongoing study of the western slope of Pikes Peak, located within the Front Range of the Central Rocky Mountains in Colorado, has revealed a shift in treeline typology from abrupt to diffuse over the last 70 years. This shift has resulted in an 18-meter elevation increase of the treeline since 1938 (Elwood, 2012). Furthermore, these shifts are closely correlated to observed increases in regional temperatures (Elwood, 2012).

To determine the mechanisms enabling treeline advance on the western slope of Pikes Peak, it is necessary to study a comparable control site, preferably situated at a similar elevation, which is devoid of trees. The juxtaposition of tundra and treeline allows us to differentiate between local macro-scale climatic effects and the specific influence of the forest on the microclimate. Fortunately, the diffuse treeline on Pikes Peak is located adjacent to a rockslide area, providing an ideal comparative microsite similar to the tundra above timberline, but at an identical altitude of the treeline ecotone. Studies exploring the microclimatic dynamics of the diffuse treeline have shown that the treeline exhibits differential heating in comparison to the adjacent rockslide. The treeline achieved a higher daily temperature than the rockslide by an average of 4.5 degrees F. Also, after initial solar input, the treeline achieved peak daytime temperatures approximately 2 hours prior to the rockslide (Johnson, 2011). Evidence of increased daily heat storage in the treeline suggested that the presence of mechanisms, induced by the presence and spatial patterns of the trees, initiated positive feedbacks and increased localized warming.

Logically, subsequent studies explored possible mechanisms at the root cause of this differential heating. Hypotheses concerning increased sensible heat transfer from tree canopies, increased heat capacity due to high soil moisture in the transition zone, and decreased advective heat loss due to sheltering effect of trees were investigated (Anderson, 2012). Unfortunately, none of these mechanisms could be firmly correlated to the differential heating exhibited within the diffuse zone. The most promising postulation reached in 2012 was the influence of wind on differential heating, and the complex sheltering effects that trees have on their microclimate. These facilitative feedbacks were deemed most plausible for impacting heating dynamics near the soil surface, and therefore deserve further investigation.

Goals of this Study

In an effort to gain a higher resolution profile of differential heating and its potential effects on advance of the Pikes Peak treeline, this study explores micrometeorological feedbacks at the leading edge of the transition zone. Is there evidence of a positive feedback involving microsite facilitation, wherein a tree modifies the local environment it occupies, improving the site for itself and fostering the growth of subsequent trees (Resler, 2005)? If so, what changes do the trees effect on their microclimate that increases favorability of growing conditions? Ultimately, how does the influence of treeline form create a positive feedback for additional treeline advance?

Answering these questions will better our understanding of diffuse treelines and their tendency to advance. By analyzing micrometeorological feedbacks leading to advance, this research will help inform the discussion of how treeline spatial structure either contributes to or results from advance. However, in order to answer these questions, the treeline microclimate and its heating dynamics must first be discussed. Then, the potential impacts of the diffuse treeline form on microsite wind and heating dynamics will be explored, Finally, the degree to which these mechanisms modify the microclimate *above* the altitudinal limit of treeline will be examined to determine the facilitative role treeline plays in its own advance.

The Treeline Ecotone

Microclimate Dynamics

In a broad sense, the ‘timberline’ is the highest elevation at which trees occur with a stature and density similar to those within the closed-canopy sub-alpine forest; the ‘treeline’ is the upper altitudinal limit above which trees can no longer grow (Smith, 2003). The immediate environment and associated weather conditions between these two thresholds encompasses the treeline ecotonal microclimate. Within this microclimate, the interactions of different climatic occurrences hold the greatest importance for the biological processes of trees. For instance, the absorption of heat at shallow soil depths plays a key role in root development and growth (Körner and Paulsen, 2004). Additionally, the heat exchange between soil and near surface air is important due to its influence on the boundary layer, a warm parcel of air near the ground critical for seedling survival (Smith, 2003). The boundary layer exhibits more efficient heat gain from ground surface radiation because mixing from the wind influences it very little. The interaction between local winds and microsite structure ultimately affects the thickness of the warm boundary layer, the height to which seedlings can grow, and seedling survivorship (Smith, 2003). These interactions obviously differ according to immediate microclimatic conditions, suggesting that microsite structure and form influence these climatic occurrences.

Specifically, when discussing an advancing diffuse treeline, the microclimatic factors of most importance are those that effect seedling establishment and growth. Emergent seedlings of treeline conifers are more indicative of climate change than adult trees and the development of these seedlings is often most attributable to treeline advance (Germino, 2002). While many factors can contribute to seedling mortality, trees require minimum seasonal temperatures to grow additional biomass (Körner, 1998) and conduct photosynthesis (Germino, 2002). As such, local temperatures are a critical component of the microclimate.

Local air temperatures and soil temperatures play different roles in affecting tree establishment and growth. Low air temperatures stress tree growth by markedly reducing photosynthetic rates and the utilization of photosynthetic products for vertical growth (Grace, 2002). Similarly, low soil temperatures severely constrain root growth and shoot functioning, imperative processes for tree development (Körner, 1998). While these constraining factors are largely responsible for impeding overall seedling growth within the microclimate, treeline advance surely requires seedling survival and growth *above* the current treeline microclimate. As such, observational evidence suggests that it is not the seedling's initial establishment, but the subsequent emergence from the warmer boundary layer near the ground, which is decisive for the development of a tree (Körner, 1998). If this theory holds true, then processes that influence the warm boundary layer should play a significant role in treeline advance. Investigations into the effect that trees shelter their microclimate by increasing frictional drag and reducing wind speeds have revealed that treeline structure may modify microclimatic conditions, enabling greater seedling survivorship (Smith, 2003). Microclimate modifications due to increased tree density affect winds by creating a favorable climate in lee of the treeline in which seedling can establish. These steps of microsite facilitation suggest that treeline form can affect the upslope climate and raise the maximum altitude at which a particular tree might survive (Smith, 2003). In order to investigate the role of boundary layer dynamics, we must define the microclimatological parameters of interest.

A suitable microclimate comprises the temperatures at or above the limit of a treeline's physiological needs, extending from the transition zone into the beginning of the alpine zone. In order to understand the microclimatic conditions that most impact seedling establishment and growth within this ecotone it is necessary to measure temperatures at shallow soil depths and in the air near the ground. These areas are important because they reflect energy exchange within the critical boundary layer that seedlings establish themselves. Specifically, the thermal changes exhibited from 10cm below the soil surface to 2.5m above the soil are vital to understanding potential interactions affecting the boundary layer.

Boundary Layer Effects

Motion in the air is nearly always turbulent, except for a thin layer of air at the ground surface known as the laminar boundary layer (Geiger, 2003; Oke, 1987). This thin layer adheres with great tenacity to the ground surface, resisting the mixing effects of turbulent airflow, due to the frictional drag that surface elements exert on turbulent flow (Geiger, 2003; Oke, 1987). The depth of this layer is heavily influenced by wind speeds, exhibiting greater thickness at low speeds and a gradual decrease in thickness as wind speed and turbulence increases (Geiger, 2003). In this layer, heat is transferred primarily by conduction, which presents a formidable barrier to the exchange of energy from the ground into the atmosphere.

At treeline, this boundary layer is the parcel of air near the ground, which is influenced by diurnal heating, moisture content and momentum transfer to, or from, the ground surface (Plate, 1970). Boundary layer dynamics have been found to create a significant mechanistic effect on seedling establishment by fostering favorable growing conditions close to the ground surface (Germino, 2002). In order to determine how the boundary layer facilitates seedling survivorship, it is important to fully understand the microclimatic factors affected by the boundary layer.

At high elevations, diurnal heat exchange is driven by the presence and intensity of solar radiation. Around midday, the input of energy into the treeline peaks and surface soils absorb solar radiation, increasing temperatures. Heat is then transferred either via conduction into lower layers of soil or via convection into the parcel of air just above the ground surface. As heat radiates away from the soil (the source of solar heating), it becomes mixed into the air above it by winds, creating a stratified temperature gradient. Warmest temperatures exist at the bottom of this gradient, closest to the ground, in a plane that receives zero air displacement due to wind. The zero-plane displacement is the point at which wind speeds are reduced to zero due to the frictional drag generated by trees or other elements of surface microtopography (Oke, 1987). The height of this plane largely influences the thickness of the boundary layer due to its dependence on wind speeds (Oke, 1987). Therefore, the extent to which the boundary layer can absorb conducted heat from the ground surface, and the height to which this warm parcel of air can extend is highly dependent on the zero-plane displacement upon wind speed. As such, the presence of roughness elements, like trees, which reduce wind speeds, increase the zero-plane displacement, and bolster the boundary layer, plays a large role in the heat exchange that occurs within a treeline.

Interestingly, this process of heat exchange seems to occur differently within the treeline in comparison to tundra (Beringer, 2001; Johnson, 2011). Observed local warming within treeline does not occur in the absence of trees and the treeline exhibits greater daily heat gain than adjacent tundra (Beringer, 2001; Johnson 2011). Hypothesis concerning differential heating in the treeline posit that accelerated heating could result from the microclimatic influence of trees on soil-air heat exchange, leading to greater heat accumulation near the ground surface amongst the trees (Johnson, 2011). This theory is reinforced by findings that differential heating between treeline and arctic tundra resulted from a 2° C difference in near surface air temperatures between each respective biome (Beringer, 2001). These discoveries suggest that accumulated heat in the boundary layer within treeline results in greater heat gain at the treeline as opposed to in the tundra, where trees are absent. Therefore, microclimatic warming seems largely coupled to the dynamics of the boundary layer, and within treeline there exist feedbacks that increase the presence and influence of this boundary layer.

The Influence of Treeline Form

As previously mentioned, one major factor that influences boundary layer thickness is the effect of wind speeds on the zero-plane displacement. The magnitude of the wind's impact is largely regulated by the frictional drag force of the surface elements present in the immediate microclimate. At treeline, this drag force is created by the presence of trees. As such, numerous factors pertaining to the spatial distribution, density, and treeline structure all impact the influence that trees have on reducing wind speeds and sheltering microclimate.

The extent to which wind speeds are reduced on the leeward side of trees or other roughness elements is known as the 'shelterbelt effect'. The establishment of trees in a microclimate can improve downwind site conditions by reducing wind by 80% for a distance 3-5 times the height of the trees (Resler, 2006). This reduction in wind also improves site conditions by causing a warm area downwind of the trees (Oke, 1978). These microsite improvements due to tree establishment are important drivers for further tree growth. As trees establish themselves within a microsite, their presence modifies the local environment and makes local conditions more favorable for additional seedlings to grow (Resler, 2006). This role of microsite modification due to the shelterbelt effect is paramount in its implication on the boundary. In lee of shelter, such as that created by treeline, a new and thicker boundary layer is formed (Plate, 1970). As boundary layer thickness is increased, the shelterbelt effect uncouples individual trees from the negative effects of wind and cold temperatures, generating a more favorable microclimate (Smith, 2009). This favorable microclimate leads to great seedling establishment and, ultimately, to trees with forest-like stature (Smith, 2003). As seedlings grow upwards into the upper limit of the favorable boundary layer generated by the sheltering effect of neighboring mature trees, their increased height facilitates a new shelterbelt effect on their surroundings, which leads to further potential seedling establishment. This positive feedback concerning the effect of increased tree density on increased seedling establishment appears to be a fundamental mechanism driving the formation of new subalpine forest beyond existing limits because of how the treeline creates favorable growing conditions beyond its own extent (Smith, 2009).

Therefore, by investigating the role that the treeline can play as a shelterbelt, identifying the resulting influence on the zero-plane displacement, and then juxtaposing these finding against an adjacent control site (absent of trees), this study hopes to gain greater insight into the overall impact of the Pikes Peak treeline on its microclimate and on the climatic conditions in the higher elevation tundra. Finally, the potential link between microclimatic modifications perpetuated by the treeline and the observed differential heating between treeline and tundra will be examined for causality.

HYPOTHESES

While differential heating between treeline and tundra microclimates has been observed before (Johnson, 2011; Beringer, 2001), few researchers have investigated possible mechanisms for this phenomenon. On Pikes Peak, the processes of increased canopy heating, soil moisture, and wind sheltering within the treeline have been studied as potential causal processes for differential heating (Anderson, 2012). While none of these mechanisms were found to be significantly correlated to greater treeline warming, the wind-sheltering hypothesis, which was only studied at 8m above the ground surface, held the most interest and deserved greater exploration and a higher resolution data set (Anderson, 2012).

The goal of this study is to first substantiate previous findings of differential heating between treeline and an adjacent rockslide area over the summer season on Pikes Peak and provide a high-resolution dataset of microclimatological parameters associated with each microsite. Then, possible mechanisms for this differential heating will be explored, specifically, the sheltering effect of treeline form and its subsequent effect on boundary layer dynamics and heat accumulation within the treeline. This study hypothesizes that shelterbelt effects associated with diffuse treelines initiate microclimate modifications, creating favorable conditions for seedling establishment beyond the edge of the forest. As seedling establish at the leading edge of the treeline, they modify their own microclimate, creating a positive feedback for continued treeline advance. Additionally, increasing tree density at the leading edge causes a greater sheltering effect, increasing the zero-plane displacement and thickening the warm boundary layer, which allows for greater heat storage near the ground surface within treeline. Finally, this ‘leading edge’ hypothesis asserts that the dynamics between wind and treeline form help explain the pattern of treeline advance into upper and colder altitudes.

METHODOLOGY

For this study, two transects were established on a north-western aspect of the western slope of Pikes Peak in the same approximate rockslide and treeline regions utilized by Johnson (2011) and Anderson (2012). Both transects were oriented perpendicular to the slope's fall line. The 'treeline' transect began at the bottom edge of the diffuse zone in the treeline, where tree density begins to decrease and average canopy height is ~10m, and extended to the leading edge of the diffuse zone. The 'rockslide' transect was established in an adjacent talus field, characterized by rocky tundra devoid of any tree life. Both of these transects begin at an elevation of approximately 11,830 ft. and extend to an altitude of 12,030 ft. (See Image 1)

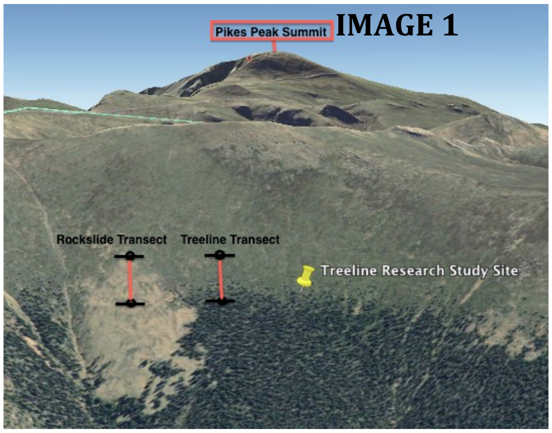


IMAGE 1

Meteorological stations were constructed at the lower and upper extent of each transect. Each of the four main stations was designed and constructed to capture specific meteorological data at multiple height intervals. To record this information, each main station consisted of a tower equipped with anemometers and air sensors to capture wind speeds, air temperatures, and relative humidity at .5m, 1m, 2.5m, and 10-meter heights. At the base of each tower, an air sensor was installed at a height of 10cm and soil sensors were buried at depths of 3cm, 5cm, and 7cm. On either side of each main station, two outrigger substations were established approximately 20ft across the slope. Each substation consisted of one air sensor at a height of 10cm and two soil sensors at depths of 5 and 10cm. All of these stations utilized Onset Computers' HOBO Data Loggers to record temperatures and wind speeds at intervals of 30 seconds, averaging these observations over a 5-minute period.

Data Loggers were launched in early June and recorded observations until late August during the summer of 2012. Data was downloaded periodically throughout the summer season and analyzed to determine trends indicating differential heating and shelterbelt effects. Additionally, soil samples from each station were analyzed for soil moisture content in order to calculate the thermal conductivity of the soil and, thus, the Soil Heat Flux. These measurements were utilized in an effort to support the hypotheses stated earlier and explored below.

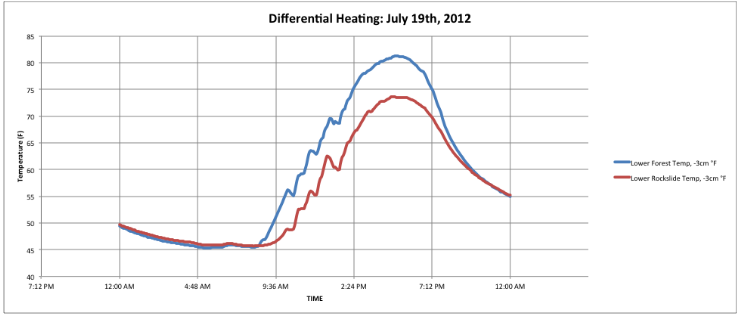
RESULTS

Differential Heating

July 19th, 2012 Case Study

Results confirm the 2011 treeline microclimate findings of differential heating between the treeline and the rockslide (Anderson, 2012). Near surface soils (at 3cm depths) in the treeline and the rockslide heat up differently in response to solar input (Figure 1). For instance, the rate of warming in the treeline soil departs dramatically from the rockslide's rate of warming around 8:30 AM. Consequently, when the solar input is removed (sunset at 5:50 PM), the treeline and rockslide soils begin to cool at similar rates until 9 PM, when soil temperatures in the treeline and the rockslide are nearly identical.

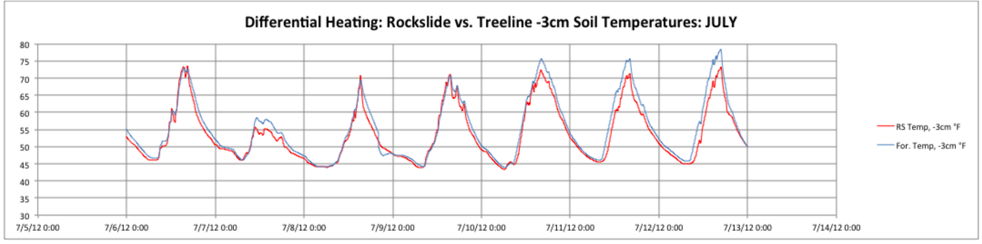
Figure 1: Differential Heating between treeline and rockslide on July 19th, 2012.



Seasonal Variability

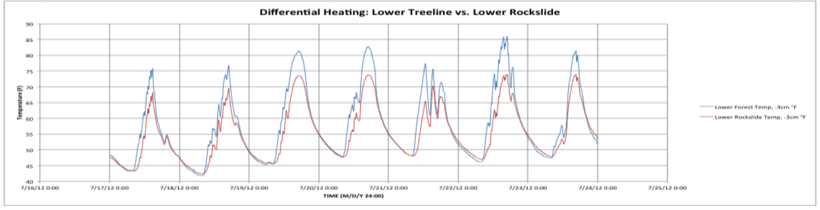
Interestingly, the strong signal of differential heating seen in mid-July is not as apparent throughout the entire summer season. In early July, the soil temperatures at 3cm depths in the treeline and the rockslide are very closely tied together, with only some days recording higher temperatures in the treeline.

Figure 2: Differential Heating between rockslide and treeline in early July.



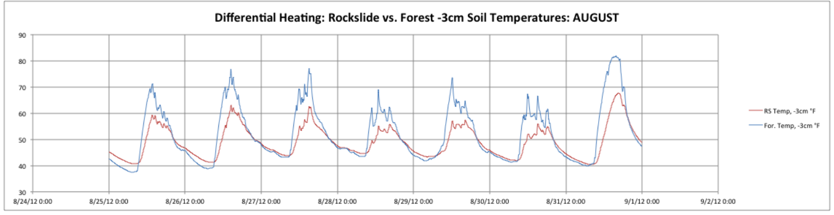
In mid-July, the difference in daily maximum temperatures between the treeline and the rockslide becomes larger, and the evidence of differential heating more apparent (Figure 3).

Figure 3: Differential Heating between rockslide and treeline in mid-July.



Finally, at the end of the observational period in late August, the presence of differential heating become much more obvious (Figure 4). The treeline soil achieves a much higher temperature maximum earlier in the day than the rockslide soil.

Figure 4: Differential Heating between rockslide and treeline in late August.

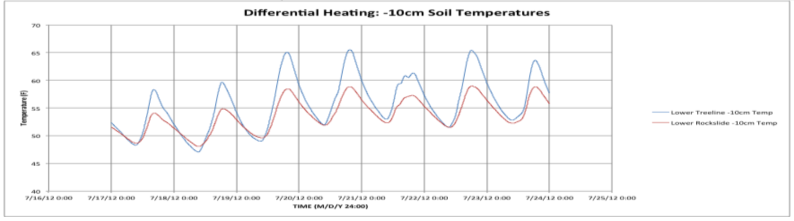


Early in the summer, when heat input from solar radiation is strong, the rockslide and the treeline heat up in roughly the same way. However, late in the summer, when solar input decreases, the treeline system has the advantageous ability to accumulate and store heat better than the rockslide.

Deeper Soil Depths

The figures above express the strength of differential heating and its effect on shallow soil temperatures. During one week in July, which exhibited the most significant differential heating, average daytime soil temperatures at 3cm depths in the treeline were 8.15 °F higher than corresponding temperatures in the rockslide (See Figure 3). However, differential heating between the treeline and the rockslide also persists into deeper soil layers. At 10cm depths, soil temperatures are far less susceptible to fluctuations occurring near the ground surface and therefore reflect the net diurnal temperature changes occurring in the soil. The differential heating is more strongly pronounced at deeper soil depths, with the treeline soil heating up much faster and achieving a higher daytime temperature than the rockslide soil. (Figure 5)

Figure 5: Differential Heating between treeline and rockslide at 10cm soil depth.



Soil Heat Flux

The net accumulation of heat in the treeline can be investigated further by looking at the soil heat flux from 3-10cm soil depths. Heat flux is positive during the day because heat is being transferred into the soil, whereas the flux is negative at night due to convective cooling near the ground surface. On average, the treeline soil achieves greater heat gain than the rockslide throughout the day due to differential heating. While nightly heat loss is sometimes greater in the treeline, on average, heat losses are similar in both the treeline and the rockslide during mid-July (Figure 6). However, in late August, the treeline soil heat flux is greater during the day and nightly heat losses are less than in the rockslide (Figure 7).

Figure 6: Soil Heat Flux between Treeline and Rockslide: JULY

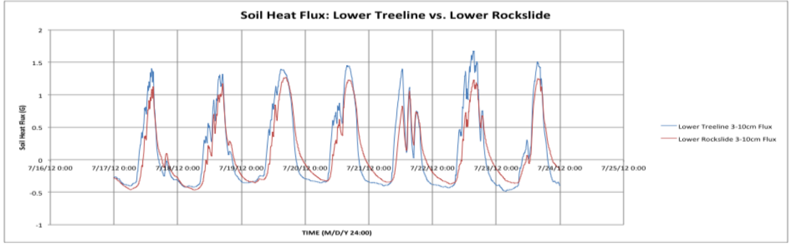
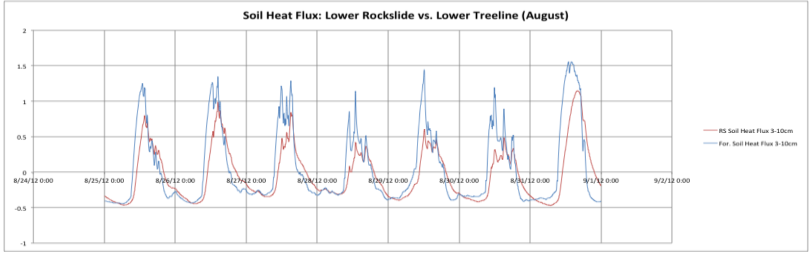


Figure 7: Soil Heat Flux between Treeline and Rockslide: AUGUST



These figures suggest that the net flux of heat over time is into the treeline soil because it consistently gains a larger daytime heat flux than the rockslide. This effect of differential heat gain can be seen moderately in the early summer (Figure 8), but becomes especially pronounced, with the treeline exhibiting greater heat gain than the rockslide, as the season progresses (Figure 9).

Figure 8: Daytime heat gain in early July.

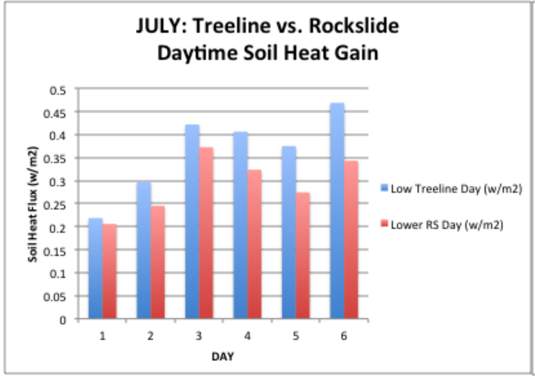
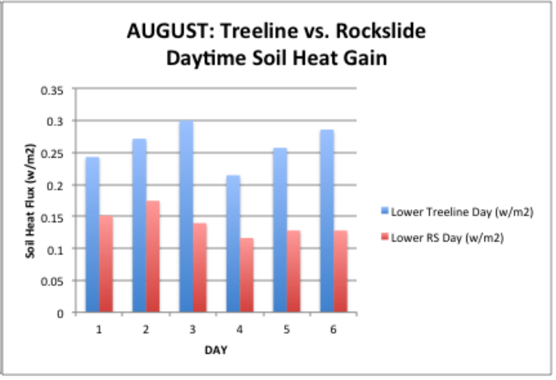


Figure 9: Daytime heat gain in late August.



However, as shown by Figure 2, the differential heating in the treeline that occurs in early July is less strong than in the late summer. This may be due to greater nighttime heat losses in the treeline compared to the rockslide during July (Figure 10). However, in August, when the treeline system is accumulating more heat gain during the day, differences in nightly heat losses are much less significant (Figure 11). While the treeline gains much more heat during the day, its nightly losses are paired closely to the rockslide, which supports observations of increased differential heating in the later summer season.

Figure 10: Nightly heat loss in early July.

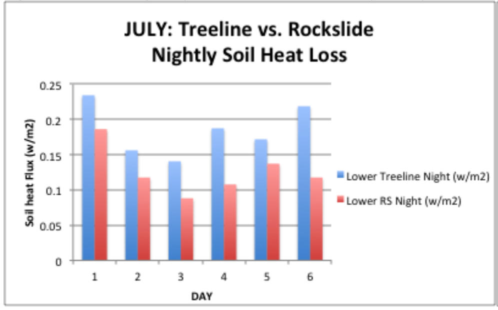
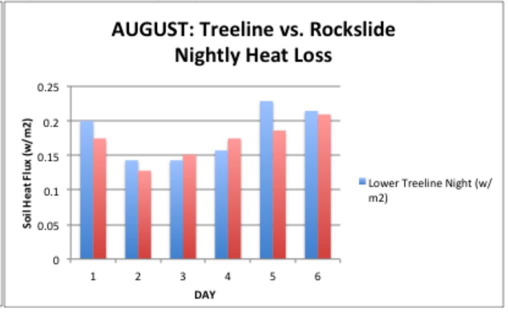


Figure 11: Nightly heat loss in late August.



Since the treeline gains a greater daily heat flux on average than the rockslide, it seems that the treeline system continually accumulates heat throughout the summer, increasing the treeline system's overall heat capacity. As the capacity to retain heat in the treeline increases throughout the summer season, the proportion of net heat that is lost at night decreases within the treeline. In late August, the rockslide experiences more nightly heat loss than daytime heat gain while the treeline system is accumulating and storing heat within its soil (Figure 12A). Observations of net heat flux indicate that, in August, the treeline continues to accumulate heat while the rockslide exhibits an overall negative net heat flux (Figure 12B).

Figure 12A: Diurnal soil heat flux in treeline vs. rockslide: AUGUST

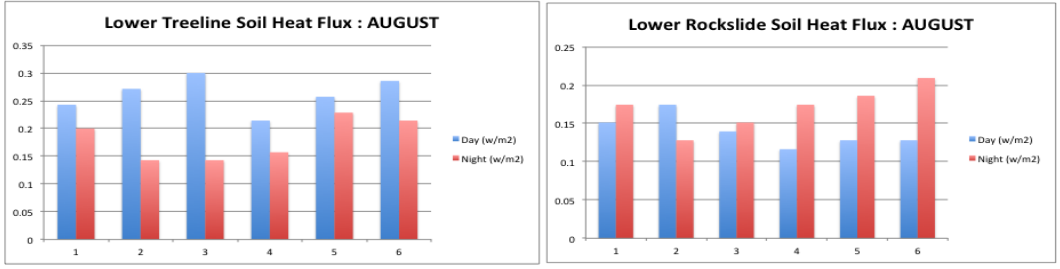
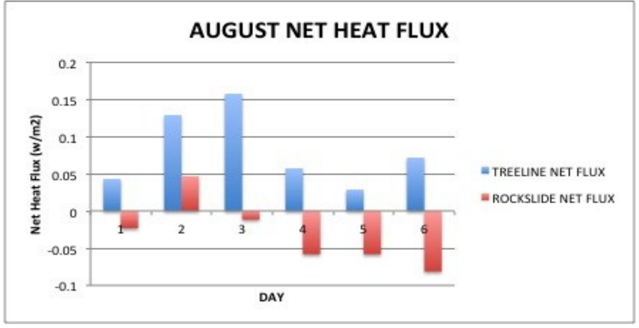


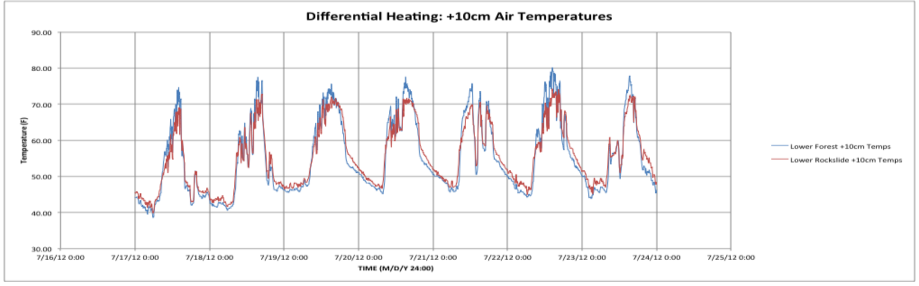
Figure 12B: Net heat flux in treeline vs. rockslide: AUGUST



Air Temperatures

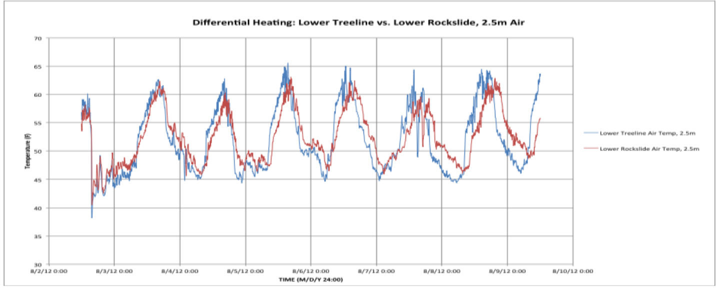
Air temperatures in the rockslide and treeline exhibit diurnal heating and cooling patterns similar to those in the soil, but air temperatures are much more variable due to their dependence on radiative heat transfer near the ground surface. Additionally, air temperatures fluctuate due to the constant mixing of the local climate. However, by measuring air temperatures close to the ground surface we can negate the effects of air mixing and focus solely on the relationship between shallow soil temperatures and near surface air temperatures. Figure 13 shows that the observed differential heating persists into the air at a height of 10cm. Similar to what was observed in the soil, air near the ground surface in the treeline heats up faster and to a higher maximum daytime temperature than the rockslide.

Figure 13: Differential Heating between treeline and rockslide in Air at 10cm



Furthermore, the effect of differential heating can be traced into air layers higher off of the ground. In early August, the air at 2.5m within the treeline heated up faster and to a higher maximum daily temperature than the air at 2.5m in the rockslide (Figure 14).

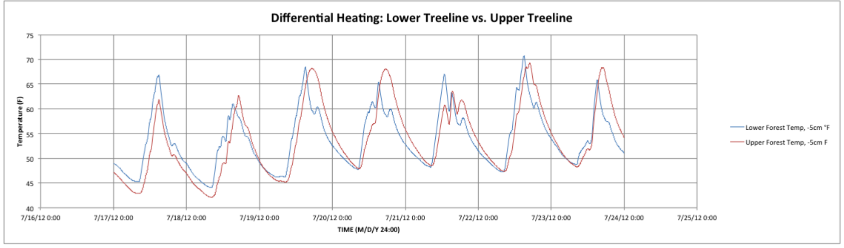
Figure 14: Differential Heating between treeline and rockslide in Air at 2.5m



Lower vs. Upper Treeline Heating Patterns

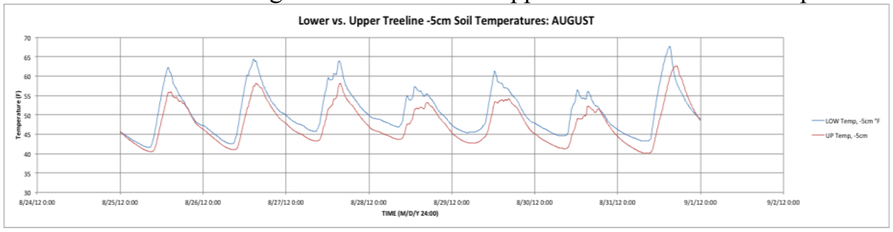
The pattern of differential heating is far less significant between the lower and upper treeline stations. In July, the soil at 5cm depth in the treeline heats up slightly faster but does not achieve a higher daily maximum temperature than soil in the rockslide.

Figure 15: Differential Heating between lower and upper treeline at 5cm soil depth: JULY



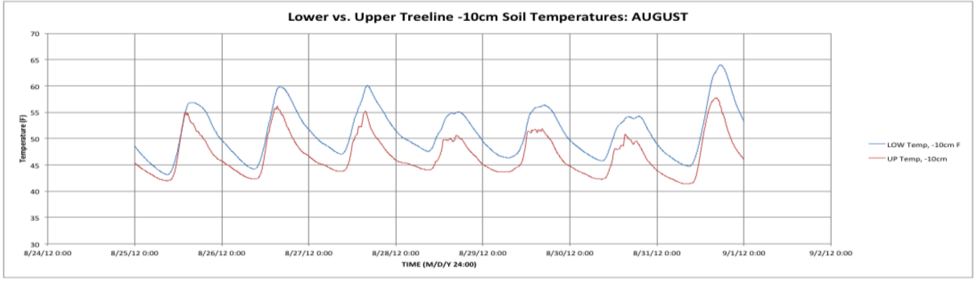
However, in August the presence of differential heating between the lower treeline station and the upper station is far more significant (Figure 16). While the lower treeline station reflects the effects of accumulated heat within the diffuse treeline system, the lack of trees at the upper treeline station decreases the ability to absorb and retain heat when solar input decreases late in the season. This explains why the upper treeline station exhibits less daily heat gain later in the season.

Figure 16: Differential Heating between lower and upper treeline at 5cm soil depth: AUGUST



In addition, the differential heating between the lower and upper treeline stations extends into the 10cm soil depths (Figure 17). This increased differential is further evidence of the accumulated heat in the treeline and its impacts on heat capacity when solar input is decreased.

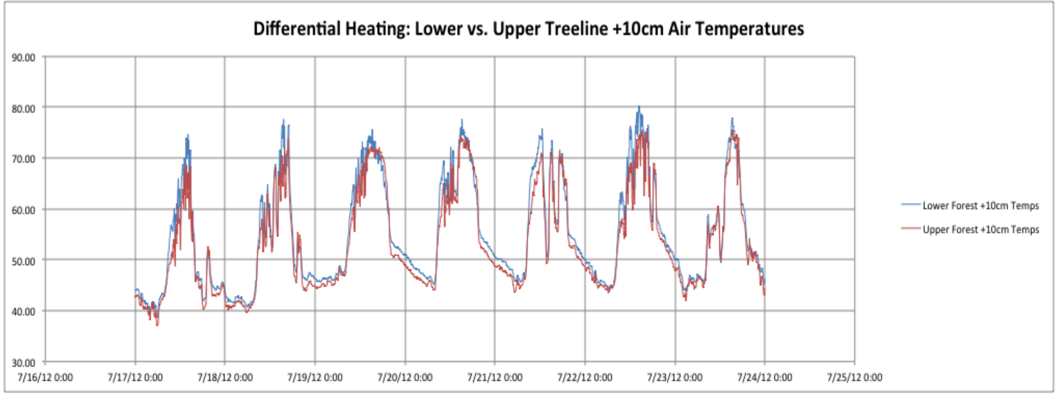
Figure 17: Differential Heating between lower and upper treeline at 10cm soil depth: AUGUST



Lower vs. Upper Treeline Air Temperatures

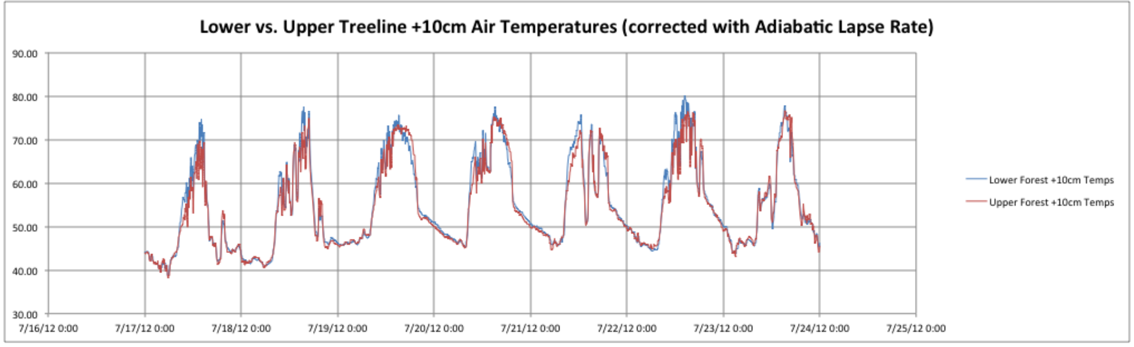
The pattern of differential heating is also observed when comparing air temperatures between the lower and upper treeline stations. While small, there is a slight difference between daily maximum temperatures recorded at the lower treeline and upper treeline stations (Figure 18).

Figure 18: Differential Heating between lower and upper treeline in Air at 10cm: JULY



However, this may simply be the result of the altitudinal difference between the two stations. When the data is corrected for the adiabatic lapse rate associated with a difference of 200’ in elevation, the differential heating almost disappears completely.

Figure 19: Lower vs. Upper Treeline +10cm Air Temperatures, corrected for Adiabatic Lapse Rate.



BOUNDARY LAYER DYNAMICS

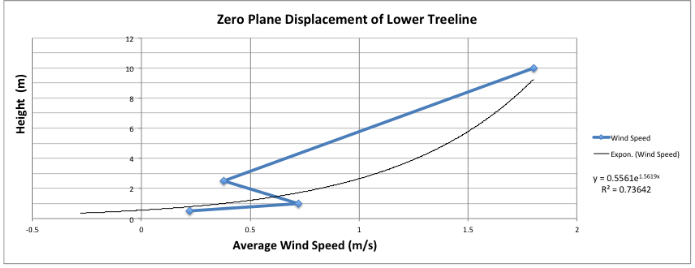
Zero-Plane Displacement

By reducing wind speeds, the trees in the diffuse zone shelter their localized microclimate and reduce air turbulence in the layer closest to the ground. The effect that the treeline has on reducing local wind is important because of its implications on the observed differential heating between treeline and the rockslide.

The presence of this zero plane displacement, where very little air mixing occurs, allows solar input to be more effectively transferred into the soil without the influence of advective heat loss due to wind. The differential heating observed in treeline soil could result from the presence of a thicker zero plane displacement within the trees.

As expected, the zero plane displacement in the treeline is significantly larger than in the adjacent rockslide (Figures 20 and 23). The presence of the trees, which are roughly 10 meters tall, decreases localized wind speeds in the diffuse zone and prevents mixing the boundary layer that extends 55.61cm off of the ground.

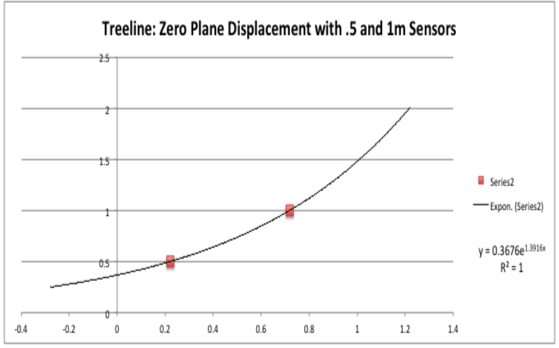
Figure 20: Zero Plane Displacement in Lower Treeline = 55.61cm



Interestingly, there appears to be two distinct zero plane displacements within the treeline due to the canopy structure of the trees. As wind descends into the diffuse zone, it is affected by the upper canopy differently than it is below the branch structure, effectively creating two stratified layers of air. Figure 21 shows the zero plane displacement generated by the upper canopy, while Figure 22 illustrates the zero plane displacement resulting from wind dynamics below the tree canopies.

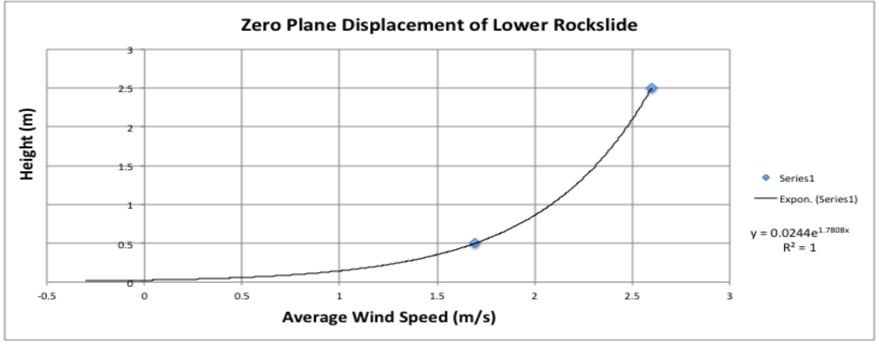
Figure 21: Upper Canopy**,** ZPD = 1.71m

Figure 22: Lower Canopy, ZPD = 36cm



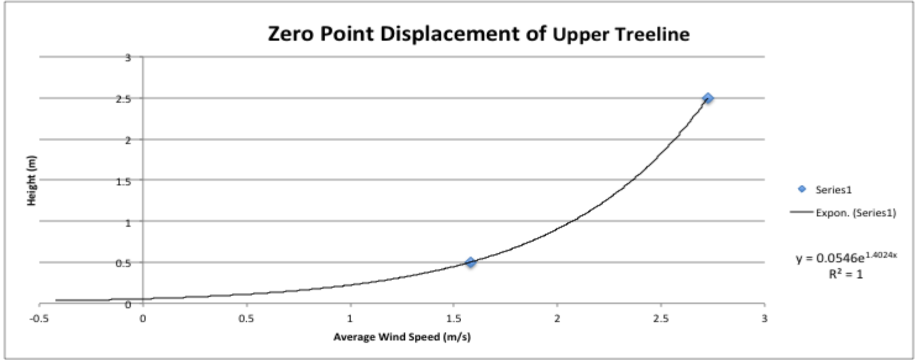
On the other hand, in the rockslide, where no such obstructions exist to decrease wind speeds, the zero plane displacement only persists 2.44cm off of the ground (Figure 23).

Figure 23: Zero Plane Displacement in Lower Rockslide = 2.44cm



Interestingly, the zero plane displacement of the upper treeline station (Figure 24) is more than double the height of the rockslides. This suggests that even the small presence of trees near the upper treeline station impacts air mixing near the ground surface.

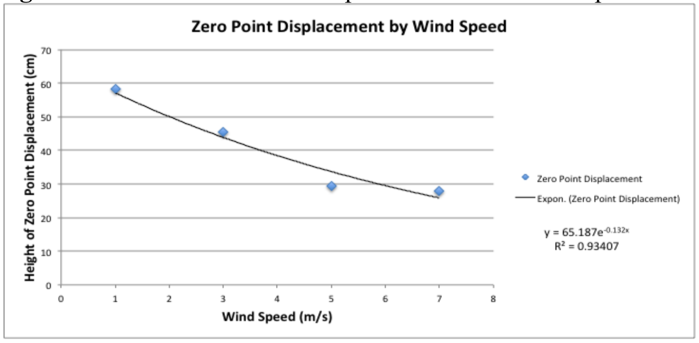
Figure 24: Zero Plane Displacement in Upper Treeline = 5.46cm



<u>Effect of Wind Speed on Zero Plane Displacement</u>

To understand how the zero plane displacement is affected by different wind speeds within the treeline, its height was calculated for varying speeds measured by the 10m high anemometer. As expected, when wind speeds are low the zero plane displacement is larger than when wind speeds are high. Interestingly, as Figure 25 suggests, the relationship between wind speed and the corresponding zero plane displacement appears exponential: no matter how fast wind speeds are, there will always be an air layer near the ground surface that does not exhibit mixing. In the case of the lower treeline transect, even when the station was experiencing maximum wind speeds, the zero plane displacement remained around 28cm tall.

Figure 25: The effect of Wind Speed on Zero Plane Displacement



THE LEADING EDGE HYPOTHESIS

The Shelterbelt Effect

The diffuse treeline has a significant effect on wind dynamics at its leading edge. When wind blows upslope or across the slope, the treeline effectively creates a ‘shelterbelt’ environment where air turbulence is decreased due to the aerodynamic roughness of the trees. To understand this effect, it is helpful to correlate wind speeds at the lower treeline station to speeds at the upper treeline station when wind is both upslope and downslope. Figure 26 illustrates that, when wind direction is downslope, and there are no impediments to wind speed, the correlation between wind speeds at the lower and upper treeline stations is fairly strong ($R^2 = 0.59$). However, when wind direction is upslope, trees in the diffuse zone impede wind speeds. There are numerous instances when there is zero wind speed in the lower treeline at the same time as high wind speeds are observed in the upper treeline. As a result, when wind direction is upslope the correlation between wind speeds at the lower and upper treeline stations is far less strong ($R^2 = 0.18$).

Figure 26: Downslope Wind: R^2 Value = .59

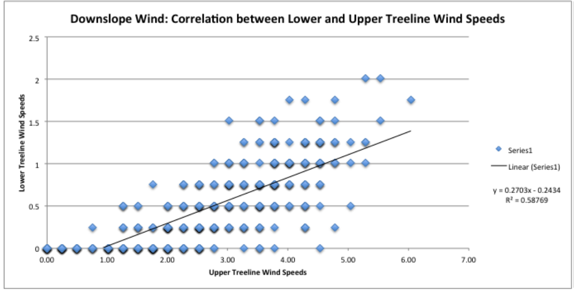
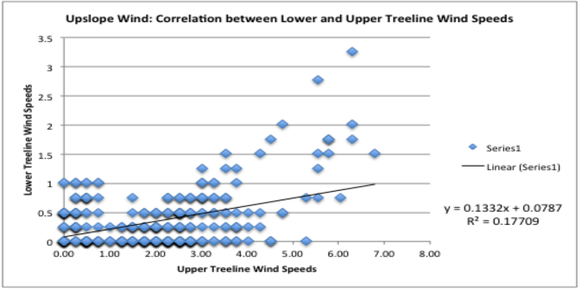


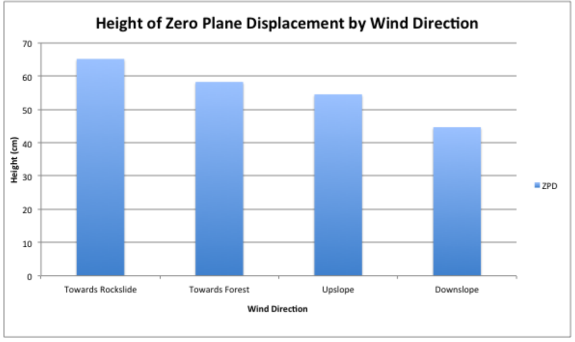
Figure 27: Upslope Wind: R^2 Value = .18



Effect of Wind Direction on Zero Plane Displacement

The presence of the treeline has an effect on wind speeds that depends on the wind direction (Figures 26 and 27). Consequently, the direction of the wind and its interactions with the treeline also plays a role in dictating the zero plane displacement within the diffuse zone. Figure 28 shows that when wind direction is north, blowing across the slope towards the rockslide, the zero plane displacement is highest at 65.19cm. This is due to its longer fetch; as the wind travels over the tree canopies it loses energy and its ability to mix air within the diffuse zone. On the other hand, downslope wind produces the lowest zero plane displacement because there exist less obstructions to slow the winds before they interact with the diffuse zone.

Figure 28: The effect of Wind Direction on Zero Plane Displacement



The Impact of Diffuse Treeline on the ‘Leading Edge’

The wind profile in the diffuse zone depends greatly on the fetch and roughness of the surfaces it must travel over before encountering the treeline. At times, these factors greatly inhibit the ability of winds to penetrate into and mix air within the diffuse zone. For instance, when winds are out of the west and are blowing upslope, the effect that they have on the upper treeline is heavily dependent on the sheltering dynamics of the diffuse zone. This effect can be seen in its impact on the zero plane displacement at the upper treeline station. When winds are upslope, the zero plane displacement more than doubles in height, indicating the powerful shelterbelt effect of the diffuse treeline.

Figure 29: Dowslope Wind: ZPD = 6.32cm

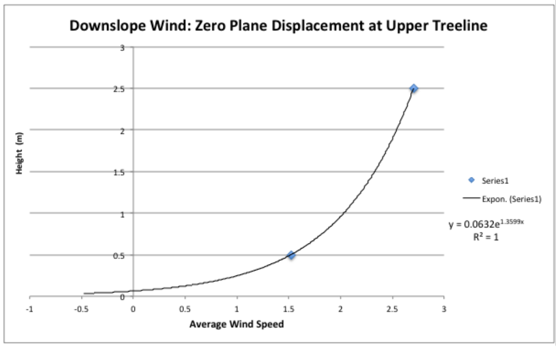
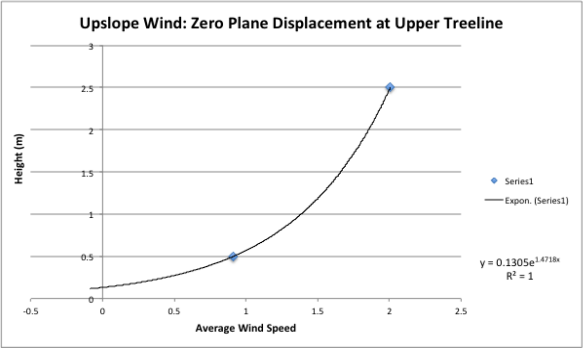
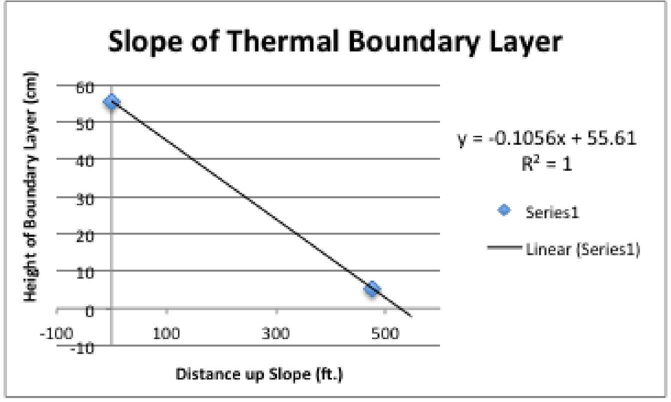


Figure 30: Upslope Wind: ZPD= 13.05cm



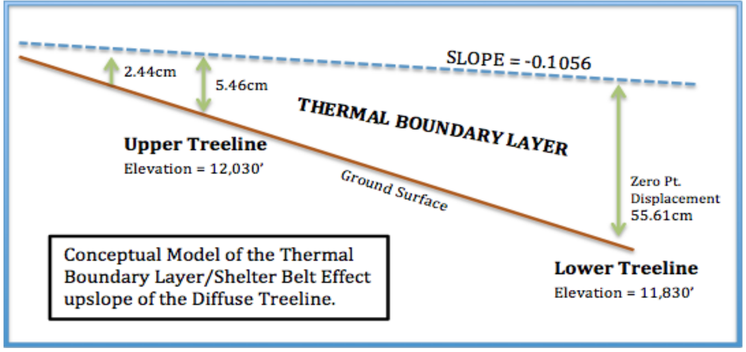
As elevation increases in the treeline transect, the height of the zero plane displacement decreases. This is mainly due to changes in tree density in the tundra and thus, the drag on wind speeds exerted by the presence and form of established trees. To understand how boundary layer thickness decreases with elevation gain, it is easiest to consider the slope as if it were flat. Figure 31 illustrates how the boundary layer thickness decreases from the lower station (Elevation = 11,830’) to the upper treeline station (Elevation = 12,030’) by 50.15cm over a 475’ distance across the ground surface. This change in thickness equates to a slope of -0.1056. The overall effect of the diffuse treeline can be quantified by calculating how far upslope it influences the thickness of the thermal boundary layer before the boundary layer reaches the height seen in the rockslide (2.44cm). At a distance of 522’ upslope from the lower treeline station the thermal boundary layer returns to the thickness seen in the rockslide, a proxy for the boundary layer without the influence of the treeline.

Figure 31: Slope of Thermal Boundary Layer as it extends upslope.



Finally, Figure 32 shows conceptually how the tapering thermal boundary layer fosters the growth pattern of an advancing diffuse treeline. The boundary layer in the figure below is decreases in height from 55.61cm, at the lower treeline, to 5.46cm, at the upper treeline, and finally to 2.46cm, the height of the zero-plane displacement in the rockslide which serves as a proxy for the boundary layer thickness in the upper tundra where the effect of the diffuse treeline is negligible.

Figure 32: Conceptual Model of Thermal Boundary Layer



The sheltering effects of the leading edge of treeline create opportunity for seedling establishment by increasing the zero plane displacement in the tundra soil above the treeline. As saplings grow into the upper limits of their thermal boundary layer, their increased density pushes the zero plane displacement even higher. This positive feedback loop, associated with ‘reach and fill’ advancement patterns, could be increasing rates of treeline advancement at the ‘leading edge’.

DISCUSSION

Differential Heating

Feedbacks that occur within treelines modify the microclimate and increase local warming. By creating a microclimate that exhibits favorable temperatures for tree survival, these feedbacks may contribute directly to treeline advance. In studying the microclimate at treeline and tundra on Pikes Peak, this investigation observed similar patterns of differential heating seen by previous researchers, thus corroborating findings by Johnson (2011) and Anderson (2012) that the presence, and possibly structure, of the treeline intensifies local heating. Johnson’s study revealed that daytime temperatures in the treeline reached a higher level of maximum heating faster than the rockslide in response to solar input (Johnson, 2011). Anderson further developed this theory by observing that at shallow soil depths, the treeline warmed an average of 7° F more than the rockslide during the day (Anderson, 2012).

This study substantiates the pattern of differential heating at the treeline of Pikes Peak; during a week in July, which exhibited the greatest signal of differential heating, shallow soil temperatures differed by an average of 8° F between treeline and the rockslide (see Figure 3). In addition to soil temperatures, the signal of differential heating between the treeline and the rockslide is also present in the air at 10cm and 2.5m, where temperatures differed by only several degrees. This suggests that within the treeline, soil and near surface air temperatures are coupled and exhibit analogous patterns of local heating. This study observed differential heating for the third consecutive year at the treeline study site, suggesting that this pattern of warming is not a fluke occurrence. As such, it seems highly likely that feedbacks exist at the leading edge of the treeline that not only cause increased warming amongst the trees but may also lead to greater heat accumulation throughout the season.

Interestingly, this study uncovered aspects of the differential heating not yet discussed by previous researchers: the magnitude and strength of differential heating was found to be lower in the beginning of the study period and higher at the end of the study period. Since the study took place over the summer, one possible cause of this increased differential heating could be treeline's response to increasing solar input throughout the study period. However, in the northern hemisphere, shortwave radiation from solar input achieves peak levels around June 22, and then begins to gradually decrease until achieving its lowest levels around December 22 (Marshall, 1996). As such, observations of this study that reveal stronger differential heating in August over June (Figure 2 vs. 4) suggest that changing solar radiation is not responsible for net gain in heating differences.

To investigate this seasonal anomaly in more detail it is helpful to interpret the soil heat flux and investigate how heat is being transferred into and out of the treeline system. In early July, the treeline soil gains slightly more heat during the day and loses slightly more heat at night than the rockslide (Figures 8 and 10). However, by late August, the treeline soil exhibits far greater daily heat gain than the rockslide, while nightly heat losses become more closely related, with the rockslide occasionally losing more heat than the treeline (Figures 9 and 11). Furthermore, in late August, the treeline continues to experience a positive net heat flux (more heat input than output) while the rockslide begins to exhibit a negative net heat flux (Figure 12B), suggesting that rockslide system responds differently than the treeline to decreasing solar input in the late summer season. With the main difference between treeline and rockslide being the presence of trees, these findings suggest that the trees are less influenced by decreasing solar input and that trees insulate their microclimate from heat loss proportional to heat gain.

One possible explanation for this phenomenon of differential heating between treeline and rockslide, that could also explain heightened thermal differences late in the summer season, asserts that the trees could be accumulating heat via microclimatological feedbacks (Johnson, 2011). Another possible explanation is that, instead of accumulating heat, the trees simply prevent nightly heat loss more effectively than the rockslide. If the treeline is storing heat more effectively than the rockslide, there must exist some physical characteristics of the treeline ecotone that enable heat retention. While research suggests that warming of near surface air during the day permits greater heat retention near the ground within treeline during the night (Gieger, 2003), this study reveals that near surface air temperatures within treeline are lower than the rockslide at night, even in August. Therefore, investigation into the dynamics of the near-ground boundary layer and its ability to hold heat within the treeline should inform the discussion of how increased heat accumulation within treeline may exacerbate the strength of differential heating (Fitzjarrald, 1993).

Boundary Layer Dynamics

As a possible mechanism for creating differential heating between the treeline and the rockslide at shallow soil depths and in the near-surface air parcel, this study explores the existence of the boundary layer and its effect on heat storage within the treeline system. An important indicator of boundary layer thickness is the zero-plane displacement; the height above the ground at which wind speeds are reduced to zero by frictional forces exerted by surface roughness elements. This study, using wind speed data, calculated this plane for both the treeline and the rockslide. As expected, the averaged zero-plane displacement within treeline during the study period (55.61cm) is far larger than in the rockslide (2.44cm) due to the influence of trees and their sheltering effect. Interestingly, the average zero-plane displacement in the upper reaches of the treeline transition zone was slightly larger than the rockslide (5.46cm), suggesting that even the limited presence of adjacent trees influenced the wind's ability to mix air near the ground. As shown in other research, observations suggest that this plane is highly dependent on wind speeds; when local wind speeds increased the zero-plane displacement was decreased, and when winds ceased, the plane increased its height (Figure 25). However, despite fluctuations due to wind speed, it is important to note that the exponential relationship between height of zero-plane displacement and wind speed suggests that even under maximum wind speeds, the tree's presence within the treeline ecotone enables the existence of relatively thick boundary layer, bereft of mixing from wind. This is important to establish because its highlights the power of the treeline to maintain a layer of calm warm air near the ground surface.

To further understand how the zero-plane displacement is influenced by the presence and distribution of trees within the transition zone between forest and tundra, the overall sheltering effect of the treeline must be explored. Shelterbelts, generally perpendicular to the prevailing wind direction, exist as narrow and long obstacles within the boundary layer (Wang, 1995). The 'shelterbelt effect' exerts drag on the local wind, reducing the momentum of turbulent flow. The airflow in lee of a shelter is determined not only by drag force of the shelterbelt, but also by the entire structure, width, and permeability of the belt (Wang, 1995; Plate, 1970). Width of the shelterbelt, defined as the shorter dimension or depth of the shelter, significantly changes the perturbed pressure field around the shelter, which affects the location of minimum wind speed and the recovery of the wind in the lee of the shelter (Wang, 1995). As such, the spatial structure of diffuse treelines may hold important implications on their effect to shelter downwind microclimates, and increase the zero-plane displacement at the leading edge of treeline.

This study investigates the sheltering effects of treeline form by correlating wind speed at the lower and upper treeline by wind direction as a measure of treeline's influence on nearby microclimates. Stronger correlations in wind speeds between lower and upper treeline in response to downslope, as opposed to upslope, winds supports the obvious sheltering effect of the forest. However, to understand the implications this sheltering has on the boundary layer, the zero-plane displacement level at the upper leading edge of treeline is used as an indicator of the influence that the lower treeline may exert on the tundra above. During the study period, upslope winds produced an average zero-plane displacement of 13.05cm at the upper treeline, more than double the height produced by downslope winds (6.32cm). Reduction in wind at the boundary layer due to sheltering from nurse vegetation can dramatically increase tree seedling survival in the timberline ecotone (Smith, 2003). While it is commonly known that treelines exhibit directional feedbacks associated with prevailing wind direction (Alftine, 2004), as evidenced by ribbon-like and island treeline forms, the role these feedbacks could play in treeline advance has not yet been fully explored. Consequently, the shelterbelt effects exerted by the diffuse treeline of Pikes Peak onto the upper treeline illustrate microclimatological modifications important to the critical boundary layer needed for seedling establishment. These microclimatological feedbacks could be of the upmost importance as a mechanism for treeline advance.

While these theories help explain how wind, and its interactions with trees, may influence the spatial patterns of seedling establishment beyond the edge of the closed-canopy forest, it doesn't completely elucidate how treeline advances upwards in elevation. Wind direction is variable in alpine climates and, consequently, prevailing upslope winds cannot simply be pointed to as the means for advancement. However, the application of these ideas can be helpful in understanding potential mechanisms for treeline advance.

Summary of Findings

To conclude, this study of microclimatological occurrences within the Pikes Peak treeline exposed a number of noteworthy findings. Firstly, the presence, and high resolution snapshot, of differential soil and air heating between the treeline and the rockslide corroborates previous findings. Furthermore, observational evidence of this pattern for the third year in a row reinforces it legitimacy, and rules out the possibility of fluke occurrence. Secondly, the nature of differential heating and its increased strength later in the summer season suggests that the treeline system accrues a greater ability to retain heat over the summer, despite decreasing solar input, and that it possesses a means of accumulating heat not seen in the rockslide. Thirdly, the dynamics of the boundary layer as a possible mechanism for greater heating were explored by tracing the reach of differential heating into the air and by analyzing the height of the boundary layer. Finally, the downwind effects of the diffuse treeline were investigated to determine how treeline structure might act as a shelterbelt, modifying the microclimate just beyond its leading edge. This study demonstrated the potential role of the boundary layer to affect localized heating patterns, the influence of treeline as a shelterbelt, and the subsequent effects that this shelter has on the boundary layer, however the connection between these findings and increased seedling establishment, a requirement for treeline advance, has yet to be empirically proven within the treeline at Pikes Peak. This study lays the theoretical groundwork for future research connecting shelterbelt, and the resulting boundary layer effects, to greater seedling establishment at the leading edge, and subsequent advance of treeline.

FUTURE RESEARCH

To better understand the feedbacks occurring at treeline on Pikes Peak, additional research into the shelterbelt effects of the diffuse structure must be conducted. Through this investigation, I have determined that treeline structure has a quantifiable effect on the adjacent microclimate. The presence of trees impedes airflow and helps improve the local climate by increasing the zero plane of displacement.

As such, future research should first corroborate the findings of this study. An in-depth analysis of wind speeds at multiple altitudes along each transect would help examines shelterbelt effects at a higher resolution. Furthermore, a more precise exploration of wind speeds from ground level to one meter along each transect will provide further insight to the height of the zero-plane displacement.

Future research should also delve into studying the spatial distribution of seedling and their relative location to ‘parental’ tree islands. Is there evidence of small-scale local shelterbelt effects enabling seedling establishment? Do most of the young trees exist in lee of larger adult trees? If so, do they exhibit similar heights, indicating the growth-inhibiting power of the boundary layer? These questions should be explored in order to see if there is spatial evidence of shelterbelt effects as a result of the treeline’s diffuse structure.

Lastly, additional investigation of the microclimatological benefits of the diffuse treeline should be analyzed. In addition to warming, what other improvements are associated with shelterbelt effects? Are these benefits initiating seedling establishment and growth? And, could the growth response associated with these changes in microclimate be responsible for initiating a positive feedback for treeline advance? These questions should provide a launching point for many possible explorations into the dynamics of treeline structure and its subsequent effect on altering the microclimate.

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