How Often Vertical Air Mass Transitions Occur in Association with Ridges on Mount Washington During the 2017-2018 Fall Season

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Abstract: The summit of Mount Washington is warming slower than the surrounding lower elevations, contrary to other mountain ranges which are experiencing higher warming trends. This also contradicts global climate model projections which suggest higher elevations should be warming faster than nearby lower elevations. The unusual elevation-dependent warming trends at Mount Washington could be driven by the summit being exposed to the free troposphere for approximately 50% of the year. As a first step toward testing this hypothesis, the impacts of free tropospheric exposure at the summit must be understood. The impacts of vertical changes in air masses at the summit of Mount Washington on climate variables during ridge passages were analyzed during the fall of 2017. Summit variables, such as temperature, dewpoint wind speed and wind direction from Mount Washington Observatory, were used to identify vertical air mass changes. Characteristics, such as a rapid change in dewpoint or wind speed, assisted in determining times of transitions. The NOAA ESRL-PSD snow-level radar at Plymouth State University, which can detect turbulence at the top of the boundary layer, and radiosonde data from the National Weather Service station at Gray, Maine help to support the height of the boundary layer in between them at Mount Washington under a synoptic scale ridge.

A total of 25 cases of ridge passages were identified by summit station pressure and Weather Prediction Center surface analysis maps. Of these 25 cases, 19 were associated with an air mass transition at the summit, 6 had no transition, and. Dewpoint, correlation between dewpoint and temperature, and wind speed were found to be the most effective variables during the fall season to determine a transition. A negative correlation of dewpoint and temperature was particularly indicative of a transition from moist boundary layer and dry free tropospheric air. This analysis suggests that most transitions occurred because upslope winds decreased with the approach of a ridge and the weak winds could no longer push boundary layer air up on the summit, thus exposing it to the free troposphere. Frequently, temperature increased by >1°C and dewpoint decreased by over 10°C. These results suggest that mountain slopes sufficiently high above their surrounding lower elevations may be experiencing a significantly different climate because of exposure to the free troposphere than they would if they were always in the boundary layer.

Keywords: boundary layer, free troposphere, subsidence, Mount Washington, climate

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1. Introduction

Specific ecosystems rely on climates associated with higher elevations. While populations rely on meltwater from mountains as a freshwater source. Yet mountain climates globally are changing unexpectedly and rapidly, and the reasons are not well understood (Rangwala and Miller 2012). Changes on mountain climates tend to be regionally driven by small scale weather patterns (Siedel et al. 2009: Rangwala and Miller 2012). Without fully understanding the changing mountain climate, the ecosystems which have nowhere nearby to migrate may become endangered, and populations that rely on the freshwater may experience crisis.

Current climate models indicate that higher elevations should experience greater rates of warming than surrounding lower elevations. However, this is not true for all mountains. The Andes and the Colorado Rockies are warming slower, and in some areas cooling (Rangwala and Miller 2012; Pepin and Losleben 2002). This pattern is also true for the summit of Mount Washington which is warming slower than the surrounding elevations (Fig. 1). When compared to the 30-year climatology of the surrounding stations, Mount Washington and Mount Mansfield have smaller positive trends in all seasons.

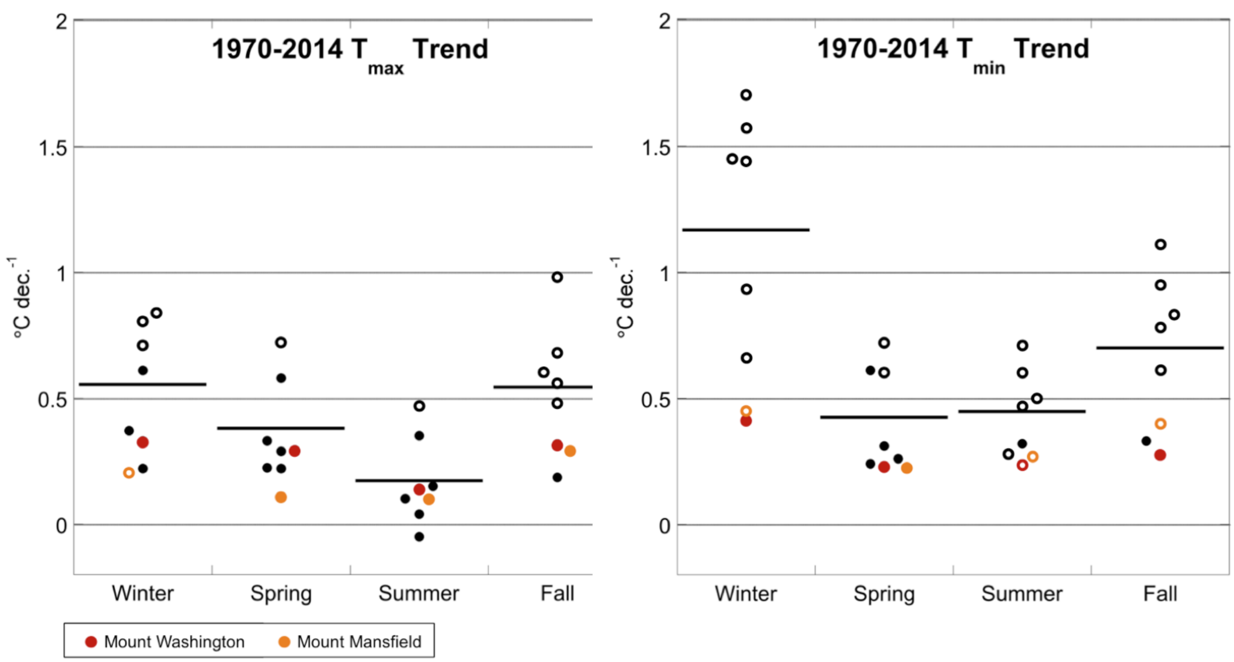

Figure 1 : Minimum and maximum temperature trends from six surrounding lower elevation sites (black dots) with the average represented as the vertical black line. Statistically significant trends (using Sen's Slope) at $p<0.05$ are indicated by an open circle. (Wake et al. 2014a, 2014b).

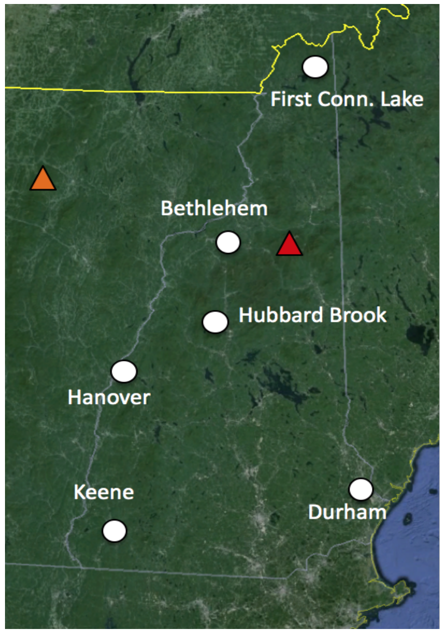

Figure 2 : A map showing location of the lower elevation sites (white dots), Mount Mansfield (orange triangle), and Mount Washington (red triangle).

Past studies indicate that the montane temperature trends may be driven by small scale weather patterns while other studies point toward the trends being dependent on elevation (Pepin and Norris, 2005; Pepin and Siedel 2009; Rangwala and Miller 2012). Another idea, presented by Kelsey (2018), indicates that vertical air mass shifts can influence daily high and low temperature values, thus influencing temperature trends recorded for these higher elevations. This includes shifts between the free troposphere (FT), entrainment zone (EZ) and the planetary boundary layer (PBL) which cause dramatic changes in temperature, dewpoint, wind speed and wind direction. Lower elevations would remain in the PBL and would not be affected by these transitions.

Factors such as insolation, synoptic events, convection and orography can influence the height of the PBL (Stull 2017; Kelsey, 2018). The PBL experiences daily diurnal cycles driven by insolation. The PBL grows via convection due to daytime heating and can displace free tropospheric air along mountain slopes. Factors on the synoptic scale can drive changes in air mass structure as well. This includes high pressure systems that can have subsidence and low-level divergence, which pushes PBL air down, decreasing its height. At night, the upper PBL decouples from the radiationally-cooled PBL and this upper "residual layer" retains the properties it had as part of the convective PBL. Other processes that change the height of the PBL locally on mountains are orographic lift and anabatic flows (Stull 2017)

This study will investigate vertical air mass transitions and the impacts on montane climate by analyzing Mount Washington summit variable data during anticyclonic systems from Mount Washington Observatory. Anticyclonic systems were chosen due to the simple atmospheric structure. The subsidence will cause air to be forced down and warmed adiabatically, this creates a bigger inversion and makes it easier to indicate the difference between the PBL and FT. High pressure systems tend to be stronger in the cold season which increases this affect. For this analyses the fall season will be used exclusively because this season experiences the greatest variation from the average temperature of the lower surrounding elevations. During the colder months, there is less of a signal due to the diurnal growth of the boundary layer because of the lower sun angle, making PBL growth almost nonexistent and not a factor when looking at cases. Analyzing cases of ridge passages over the New England area during fall season can lead to a stronger understanding of how vertical air mass transitions affect summit variables.

2. Data

Data for the fall season of 2017 was retrieved from the Observatory on the summit of Mount Washington, located at 1917 m above sea level. The measurements are recorded every minute and includes temperature and relative humidity, which is measured with a Campbell Scientific HMP45. Pressure measurements from an NWS ParoBaro Scientific barometer as well as wind speed and wind direction measured with an RM Young propeller anemometer and/or a pitot static tube and wind vane. The pitot static tube is the primary operational anemometer except when sustained wind speeds drop below ~13 m s^{-1} because winds this slow do not provide enough force to vane the pitot into the wind accurately.

Due to the size of anticyclonic system, the data from other locations can be used to support indicated times of transitions. The National Weather Station in Gray, ME is located 91 km to the southeast of the summit. The station launches radiosondes twice daily. These upper air soundings give detailed temperature, dewpoint and wind profiles that can be similar to those at Mount Washington when synoptic scale ridging is present. These can indicate the height of PBL based on the temperature and relative humidity readings which would show the dry FT layer (GlobeFeed 2018). There is also a NOAA ESLR-PSD Snow Level Radar (SLR) at Plymouth State University in Plymouth, New Hampshire. The SLR emits an electromagnetic signal that often reflects off turbulence at the top of the PBL and/or in the EZ. The data from these other locations aid in supporting vertical air mass transitions observed at the summit of Mount Washington.

Figure 3 : Location of the Snow Level Radar at Plymouth State University, the Grey ME NWS station, and the Mount Washington Observatory.

3. Methods

To determine ridge passages over the summit, 1-minute summit pressure data was smoothed using a 500-data point running mean to remove small scale variability and to retain low frequency variability associated with large-scale pressure centers. . Then, ridge passages were found by finding times of local maximums with a prominence of 1 hPa. Each case was compared to the SLP analyses maps from the Weather Prediction Center archives. This step verified ridge passages over the summit.

One-minute temperature, dewpoint, wind speed, and wind direction data from the summit were used to determine transitions for the fall (September-November) of 2017. The pitot static tube was favored over the RM Young except for when winds were light and variable, these situations favored the RM Young data. In addition, the correlation across an hour (60 data points) between temperature and dewpoint was calculated to help identify the different vertical air masses. The correlation when the summit is in the PBL would likely be positive due to rising air that is warmer and moister than descending air during the day. Meanwhile, the correlation is likely to be negative in the EZ because of the mixing of relatively cool/moist PBL air with relatively warm/dry FT air, or the lower FT because of decreases in dewpoint as temperature increases with height. Wind direction angular dispersion was and wind speed variance were calculated and analyzed as potential indicators of EZ air since the EZ should be a high shear layer from mixing of different wind speeds and directions All aforementioned meteorological variables were analyzed at least 12 hours before and after the peak Mount Washington station pressure, and often for longer periods to find evidence of any air mass transitions associated with the ridge passage.

For each case, images from the SLR and soundings from KGYX were collected to corroborate transitions indicated by the summit data. After analysis, the cases were then categorized as to whether transitions occurred, transitions that did not occur, and those left inconclusive. Inconclusive cases were cases in which conclusions could not be made. These cases may have been influenced by more than one forcing which made it hard to conclude the air mass at the summit. For each transition, the time series plot, SLR images, and soundings from the NWS station was utilized to better comprehend how the variables changed during and after transitions.

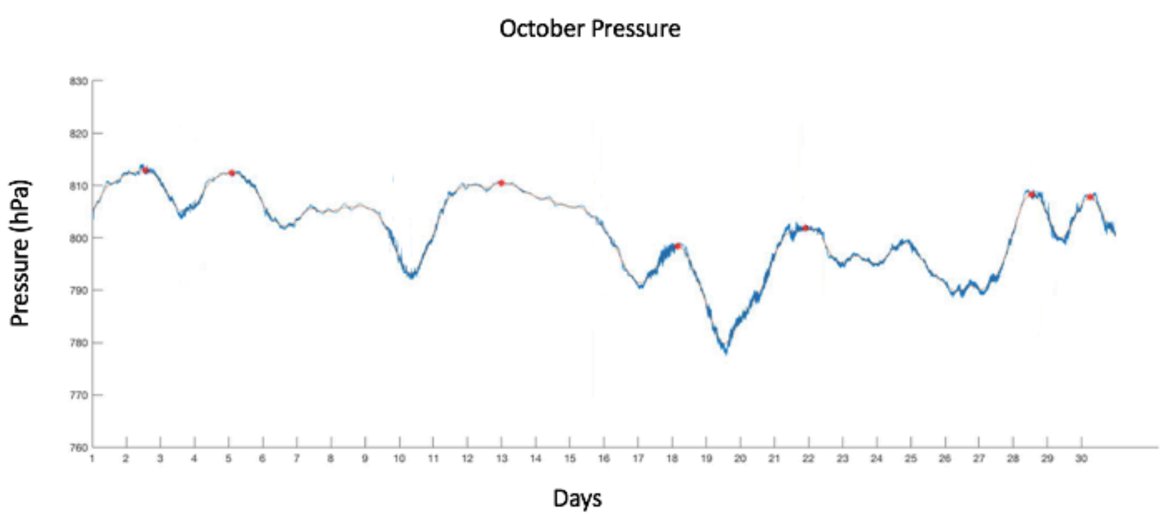

Figure 4: Time series of Mount Washington station pressure data (every 1-minute, dark blue), 500-minuterunning average station pressure (light blue), and marked peaks (red stars)

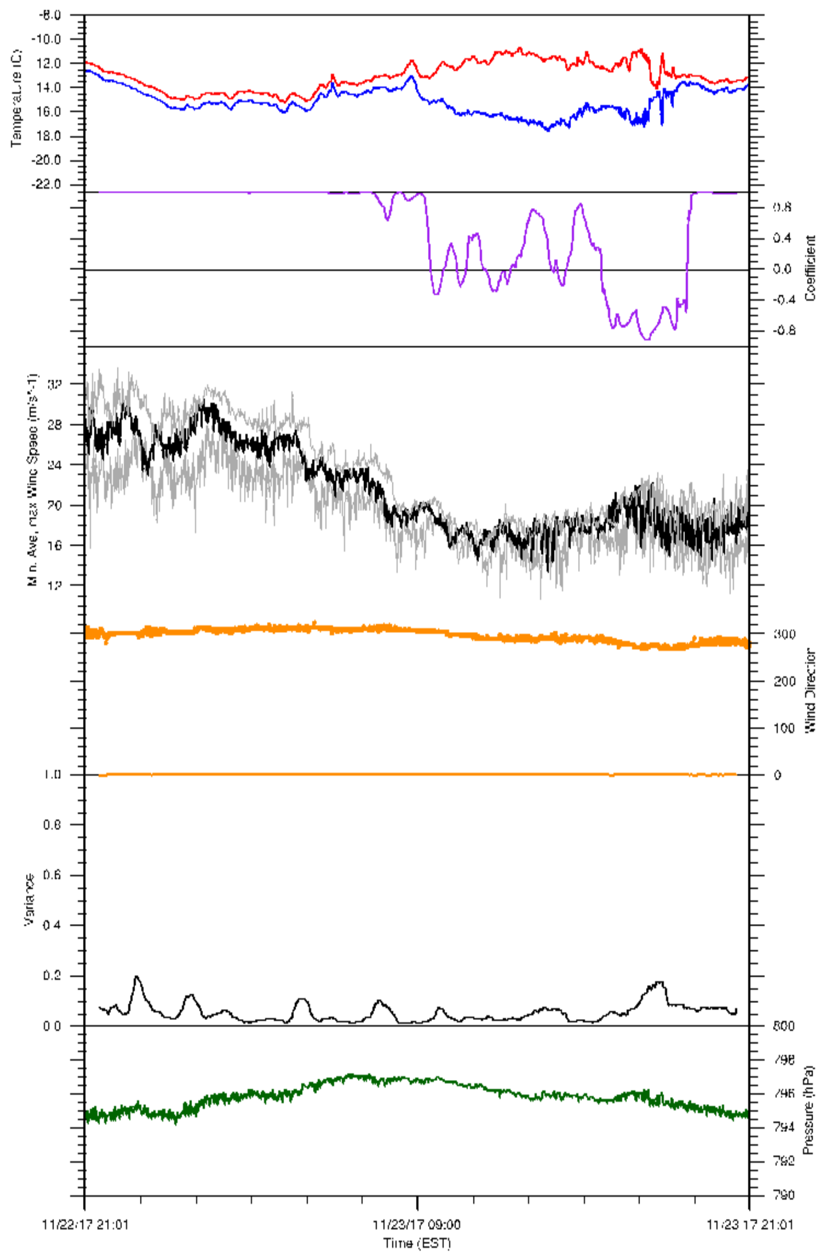

Figure 5: Time series plot of summit variables during the ridge case for 23 November 2017.

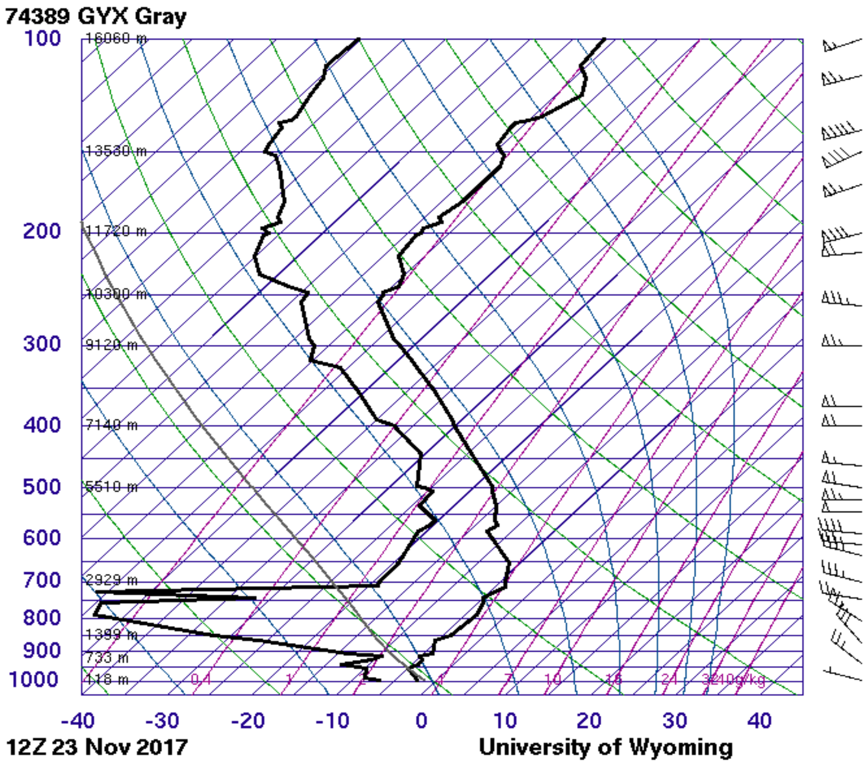

Figure 6 : Sounding from NWS at Gray, Maine (KGYX) for 1200 UTC 23 November 2017.

4. Results and Discussion

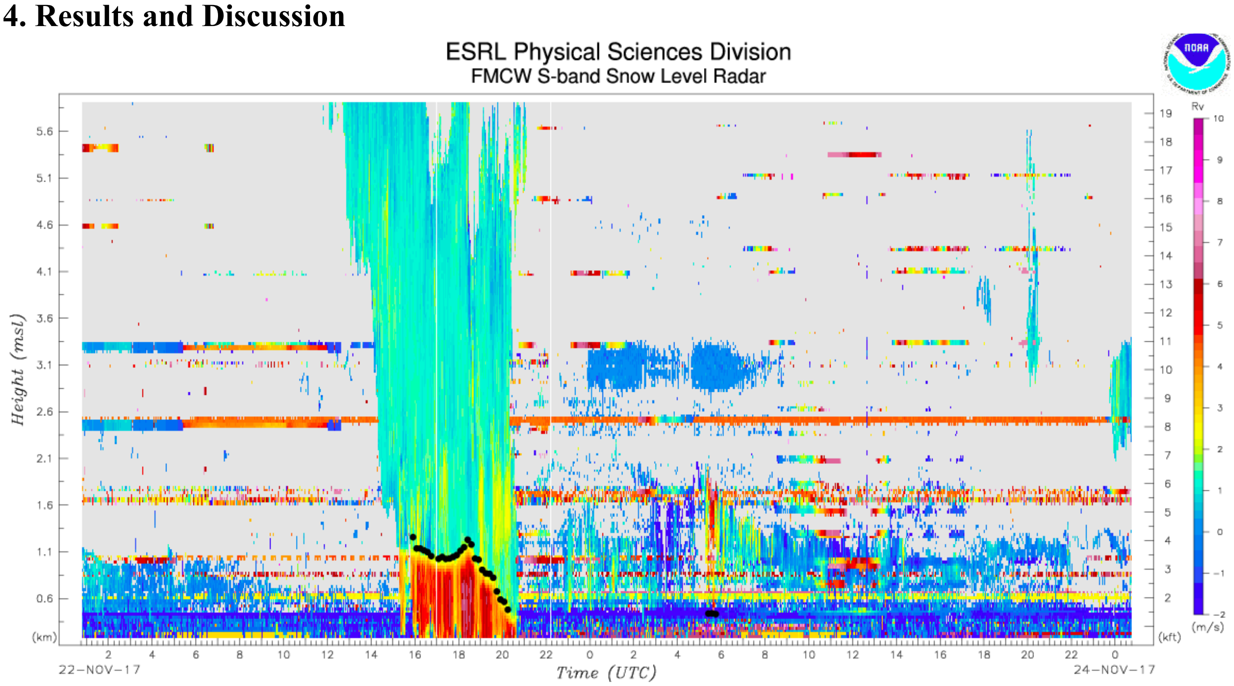

Figure 7: NOAA ESRL-PSD snow-level radar vertical velocity image from Plymouth State University.

From the summit station pressure analysis, 25 cases of ridges were identified of which 19 were transitions, 6 were not (fig 8). Originally 26 cases were determined from the station pressure analyses, but after the cases were compared to the SLP surface maps, 6 October 2017 was removed as a case. The SLP analyses had a meandering front across New England causing occasional light rain. The closest ridge was centered well offshore of the Mid-Atlantic and never sent any ridge axis through New England.

The case of 23 November 2017 is shown in Figures 5-7 as an example case of an air mass transition. The time series (fig 5) shows a decrease in correlation to around zero between temperature and dewpoint around 0900 EST on 23 November 2017. This is happening alongside an increase in temperature and a decrease in dewpoint which corresponds to the FT. This transition to the FT coincided with increasing pressure and decreasing wind speed at the summit. Since the PBL height over Plymouth, NH, at ~1.1 km was well below the summit elevation as indicated by the SLR (Fig. 7), the 22-30 m s-1 winds were pushing PBL air up the side of the mountain and over the summit and creating an orographic cloud. As the ridge passed over and the horizontal wind speed decreased, the 18-20 m s-1 winds were no longing moving PBL air up to the summit, causing a transition into the FT.

This process of winds pushing PBL air up to summit is common during the cold seasons when the diurnal PBL growth is minimal. Strong wind speeds of 30 to 40 m s^{-1} can cause PBL advection up to the summit, although in some other cases winds as low as 15 m s^{-1} were strong enough to bring PBL air to the summit as the ridge leaves the area the winds increase and start pushing PBL air back over the summit, causing a transition back into the PBL.

Other transition types were found to occur at the summit and change the air mass at the summit. East winds were found to advect moist air into the area. this moist air if pushed up to the summit could cause a transition into more saturated air and make vertical transitions harder to investigate. Subsidence associated with the increased subsidence may also cause downward motion of the PBL height, causing the transition into the FT during times when the PBL was supposed to be increasing with diurnal heating. When subsidence decreases, diurnal growth causes the PBL to increase in height again.

Transitions due to horizontal winds, subsidence, or air advection all had different signals in the summit variables. The FT was thought to be characterized by higher wind speed compared to the PBL. When looking at cases of transitions that were caused by winds no longer pushing PBL air up to the summit, the wind speeds continued to decrease even after the summit entered the FT. This was caused by the decreased pressure gradient associated with a high-pressure system. During these transitions, due to the Venturi effect, wind speed became a good indicator. During a transition from the PBL into the FT, the winds increase dramatically because the air gets pushed between the summit and the EZ, but only for a short time. The correlation between temperature and dewpoint was a robust indicator of transitions between the PBL into the FT. The air characteristics of both layers are vastly different when temperature and dewpoint are compared. In general, the dewpoint alone was a strong indicator. The FT air is much dryer and always had a lower dewpoint in these cases. The EZ would have a varying dewpoint, making dewpoint variable the best for determining the EZ. In some instances, the wind variation also proved helpful in determining transitions. Even when wind speeds did not follow the expected pattern, wind variation did decrease in the FT for some cases. For all cases, multiple variables had to be considered, no single variable could determine whether a transition occurred or not. Looking at the time series plots and analyzing correlation and wind speeds together did give the best indication of a transition.

Cases with transitions were used to gather, maximum and minimum temperature and dewpoint values for each air mass transition during ridge passage. This included temperature values for the PBL air before the transition, the FT air after the transition, and once the summit returned into the PBL. These values were compared to each other to determine how much a transition into the FT affected the daily minimum and maximum temperature.

This study of transitions between the FT, EZ and PBL during ridge passages gave better understanding of how varying air masses affect summit variables. Transitions from PBL to FT caused an increase in daily temperature in 78.9% of cases. When the temperature of the FT was compared to the PBL there was a on average, 6.81 ˚F increase in temperature, and when comparing all FT air to PBL air there was an average the FT 4.17 ˚F warmer than the PBL.

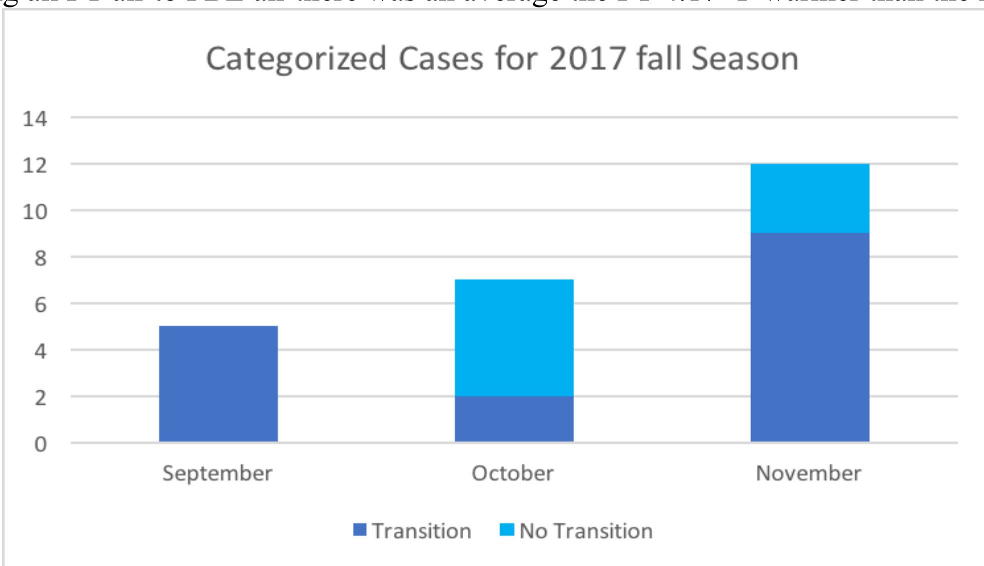

Figure 8: Plot indicating the number of ridges associated with a vertical air mass transition or no transition at Mount Washington.

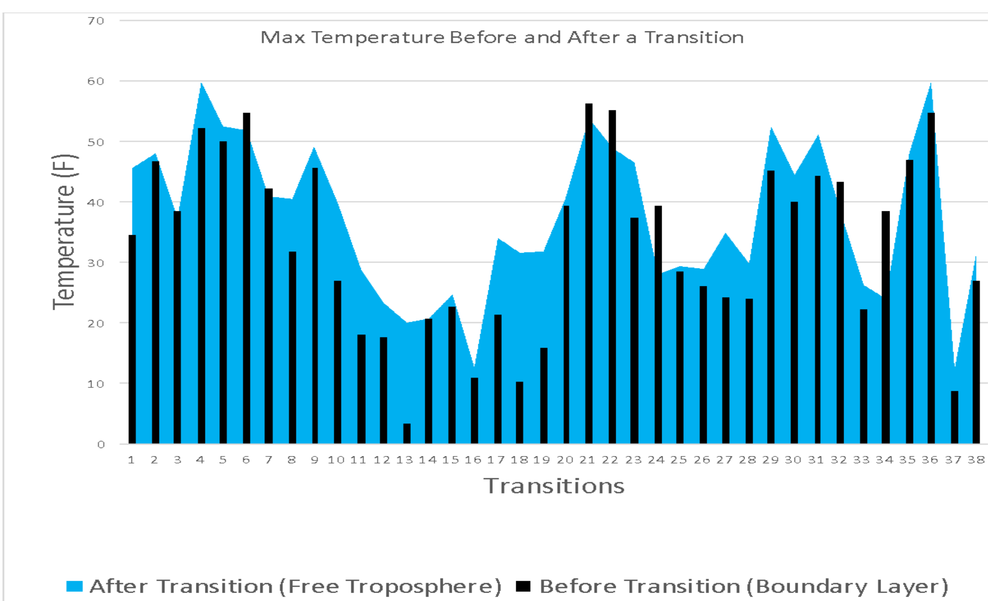

Figure 9: Plot representing air temperature of Boundary Layer Air (black bars), and air temperature of free troposphere before and after transition (blue plot behind bars)

5. Conclusion

This study of transitions between the FT, EZ and PBL during ridge passages gave better understanding of how varying air masses affect summit variables. Transitions from PBL to FT caused an increase in daily temperature in 78.9% of cases. When the temperature of the FT was compared to the PBL there was a on average, 6.81 ˚F increase in temperature, and when comparing all FT air to PBL air there was an average the FT 4.17 ˚F warmer than the PBL.

After analyses of all variables from the Mount Washington Observatory, how the variables change based on transition is understood, and the correlation between dewpoint and temperature is recognized to be the strongest indicator of a transition. Wind speed is the next best indicator, as spikes in its speed indicate a transition from the PBL into FT.

These cases are a good start to understanding how the vertical structure on the summit of Mount Washington affects the climate record, but more cases must be analyzed to understand the statistical effect of the vertical air mass transitions. Future studies of transitions at higher elevation should include more years and seasons as well as other synoptic events.

6. References

Conrad, V., 1941: Structure of the weather at Mount Washington. Mount Washington Observatory Bull., 2-4.

GlobeFeed.com, 2018: Distance calculator, Accessed June 22 2018, https://distancecalculator. globefeed.com/US_Distance_Result.asp?fromplace=National%20Weather%20Service%2C%20 Weather%20Lane%2C%20Gray%2C%20ME%2C%20USA&toplace=Mt%20Washington%20A uto%20Rd%2C%20Jackson%2C%20New%20Hampshire%2C%20USA&dt1=ChIJY8Pbp-hiskwRSC3SnP4c3kU&dt2=Ei1NdCBXYXNoaW5ndG9uIEF1dG8gUm QsIEphY2tzb24sIE5IIDAzODQ2LCBVU0EiSCpGChQKEgnr6H7T842zTBElJtDLAv-5bRIUChIJ_30SoVeXs0wRbe_0oQ2wUrYaGAoKDUwCYxoVwvZ_1RIKDQdkZhoVANuL1Q &sr=dc.

Kelsey E., Bailey A., Murray G., 2018: The Impact of Mount Washington on the height of the boundary layer and vertical structure of temperature and moisture.

Pepin N. and Losleben M. (2002) Climate change in the Colorado Rocky Mountains: free air versus surface temperature trends. Int. J. Climatol. **22**, 311–329, https://doi.org/10.1002/ joc.740.

Pepin N. and Norris J. R., 2005: An examination of the differences between surface and free-air temperature trend at high-elevation sites: Relationships with cloud cover, snow cover, and win*d. J. Geophys. Res.,* **110***,* https://doi.org/10.1029/2005JD006150.

Pepin N. and Seidel D.J., 2005: A global comparison of surface and free-air temperatures at high elevations. *J. Geophys. Res.* **110**, https://doi.org/10.1029/2004JD005047.

Rangwala I., and Miller J. R., 2012: Climate change in mountains: a review of elevation-dependent warming and its possible causes, *Springer*, https://doi.org/10.1007/s10584-012-0419-3.

Seidel T.M., Weihrauch D.M., Kimball K.D., Pszenny A., Soboleski R., Crete E., and Murray G., 2009: Evidence of Climate Change Declines with Elevation Based on Temperature and Snow Records from 1930s to 2006 on Mount Washington, New Hampshire, U.S.A. Arctic, Antarctic, and Alpine Research, **41**, https://doi.org/10.1657/1938-4246-41.3.362.

Stull, R., 2017: Practical meteorology: an algebra-based survey of atmospheric science, Sundog Publishing, 940 pp.

Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, 670 pp.

Wake, C.P., E. Burakowski, and P. Wilkinson, 2014a: Climate Change in Northern New Hampshire. Past, Present, and Future. The Sustainability Institute, 78 pp.

Wake, C.P., E. Burakowski, P. Wilkinson, K. Hayhoe, A. Stoner, C. Keeley, and J. LaBranche, 2014b: Climate Change in Southern New Hampshire. Past, Present, and Future. The Sustainability Institute, 86 pp.