Reviewer 1 (Stephen Dery) Response

Thank you for your thoughtful and insightful review comments on this paper. We have endeavoured to address them and think that by addressing them the resulting manuscript is greatly improved.

General Comments:

1) The abstract lacks key information such as the period of study and the specific study site (Fortress Mountain in southwestern Alberta, Canada).

This information has now been included in L12-16

"To determine if specific turbulent motions are responsible for warm and dry air advection during blowing snow events, quadrant analysis and Variable Interval Time Averaging was used to investigate turbulent time series from the Fortress Mountain Snow Laboratory alpine study site in the Canadian Rockies, Alberta, Canada during the winter of 2015-2016"

2) Section 2.1 should provide a short description of the study area and its climate. Provide the coordinates and elevation of the blowing snow study site, some information on the local topography and climate to provide the reader some geographical context.

The following paragraph has now been added at the beginning of Section 2.1

"Fortress Mountain Snow Laboratory (FMSL) is located in the Kananaskis Valley in the Canadian Rockies of southwestern Alberta, Canada. FMSL is surrounded by very complex terrain, with multiple nearby 2900m peaks having >100m vertical rock faces. The blowing snow study site is situated on a plateau at 2000m at the base of a closed ski resort, providing ample upwind fetch with minimal obstruction from trees or buildings (Figure 1 inset). Winter air temperatures at the FMSL blowing snow site typically range from -20° to +5℃, with frequent midwinter downslope chinook (föhn) wind events. Snow depth at the blowing snow site remains fairly constant through the midwinter at approximately 1 metre, with fresh snowfall frequently redistributed by wind events."

3) Are ultrasonic humidity measurements also available at the FMSL during this field campaign? If so, it would be quite interesting to see if blowing snow sublimation, and hence humidity, responds to the rapid air temperature and wind speed fluctuations during blowing snow events.

No, this data is not available, though, as mentioned in the conclusions, we would also be interested in analyzing these data in this context.

In any case, if both ultrasonic air temperature and wind speed data are available during the five blowing snow events, why not plot the corresponding sensible heat fluxes observed along with the meteorological data shown in Figure 2? At the very least, Figure 2 should include the corresponding wind speed data for all three sites.

Thank you for the suggestion. The corresponding wind speed data has been added to a supplemental figure, as well as highlighting periods conducive to blowing snow in Figure 2. We considered including the sensible heat flux estimates but to do so is full of uncertainty and likely errors and so is problematic for the following reason. Eddy-covariance calculations rely on assumptions of horizontally homogeneous terrain, time series stationarity, and identifying the single correct physical reference frame. Given the *highly non-stationary processes we are discussing, it is not possible to select standard time frames for covariance calculations and would also be difficult to ascribe much meaning to these estimates, much as our earlier work identified problems in linking snow particle transport to EC estimates of shear stress. We think that including estimates of these fluxes would increase the uncertainty of the manuscript substantially and that the methods of estimating heat fluxes during such non-stationary flows needs to be reassessed in a very fundamental way. Essentially, we think that this analysis shows fundamental problems with using EC estimates of sensible fluxes over snow as earlier identified by Helgason and Pomeroy (2012) and suggested by Harding and Pomeroy (1996).*

4) At no point does the text specify whether the relative humidity data recorded at the three other FMSL stations are with respect to water or to ice. Standard meteorological instruments usually provide the former, and so if this is the case, the relative humid- ity data must be converted to respect to ice to make any claims or conclusions about the absence of saturation during these five blowing snow events.

We agree and were showing relative humidity with respect to ice.

It should also be clear that the Powerline site is sheltered by trees and hence does not likely experiment blowing snow and may not reveal evidence of thermodynamic feedbacks from its sublimation.

Thank you. We mostly agree, though the patchy nature of the forest means that air masses measured in the clearing would be influenced by blowing snow. The other two sites are fully in the blowing snow flow zone. The introduction of the Powerline site has been changed as follows: "The nearest complementary site is a sheltered forest (Powerline) station approximately 400 m away and 30 m higher in elevation [Smith et al., 2017]. Additionally, there are two exposed sites, including a ridgetop (Canadian Ridge) and lee side of ridge (Canadian Ridge North) that are both approximately 600 m downwind and 200 m higher in elevation. The Powerline station receives much less wind than the exposed sites or the blowing snow site and is much less susceptible to snow redistribution."

5) Table 1 (mis-labelled as Table 2)

Corrected

provides data on Monin-Obhukhov lengths but it is not clear how these are derived. Similarly the definition for turbulence intensity reported in this table is not defined in the text.

These two variables have now been mathematically defined with citations in the text.

6) Blowing snow conditions are stratified into "sweep" events (u' > 0, w' < 0) and "ejec- tion" events (u' < 0, w' > 0); yet there may also be blowing snow conditions when the horizontal and vertical wind speed anomalies are both of the same sign; therefore it is unclear why observations are provided only for the sweep and ejection events.

There are two reasons why we have focused on sweep and ejections motions. The primary reason is that they disproportionately contribute to Reynolds stress in turbulent boundary layers. When calculating friction velocity or other turbulence metrics that utilize velocity fluctuations, these motions have a significant influence. Second, this influence is connected to a history of coherent feature. identification in turbulence. Sweeps and ejections have been associated with specific bursting mechanisms, hairpin packet structures, and other theories of boundary layer flows. Outward and inward interactions (when u' and w' *are of the same sign) do not make the same, nor have the same connections been made to vortical features in boundary layer flows.*

The following sentences have been added to the text "The subsequent analysis focuses on sweeps $(u' > 0, w' < 0)$ *and ejections* $(u' < 0, w' > 0)$ *as they disproportionately contribute to the total surface Reynolds stress, are frequently used in models of turbulent boundary layer structures, have been identified to play crucial roles in boundary layer heat flux and aeolian transport [e.g. Bauer et al., 1998; Adrian et al., 2000; Garai and Kleissel, 2011; Aksamit and Pomeroy, 2017]. Please refer to Wallace [2016] for a recent review of the theory and experiments surrounding quadrant analysis and sweep-ejection cycling."*

7) Further to this, is an assumption made that blowing snow particles have no inertia and respond instantaneously to wind speed fluctuations?

No, this assumption is not made in the text, nor is it necessary for our results. It is unclear to the authors how this conclusion was made by the reviewer.

Specific Comments:

1) **P. 1, line 19: Fix the language in "model modeled described provides".**

   This line has been changed to "The recurrence model described herein provides a significant step towards a more physically-based blowing snow sublimation model"

2) **P. 1, line 27: Snow at the surface is often subjected to transport by wind only in relatively open and windy areas; areas such as the boreal forest and taiga are much less prone to wind transport of snow. The statement here should not be so general given blowing snow is not important component of the water budget in all areas experiencing snow.**

   Thank you – very true. We have clarified these statements as the following: "However, after snow has fallen, it is often subjected to sublimation while at rest or amplified in-transit sublimation during redistribution. Blowing snow redistribution can result in vast amounts of frozen water moving between basins or, in the case of sublimation, being removed entirely from the surface water budget in wind swept regions."

3) **P. 2, lines 48-50: Some prior studies (e.g. Grazioli et al. 2017; Déry and Yau 2001) have explored turbulent mixing and entrainment of dry air into the atmospheric boundary layer with impacts to the blowing snow sublimation and should be cited here.**

   Thank you. These citations have now been mentioned and included.

4) P. 2, line 54: Delete "in order".

Corrected.

5) P. 2, line 59: Insert "air" before "temperature".

Inserted.

Are the relative humidity data with respect to water or to ice?

This has been clarified and is presented with respect to ice.

6) P. 3, line 64: Perhaps this subsection could be titled "Field data"?

This title has been changed accordingly.

7) P. 3, line 75: How strong were the winds during the chinook event on January 21, 2016?

This line has been changed as follows: "This additional night, January 21, 2016 had much stronger winds, gusting up to 15 m s^{-1} *because of the presence of a chinook event."*

8) P. 3, lines 76 and 77: The degree symbol is missing in the air temperature values reported here and elsewhere in the paper.

This has been corrected throughout the text

9) P. 3, line 83: Rather than "protected" use "sheltered".

This has been changed.

10) P. 3, line 84: Replace "include" by "including".

This has been changed.

11) P. 3, lines 87-89: At what temporal scales of the meteorological measurements are these coefficients of determination valid for? What are the associated probability values and sample numbers for each?

These values have been added to the text.

12) P. 4, Figure 1 and caption: Should the arrow on the map indicate the "Predominant" wind direction?

This has been changed. Thank you.

13) P. 4, Table 1: Note that this table is reported as "Table 2" but it should instead be "Table 1".

This has been changed.

Under "Date", the years for the events should also be reported.

This has now been changed. Thank you.

There is disparate information provided for the meteorological data, namely the range for wind speeds and Monin-Obhukov lengths and means for air temperatures. It would be more useful to have mean values and corresponding standard deviations for all events.

Thank you for the suggestion. Table 1 has been updated accordingly.

What do the "lower" and "upper" air temperature measurements mean?

We have clarified that we are referring to specific anemometers. Throughout the text, we have replaced the "upper" and "lower" designations with numeric 140 cm and 20 cm heights to differentiate between the two anemometers.

At what depth are the snow temperature measurements collected? Why not report one decimal value for the snow temperature measurements in a similar fashion as to the air temperatures?

These are snow surface measurements made in the first mm of the snow surface. These measurements were made manually and reported in a field notebook on the days of the experiment. Unfortunately, the temperatures were not recorded to the first decimal place so that precision did not exceed the accuracy of the thermometers used.

Apart from these meteorological variables, why not report the mean and standard deviation in relative humidity with respect to ice?

The formatting of the table has been changed in accordance with this suggestion.

14) P. 5, line 108: What does the subscript "v" denote in "kv"?

We have clarified that k_v *refers to a user defined threshold in the VITA equation.*

15) P. 5, line 110: Move "criterion" to just after "analysis". Insert a comma after "1989]".

This has been changed.

16) P. 5, line 113: In Equation (2), is a negative sign needed before "air" given the absolute value of this quantity is taken?

Equation 2 (and much of section 2.2) has been now been rewritten for clarity. This redundancy is no longer present in the text.

17) P. 5, lines 113 and 114: Equation (2) has a term v' but the next line refers to w'.

This inconsistency has now been corrected.

What does the subscript "Q" refer to in "kQ"?

We have clarified that k_Q *refers to a user defined Quadrant threshold event identification algorithm.*

18) P. 6, line 128: Are the relative humidity data discussed here with respect to water or to ice? Standard meteorological instruments provide the former and so should be converted to respect an ice surface to establish whether saturation is indeed achieved, or not, during blowing snow events in subfreezing conditions.

These measurements are made with respect to ice and this has been clarified in the text.

19) P. 6, Figure 2: The color legend on the bottom right of the plot shows the air temperature in blue and the relative humidity in red; yet the tick labels on the y-axes show air temperature in red and the relative humidity in blue. As such it is not possible to interpret this plot. It would also be useful for interpretation of the meteorological time series to know when blowing snow was occurring during the 5 events shown here, perhaps as grey shading on the plots.

Thank you for noting this discrepancy. The coloring on these plots has been corrected. There were no blowing snow particle detectors at these stations so it is not possible to definitively say exactly when blowing snow was present. We highlighted times when the 15-minute average windspeed was greater than 3 m/s, a threshold for transport that has been noted at blowing snow study site previously. We have also included complementary time series of snow depth measurements and wind speeds in the document supplement, but a definitive highlighting of events is not possible.

20) P. 6, line 135: Again, specify if the relative humidity measurements are with respect to water or ice.

This has been clarified when the data is introduced on line 133.

At what temporal frequency are these data presented and at what measurement height?

It has been added to the caption that these are 15 minute average values at approximately 2 m heights.

Why not add the corresponding wind speed data here?

This has been included in the updated document supplement. Relevant blowing snow transport threshold information has now been included in the updated figure.

In the caption, change the text to "Flagged data have" and perhaps add a note that the y-axis scales vary between panels.

This has been changed.

The caption also states that there is limited correlation between sites for both variables yet on p. 3, line 88 it was reported there was high coefficients of determination for air temperature with lesser values for relative humidity.

This has been clarified. There is a high correlation.

21) P. 7, Figure 3: On the y-axis labels, spell out "Temperature".

This has been changed.

22) P. 9, line 158: Add the corresponding years for the events.

This has been added. Thank you.

23) P. 9, Figure 4: On the y-axis label, spell out "Temperature".

Changed.

24) P. 10, Figure 5: A color legend is missing from this plot and so the results cannot be interpreted.

This has been added.

25) P. 11, lines 190-191: Delete “It is interesting to note that” and start the sentence with “The probability”.

This has been changed.

26) P. 11, lines 201 and 203: Equation (3) includes a “KV” term but on line 203 the text refers to “KQ”. Note also the text includes both upper case and lower case letters for these subscripts.

We have corrected the inconsistency in letter case. The use of k_V in equation 3 and k_Q in the following paragraph is, however, correct. As both k_V and k_Q are necessary for the modified VITA analysis, we restricted our model to events generated for one standard value of k_Q and analyzed those results.

27) P. 12, lines 211-212: What do all the subscripts used here mean?

These subscripts have been removed and the data has been moved to a new Table 2 that is much easier to interpret. Thank you for the motivation.

28) P. 12, lines 212-213: Fix the language in “common characteristic topographically induced flow.”

This line has been changed to “This suggests persistent flow features at this site from one night to the next that may be due to a persistent topographically induced flow feature or turbulence generating mechanism at the study site.”

29) 12, lines 228-229: It should be clear that these statements apply to the study site only and cannot necessarily be generalized.

Comments along these lines have been added to the last paragraph of the discussion and the last paragraph of the conclusions, as well as suggestions for how further investigation will reveal what of these bursting parameters can be regarded as universal.

30) P. 12, line 231: Replace the semi-colon by a comma after “[1993]”.

This has been changed.

31) P. 12, line 234: Again, it might be useful to refer to prior studies such as Déry and Yau (2001) and Grazioli et al. (2017) that have considered turbulent mixing and dry/warm air entrainment effects on blowing snow sublimation.

Thank you. These additional studies has been referenced.

32) P. 12, line 235: Did all of these studies report humidity values with respect to ice saturation or with respect to water?

Thank you for bringing up this point. Unfortunately, this information is not included in all the mentioned studies.

33) P. 13, line 240: It is unclear what the statement "and thermodynamic feedback may require unphysical saturation bounds to be enforced" means. The Déry and Yau (1999) study imposed air at saturation with respect to ice at a lower boundary condition (at the surface) in their numerical model, a valid assumption over a snowpack. Please clarify this statement and how it relates to the present results.

Thank you for bringing this to our attention. This sentence has been removed as we were largely reiterating a point made at the beginning of that paragraph.

34) P. 13, line 250: Write as "1 s".

This has been changed.

35) P. 14, lines 270-272: Again, it is unclear if this statement is accurate given it is not known if the reported relative humidities are with respect to water or to ice. In any case, it is quite possible that the Fortress Mountain Snow Laboratory site is prone to downsloping winds aligned with the valley setting, thus leading to adiabatic warming and dry air intrusions near the surface. This may not be representative of other sites however, that experience blowing snow and so the results must be interpreted with caution as they may not be generalizable to other sites.

The relative humidity is with respect to ice for temperatures below zero. It has been clarified throughout the discussion and conclusions that these are not claims about behaviour in all boundary layers, and all turbulence phenomena are local in nature. The site receives predominately upslope flows from the valley bottom during most of the blowing snow events described here.

36) P. 15, line 300: This should read "Canada Foundation".

This has been changed.

37) P. 15, line 311: Note the extra spaces in "effect".

This has been changed.

38) P. 16, line 320: Insert the article # 4679 here.

This has been added.

39) P. 16, line 340: Add the volume and page numbers for this reference.

This has been changed.

40) P. 17, line 352: Is the number in parentheses "(12)" the volume number? If so, then remove the parentheses.

This has been changed.

REVIWER 2 (Graham Sexstone)

Thank you for this thoughtful and detailed review. We have worked to address the reviewer's comments in the updated manuscript which has benefited significantly from the edits.

General comment:

1) **While this paper is generally well written, it is sometimes missing adequate detail and definition needed for the reader to adequately understand what was done. I would like to encourage the authors to go through the manuscript and provide more relevant background material and methodological details/definitions where needed. This is especially the case in the abstract section. I've outlined some areas that need more detail in my specific comments below. Although the authors have published many papers utilizing this dataset, this paper needs to be stand alone and the reader should not need to have read these previous publications in order to understand the details relevant to the current study. The length of this manuscript is rather short so expanding sections where additional detail is needed should not cause any issue.**

    Thank you for this suggestion. The manuscript has now been expanded in the results, discussions, and conclusions sections as detailed below.

Specific comments:

1) **Lines 1 - 2: Does it make more sense for the title of the paper to be "Warm-Air Entrainment and Advection during Alpine Blowing Snow Events" based on the study design?**

   That is a very good point. We have changed that.

2) **Lines 12 - 15: "Atmospheric sweep and ejection motions" should be further defined here.**

   In order to avoid technical language in the abstract, this sentence has now been changed to "To determine if specific turbulent motions are responsible for warm and dry air advection during blowing snow events, quadrant analysis and Variable Interval Time Averaging was used to investigate turbulent time series from the Fortress Mountain Snow Laboratory alpine study site in the Canadian Rockies, Alberta, Canada during the winter of 2015-2016."

3) **Lines 16 – 17: Define "event magnitude" on line 18.**

   This sentence has been changed to "A simple scaling relationship was derived that related the frequency of dominant downdraft and updraft events to their duration and local variance."

4) **Lines 19 – 20: The "recurrence model" is not well defined. Also, the use of "model modeled described" should be revised.**

   This sentence has been changed as follows: "The downdraft and updraft scaling relationship described herein provides a significant step towards a more physically based blowing snow sublimation model with more realistic mixing of atmospheric heat."

5) **Lines 20 – 22: Again, return frequencies and event durations is not well defined here.**

This phrasing has been removed.

6) **Abstract: More details about what the experiment was and where is was completed are generally needed in this section. The abstract needs to provide enough context for it to stand alone.**

Thank you for this suggestion. We have now clarified the location of the study site, what kind of data we analyzed, and which methods were used to determine our conclusions.

7) **Lines 36 – 37: This sentence needs further explained/rewritten. Are you suggesting that turbulent fluxes are calculated as a snow energy balance residual? This is not the case in most physically based snow models.**

Thank you, this has been clarified. While physically-based blowing snow models often include terms for turbulent flux contributions, the energy balance is never closed, and these residuals are typically attributed to different processes that were imperfectly calculated. The exact contribution of latent heat is poorly understood, especially in this environment, as the true blowing snow sublimation contribution is often only seen as the piece that is missing from the final balance. We have clarified our phrasing in the text as follows.

"To accurately calculate all contributions to boundary layer energy balances, latent heat flux estimates rely on an accurate sublimation model, and a precise understanding of how much energy is available for snow particle phase change."

8) **Lines 55 – 56: Further define VITA thresholds here?**

We have changed the phrasing to "VITA parameters" and included a more thorough explanation of the VITA analysis in section 2.2

9) **Lines 56 – 60: It would be helpful to more specifically call out the "Blowing snow study site" in the text here so the reader isn't confused by the other meteorological sta- tions when first referencing Fig 1. Furthermore, I suggest saying "These data are sup- plemented by observations of nearby temperature, relative humidity, and wind speeds at three additional meteorological stations within FMSL. . ."**

Thank you, these sentences have been changed as follows: "Data used to validate this model consist of field measurements of three-dimensional wind velocities and sonic temperatures during blowing snow events at the blowing snow study site in the Fortress Mountain Snow Laboratory (FMSL), Canadian Rockies (Figure 1). These data are supplemented by observations of nearby temperature, relative humidity, and wind speeds at three additional meteorological stations within FMSL. This provides a boarder environmental context in which to understand potential thermodynamic feedback mechanisms beyond the blowing snow study site scale."

10) **Lines 60 – 62: "return frequency" of what and "event magnitude" of what? Need to define these here.**

This sentence has been changed as follows: "The scaling relationship also gives a real-world context for recent numerical studies on the impacts of non-stationarity on blowing snow sublimation rates."

11) **Lines 65 - 66: Two ultrasonic sensors at which sites? Clarifying the site descriptions in the introduction will help make this clearer.**

    We have clarified that we are referring to measurements at the blowing snow study site.

12) **Lines 101 – 102: VITA and quadrant analysis thresholds are discussed here before they are introduced in the subsequent equations which is confusing upon first read.**

    This has been clarified in the text. Section 2.2 has been significantly rewritten.

13) **Lines 114 – 115: How were the ranges in the user identified thresholds in equation 1 and 2 that were tested in this study identified and defined?**

    This has been clarified in the text. Section 2.2 has been significantly rewritten.

14) Lines 116 - 118: Can you comment on the turbulent conditions that are not consid- ered as sweeps or ejections when u' and w' are of the same sign? Are those potentially important turbulent conditions that need to be evaluated and considered in subsequent studies?

This has been clarified in the text. Section 2.2 has been significantly rewritten.

14) **Lines 135 – 137; Figure 2: The colors of the y-axis scales on these plots should be revised to match the line color reflected in the figure legend (i.e. temperature y-axis scale should be blue and RH y-axis scale should be red.**

    This colouring has been corrected. Thank you.

15) **Lines 139 – 144: Consider moving this information to methods section.**

    This information is originally presented in the last paragraph of the methods section, but is reiterated here for clarity for the reader.

16) **Lines 167 – 169; Figure 4: Can you comment further on how the influence of the stabile atmospheric conditions and colder temperature near the surface may have resulted in the greater warmer deviations at the lower anemometer? These near surface temperature gradients over a snowpack are especially pronounced at night- time as compared to daytime conditions (see Figure 3 from Sexstone et al. 2016; https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.10864). Therefore, in the absence of this steep air temperature gradient (more characteristic of daytime conditions), would we expect to see such strong temperature deviations associated with sweep and ejection motions?**

Thank you for this interesting question. The sign and magnitude of the temperature deviations is directly related to the instantaneous gradient of air temperatures found during any measurement. For example, *research in daytime convective boundary layers has found relative cold air contributions down to warm surfaces during sweep events (Garai et al,). We have added the following comments in the discussion:*

"Over short timescales, there is a direct physical relationship between temperature profiles and temperature deviations during mixing events. This is physically intuitive if one considers the relative temperature change at a doorway when opening a door of a warm building to cold surroundings. Because of this dependence on instantaneous conditions during a mixing event, however, relationships between average temperature deviation magnitudes and long-term temperature gradients are much less certain. Over the nights of investigation, there is no monotonic relationship between increases in average 140 and 20 cm sonic temperature differences and average sweep event temperature deviations. For example, on March 3, 2016 there was an average temperature difference of 0.9 ℃ between anemometers, but the average downdraft (sweep) deviation was only +0.24 ℃. This is a smaller contribution than on January 21, 2016 where the air temperature difference was 0.5 ℃ and the average sweep deviation was +0.28 ℃. That is, one should exercise caution if attempting to downscale long-term statistics to represent these purely local surface processes."

17) **Lines 162 – 163: Based on their frequency, is it likely that the high resolution temperature increases associated with sweep and ejection motions could be resolved in the 15-min time-averaged data?**

    This question is unclear to the authors. The temperature deviations are measured as deviations from the 15-minute mean. Therefore, there would be no deviation if we changed the resolution of the deviations to match the mean. One would absolutely find evidence of these temperature fluctuations if looking at the 15-minute standard deviations associated with 15-minute mean data.

18) **Line 189: I didn't see further discussion of this mixing process in the discussion section according with this statement. It would be good to elaborate on this in the discussion.**

    An additional three paragraphs have been added to the discussion.

19) **Lines 243 – 244; Figure 6: Consider swapping the Ejections and Sweeps columns on this figure to be consistent with the presentation in other figures throughout the paper.**

Thank you, this has been corrected.

20) **260 – 262 – Can you elaborate here on how you expect including these scaling relationships would alter biases in existing blowing snow sublimation models? For ex- ample, if a simulation of blowing snow sublimation was completed with existing models as well as using this scaling relation for warm-air advection, how would the results change?**
21) **263 – Please elaborate on the important environmental conditions that should be/need to be represented in future studies to further develop understanding of warm and dry air advection during blowing snow events. Given the study was completed at one study site only, it cannot be generalized that the study results could be applied to all snow covered environments where blowing snow occurs. What are the limiting environ- mental conditions of the current study (e.g., blowing snow events only observed during nighttime conditions over a limited range of atmospheric stability. . .or only sweep and ejection motions where analyzed?) and how can these be overcome in future experiments.**

Thank you for the interesting questions. The following paragraphs aimed at illuminating these topics have been added to the discussion:

"Over short timescales, there is a direct physical relationship between temperature profiles and temperature deviations during mixing events. This is physically intuitive if one considers the relative temperature change at a doorway when opening a door of a warm building to cold surroundings. Because of this dependence on instantaneous conditions during a mixing event, however, relationships between average temperature deviation magnitudes and long-term temperature gradients are not guaranteed. Comparing the nights of investigation, there is no monotonic relationship between increases in average 140 and 20 cm sonic temperature differences and average sweep event temperature deviations. For example, on March 3, 2016 there was an average temperature difference of 0.9 ℃ between anemometers, but the average downdraft (sweep) deviation was only +0.24 ℃. This is a smaller contribution than on January 21, 2016 where the air temperature difference was 0.5 ℃ and the average sweep deviation was +0.28 ℃. This is likely because long-time averages oversimplify the turbulent bursting process, and why eddy-covariance methods are suggested over bulk profile approaches to turbulent fluxes [Foken, 2006].

However, the present research has suggested a simple similarity scaling of the return frequency of turbulent events of intensity k_V as identified by modified VITA analysis, through the exponential relationship of Kailas and Narasimha [1994]. Such an empirical correction is compatible with the attached-eddy hypothesis [Taylor] and other similarity-scaling models of the turbulent boundary layer if the magnitude and frequency of bursts were defined to scale up with an increase in the size of turbulent eddies away from the surface. This scaling is evident in a decrease of characteristic frequencies of turbulent events when moving from 20 cm to 140 cm measurements (Table 2, document supplement), and a natural increase in modified VITA thresholds as the magnitude of turbulence measurements increases in Eq (1) and (2) for fixed k_V and k_Q.

This view of boundary layer mixing provides a simple platform with which to model and investigate a gust-driven regeneration function of warm-dry air in the near-surface for blowing snow sublimation calculations. The inclusion of such a statistical recurrence model could provide an empirically defined quasi-periodic source of warm and dry air to blowing snow simulations. For example, this could be included in conservation of heat equations as a natural evolution of the constant entrainment and advection functions introduced by Bintanja [2001]. In this way, it is possible to represent the mixing of distinct parcels of air of different temperatures through commonly studied turbulent structures. Such a recurrence model would be computationally efficient and a significant step towards a physically based blowing snow sublimation model.

Future high temporal resolution studies of blowing snow particles, air temperature and water vapour during sustained periods of above-snow-transport-threshold wind speeds would greatly benefit the research community. Short timescale thermodynamic feedbacks to humidity from sublimation could come from similar high frequency coupling analysis with closed path hygrometers or gas analyzers at multiple heights during blowing snow events. Fast response particle detectors could give further insight into relationships between atmospheric and particle motions. This would allow a more complete understanding of the advection-thermodynamic feedback balance during blowing snowstorms and advance the seminal profile studies of Schmidt [1982]. As advection processes are local by nature [e.g. Harder et al., 2016], characteristic frequencies of turbulent events will vary with location and atmospheric conditions. The small range of values of N_0 measured at this site during five months of this campaign suggests common flow phenomena will possibly dominate and aid in more universal applications of entrainment modeling, at least within specific seasons."

In the conclusions, we have also suggested a longitudinal study would be greatly beneficial for understanding the variance in parameters necessary for this simple bursting model.

23) Line 269: Conclusions section should be numbered section 5.

Corrected. Thank you.

24) Lines 270 – 272: Leading the conclusions section with a sentence about saturation of water vapor during blowing snow events doesn't really fit with the scope of this paper since it was not a measurement directly made at the blowing snow site and only observed at auxiliary meteorological stations.

Thank you. This has been moved to another section of the conclusions.

Garai, A., and J. Kleissl (2011), Air and Surface Temperature Coupling in the Convective Atmospheric Boundary Layer, *J. Atmos. Sci.*, *68*(12), 2945–2954, doi:10.1175/JAS-D-11-057.1.

Warm Air Entrainment and Advection during Alpine Blowing Snow Events

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Abstract. Blowing snow transport has considerable impact on the hydrological cycle in alpine regions both through the redistribution of the seasonal snowpack and through sublimation back into the atmosphere. Alpine energy and mass balances are typically modelled with time-averaged approximations of sensible and latent heat fluxes. This oversimplifies non-stationary turbulent mixing in complex terrain and may overlook important exchange processes for hydrometeorological prediction. To determine if specific turbulent motions are responsible for warm and dry air advection during blowing snow events, quadrant analysis and Variable Interval Time Averaging was used to investigate turbulent time series from the Fortress Mountain Snow Laboratory alpine study site in the Canadian Rockies, Alberta, Canada during the winter of 2015-2016. By analyzing wind velocity and sonic temperature time series with concurrent blowing snow, such turbulent motions were found to supply substantial sensible heat to near surface wind flows. These motions were responsible for temperature fluctuations of up to 1°C, a considerable change for energy balance estimation. A simple scaling relationship was derived that related the frequency of dominant downdraft and updraft events to their duration and local variance. This allows the first parameterization of entrained or advected energy for time-averaged representations of blowing snow sublimation and suggests that advection can strongly reduce thermodynamic feedbacks between blowing snow sublimation and the near-surface atmosphere. The downdraft and updraft scaling relationship described herein provides a significant step towards a more physically-based blowing snow sublimation model with more realistic mixing of atmospheric heat. Additionally, calculations of return frequencies and event durations provide a field-measurement context for recent findings of non-stationarity impacts on sublimation rates.

1 Introduction

At least 40% of the world's population relies on the seasonal snowpack as a temporary reservoir of winter snowfall that then provides meltwater in spring and summer for downstream water use [Meehl et al., 2007]. However, after snow has fallen, it is often subjected to sublimation while at rest or amplified in-transit sublimation during redistribution. Blowing snow redistribution can result in vast amounts of frozen water moving between basins or, in the case of sublimation, being removed entirely from the surface water budget in wind swept regions. Blowing snow particles are highly susceptible to sublimation because of their high curvature, large surface area to mass ratio, and high ventilation rates [Dyunin, 1959; Schmidt, 1982].

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While estimates may vary with climate, in the Canadian Rockies, blowing snow transport has been found to be responsible for sublimating up to 20% of the yearly snowfall [MacDonald et al., 2010].

Snow sublimation is typically studied at large temporal and spatial scales within hydrometeorological modeling frameworks because of the complexity of the processes and the difficulty of particle transport tracking [e.g. Pomeroy et al., 1993; Pomeroy and Essery, 1999; Déry and Yau, 2002; Lenaerts et al., 2012; Groot Zwaaftink et al. 2013; Musselman et al., 2015]. To accurately calculate all contributions to boundary layer energy balances, latent heat flux estimates rely on an accurate sublimation model, and a precise understanding of how much energy is available for snow particle phase change. While latent and sensible heat exchanges between the turbulent atmosphere and snow particles can be represented by a system of coupled partial differential equations, they require forcing terms for dry-air entrainment and horizontal advection that are still poorly understood and have not been based on observed physical mechanisms, if they are included at all [Bintanja, 2001]. The decrease in temperature and increase in humidity in the atmosphere caused by snow sublimation may play a crucial limiting role in snow sublimation, but many blowing snow models struggle to capture the process of this feedback, which can result in unrealistic atmospheric conditions in near-surface boundary layers and subsequent errors in calculations of the blowing snow sublimation rate [Pomeroy and Li, 2000, Dery and Yau, 1999, 2001; Groot Zwaaftink et al. 2013; Musselman et al, 2015]. Numerical investigations of snow sublimation from a numerical modeling approach have recently provided new insights into non-steady state aspects of sublimation [Dai and Huang, 2014; Li et al., 2017; Sharma et al., 2018] and the efficacy of the nearly-universally used Thorpe and Mason [1966] model [see Schmidt, 1972] at high temporal and spatial resolution [Sharma et al., 2018]. Extending non-stationary sublimation models to alpine and other complex terrain environments could lead to reduced uncertainty in blowing snow sublimation models. Little research has been conducted to better understand the energy available for snow sublimation from entrainment or advection processes in natural atmospheric turbulence or the influence that resultant air temperature fluctuations may exert on sublimation rates. Recently, Grazioli et al. [2017] found that over long timescales, persistent katabatic winds in Antarctica provide a consistent supply of unsaturated air that can contribute to significant snow sublimation. In East Antarctica, they calculated up to 35% of total yearly snowfall can be lost in this manner.

The objective of this research is to investigate turbulent structures down to sub-second timescales and identify their synchronization with near-surface temperature fluctuations. The study investigates the unsteady processes affecting blowing snow particle energy balances to better understand the form of advection and entrainment correction terms for sublimation calculations. To this end, a scaling relationship previously applied to near-neutral atmospheric surface layer data is tested to represent turbulent event frequency as a function of Variable Interval Time Averaging (VITA) parameters. Data used to validate this model consist of field measurements of three-dimensional wind velocities and sonic temperatures during blowing snow events at the blowing snow study site in the Fortress Mountain Snow Laboratory (FMSL), Canadian Rockies (Figure 1). These data are supplemented by observations of nearby temperature, relative humidity, and wind speeds at three additional meteorological stations within FMSL. This provides a broader environmental context in which to understand potential thermodynamic feedback mechanisms beyond the blowing snow study site scale. The scaling relationship also gives a real-world context for recent numerical studies on the impacts of non-stationarity on blowing snow sublimation rates.

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2 Methods

2.1 Field Data

Fortress Mountain Snow Laboratory (FMSL) is located in the Kananaskis Valley in the Canadian Rockies of southwestern Alberta, Canada. FMSL is surrounded by very complex terrain, with multiple nearby 2900m peaks having >100m vertical rock faces. The blowing snow study site is situated on a plateau at 2000m at the base of a closed ski resort, providing ample upwind fetch with minimal obstruction from trees or buildings (Figure 1 inset). Winter air temperatures at the FMSL blowing snow site typically range from -20° to +5°C, with frequent midwinter downslope chinook (föhn) wind events. Snow depth at the blowing snow site remains fairly constant through the midwinter at approximately 1 m, with fresh snowfall frequently redistributed by wind events.

Ultrasonic temperature and wind velocity time series were observed at the FMSL blowing snow study site using two Campbell Scientific CSAT3 sonic anemometers sampling at 50 Hz from November 2015 to March 2016. The anemometers were positioned on the same mast at heights above the snow surface varying over 0.1-0.4 m and 1.4-1.7 m with snow surface accumulation or erosion. These anemometers will be referred to as the 20cm and 150cm anemometers throughout the remaining text. Extensive analysis of this dataset has already provided new insights into the turbulent mechanisms for blowing snow transport [Aksamit and Pomeroy, 2016, 2017, 2018]. The turbulent structures scrutinized here have previously been coupled with Particle Tracking Velocimetry (PTV) and high-speed video analysis of Aksamit and Pomeroy [2017, 2018] to better understand the wind-snow coupling. For each night (20 Nov, 4 Dec, 2015 and 3 Feb, 3 Mar 2016), the time series spanning the entire duration of blowing snow video recording (from 18:00 local time to the end of video collection, approximately 23:59) was divided into 15-minute intervals and analyzed. One additional night of meteorological data was analyzed to compare energy transport mechanisms under much windier conditions, even though PTV analysis was not available. This additional night, January 21, 2016 had much stronger winds, gusting up to 15 m s^{-1} because of the presence of a chinook event. In this valley, these events have been previously associated with high blowing snow sublimation rates [MacDonald et al., 2018]. The mean temperatures varied from -7°C during the previous three days to +3°C during the night of Jan 21. This resulted in a much larger difference between air and snow surface temperatures, and provided an interesting comparison of conditions that are critical for snow sublimation at short timescales [Sharma et al., 2018].

Three other FMSL stations near to the blowing snow measurement site provide complementary 15-minute relative humidity (with respect to ice), air temperature and wind speed measurements (Figure 1). As relative humidity measurements were not available at the blowing snow study site during the 2015-2016 study season, these additional stations provided downwind test sites for evidence of the occurrence of large-scale thermodynamic feedbacks. The nearest complementary site is a sheltered forest (Powerline) station approximately 400 m away and 30 m higher in elevation [Smith et al., 2017]. Additionally, there are two exposed sites, including a ridgetop (Canadian Ridge) and lee side of ridge (Canadian Ridge North) that are both approximately 600 m downwind and 200 m higher in elevation. The Powerline station receives much less wind than the exposed sites or blowing snow site and is much less susceptible to snow redistribution. Temperature and relative humidity

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from a previous study spanning January to March 2015 at the blowing snow study site showed a good correlation with the three nearby sites over a sample of 3,700 15-minute averages. R^2 values for air temperature between the blowing snow site and Canadian Ridge, Canadian Ridge North, and Powerline were 0.82, 0.83, and 0.97, respectively, and were 0.61, 0.62, and 0.80, for relative humidity, respectively. All correlation coefficients were statistically significant at 99.99%. Meteorological variables at the blowing snow study site can be found in Table 1. The Monin-Obukhov stability parameter, ζ, was calculated following Monin [1970] and Stull [1988] such that

$$\zeta = \frac{z}{L},$$

$$L = -\frac{u_*^3 \theta_0}{\kappa g \overline{w'\theta'}}$$

where θ_0 is the potential temperature at the 20 cm anemometer, and $u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$. We use the sonic temperature in lieu of potential temperature as suggested by Stull [1988] as there were no atmospheric pressure measurements at the study site. Turbulence intensity was calculated as

$$I = \frac{\overline{u'^2 + v'^2 + w'^2}}{(\overline{u}^2 + \overline{v}^2 + \overline{w}^2)^{1/2}}.$$

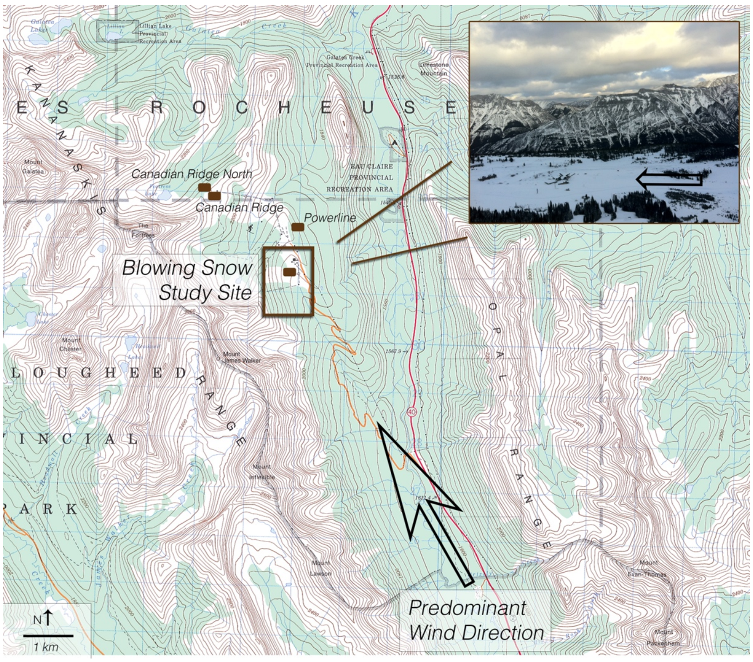

Figure 1: Overview of blowing snow study site and adjacent micrometeorological stations at the Fortress Mountain Snow Laboratory in the Kananaskis Valley, Alberta, Canada. The prominent down-valley wind direction is noted on the map and on the site photo inset. Topographic map produced by the Canada Centre for Mapping, Natural Resources Canada, © Her Majesty The Queen in Right of Canada.

Date	140 cm Wind Speed (m s^{-1})	Monin-Obukhov (non-dim)	Air Temp 20cm, 140 cm (°C)	Snow Surface Temp (°C)	Turb. Intensity range (%)
Nov 20, 2015	3.8 (1.7)	0.06 (0.07)	-10.4 (1.06), -9.7 (0.9)	-11*	93.3 (45.0)
Dec 4, 2015	4.1 (1.8)	4.6e-4 (1.7e-4)	-4.2 (0.4), -3.9 (0.4)	-4	72.7 (31.8)
Jan 21, 2016	5.5 (2.2)	6.4e-4 (2.4e-4)	2.1 (0.7), 2.6 (0.7)	-2*	66.8 (36.6)
Feb 3, 2016	3.5 (1.7)	0.02 (0.02)	-10.3 (0.5), -9.9 (0.6)	-10	66.6 (26.6)
Mar 3, 2016	3.4 (1.7)	4.0e-3 (3.1e-3)	-3.2 (0.9), -2.3 (0.7)	-5	94.8 (57.9)

Table 1: Meteorological Variables for Five Nights of Observations. *Snow surface temperature taken from the nearby Powerline meteorological station.

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2.2 Modified VITA Analysis

Variable Interval Time Averaging (VITA) is a method of timeseries analysis that identifies significant turbulent events as periods of high local variance. For a given timeseries $f(t)$, the VITA method selects times such that

$$\hat{f}(t,T) = \frac{1}{T}\int_{t-T/2}^{t+T/2} f(t)^2 dt - \left[\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} f(t)dt\right]^2 > k_V\, \overline{f^2}, \qquad (1)$$

where T is a statistically or experimentally determined averaging time, k_V is a user-defined VITA threshold, and the overbar indicates a spatial or temporal average. For the analysis conducted here, as in a previous blowing snow investigation at this site [Aksamit and Pomeroy 2017], $f(t)$ is taken to be the instantaneous Reynolds stress $\tau(t) = -\rho_{air}u'(t)w'(t)$, where u' and w' are the instantaneous fluctuations around 15-minute averages of streamwise and vertical velocities. Eq (1) needs two user-defined parameters, the temporal neighborhood T and the magnitude threshold k_v. To increase objectivity, and connect our turbulent events to extensively-studied and physical turbulent structures, a modified VITA analysis used here also includes a quadrant hole analysis criterion [Lu and Willmarth, 1973; Morrison et al., 1989]. Subsequent to finding a time meeting the conditions defined by Eq 1, we then identify the neighborhood surrounding that time where τ also exceeds a given threshold, k_Q, often called the "quadrant hole" value:

$$|\tau(t)| \geq k_Q\rho_{air}\sqrt{\overline{u'^2} + \overline{w'^2}}. \qquad (2)$$

The modified VITA analysis was conducted over a range of thresholds ($0.01 \leq k_V \leq 0.05, 0.05 \leq k_Q \leq 4$) and averaging times ($0.5 \leq T \leq 40$ s) found in the boundary layer and sediment transport literature [Morrison et al. 1989; Narasimha and Kailas 1987, 1990; Bauer et al. 1998; Sterk et al. 1998; Wiggs and Weaver 2012]. This provides a relatively robust gust identification scheme that delimits significant turbulent events of varying duration and velocity magnitude. The subsequent analysis focuses on sweeps ($u' > 0, w' < 0$) and ejections ($u' < 0, w' > 0$) as they disproportionately contribute to the total surface Reynolds stress, are frequently used in models of turbulent boundary layer structures, have been identified to play crucial roles in boundary layer heat flux and aeolian transport [e.g. Bauer et al., 1998; Adrian et al., 2000; Garai and Kleissel, 2011; Aksamit and Pomeroy, 2017]. Please refer to Wallace [2016] for a recent review of the theory and experiments surrounding quadrant analysis and sweep-ejection cycling. The modified VITA algorithm categorized a turbulent event as a sweep or ejection if the parameterized curve $s(t) = \langle u'(t), w'(t)\rangle$ passes through only one of the two quadrants during the event (Q2 for ejections and Q4 for sweeps).

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In this study, the concurrent sonic temperature signal response was also measured and the fluctuation from the 15-minute mean air temperature was computed to identify the presence of relatively warmer or colder air during a particular event with respect to mean conditions. For the air temperatures during this study, CSAT3 anemometers have an error of less than ±0.002°C, which is considered negligible [Campbell Scientific, 2018]. Following Kailas and Narasimha [1994], events detected with larger thresholds are referred to as "stronger" or "more intense."

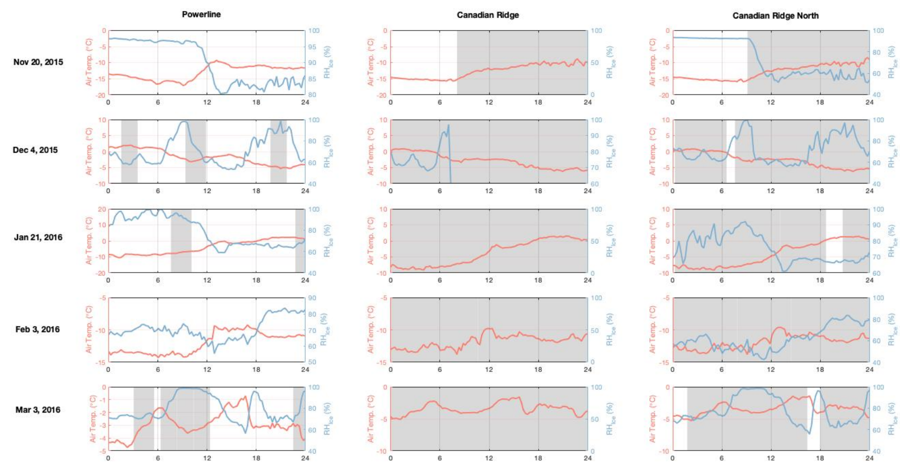

Figure 2: 15-minute average temperature and relative humidity measurements at approximately 2 m above the snow surface during the five nights of investigation at three nearby micrometeorological stations. Flagged data have been removed from the time series and presented as gaps. Shaded gray areas are times when concurrent average wind speeds were above 3 m s^{-1}. Note the correlation between sites for both variables, and the varying y-axes between plots.

3 Results

3.1 Modified VITA Results

During each blowing snow storm, there was no definitive evidence of humidity saturation or thermodynamic feedback at two of the three nearby weather stations (Figure 2). Unfortunately, RH data were unusable at the Canadian Ridge site for four of the five nights. Increases in RH were typically coupled with decreases in air temperature, and were transient in nature. The complex topography and enhanced turbulent mixing at FMSL may be responsible for this as indicated by the modified VITA analysis below. Indeed, though all three sites are situated in close proximity to each other, there is limited correlation for meteorological variables between all three, suggesting incredibly complex wind flow and energy fluxes in this alpine zone.

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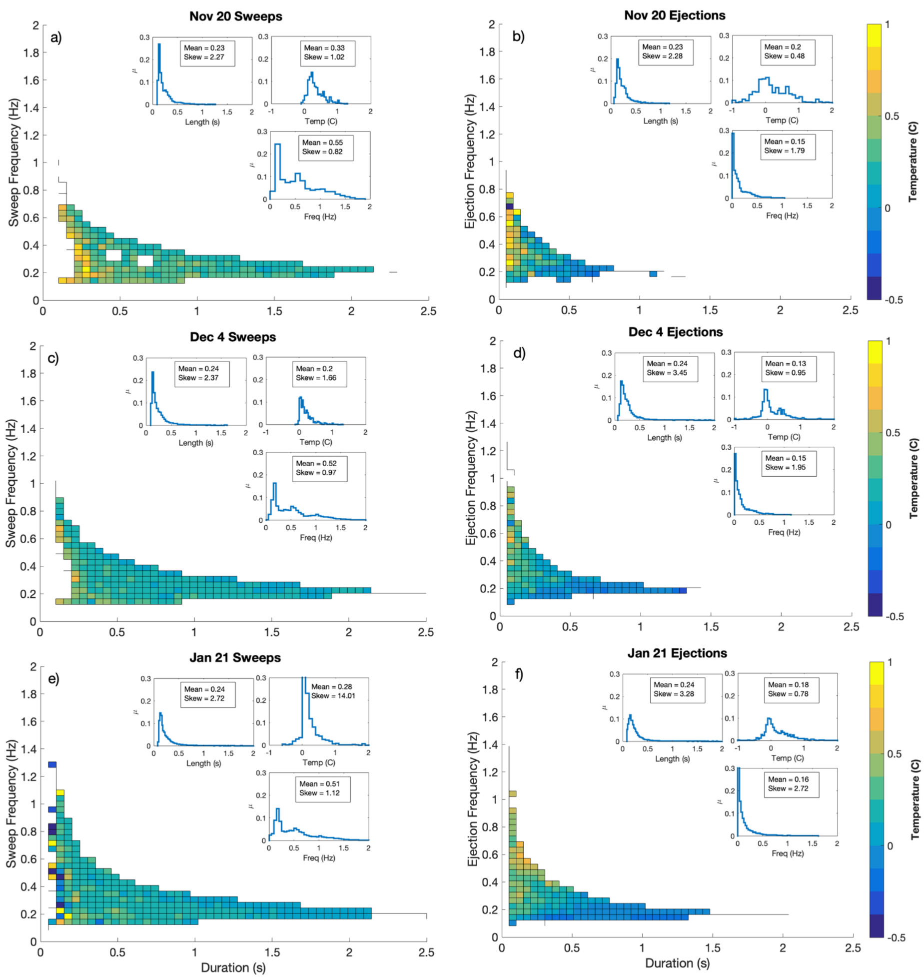

Figure 3: Bin-averaged temperature fluctuations of near surface anemometer from the 15-minute mean for events of specific return frequency and event duration for recordings over each blowing snow storm. Insets are plots of probability distribution functions of event duration, temperature deviation and event frequency for each storm and type of event.

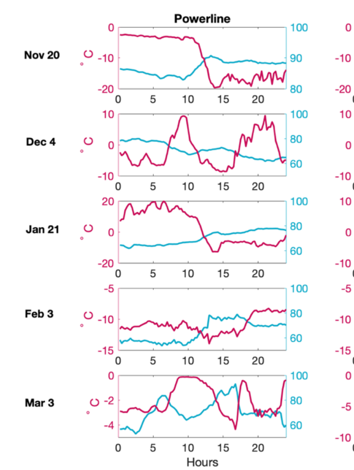

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Figure 2: Temperature and relative humidity measurements during the five nights of investigation at three nearby micrometeorological stations. Flagged data has been removed from the time series and presented as gaps. Note the limited correlation between sites for both variables.

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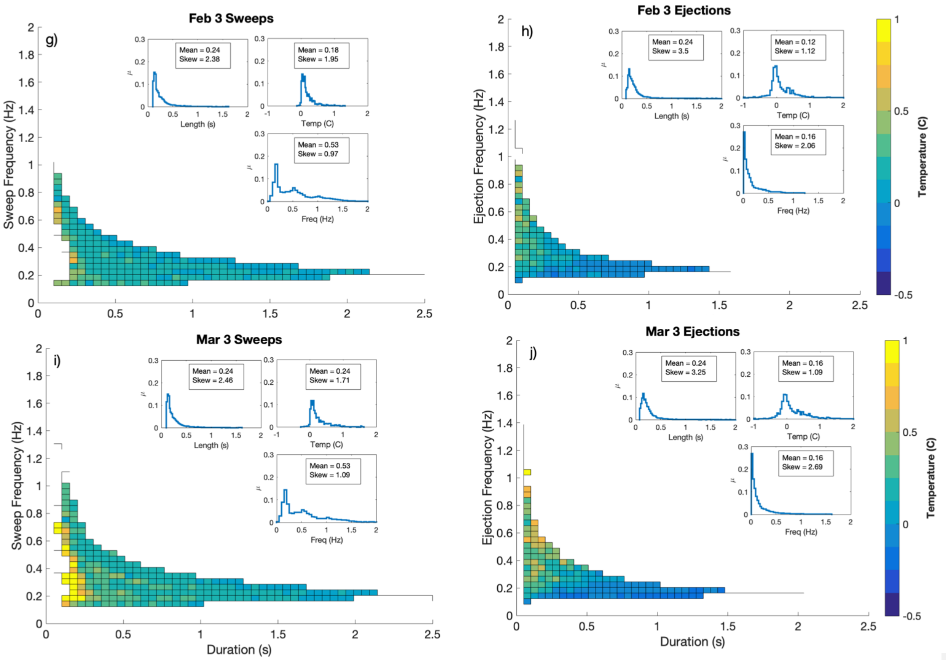

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For each VITA-identified event, instantaneous temperature deviations from the 15-minute mean were computed to represent the magnitude and sign of turbulent temperature mixing with respect to slower meteorological changes over the nights. Aksamit and Pomeroy [2017] noted that there is no objective choice of averaging time or event threshold for the modified VITA analysis. As such, sonic temperatures during active turbulent events were examined over a variety of thresholds to determine a range of behaviour. The recurrence frequencies and average durations of sweep and ejection events for each threshold combination illustrated the average prevalence of sweep or ejection motions. Further sensitivity analysis of the impact of VITA parameters on wind-snow coupling has been conducted by Aksamit and Pomeroy [2017].

For each blowing snow storm, 3D point-clouds of mean recurrence frequency, event duration and event temperature deviation were calculated for the 20 cm sonic anemometer. Each point represents the values from one choice of averaging time and modified VITA thresholds for a 15-minute observation period as discussed in Section 2.2. The 3D plots contain significant overlap, so for clarity, the mean temperature deviations were averaged over small ranges of event duration and frequency, as

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shown in Figure 3. Inset in each subplot are three probability distributions computed from the original point-clouds for each blowing snow storm: distributions of temperature deviation, event duration, and event frequency. Mean and skewness values are noted next to each distribution.

The analysis revealed for the four non-chinook blowing snow storms (Nov 20, 2015; Dec 4, 2015; Feb 3, 2016; Mar 3, 2016) that sweeps consistently brought warmer air to the near-surface anemometer. This can be seen as the coloured temperature plots show average temperature deviations greater than zero for nearly all event duration and frequencies over each storm. Probability distributions show very few sweep events with negative temperature deviations, as well as a consistent positive mean and skewness. The chinook storm on January 21, 2016 had a positive mean and skewness, but exhibited short cold air bursts as well. Mean temperatures for sweeps were warmer than ejections for all blowing snow storms.

Moved up [1]: **Figure 3: Bin-averaged temperature fluctuations of near surface anemometer from the 15-minute mean for events of specific return frequency and event duration for recordings over each blowing snow storm. Insets are plots of probability distribution functions of event duration, temperature deviation and event frequency for each storm and type of event.**

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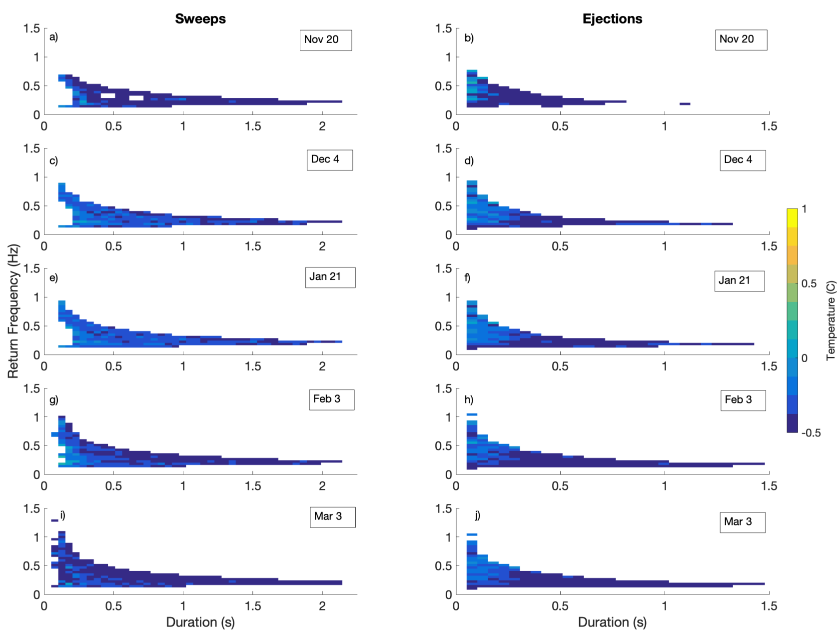

Figure 4: The same measurements as shown in Figure 3, now subtracting the upper (140 cm above the surface) anemometer mean from the near-surface (20 cm) sweep and ejection temperatures for various blowing snow storms. Note the predominantly colder fluctuations.

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Modified VITA analysis on the 140 cm anemometer wind and temperature time series showed similar results. Interestingly, analysis comparing 20 cm anemometer event temperatures to the 140 cm anemometer means revealed near-surface sweeps often occur with colder signatures than the nearby 140 cm anemometer means (Figure 4). This is in contrast to what was found relative to surface temperatures. As these measurements were all made during the night and over a continuous snowcover with a slightly-stable temperature profile, this indicates relatively warm upper-air mixing with cold near-surface air that resulted in a mixed temperature value between the two anemometer means. For example, blocks on the left side of Figure 3i show a group of sweeps that were 1°C warmer than the mean temperature of the 20 cm anemometer (bright yellow), but in Figure 4i, the same group of sweeps were 0.5°C colder than the 140 cm anemometer mean (dark blue). Color scales are equivalent in Figures 3 and 4. This effect is further supported by the mean anemometer temperatures detailed in Table 1.

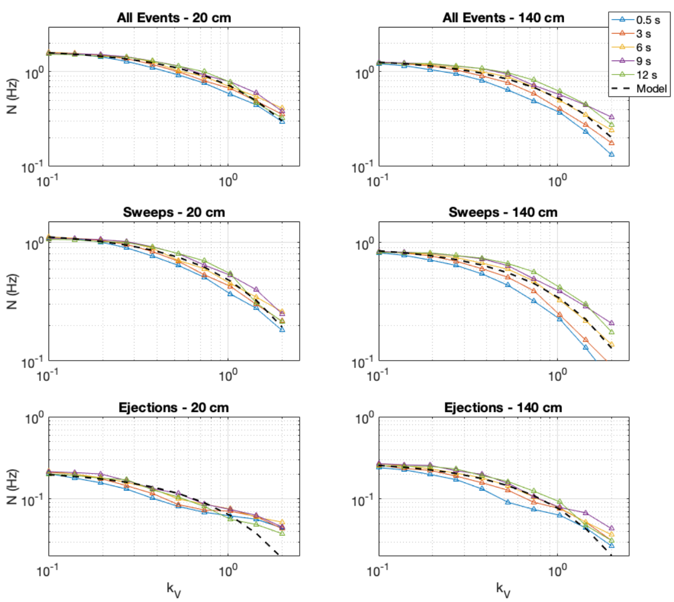

Figure 5: Example of variation of event frequency (N) over VITA thresholds (k_V) for different averaging times ($0.5 < T < 12$ s) at $k_Q = 1$ for one 15-minute study period on December 4. Least-squares fitted Eq. 1 curves are overlaid as dashed line for each collection of events: All modified VITA events, sweeps, and ejections as identified at the 20 cm (low) or 140 cm (high) anemometers.

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Ejections present a less clear story but also appear very effective for surface layer mixing. Depending on the intensity of the events detected, ejections could be either warmer or colder than the 20 cm anemometer mean (Figure 3). Over all blowing snow storms, ejection temperatures had a lower mean and were less positively skewed. This can be explained by their physical definition of moving air vertically away from the cold snow surface. During periods of greater atmospheric stability (November 20 and March 3) there was more variability in the temperature contributions from ejections. This may indicate stable layers of varying strength were able to form and cause less uniform mixing near the snow surface. When Monin-Obukhov coefficients were closer to zero (Table 1), indicating more neutral conditions, there was less variability in ejection temperatures, indicating a smaller range of temperatures during ejection induced mixing. This can be seen by a comparison of Table 1 values and Figs 3 and 4 probability insets. This mixing process is discussed in more detail in Section 4.

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Over all nights, sweeps were of longer duration than ejections and had a higher frequency of occurrence. The probability curves in Figure 3 show a second sweep return frequency peak around 0.5 Hz for all nights. This is not present in the ejection frequency probabilities, which only has a single low frequency peak. These sweep and ejection motions have not been connected to a specific flow topology in these experiments (e.g. a hairpin bursting process) due to the complexity of the flow in this complex terrain. It very well may be the case that the sweep signatures are caused by both outer-layer and inner-layer motions as previously suggested by Aksamit and Pomeroy [2017]. The ejections occur less often because of the rarity of large positive w' values close to the snow surface, and are thus present only during a less common generating mechanism.

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3.2 Scaling Relation

Though several differences in the datasets exist, the near-neutral and slightly-stable conditions found during the blowing snow storms sampled suggest a Kailas and Narasimha [1994] scaling relationship may exist:

$$N = N_0 e^{-\alpha(k_V-1)}. \quad \textbf{(3)}$$

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Here, N is the recurrence frequency of a given modified VITA turbulence event type, N_0 and α are fitting parameters with N_0 known as the characteristic frequency. This scaling analysis focused on the case where $k_Q = 1$ as this resulted in a good compromise between too many and too few events detected and is a standard value previously used for turbulent motion identification at this site [Aksamit and Pomeroy, 2017]. Though the present modified VITA analysis involves an additional step in the identification algorithm as compared to the original work of Kailas and Narasimha [1994], a similar invariance (small standard deviation) in the log of the return frequency, $log(N)$, was present over varying averaging times T for each VITA threshold k_V. This resulted in a good fit of Eq. 1 for the return frequencies of the total number of modified VITA events, as well as for sweeps and ejections individually. One example of this fitting for one 15-minute period on December 4 is shown in Figure 5. The squared ℓ^2-norm of the residuals for each minimized least-squares fit are presented in the document supplement, as are the characteristic frequencies, N_0.

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Anemometer Height	All Events	Sweeps	Ejections
20 cm	0.80 (0.08)	0.49 (0.04)	0.1 (0.03)
140 cm	0.54 (0.03)	0.35 (0.01)	0.09 (0.02)

Table 2: Mean characteristic frequencies N_0 for turbulent events at both blowing snow site anemometers. The standard deviation of nightly means is shown in parentheses and indicates minimal changes between nights.

Total mean values (and standard deviations between nightly means) of N_0 are detailed in Table 2, for all turbulent events, only sweeps, and only ejections at both 20 cm and 140 cm anemometers. There was little variation of N_0 between nights of observation as seen in the relatively small standard deviation values. This suggests persistent flow features at this site from one night to the next that may be due to a persistent topographically induced flow feature or turbulence generating mechanism at the study site. As could be expected from the analysis presented in Figure 3, the characteristic return frequencies (N_0) of all turbulent events and for sweep events were greater than those for ejections. Of particular interest in this scaling relationship is a clear difference between N_0 for the 140 cm and 20 cm anemometer observations for both total events and solely sweep events. Over all nights, the characteristic frequency for total events was lower at the 140 cm anemometer, which corresponded with a drop in the number of sweeps, whereas the characteristic frequency of ejections was nearly identical at both heights. The threshold criteria in Eq. (1) and (2) varies for measurement location and time, scaling by mean values calculated over each observation period at each anemometer. This implies that there were fewer relatively-large sweeps away from the surface, and a possible shift in turbulent structure dynamics. As well, this supports the suggestion in Section 3.1 that the mechanisms generating sweeps and ejections may be different, with less common flow features resulting in the ejections.

4 Discussion

The same strong sweep events that have been previously found to be highly relevant for blowing snow initiation and transport at this site [Aksamit and Pomeroy, 2017], are also responsible for advecting warmer-than-average air to the near-surface layer. This is a critical insight for blowing snow sublimation modeling as the periods with greater than average blowing snow transport coincide with the presence of warmer than average air (sweeps).

Previous theoretical work has concluded that suppression of sublimation of surface and blowing snow may occur if moisture fluxes near the surface are counterbalanced solely by diffusion [Bintanja, 2001]. Dover and Mobbs [1993], Dery and Taylor [1996], Dery and Yau [1999, 2001], Groot Zwaaftink et al. [2013] and others have suggested that blowing snow sublimation could be a self-limiting process when thermodynamic feedbacks are included in a steady-state boundary layer model. However, these models did not account for warm- or dry-air entrainment, nor the temporal correlation of transport bursts with warm-air entrainment. This missing forcing term may explain the lack of evidence of saturation in blowing snow field studies in the steppes of Russia, high plains of Wyoming (USA), prairies of Saskatchewan, alpine mountains of Alberta and arctic tundra of

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the Northwest Territories (Canada), and East Antarctica [e.g. Dyunin, 1959; Schmidt, 1982; Pomeroy and Li, 2000; Musselman et al., 2015; and Grazioli et al., 2017]. The evidence of frequent regeneration of warm air near the surface through advection or entrainment processes helps explain the discrepancy with diffusion-dependent models.

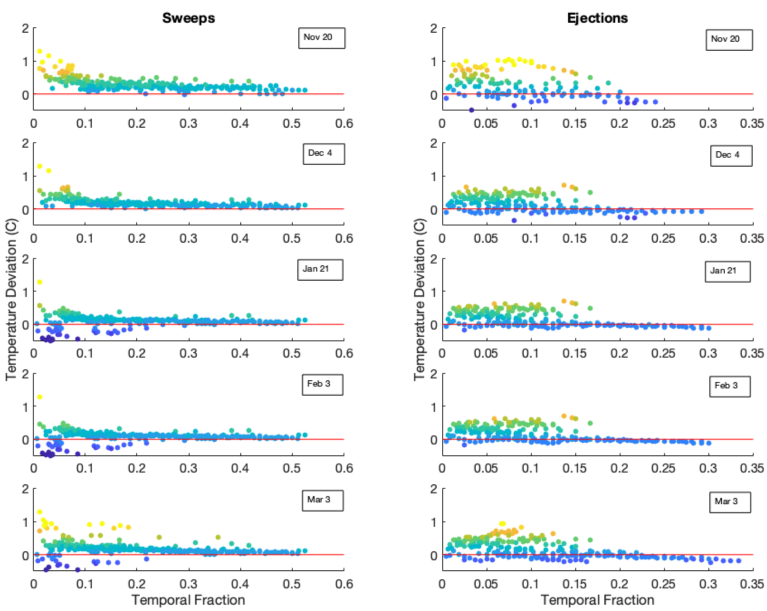

Figure 6: Fraction of time series occupied by sweep and ejection events of specific temperatures at the 20 cm anemometer. Refiguring of data in Figure 3 with same color scale. Colors here also correspond to y-axis values.

Recent model simulations by Sharma et al. [2018] and Dai and Huang [2014] have shed light on the importance of temperature and wind speed fluctuations at the timescales of the sweep and ejection processes highlighted here. The comparison of the Sharma et al. [2018] large-eddy-simulation-driven sublimation model with the widely used steady-state model of Thorpe and Mason [1966] revealed that transient sublimation rates approached the steady-state model only after time periods ranging from 10^{-2} to 10 s, depending on particle diameter and ventilation rates. At the velocities and particle sizes typical for the present study, their time to model relaxation was around 1 s. Furthermore, Dai and Huang [2014] found transient rates of sublimation in the saltation layer that reached steady-state only after 0.5-2 s. These modeled relaxation times are precisely in the range of

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turbulent warming and cooling events show in Figure 3. Figure 6 redisplays the data from Figure 3 with the temporal fraction of modified VITA events calculated as the product of average event duration and frequency. For each night, one can find strong ejection events contributing air temperatures 1°C warmer than the mean for 15% of the time, and warm sweeps for up to 20% of the time.

In addition to the timescale considerations and transient regimes in blowing snow sublimation calculations, Sharma et al. [2018] found temperature fluctuations of 1°C can affect instantaneous sublimation rates by as much as 100%. Given that gusts causing temperature fluctuations of this order occur up to 35% of the time, this advected energy warrants further investigation and inclusion in future models. Fortunately, a parameterization for mechanically-explained advected energy may be possible through the simple exponential scaling relationships of Kailas and Narasimha [1994].

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Over short timescales, there is a direct physical relationship between temperature profiles and temperature deviations during mixing events. This is physically intuitive if one considers the relative temperature change at a doorway when opening a door of a warm building to cold surroundings. Because of this dependence on instantaneous conditions during a mixing event, however, relationships between average temperature deviation magnitudes and long-term temperature gradients are not guaranteed. Comparing the nights of investigation, there is no monotonic relationship between increases in the average 140 cm and 20 cm sonic temperature differences and average sweep event temperature deviations. For example, on March 3, 2016 there was an average temperature difference of 0.9°C between anemometers, but the average downdraft (sweep) deviation was only +0.24°C. This is a smaller contribution than on January 21, 2016 where the air temperature difference was 0.5°C and the average sweep deviation was +0.28°C. This is almost certainly because long-time averages oversimplify the turbulent bursting process, and why eddy-covariance methods are suggested over bulk profile calculations of turbulent fluxes [Foken, 2006].

The present research has, however, suggested a simple similarity scaling of the return frequency of turbulent events of intensity k_V as identified by modified VITA analysis, through the exponential relationship of Kailas and Narasimha [1994]. Such an empirical correction is compatible with the attached-eddy hypothesis [Townsend, 1976; Marusic and Monty, 2019] and other similarity-scaling models of the turbulent boundary layer if the magnitude and frequency of bursts were to be defined to scale accordingly with an increase in the size of turbulent eddies away from the surface. This scaling is evident in a decrease of characteristic frequencies of turbulent events when moving from 20 cm to 140 cm measurements (Table 2, document supplement), and a natural increase in modified VITA thresholds as the magnitude of turbulence measurements increases in Eq (1) and (2) for fixed k_V and k_Q.

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This view of boundary layer mixing provides a simple platform with which to model and investigate a gust-driven regeneration function of warm-dry air in the near-surface for blowing snow sublimation calculations. The inclusion of such a statistical recurrence model could provide an empirically defined quasi-periodic source of warm and dry air to blowing snow simulations. For example, this could be included in conservation of heat equations as a natural evolution of the constant entrainment and advection functions introduced by Bintanja [2001]. In this way, it is possible to represent the mixing of distinct parcels of air

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of different temperatures through commonly studied turbulent structures. Such a recurrence model would be computationally efficient and a significant step towards a physically-based blowing snow sublimation model.

Future high temporal resolution studies of air temperature and water vapour during sustained periods of above-snow-transport-threshold wind speeds would greatly benefit the research community. Short timescale thermodynamic feedbacks to humidity from sublimation could come from similar high frequency coupling analysis with closed path hygrometers or gas analyzers at multiple heights during blowing snow events. This would allow a more complete understanding of the advection-thermodynamic feedback balance during blowing snow storms and advance the seminal profile studies of Schmidt [1982]. As advection processes are local by nature [e.g. Harder et al., 2016], characteristic frequencies of turbulent events will vary with location and current atmospheric conditions. The small range of values of N_0 measured at this site during five months of this campaign suggests common flow phenomena will possibly dominate and aid in more universal applications of entrainment modeling, at least within specific seasons.

5 Conclusion

During an alpine blowing snow field campaign, analysis of turbulence timeseries and sonic temperatures indicate that exceptional warm air entrainment and advection events can be associated with specific turbulent structures. Over 5 nights of investigation sweeps brought relatively warm air to the snow surface, up to 1°C warmer than average near-surface temperatures. These parcels of air may also be relatively cold compared to temperatures measured only 1.2 m above, further adding to the complexity of the physics of blowing snow sublimation. Ejections also result in strong but less consistent temperature mixing. The current lack of understanding of advection or entrainment during snow transport may explain why the thermodynamic feedback parameterizations necessary in many blowing snow sublimation models are unphysical. In fact, field measurements of atmospheric conditions during these blowing snow events showed no evidence of significant sublimation feedbacks, let alone saturation of relative humidity. An enhanced influence of mechanical mixing in boundary layers with inhomogeneous temperature distributions, for example where there is topographically induced cold-air pooling or flow separation, may explain why sublimation rate observations and estimates can be high and can vary from study to study. The present research indicates that including a supply of warm and dry air from different near-surface regions of the flow is a physically-accurate modeling assumption. A better representation of turbulent mixing in these regions is likely necessary for the improvement of sublimation rate estimates.

At present, further investigation of the connection of blowing snow sublimation to specific atmospheric structures would be beneficial. Specifically, vertical profiles of high frequency temperature and humidity measurements are necessary to illuminate the impact of penetrating low frequency gusts on warm, dry-air regeneration at the surface during blowing snow sublimation in different environments. This analysis would require a closed-path style water vapour measurement as snow particles could otherwise impact the signal quality. Such an experiment could provide high-resolution temperature and complementary water

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vapour measurements to more directly measure the influence of gusts on sublimation rates and begin to address discrepancies in sublimation found in different climates. As well, longitudinal studies of heat flux in near-surface layers would provide better insight into the connection between average boundary layer profiles and the presence of turbulent events of specific magnitude, frequency, and duration.

Author Contributions NA and JW designed the experiment and contributed to the evaluation of the results. NA performed the field experiment and analysis. Both authors contributed to the writing of the manuscript.

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