Article

Surface Melt on Ross Ice Shelf Interior during a Downsloping Wind Event

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Abstract: On January 8, 2005, a surface melt event began on the interior portion of Ross Ice Shelf. While many surface melt events on Ross Ice Shelf are caused by the advection of warm air onto the shelf from the Ross Sea, surface winds during this event were directed offshore and the spatial pattern of surface melt was inconsistent with the Southern Ocean serving as a heat source. Rather, due to the interior location of the surface melt coupled with prevailing wind direction and surface temperature data it is thought that adiabatic warming of Föhn winds is the driving cause of this melt event. Passive Microwave (SSM/I) imagery was used to determine surface melt occurrence and the event's extent. Spatial patterns of surface melt were then compared to NCEP/NCAR reanalysis output for several synoptic weather variables including surface temperatures, sea level pressure and surface vector winds. Synoptic-scale weather conditions were consistent with those that would produce downsloping wind (föhn) conditions in the interior of the Ross Ice Shelf where the anomalous surface melt was located.

Keywords: Antarctica; Surface Melt; Ross Ice Shelf; Föhn Winds; Remote Sensing

1. Introduction

Ross Ice Shelf, Antarctica, is the world's largest and southernmost ice shelf. While typical conditions there preclude the appearance of surface melting, the lack of persistent summer melt provides an opportunity to isolate specific meteorological conditions that can temporarily increase temperatures above 0°C. The majority of surface melting on Ross Ice Shelf is caused by an inflow of relatively warm maritime air over coastal regions [1], previously modified by an upward sensible and latent heat flux over offshore polynyas [2]. However, there have been several instances of surface melting that are better explained by the presence of downsloping "Föhn-like" winds from either the Transantarctic Mountains or down the ice streams on the eastern edge of the shelf (e.g. Bindschadler and MacAyeal, formerly Ice Streams D and E respectively).

Warm downsloping winds are well-documented in non-polar regions, particularly in the Alps as föhn winds [3], the Rocky Mountains as Chinook winds [4] and the Sierra Nevada as Santa Ana winds [5]. There is a growing body of literature showing their effect on both Greenland [6] and on the Antarctic Peninsula. Recent works [7-10] have outlined the presence of downsloping winds leading to surface melt on more temperate Antarctic ice shelves such as Larsen, which appear to be driven by prevailing westerly flow over the Antarctic Peninsula [11].

Föhn winds have been documented in the dry valleys region of the northern Ross Ice Shelf [12,13]. While downsloping winds on Ross Ice Shelf are typically cold, density-driven katabatic winds, the presence of a surface low in the Ross Sea can draw air down the steep topography around Ross Ice Shelf causing the air to warm adiabatically as it descends [14]. Such winds are associated with extreme warm events in the dry valleys. However, most downsloping winds on the Ross Ice Shelf are not associated with temperatures warm enough to facilitate surface melting. Both katabatic processes as well as the presence of the offshore Ross Sea cyclone [15,16] contribute to the development of downsloping winds. There is both an adiabatic and a turbulent mixing component to warm downsloping winds over Ross Ice Shelf when the source region for the air is over West Antarctica [17]. Turbulent mixing can disrupt the semi-permanent inversion over Ross Ice Shelf and warm the surface by mixing down warm air from aloft. Downsloping winds originating over East Antarctica were found to be predominately katabatic in nature and therefore had a cooling effect on the temperatures across Ross Ice Shelf.

Surface melting is known to have contributed to the breakup of the Larsen B ice shelf in 2002 [18], though the larger and colder Ross Ice Shelf is not currently at risk of collapse. Surface melting arises from the full meteorological conditions at a time, but different processes may be dominant in any single melt event. In particular, melting may occur on clear-sky days in response to intense insolation, by advection of heat from warmer regions such as ice-free parts of the Southern Ocean, by föhn-type winds, or perhaps in other ways [19, 1, 9, 10, 20, 21]. During times of marginal temperatures that may be slightly below freezing, the downsloping component of winds may serve to enhance the potential for surface melting. However with increases in temperature projected over the course of the next century [22,23,24], this may increase the frequency and intensity of föhn melt events, which may have further implications toward ice shelf stability.

This work examines a case study of large-extent surface melt identified by passive microwave satellite imagery, located near the southern grounding line of Ross Ice Shelf, which is thought to be caused primarily by downsloping föhn-like winds. The event occurred in two phases, the first of which lasted from Jan 8-9, 2005 and the second from Jan 12-17, 2005.

2. Data and Methods

2.1 Passive Microwave Satellite Imagery and Melt Detection Algorithm

Surface melt occurrence was determined using SSM/I passive microwave (19GHz horizontally-polarized and 37GHz vertically-polarized) brightness temperature [25] and the Cross-Polarized Gradient Ratio (XPGR) [26, 27]. This method is able to determine the presence of melt at the satellite overpass time at a resolution of 25km. Melt detection is dependent on changes in the dielectric constant of the ice shelf surface as ice, firn, and snow begin to melt. The output is then reclassified as binary values indicating areas with melt if the XPGR exceeds an empirically-established threshold, or no melt if the XPGR does not exceed the threshold. After reclassification, the melt values were masked, to include only areas on the Antarctic Ice Sheet and seven major Antarctic Ice Shelves. A surface melt dataset extending from 1987-88 through 2009-10 was created [1] but a subset of the data from January 8-26 2005 was useful to delineate this particular surface melt event.

2.2 Comparison to Synoptic-Scate Weather Conditions

Synoptic weather conditions were then compared to NCEP/NCAR reanalysis-derived [28] weather variables including sea-level pressure, vector winds, surface air temperature, and potential temperature. Reanalysis output is available at a 2.5^{o} x 2.5^{o} spatial resolution then is interpolated by the NOAA/ESRL Physical Science Division and made available on their website. While data are available as frequently as 6-hourly, daily data are used in this study to coincide with the daily temporal resolution of the SSM/I surface melt data. Temperatures aloft were also examined at 925mb and 850mb to examine the role that turbulent mixing of inversions may play in raising temperatures above the freezing point.

3. Results

On January 8, 2005, a surface melt event occurred on the interior portion of the Ross Ice Shelf, near latitude 85^{o}S (Figure 1). While this was not a long-duration event, it is notable for its location—nearly 900 km from the Ross Sea. Surface Melt was confined to the southernmost extent of Ross Ice Shelf (82-85^{o}S) below the Transantarctic Mountains and at the base of the Bindschadler and MacAyeal Ice Streams. Typically-warmer regions along the northern coast are melt-free. Other surface melt events in the satellite record typically centred over strictly the Bindschadler and MacAyeal ice

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streams, the McMurdo Island region on the northwest corner of Ross Ice Shelf, or both of these regions.

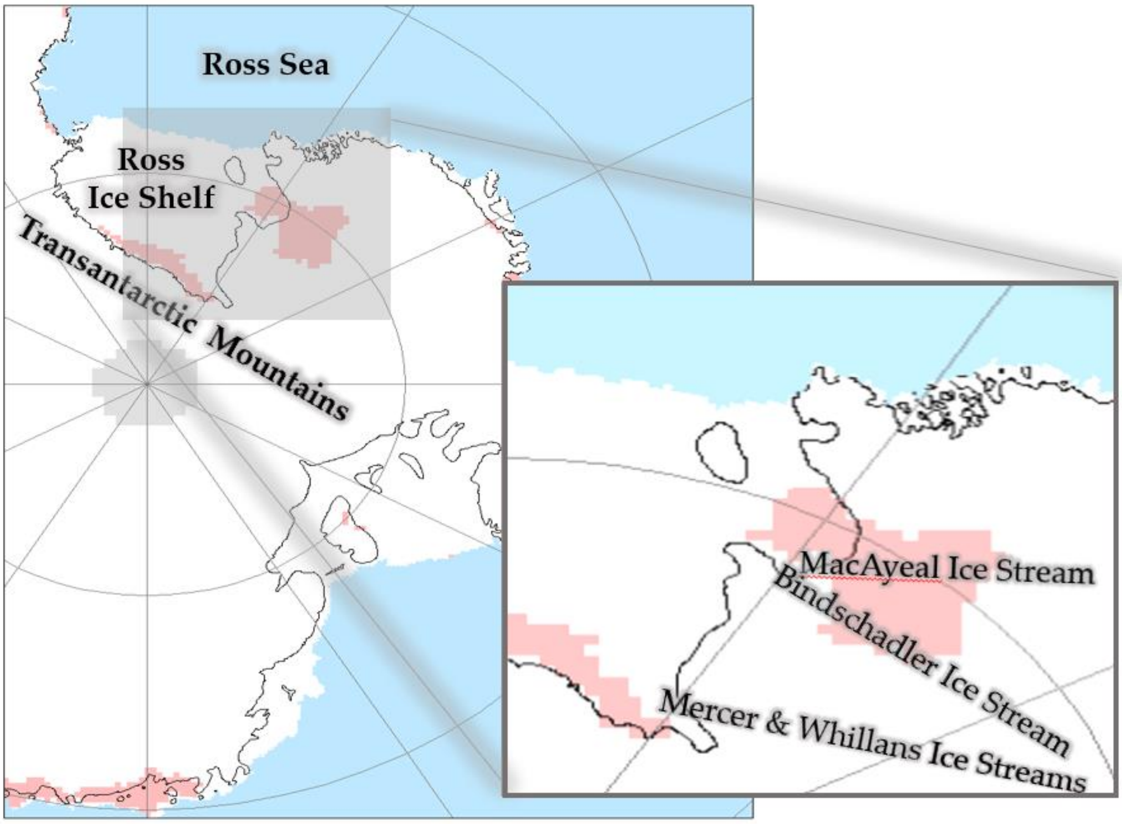

Figure 1. XPGR Surface Melt Occurrence (Pink) for West Antarctica, January 8, 2005.

The January 2005 surface melt event began on Jan 8 and continued for two days before the majority of the ice re-froze on Jan 10. A second phase of the event, smaller in extent but longer in duration, began on Jan 12 and extended to Jan 17 with the last residual melted region freezing again on Jan 26. There was a decreased melt extent along the Bindschadler and MacAyeal ice streams during the second phase of the event as well, with these ice streams becoming melt-free by Jan 14. Throughout both phases of the event, surface melting was confined to areas where surface air flow converged and descended, and melt was absent from areas along the coastline. Notably, this melt event was one of only two similar events identified across the entire 1987-2010 record.

NCEP/NCAR Reanalysis (Figure 2) shows the presence of a surface low pressure system (2a) and accompanying clockwise circulation (2b) in the Ross Sea on January 8 2005. Higher sea-level adjusted pressures were seen on the Antarctic Plateau, particularly west of Ross Ice Shelf. This synoptic pattern is consistent with offshore winds. Synoptic wind patterns are further modified by the rugged topography of the Transantarctic Mountains. During downslope wind events, air trajectories follow the natural drainage patterns in the topography with air flow mirroring the ice flow beneath. Therefore, downsloping winds will be strongest where ice flow is naturally faster, in the various ice streams along the grounding line. It is along these ice streams, particularly Ice Streams A (Mercer) and B (Whillans) and Ice streams D (Bindschadler) and E (MacAyeal) that surface melt was observed during the January 2005 melt event.

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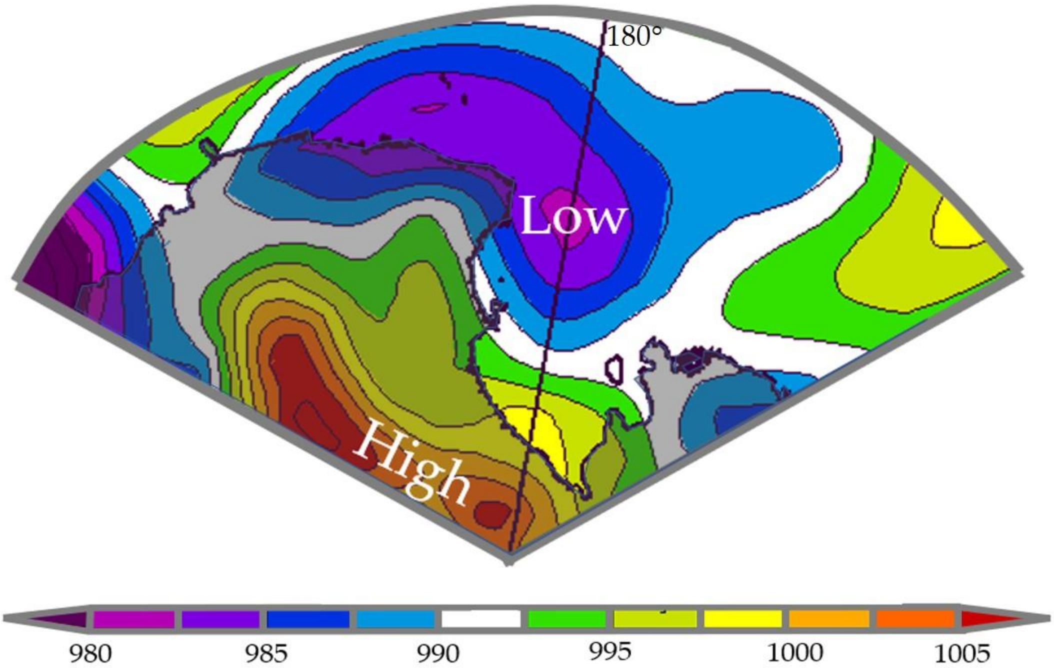
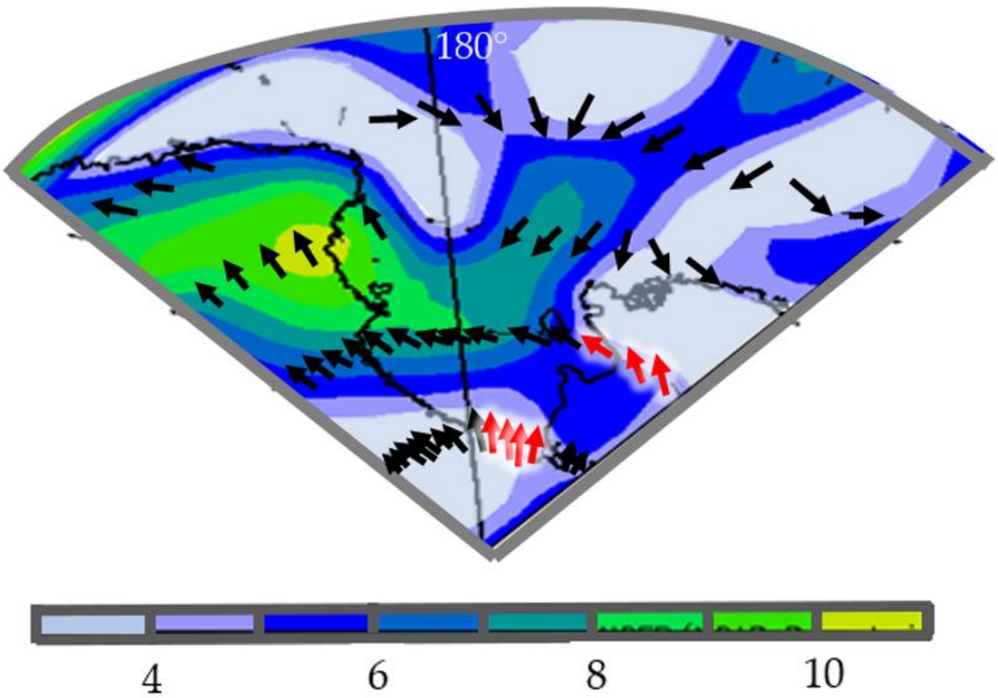


(a)



(b)

Figure 2. NCEP/NCAR Reanalysis [28] (a) Sea Level Pressure (mb) and (b) Surface Vector Winds (m/s) for West Antarctica, January 8, 2005. [Modified from NOAA ESRL PSD 2019]

Surface Temperatures (Figure 3a) are near 273K across much of Ross Ice Shelf on January 8, 2005. Above-freezing temperatures were somewhat north of the area experiencing the surface melt, which

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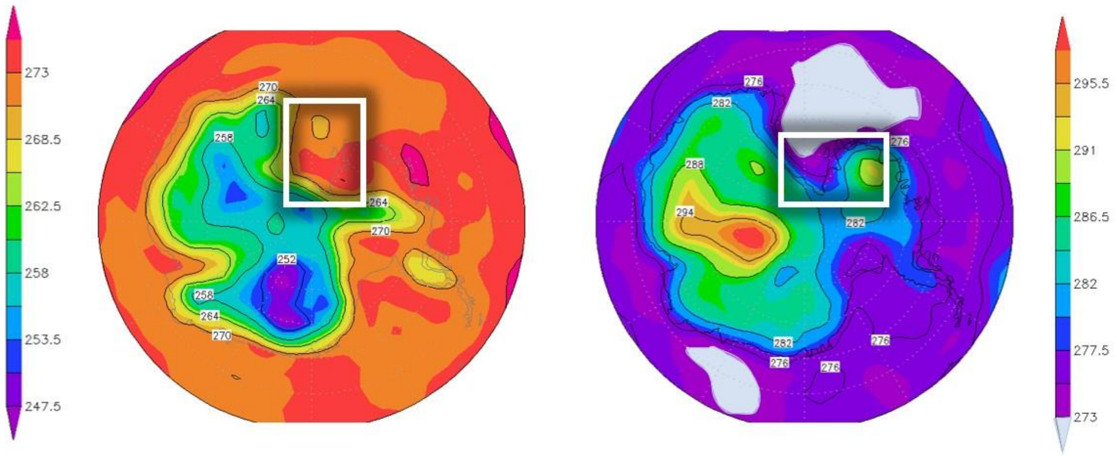
was immediately adjacent to the base of the Transantarctic Mountains. Temperatures over the Ross Sea were below freezing--approximately 270K. Again, this is consistent with the absence of surface melt along the northern, coastal edge of Ross Ice Shelf. The 264K isotherm was along the Transantarctic Mountains, which also corresponded to the (expected) lack of surface melting at the higher elevations nearly 2km above Ross Ice Shelf.



(a) **(b)**

Figure 3. NCEP/NCAR Reanalysis [28] (a) Surface Air Temperature and (b) Surface Potential Temperature for Antarctica, January 8, 2005 [Modified from NOAA ESRL PSD 2019]. White highlighted regions indicate areas of enhanced T and Θ gradients.

Potential Temperature is a theoretical maximum temperature that air would have if it were forced to descend dry adiabatically to 1000mb without mixing with its environment. Potential temperatures (Figure 3b) across the Antarctic Plateau indicate the possibility of a föhn melt mechanism inducing surface melting because all potential temperature values are well above 273K. Potential temperatures near 280-281K are located upwind of the Mercer and Whillans Ice Streams. This area is the local minimum for potential temperature, however this is the region directly upwind of the southernmost surface melt conditions. Potential temperatures of up to 291K extend across Marie Byrd Land upwind from the Bindschadler and MacAyeal Ice Streams, and just over 282K across the Transantarctic Mountains. While potential temperatures above the Transantarctic Mountains are higher than temperatures across Ross Ice Shelf, turbulent mixing would likely decrease the temperatures of descending air parcels.

4. Discussion

Most surface melting on Ross Ice Shelf is caused by relatively warm, moist winds advecting sensible and latent heat from the Ross Sea onto the distal edge of the shelf [1]. However, during the January 8, 2005 event, winds were directed offshore, with air sourced over the Transantarctic Mountains coming across Ross Ice Shelf from the south. Surface melt was found predominately along the grounding line at the base of the Transantarctic Mountains. Melt was largely absent from coastal regions that by virtue of their lower latitude and proximity to the Ross Sea are typically warmer than the interior of the ice shelf. Such a spatial pattern of surface melt is inconsistent with advection of warm air from the Ross Sea or melt generated from abnormally high solar radiation. If these processes were occurring, surface melt would be located not in the southern region of the ice shelf, but near the northern coastal region. In this melt event, melt was likely generated via processes similar to föhn winds, where adiabatic warming of downsloping air caused surface temperatures to rise above 0^{o}C and an area of melt to form at the base of the mountains.

A Föhn-like surface melt mechanism (Figure 4) is occurring due to the increase in temperature at the dry adiabatic lapse rate as winds descend the Transantarctic Mountains and/or the Bindschadler/MacAyeal Ice Streams to the surface of the ice shelf. During the January 2005 melt

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event, the initial air temperature at the top of the Transantarctic Mountains is 264K. As the Ross Sea Low forces the winds to descend to the Ross Ice Shelf proper, air is warmed dry adiabatically at 9.8 K/km over 2 km. This results in the transformation of sub-freezing air (264K) to above freezing air (274K). Some turbulent mixing takes place during the descent, allowing cooler air to infiltrate descending parcels, making parcel temperatures slightly cooler than would be expected by an adiabatic descent of 2km.

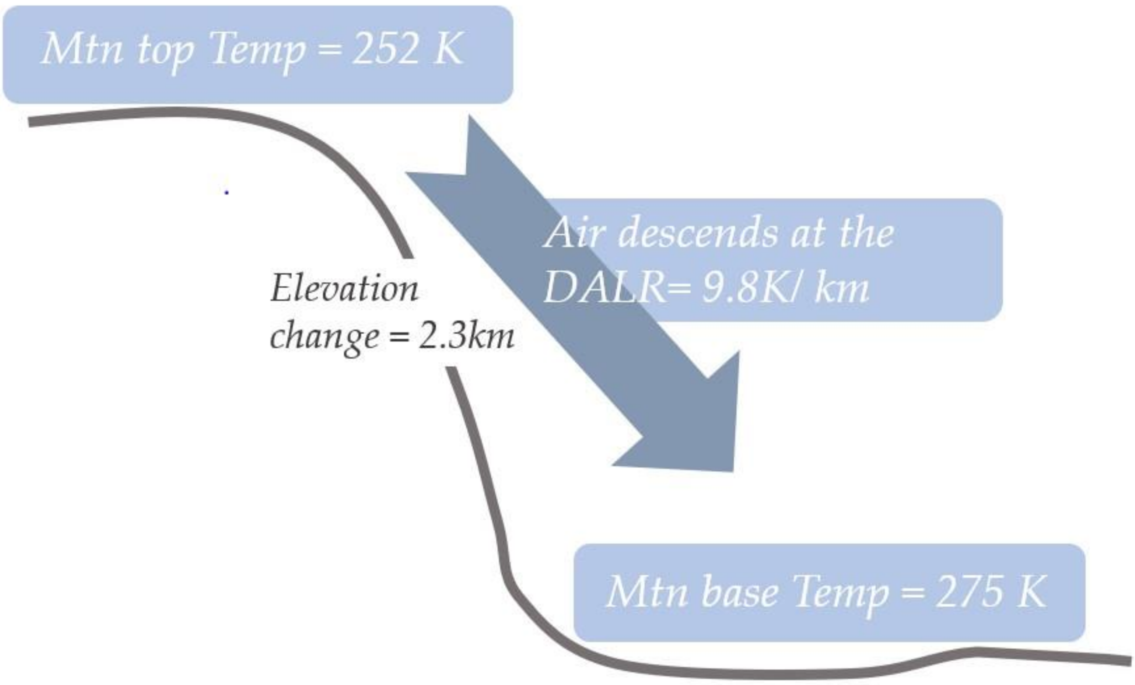

Figure 4. Föhn melt mechanism at base of Transantarctic Mountains. Note: The actual mountain base temperature will vary, and likely be slightly lower than this depiction, due to entrainment, or, mixing with the surrounding environment during descent.

Turbulent mixing alone is insufficient to explain the rise of temperatures above the freezing point at the base of the Transantarctic Mountains. Air temperatures at 925mb and 850mb were below freezing (272K at 925mb and 268K at 850mb) over the interior of Ross Ice Shelf on Jan 8, 2005. There was no inversion present in this region and temperatures were warmest at the surface. Near the Bindschadler and MacAyeal Ice streams, temperatures at 925mb and 850mb were slightly warmer at 275K at 925mb and 272K at 850mb. Turbulent mixing likely had a stronger influence on surface melt in this location, closer to the coast.

These downsloping winds may at first appear similar to katabatic winds, which most commonly form during the polar night when radiational cooling is strongest. Katabatic winds undergo the same adiabatic temperature increases as föhn winds. However, because the density-driven katabatic winds derive from particularly cold air they will have a net cooling effect on the lower part of the ice shelf. The downsloping winds seen on January 8, 2005 are not the result of katabatic processes, but were generated by a synoptic scale pressure gradient. As a result, the air originating atop the Antarctic Plateau was not particularly cold to begin with and the air warmed as it was forced downward.

It is possible that the melt along the Bindschadler and MacAyeal Ice Streams was enhanced by warm air advection off the Amundsen Sea though the near-shore wind direction makes this possibility unlikely. Winds along the coastal region of Marie Byrd Land were light (<4 m/s) and show as moving offshore. However the coarse spatial resolution of the NCEP/NCAR Reanalysis output and the overall weak wind speeds make the true wind direction in this region somewhat ambiguous. In cases where a synoptic low resides at the boundary between the Ross Sea and the Amundsen Sea, it is possible for onshore flow to overspread across Marie Byrd Land and the föhn effect could amplify surface melt conditions.

One significant limitation of this study is the coarse spatial resolution (2.5° x 2.5°) of the NCEP/NCAR Reanalysis. This makes the exact position and extent of above-freezing temperatures somewhat unclear. However, the presence of above-freezing surface air temperatures, and the detection of surface melting through SSM/I imagery lends credence to the föhn melt mechanism hypothesis despite the poorly-resolved surface temperatures along the Ross Ice Shelf.

Future work should examine the relationship between föhn wind and calving events along the front of Ross Ice Shelf. While the Ross Ice Shelf is thought to be too thick and stable to undergo the same rapid collapse that affected the Larsen B Ice Shelf, iceberg calving is a natural process that has the potential to accelerate under warmer conditions. The presence of extreme warming events due to föhn winds in the Dry Valleys and the ability of föhn winds to increase temperatures above freezing even as far south as the grounding line at the base of the Whillans and Mercer Ice Streams (85°S) could have important implications for calving rates. Warming temperatures from anthropogenic climate change could further increase melting during otherwise marginal temperatures exacerbated by the föhn effect.

5. Conclusions

Surface melt anomalies occurring inland on the Ross Ice Shelf during the January 2005 event, while superficially appearing to have characteristics of katabatic flow, are at least partially due to the effects of Föhn-like winds. Winds at the top of the ice sheet are not sufficiently dense to drive katabatic flow, nor is synoptic circulation bringing maritime air ashore, which is the typical cause for melt in this region. Rather, the Ross Sea Low is forcing air down from the Antarctic Ice Sheet onto the Ross Ice Shelf. The areas of surface melt are confined to regions that are directly below the ice streams, which, owing to their lower elevations, would serve as preferred pathways for downsloping winds. While during katabatic flow infrared satellite imagery identifies "warm" regions within the air stream as a result of inversion mixing [29], surface melt occurrence is determined using microwave imagery instead. During the January 2005 event, conditions are not consistent with a polar night inversion. The variables most closely associated with the Föhn-like surface melt mechanism are 1) the location of synoptic scale pressure systems, 2) surface air temperatures at the top and bottom of the Transantarctic Mountains, and 3) the wind direction over the Ross Ice Shelf. Similar downsloping winds are documented in other areas of Antarctica, specifically along the Larsen C ice sheet [8]. While the Föhn-like surface melt mechanism is an uncommon occurrence, it should be noted that synoptic scale events might have a bearing on future ice melt events, especially as temperatures increase because of global climate change.

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Conflicts of Interest: The authors declare no conflict of interest

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