Large-Scale Atmospheric Drivers of Snowfall Over Thwaites Glacier, Antarctica

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Abstract  High snowfall events on Thwaites Glacier (TG, West Antarctica) are a key influencer of its mass balance, and can act to mitigate sea level rise due to ocean warming-induced ice loss. We use the output of a high-resolution regional climate model, RACMO2, in conjunction with MERRA-2 and ERA5 atmospheric reanalyses for the period 1980–2015 and show that there is a pronounced seasonal cycle in snowfall over TG, driven by the Amundsen Sea Low (ASL). We find that the total annual snowfall does not correlate significantly with the Southern Annular Mode or El Niño Southern Oscillation, but it does relate to the zonal wave three pattern over Antarctica through the coupling of the ASL with a blocking high over the Antarctic Peninsula during high snowfall events. Our results highlight that atmospheric circulation and consequent high snowfall events on TG are highly variable, and recognizing their future change will aid to improve predictions of mass balance.

Plain Language Summary  Thwaites Glacier (TG) is a large glacier in West Antarctica that is rapidly losing mass. Snowfall can help to replenish mass lost by adding mass to the surface of the glacier. In this study, we use three climate reanalyses to examine snowfall on TG and how pressure patterns in the atmosphere can lead to a large amount of snowfall in a short period of time. Climate reanalyses are computer models that combine physics equations with observations to re-create daily atmospheric conditions from 1979 to 2015. We find that a large, low-pressure system called the Amundsen Sea Low (ASL) drives snowfall on Thwaites by circulating warm and moist air masses from the ocean onto the glacier. It snows a lot on Thwaites in the austral fall, winter, and spring, and half of the total snowfall comes from high snowfall events. On high snowfall days on Thwaites, the ASL is joined by a high-pressure system over the Antarctic Peninsula. The combination of these two pressure systems is representative of a zonal wave three pressure pattern, which enables deep circulation from the Southern Ocean onto the Antarctic Ice Sheet.

1. Introduction

Thwaites Glacier (TG) is the largest glacier of the Amundsen Sea sector of West Antarctica, spanning almost 200,000 km², and is rapidly losing mass. In response to enhanced delivery of circumpolar deep water (Jacobs et al., 1996, 2011; Thoma et al., 2008), Thwaites ice shelf has thinned and the grounding line has retreated ( Dutrieux et al., 2014; Rignot et al., 2014). Mass loss from TG has increased from 87 Gt yr⁻¹ in 1979–1989 to 117 Gt yr⁻¹ in 2009–2017, leading to a total mass loss of 634 Gt over the 1979–2017 period (Rignot et al., 2019). Due to its inward sloping bed, TG is at severe risk for further, sustained retreat in the future, which could raise global sea levels by up to 0.65 m (DeConto & Pollard, 2016; Joughin et al., 2014; Seroussi et al., 2017).

While enhanced ice discharge is the main mechanism by which TG has lost mass, interannual fluctuations of TG integrated surface mass balance (SMB) in 1980–2005 are of the same order of magnitude as the annual mass loss (Donat-Magnin et al., 2020; Lenaerts et al., 2018; Medley et al., 2014). SMB, which is defined as the rate of surface mass change, has the potential to offset mass loss from enhanced ice discharge and may help to mitigate sea level rise (Medley & Thomas, 2019). Thus, a careful examination of SMB is crucial to understanding the current and future mass balance of TG. On Antarctica in general, and TG in particular, precipitation occurs predominantly in the form of snow (125 ± 16 Gt yr⁻¹), and it is generally too cold for substantial sublimation (3 Gt yr⁻¹), or melt (1 Gt yr⁻¹), to occur on the ice sheet surface (Lenaerts et al., 2018, 2019). Therefore, we ignore these components, and assume SMB and snowfall as equivalent in this study.
Few observations are available for analyzing historical snowfall on TG and the associated atmospheric circulation. Ice cores provide long-term SMB records, but only six ice cores have been sampled over TG in the last two decades, and only in the highest elevations of the glacier that are far away from the glacier terminus, the epicenter of rapid change (Medley et al., 2013). Furthermore, the sparse distribution of the ice cores means they cannot account for spatial variability in snowfall (Banta et al., 2008). Recent developments in airborne snow radar have enabled the measurement of spatiotemporal variations in snowfall over TG along multiple transects, but these are also limited to the higher elevations of TG, where annual SMB is lower than closer to the coast (Medley et al., 2013). No long-term observations of SMB exist below 1,000 m above sea level on TG, where models and short-term observations indicate SMB to be the largest (Johnson et al., 2018; Lenaerts et al., 2016). Instead, we can leverage output from regional climate models and atmospheric reanalyses to study snowfall on TG. These products allow us analyze snowfall events and related atmospheric conditions for the entire TG and the surrounding region and for an extended, continuous time period (1980–2015). In this study, a regional climate model RACMO2 is used in conjunction with global reanalysis products MERRA-2 and ERA5 to examine snowfall and the atmospheric drivers of snowfall events on TG.

Along with quantifying the spatial and temporal variability of snowfall, we also aim to understand what atmospheric patterns produce snowfall over TG. A large, climatological low-pressure system known as the Amundsen Sea Low (ASL) exerts a major influence on how air masses flow from the lower latitudes to the WAIS (Van Den Broeke, 2000). The ASL is located north of the Amundsen Sea Embayment (ASE) and experiences a semi-annual zonal oscillation from west of the Antarctic Peninsula in summer to the Ross Sea in winter, making it the epicenter of atmospheric variability in the ASE (Raphael et al., 2016; Turner et al., 2013). Identifying the dynamics of the ASL and linking those to modes of atmospheric variability such as the Southern Annular Mode (SAM) and El Niño Southern Oscillation (ENSO), will help to explain past snowfall variability and to constrain estimates of future SMB changes on TG (Holland et al., 2019; Scambos et al., 2017).

2. Data

A regional atmospheric climate model, RACMO2, run at a horizontal resolution of 5.5 km from 1979 to 2016 over the ASE and surrounding regions (Lenaerts et al., 2018), is used to examine the local atmospheric patterns and snowfall occurring near and on TG. The numerical core of RACMO2 is based on the High Resolution Limited Area Model (HIRLAM) numerical weather prediction model, while its physical schemes are adopted from the Integrated Forecast Model (IFS) by the European Centre for Medium-Range Weather Forecasts (ECMWF). It is forced at the lateral boundaries by global reanalysis ERA-Interim, and the model calculates SMB and its components individually, as it combines an atmospheric and sophisticated snow/firn model. Due to the high horizontal resolution, RACMO2 represents small-scale variability in snowfall due to topography relatively accurately, as evidenced by a comparison with airborne snow radar, as well as ground-based radar and shallow firn core observations (Lenaerts et al., 2018).

RACMO2 is used in conjunction with two atmospheric reanalysis products, ERA5 and MERRA-2, to map the climatology of snowfall on TG for their overlapping period (1980–2015). ERA5 is the latest global atmospheric reanalysis product from the European Centre for Medium-range Weather Forecasts (ECMWF) (Hersbach et al., 2020). The model has 0.25° latitude by 0.25° longitude resolution, equivalent to ~28 km by ~7 km at the location of TG. The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), is a global atmospheric reanalysis run at a resolution of 0.5° latitude (56 km) by 0.625° longitude (18 km) (Gelaro et al., 2017). We use both atmospheric reanalysis products to map atmospheric conditions associated with snowfall events, but only show results from MERRA-2 given that we found very similar results using ERA5.

Finally, a set of indices for the central atmospheric pressure and location of the ASL given by Hosking et al. (2016) is used to compare the variability and seasonal migration of the ASL to the climatology of snowfall on TG. Indices for central surface pressure and longitudinal positioning of the ASL are derived from ERA5 atmospheric reanalysis.
3. Methods

Snowfall in this study is examined over TG and nearby Smith, Pope, and Kohler glaciers and their associated ice shelves, referred to as "greater Thwaites" (TG). The flow of marine air masses onto TG produces orographic precipitation of snow as the air masses rise up the trunk of TG. Since orographic precipitation depends on elevation, and the region of TG below 1,000 m above sea level has a surface elevation slope more than twice as steep as the region above 1,000 m, TG is divided into 500 m wide elevation classes, and the TG ice shelves are included as a separate category (Figure 2). TG was defined using the IMBIE2 glacier basin and ice shelf mask (Shepherd et al., 2018), and interpolated (using nearest neighbor interpolation) onto each model grid. The surface elevation was adopted directly from each of the three models, to ensure that we accounted for the difference in horizontal resolution and subsequent terrain smoothing.

The monthly climatology of snowfall over TG was developed using RACMO2, MERRA-2, and ERA5 snowfall in each of the elevation classes. The model climatologies were then compared to the climatology for the central pressure and longitude of the ASL to develop an understanding of seasonal differences in the amount of snowfall. Time series of snowfall events were developed by averaging daily snowfall over TG in RACMO2, ERA5, and MERRA-2 from 1980 to 2015. The time series were sorted by magnitude of snowfall in ascending order and normalized to create a cumulative frequency distribution. From the cumulative frequency distribution, the 10% highest snowfall events in each model were selected and designated “high snowfall events.” The fractional distribution of high snowfall events by season was calculated along with the interannual variability in the number of high snowfall events.

For each non-summer season, we composite the atmospheric conditions (sea level pressure and 2 m temperature) during high snowfall events, and compare them to the mean conditions over 1980–2015. The composite anomalies are compared with the 1980–2015 standard deviation, and the anomaly was assumed significant in areas where the anomaly exceeds the standard deviation.

4. Results

4.1. Snowfall Climatology

Annual snowfall on grounded TG (i.e., excluding Thwaites, Dotson, and Crosson ice shelves) is remarkably consistent among the three models. From 1980 to 2015, the grounded TG received an average of 113 ± 14 Gt snowfall per year in RACMO2, 111 ± 16 Gt in ERA5, and 115 ± 15 Gt in MERRA-2. Snowfall over TG ice shelves is higher year-round in RACMO2 than in ERA5 and MERRA-2. The average snowfall is highest in the lower elevations and decreases year-round at higher elevations (Figure 1). While annual snowfall amount is highest in the 500–1,000 m elevations in all three models, this region contributes less than one tenth of the total area of TG (Figure 2). The models distribute snowfall slightly differently by elevation due to differences in horizontal resolution and associated smoothing of topography. In RACMO2, the highest average snowfall occurs in the 0–500 m elevation bin, followed by the ice shelf, while average snowfall per area is lower year-round in MERRA-2 and ERA5 and more closely distributed within the 0–500 m and 500–1,000 m elevations. This confirms the findings of Lenaerts et al. (2018), who found that RACMO2 slightly overestimates orographic precipitation on TG, and suggests that MERRA-2 and ERA5 better represent the precipitation across the lower elevations of TG.

The monthly climatology for snowfall over TG highlights strong seasonal differences in the amount of snowfall between the austral summer and winter months in all models (Figure 1). On average, there is
two to three times more snowfall over TG in the fall, winter, and spring months on the ice shelf and in the elevation classes of 0–500 m and 500–1,000 m. This seasonal variation corresponds with the semi-annual oscillation of the ASL and its climatological location relative to TG and the ASE. Each year, the ASL migrates zonally along the Amundsen Sea coastline. During the austral spring and summer months, the ASL shifts eastward to a central longitude of 100° W, east of the ASE. Later in the fall and winter months, the ASL moves westward toward a central longitude of 140° W, closer to the Ross Sea.

Corresponding with its migration, the ASL strengthens during the spring (central pressure of 972 hPa in May) and fall (central pressure of 974 hPa in October) months, and expands over both the Amundsen Sea and the Ross Sea. When the eastern edge of the ASL is positioned to the west of the ASE in the fall and winter months, warm and moist air from lower latitudes is circulated southward toward TG. However, when the ASL is positioned directly north or even east of the ASE, it can act as a blocking mechanism because air masses are then channeled away from the coastline in the embayment. This phenomenon occurs in the summer months and corresponds with low seasonal snowfall over TG. Remarkably, a short-lived (10 days long) minimum in snowfall is found in mid-June in all three models (not shown). This mid-winter minimum in snowfall is associated with the ASL positioned the furthest away from the ASE, such that its influence in driving snowfall on Thwaites is largely reduced.

4.2. High Snowfall Events

The magnitude of daily snowfall over TG is similarly distributed among RACMO2, ERA5, and MERRA-2, with most snowfall below 10 mm w.e. per day. However, the 10% highest daily snowfall events over TG ice shelves correspond to more than 60% of the total snowfall over Thwaites ice shelf and the lower elevations of TG. The location of TG in Antarctica is shown in the map inset.

Figure 2. Contribution of high snowfall events (in percentage) to total snowfall over Thwaites Glacier (TG) (RACMO2). High snowfall events contribute more than 60% of the total snowfall over Thwaites ice shelf and the lower elevations of TG. The location of TG in Antarctica is shown in the map inset.

To examine the atmospheric drivers of these high snowfall events, the mean and anomaly of surface pressure and near-surface air temperature are examined over the Southern Ocean, north of the ASE. Due to the biannual oscillation of the ASL, we expect large spatial differences in the climatological atmospheric patterns between the fall, winter, and spring seasons, when high snowfall events occur most frequently. Therefore, the drivers of high snowfall events are examined for events in each of the three seasons, and the atmospheric anomalies are taken relative to the seasonal mean surface pressure and temperature.

The mean surface pressure pattern during high snowfall events shows that the ASL is located west of the ASE in all three seasons, with a central pressure of 971.2, 971.6, and 965.5 hPa in fall, winter, and spring, respectively (Figure 3). This large-scale atmospheric setup helps to circulate oceanic air masses into the ASE and onto TG, leading to orographic precipitation. Concurrently, we find a region of anomalously high surface pressure east of the ASE of 8–12 hPa (greater than one standard deviation) above the mean. This zone forms a ridge west of the Antarctica Peninsula that helps to drive circulation into the ASE, and is most pronounced in the surface pressure anomaly for winter events, where the anomaly reaches 18 hPa over the Antarctic Peninsula. While the semi-annual oscillation of the ASL contributes to the seasonality of all snowfall on TG, this blocking high located near the Antarctic Peninsula represents a unique atmospheric signature distinctly associated with high snowfall events. Coupled with the ASL, it acts as the primary driver for meridional circulation of warm and moist marine air masses that lead to extreme snowfall on TG. While not shown, we find similar patterns in the 500 hPa geopotential height anomalies during high snowfall events.
Focusing on the mean near-surface temperature during high snowfall events, we find temperatures of \( \sim 260 \text{ K} \) over the Southern Ocean north of ASE, which is indicative of the relatively warm air mass that is advected into the area (Figure 4). This is confirmed by the patterns of the near-surface temperature anomaly. In all three seasons, we find a distinct, statistically significant positive temperature anomaly of 9–12 K (greater than one standard deviation) above the mean over the broader ASE, and extending southward over TG and neighboring glaciers, as well as more eastward, into the Antarctic Peninsula. These relatively warm air masses can hold more moisture, and produce orographic precipitation over the glacier. Combined with the atmospheric patterns in surface pressure, this signals the transport of warmer, oceanic air masses onto TG, driving high snowfall events.

A remaining question is if, and how, the high snowfall events on TG are connected with the dominant modes of large-scale atmospheric variability in the Southern Hemisphere and, potentially, the tropics. The three dominant modes can be retrieved by an orthogonal function analysis (EOF) of MERRA-2 monthly surface pressures (Figure 5), and represent the SAM (17% variance explained), and the Pacific South American Modes 1 and 2 (PSA1 and PSA2; 9% and 8% variance explained, respectively). The SAM represents the zonally averaged atmospheric pressure gradient between the midlatitudes and high latitudes in the Southern Hemisphere (Marshall, 2003) (Figure 5, left). PSA1 reflects the extra-tropical response to ENSO variability.

Figure 3. Mean atmospheric surface pressure (hPa, top row) and mean pressure anomaly (bottom row) over the South Pacific during high snowfall events on Thwaites Glacier (TG). From left column to right, the pressure and anomaly correspond with events in the fall (a and d), winter (b and e), and spring (c and f). Hatching on the anomaly figures indicates regions in which the anomaly exceeds the standard deviation from the mean surface pressure.

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Geophysical Research Letters (Marshall & Thompson, 2016) (Figure 5, center). PSA2 represents the zonal wave three pattern, consisting of three troughs over the Southern Ocean, each one coupled with a ridge eastward of the trough (Figure 5, right). This is a highly stable and dominant pressure pattern, and it is associated with a strong meridional flow onto the Antarctic Ice Sheet in between the high-pressure and low-pressure systems (Raphael, 2004).

Consistent with our finding of a clear atmospheric blocking pattern during high snowfall events and the setup of a strong meridional flow, we do not find a clear link between high snowfall events and the SAM, which represents a more zonally structured response (i.e., change in the westerly winds). We also do not find a statistical relation between TG snowfall and PSA1. However, we do see a qualitative connection with the third mode, PSA2. During high snowfall events, the ASL, coupled with a blocking high over the Antarctic Peninsula, forms a pattern representative of the western branch of the zonal wave three structure. To better quantify the potential connection, we compare the principal component time series of each of the modes (SAM, PSA1, and PSA2) with the annual total snowfall on TG from 1979 to 2015 using a Pearson linear regression. As expected, no correlation is found between the SAM and total snowfall (correlation coefficient $r = 0.04$, $p = 0.80$), and only a weak positive correlation is found between PSA1 and total snowfall ($r = 0.23$, $p = 0.17$). However, a moderate and statistically significant correlation ($r = 0.36$, $p = 0.03$), is found between

Figure 4. Mean 2 m temperature (K, top row) and mean 2 m temperature anomaly (bottom row) over the South Pacific during high snowfall events on Thwaites Glacier (TG). From left column to right, the temperature and anomaly correspond with events in the fall (left), winter (center), and spring (right). In all three seasons, there are anomalously high surface temperatures over TG and the Amundsen Sea Embayment during high snowfall events. Stippling on the anomaly figures indicates regions in which the anomaly exceeds standard deviation from the mean 2 m temperature.
total snowfall on TG and the principal component corresponding to the zonal wave three pattern (PSA2). This pattern sets up a meridional flow of warm and moist marine air masses onto TG, enhanced by the blocking high over the Antarctic Peninsula, which can lead to high snowfall events.

5. Discussion and Conclusions

Our analysis provides an explanation for the seasonality of the snowfall climatology of TG and the large-scale atmospheric drivers of high snowfall events, with an emphasis on the relative comparison of the climatology among RACMO2, ERA5, and MERRA-2 models. Snowfall on TG depends primarily on the position and strength of the ASL relative to the ASE. When the ASL is located west of the ASE, circulation about the low-pressure system drives warm air from lower latitudes into the embayment, leading to snowfall events on TG. This occurs primarily in the fall, winter, and spring seasons, during which there is 2–3 times the amount of snowfall than in summer. High snowfall events over TG are associated with the ASL positioned west of the ASE and coupled with an anomalous blocking high of 12–18 hPa over the Antarctic Peninsula. While the ASL is associated with the mean snowfall and its seasonality over TG, it is the blocking high over the Antarctic Peninsula that is uniquely associated with high snowfall events, which contribute 30%–60% of the total snowfall on TG. Whereas our preliminary analysis finds no significant link between high snowfall events and modes of internal variability in the tropics (e.g., ENSO) and Southern Hemisphere midlatitudes (e.g., SAM), future work should determine if and how these modes of variability interact with the ASL and atmospheric blocking. Additionally, we expect most, if not all, high snowfall events to be associated with atmospheric rivers, which are long, narrow plumes of moisture-loaded air that originate from lower latitudes (Wille et al., 2021). A better understanding of these phenomena, and how they establish an atmospheric connection between the midlatitudes and polar regions, will be of high importance to assessing temporal variability of snowfall over TG and its the driving mechanisms, and will pave the way for more reliable future projections of West Antarctic SMB.

While most previous studies have largely focused on annual and/or summer SMB because of the importance of surface melt (Donat-Magnin et al., 2020; Lenaerts et al., 2018), our study shows that summer snowfall is relatively low on TG compared to the fall, winter, and spring seasons. There are far fewer high snowfall events in the summer than in the non-summer seasons meaning summer snowfall contributes only minimally to the annual SMB on TG. Non-summer snowfall events contribute significantly to the SMB on TG, and have the potential to buffer the accelerating mass loss.

We find a strong similarity in both the snowfall climatology and high snowfall events among the three model data sets used in our study, which enhances our confidence in the validity of our results. This also implies that state-of-the-art reanalysis products, such as MERRA-2 and ERA5, are suitable for representing SMB and the large-scale atmospheric conditions during and leading up to high snowfall events over TG.
Our results show marked differences on sub-basin scale, in particular at low elevations and between RACMO2 and MERRA-2. Newly emerging observations, such as satellite-based altimetry from ICESat-2 (Smith et al., 2020), GPS interferometry (Larson et al., 2020), and sonic height sensors aboard automatic weather stations (Kuipers Munneke et al., 2017) can provide indications of annual snowfall, seasonal variations, and even individual snowfall events. Such accurate observations of SMM will improve estimates of current and future surface mass balance on TG.

Finally, we show that snowfall on TG is not significantly related to the SAM or PSA1 (i.e., extratropical impact of ENSO), but is, to some degree, associated to the zonal wave three pattern around Antarctica. This result indicates that TG snowfall, and particularly high snowfall events, are associated with a westerly position of the ASL and a blocking high over the Antarctic Peninsula. This atmospheric setup, in particular the positioning of the blocking high directly east of the ASL, enables a strong and deep meridional flow onto TG that drives orographic precipitation. On a larger scale, this pattern is associated with a zonal wave three mode. This link between TG snowfall and a dominant mode of atmospheric variability should be expanded upon in future work, in particular how the zonal wave three pattern will evolve in a future warming climate, and how that will affect future TG snowfall.

Data Availability Statement

MERRA-2 data are available through the Goddard Earth Sciences Data and Information Services Center (hourly data, which we converted to daily, at https://disc.gsfc.nasa.gov/datasets/M2T1NXLFO_5.12.4/summary, monthly means at https://disc.gsfc.nasa.gov/datasets/M2TMNXLFO_5.12.4/summary). ERA5 data are available through the Copernicus programme Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-monthly-means?tab=overview). Monthly RACMO2 snowfall rates are available on Zenodo (https://doi.org/10.5281/zenodo.4657362). ASL indices ( Hosking et al., 2016) are available through the University Corporation for Atmospheric Research Climate Data Guide (https://climatedataguide.ucar.edu/climate-data/amundsen-sea-low-indices).

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This work is from the TARSAN project, a component of the International Thwaites Glacier Collaboration (ITGC). Support from National Science Foundation (NSF Grant 1929991) and Natural Environment Research Council (NERC: Grant NE/S006419/1). Logistics provided by NSF-U.S. Antarctic Program and NERC-British Antarctic Survey. ITGC Contribution No. ITGC-053. We also acknowledge financial support of the University of Colorado Boulder for this study.

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