Meteorological Drivers and Large-Scale Climate Forcing of West Antarctic Surface Melt

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ABSTRACT

Understanding the drivers of surface melting in West Antarctica is crucial for understanding future ice loss and global sea level rise. This study identifies atmospheric drivers of surface melt on West Antarctic ice shelves and ice sheet margins and relationships with tropical Pacific and high-latitude climate forcing using multidecadal reanalysis and satellite datasets. Physical drivers of ice melt are diagnosed by comparing satellite-observed melt patterns to anomalies of reanalysis near-surface air temperature, winds, and satellite-derived cloud cover, radiative fluxes, and sea ice concentration based on an Antarctic summer synoptic climatology spanning 1979–2017. Summer warming in West Antarctica is favored by Amundsen Sea (AS) blocking activity and a negative phase of the southern annular mode (SAM), which both correlate with El Niño conditions in the tropical Pacific Ocean. Extensive melt events on the Ross–Amundsen sector of the West Antarctic Ice Sheet (WAIS) are linked to persistent, intense AS blocking anticyclones, which force intrusions of marine air over the ice sheet. Surface melting is primarily driven by enhanced downwelling longwave radiation from clouds and a warm, moist atmosphere and by turbulent mixing of sensible heat to the surface by föhn winds. Since the late 1990s, concurrent with ocean-driven WAIS mass loss, summer surface melt occurrence has increased from the Amundsen Sea Embayment to the eastern Ross Ice Shelf. We link this change to increasing anticyclonic advection of marine air into West Antarctica, amplified by increasing air–sea fluxes associated with declining sea ice concentration in the coastal Ross–Amundsen Seas.

1. Introduction

Since the 1990s, satellites have observed rapid and accelerating mass loss from the West Antarctic Ice Sheet (WAIS; Shepherd et al. 2012; Paolo et al. 2015; Gardner et al. 2018; Fig. 1). To date, these changes have been driven by basal melting of ice shelves along the Pacific sector, which has triggered widespread acceleration, thinning, and retreat of glaciers in the Amundsen Sea

Embayment (ASE; Pritchard et al. 2012; Mouginot et al. 2014). The latest satellite observations reveal that the rate of ice loss tripled in the last decade (Shepherd et al. 2018), potentially manifesting the early stages of WAIS collapse via marine ice sheet instability (Joughin et al. 2014; Rignot et al. 2014; Scambos et al. 2017; Turner et al. 2017a).

Similar to current summer conditions in Greenland (Graeter et al. 2018; Trusel et al. 2018), climate models project intensification of surface melting in West Antarctica with continued warming of the global atmosphere (Trusel et al. 2015; DeConto and Pollard 2016). Surface meltwater can accelerate ice loss via runoff (Bell et al. 2017) and by altering ice flow dynamics and thermomechanical properties (Zwally et al. 2002; Bell et al. 2014; Hubbard et al. 2016). Of particular concern is its ability to

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FIG. 1. Map of West Antarctica. Topographic contours are shown at a 250-m interval.

hydrofracture through ice shelves and to promote the structural collapse of ice cliffs at deep grounding lines (Wise et al. 2017). In the late 1990s and early 2000s, following rapid warming of the Antarctic Peninsula (Turner et al. 2016), strong surface melting induced the collapse of several ice shelves (Scambos et al. 2000; van den Broeke 2005; Banwell et al. 2013) leading to accelerated discharge of grounded ice into the ocean (Rignot et al. 2004). Similar intensification of surface melting around the WAIS coastal margins and major ice shelves in the Ross and Weddell sectors could increase the risk of destabilization and help unleash large contributions to sea level rise. Satellites and aerial surveys reveal sporadic melting in these areas in the present climate (Tedesco et al. 2007; Nicolas et al. 2017; Kingslake et al. 2017). However, the physical drivers of surface melt remain poorly quantified and understood owing to insufficient direct observations.

Insight into the causal nature of surface melting on the Ross sector was first gained from surface energy

balance, cloud, and upper-air measurements made at WAIS Divide in January 2016 during the Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment (AWARE; Fig. 2a; Nicolas et al. 2017). This event, among the most prominent on record, occurred during a period of high global-average temperature in the wake of the record 2015/16 El Niño. A vertically extensive plume of heat and moisture made icefall in Marie Byrd Land (supplemental Fig. 1 in the online supplemental material, hereafter Fig. S1), causing a large spike in downwelling longwave radiation at the surface. Micropulse lidar and NASA satellite observations revealed frequent thin, low-level liquid-dominated clouds over the melt region (Fig. S2). Extensive melt was also observed in January 2017 (Fig. 2b) following unprecedented retreat of Antarctic sea ice (Turner et al. 2017b). With a melt extent of 2.99 Mkm², this event virtually ties with January 2016 and 2005 (Tedesco et al. 2007) as the most extensive in the area since 1979. In terms of melt index, defined as the duration-weighted area of melting, this season ranks fourth on record. To improve projections

FIG. 2. Number of melt days in January (a) 2016 and (b) 2017 on the West Antarctic ice shelves and ice sheet margins retrieved from 19-GHz horizontally polarized T_b from the SSMIS. The AWARE atmospheric observatories at WAIS Divide and McMurdo Station (McM) are highlighted in (a). Both extensive Ross-sector melt events were driven by atmospheric-river-like moisture plumes (Fig. S1).

of ice sheet behavior and global sea level rise (Kopp et al. 2017), it is crucial to understand the physical processes governing such melt events, including the meteorological drivers and their relationships with global and regional climate variability.

The leading mode of extratropical atmospheric variability in the Southern Hemisphere, the southern annular mode (SAM), describes the location and intensity of the circumpolar westerly winds encircling Antarctica. Although long viewed as an intrinsic mode of high-latitude dynamics sensitive to radiative forcing from stratospheric O_3 depletion and greenhouse gases (e.g., Thompson and Solomon 2002), the SAM is likely influenced by tropical Pacific climate variability (Ding et al. 2012; Schneider et al. 2012), although the governing mechanisms and interactions remain unclear. The second and third leading modes define the first and second Pacific–South American (PSA) patterns (Mo and Paegle 2001). The first PSA pattern (PSA-1) exhibits a classic Rossby wave train structure with a prominent center of action off the coast of West Antarctica. It is often interpreted as the Southern Hemisphere extratropical atmospheric response to El Niño–Southern Oscillation (ENSO) activity, with a positive (negative) phase frequently excited during El Niño (La Niña) events (Karoly 1989; Fogt et al. 2011). Nonetheless, the PSA-1 can also vary independent of tropical forcing (Irving and Simmonds 2016; O’Kane et al. 2017). By

controlling atmosphere–ocean heat transport, future variability in these modes—as influenced by tropical, radiative, and other forcing mechanisms—will play a critical role in the fate of the WAIS. However, further assessment of the historical record is needed to understand the context of any future changes.

In this study, we combine atmospheric reanalysis data from 1979 to 2017 with satellite-derived surface melt, cloud cover, radiation budget, and sea ice data to diagnose atmospheric and oceanic conditions associated with surface melting in West Antarctica. A synoptic climatological approach is used to identify physical drivers and surface energy fluxes responsible for melting of the WAIS and to examine its modulation by the full spectrum of ENSO and SAM activity since 1979, thereby extending the study by Nicolas et al. (2017). Motivated by our results and recent studies of twenty-first century Antarctic climate change, we also examine how the summer climate of West Antarctica has changed over the past several decades. In particular, we relate variability and trends in ice shelf surface melt to changing atmospheric and oceanic conditions, placing the WAIS in the context of recent Antarctic Peninsula climate variability (Turner et al. 2016) and circumpolar sea ice expansion (Meehl et al. 2016a). It is demonstrated that, since the late 1990s, the coastal Ross–Amundsen sector of the WAIS has very likely warmed during the summer melt season, as confirmed by multiple

consistent and independent lines of evidence. Notably, our results confirm and extend the findings of [Turner et al. \(2016\)](#).

Section 2 describes the observational data and methods used. Section 3 isolates dominant large-scale atmospheric circulation patterns and assesses their relationships with tropical Pacific and high-latitude climate variability. Section 4 diagnoses physical processes linking synoptic forcing to surface energy input and melt occurrence around the WAIS. Section 5 examines variability and trends in regional climate and melt conditions since 1979. We conclude with a summary of the results and conclusions.

2. Data and methods

a. Surface melt detection

Ice sheet and ice shelf surface melt can be detected from space owing to the drastic increase in microwave emissivity induced by liquid water in the uppermost layer of snow/firn ([Zwally and Fiegles 1994](#); [Tedesco et al. 2007](#)). Here we expand the analysis of the Antarctic surface melt record presented by [Nicolas et al. \(2017\)](#) for the Ross sector; hence only a brief description of the algorithm is provided here.

We map daily Antarctic surface melt occurrence using horizontally polarized K-band brightness temperature T_b data acquired by a series of spaceborne microwave radiometers. We combine Scanning Multichannel Microwave Radiometer (SMMR) 18.7-GHz T_b data from NASA's *Nimbus-7* spacecraft (1979–87) with Defense Meteorological Satellite Program (DMSP) SSM/I–SSMIS (1987–2006, 2006–present) 19.35-GHz T_b data, available on a 25-km Equal-Area Scalable Earth (EASE) Grid from the National Snow and Ice Data Center (NSIDC). Gaps in the SMMR data, which are available every other day, are filled via linear interpolation of the T_b from adjacent days. Data from each sensor are calibrated to the SSMIS F17 baseline. We use a simple threshold-based algorithm for snow/ice melt detection. For each pixel and each day, melt is detected when the ascending or descending T_b anomaly exceeds the previous cold season mean T_b , from 1 April to 31 March, by 30 K.

[Tedesco \(2009\)](#) showed that this algorithm agrees well with melt inferred from AWS temperature data and that it is sensitive to extreme melt events. However, uncertainty may arise because of variability in surface conditions and sensitivity to the satellite overpass time. In high-accumulation zones covered in deep, fresh snow (e.g., along Hobbs and Eights Coast), melt may be underestimated if meltwater percolates into the snowpack prior to being observed. Melt extent is

less ambiguous in regions of relatively low accumulation such as Siple Coast.

b. Atmospheric reanalysis

We estimate the large-scale atmospheric state using 700-hPa geopotential height (Z_{700}), 2-m air temperature (T_{2m}), and 10-m wind (u_{10} , v_{10}) fields on a 1° latitude–longitude grid from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; [Dee et al. 2011](#)). Previous studies suggest that, of contemporary reanalysis products, ERA-Interim provides the most accurate depiction of large-scale Antarctic atmospheric processes (e.g., [Bromwich et al. 2011](#); [Bracegirdle and Marshall 2012](#); [Jones et al. 2016](#)). For each variable, we calculate daily means from 6-hourly fields, which are converted to anomalies by removing the smoothed seasonal cycle at each grid point.

c. Clouds and radiation

We evaluate the role of clouds and radiation in snow/ice melt conditions using the extended Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP-x) NOAA climate data record ([Key et al. 2016](#)). APP-x provides retrievals of Antarctic cloud cover derived from visible–infrared satellite radiances. Surface radiation fluxes are computed using retrieved cloud and surface properties as input to the Streamer radiative transfer model ([Key and Schweiger 1998](#)). Here we use daily cloud and radiation fields at 1400 local solar time. Evaluations against polar field observations indicate that APP-x cloud and radiation anomalies are sufficiently accurate for the study of polar climate interactions and feedbacks ([Key et al. 2016](#)). Reanalysis cloud and radiation fields, by contrast, depend on uncertain model physics and hence are not used. In particular, low-level liquid-containing clouds are common during summer ([Scott et al. 2017](#)) but tend to be poorly represented in models.

d. Sea ice concentration

Sea ice conditions can influence ice shelf surface melt by modulating air–sea heat/moisture exchange and thus the energy content of marine air masses intruding over WAIS. Here we also use sea ice concentration (SIC) fields from the NSIDC sea ice concentrations from the *Nimbus-7* SMMR and DMSP SSM/I–SSMIS passive microwave product.

e. Antarctic melt season synoptic climatology

To identify processes linking large-scale atmospheric circulation and climate variability to snow/ice melt in West Antarctica, we develop a synoptic climatology for the peak summer (December–January) melt season spanning 1979–2017. For this purpose, we employ the methods of empirical

orthogonal function (EOF) and k -means cluster analysis applied to daily Z_{700} anomalies. We first derive the three leading modes of extratropical atmospheric variability—the SAM and PSA modes 1 and 2—through EOF analysis of Z_{700} anomalies poleward of 20°S. Each principal component (PC) time series is standardized to define a daily index for each mode. Our daily SAM index strongly correlates ($r = 0.91$, $p < 0.01$) with the daily SAM, or Antarctic Oscillation, index produced by the NOAA Climate Prediction Center. We next isolate nine dominant patterns of large-scale atmospheric circulation over West Antarctica using k -means cluster analysis (Hartigan and Wong 1979). This approximates the continuum of atmospheric flow as a discrete set of nine representative Z_{700} patterns by associating each daily Z_{700} field with the nearest cluster centroid according to the squared Euclidean distance metric. To enhance interpretation of the analysis, we order the patterns using linear unidimensional scaling following Johnson and Feldstein (2010). This method organizes the centroids along a linear dimension so that similar patterns are close by and small circulation changes correspond to minor changes in cluster index.

The atmosphere and snow/ice surface interact via radiative heat fluxes, influenced by clouds and radiatively active gases, and turbulent heat fluxes, governed by atmospheric boundary layer dynamics. To diagnose physical drivers of surface melt, for each synoptic pattern, we compare satellite-observed melt signatures to atmospheric anomalies pertinent to the surface energy balance. Melt anomalies are calculated by subtracting the 1979–2017 melt frequency from the pattern-based melt frequency (number of melt days normalized by the number of days in each cluster). ERA-Interim temperature and wind anomalies enable an assessment of boundary layer dynamics while serving as a proxy for the turbulent flux of sensible and latent heat. APP-x cloud and radiation anomalies are used to decipher the sky conditions and radiation components associated with and likely driving surface melt. Of particular interest are the downwelling fluxes, as they represent heating terms in the surface energy balance.

f. Climate and surface melt indices

Relationships among WAIS surface melting and remote tropical sea surface temperature (SST) forcing are assessed by (i) correlating the occurrence frequency of each synoptic pattern with tropical Pacific climate indices, (ii) compositing daily SAM and PSA indices as a metric of their relative strength and polarity in each Z_{700} centroid, (iii) correlating the SAM and PSA indices with global SST anomalies, and (iv) regressing seasonal melt occurrence anomalies onto large-scale climate indices. In addition to our derived indices, we use the Australian Bureau of Meteorology Southern Oscillation index (SOI), the National

Centers for Environmental Prediction Equatorial SOI (ESOI), and the NOAA Earth System Research Laboratory Niño-3, -4, and -3.4 region SST indices. All correlations are computed using detrended time series.

Seasonal melt conditions are quantified using the melt index (MI), defined for a given region as the duration-weighted area of melting. We also quantify each synoptic pattern's impact on surface melt by defining a normalized melt index as the melt index divided by the number of days in each cluster.

3. Synoptic forcing and tropical linkages

Figure 3 shows the SAM and PSA signatures in the extratropical Southern Hemisphere Z_{700} and T_{2m} fields as regressions of daily anomalies onto the index for each mode. In this study, we define the positive phase of each mode to be as shown in Fig. 3. Note, however, that opposite phases have opposite impacts on T_{2m} ; that is, where the positive phase promotes cooling, the negative phase promotes warming. Intensification of the SAM induces widespread WAIS cooling (Figs. 3a,b), whereas the PSA patterns favor advective warming of the Ross sector (Figs. 3c–f).

Correlations of each mode with global SST anomalies (Fig. 4) reveal significant relationships with SST in the Pacific basin. SST structures characteristic of La Niña events, or a negative phase of the Interdecadal Pacific Oscillation (IPO), favor +SAM, −PSA-1, and +PSA-2 phases, conducive to strong circumpolar westerlies and a deep Amundsen Sea low (ASL; Turner et al. 2013). By contrast, SST structures characteristic of El Niño events, or a positive phase of the IPO, favor −SAM, +PSA-1, and −PSA-2 phases, conducive to weak circumpolar westerlies and frequent blocking over the South Pacific. Consistent with amplification of the PSA-1 via ENSO Rossby wave forcing, PSA-1 correlations are significant across a broad area of the central-eastern tropical Pacific Ocean (Fig. 4b). Strong correlations with Southern Ocean SST anomalies likely reflect the impact of atmospheric forcing on the Southern Ocean SST field (Doddridge and Marshall 2017; Stuecker et al. 2017), as well as potential influence from surface diabatic heating on Z_{700} (Holton 2004).

Figure 5 illustrates the historical impact of the SAM and ENSO on surface melt conditions in West Antarctica as regressions of seasonal melt anomalies against the SAM, PSA-1, and inverted SOI. Cooling associated with intensification of the SAM favors significant reductions in melting on the Getz, Sulzberger, and Ross Ice Shelves (Fig. 5a). A weaker and largely insignificant influence is found in the ASE region. By contrast, increasing melt on eastern Antarctic Peninsula ice shelves

FIG. 3. Regression maps of (left) daily Z_{700} (gpm per standard deviation) and (right) T_{2m} (K per standard deviation) anomalies onto the standardized PC time series (indices) for the (a),(b) SAM and (c)–(f) PSA modes. Regions where the correlation is significant at $p < 0.05$ are outlined by gray contours.

FIG. 4. Correlation maps of global SST anomalies from NOAA ERSST.v4 with the (a) SAM, (b) PSA-1, and (c) PSA-2 indices for the period 1979–2017. Regions where the correlation is significant at $p < 0.05$ are outlined by gray contours.

is consistent with an increasing incidence and/or intensity of föhn winds (Luckman et al. 2014; Elvidge et al. 2016). Relaxation of the SAM notably has the opposite effect.

El Niño episodes favor enhanced surface melting in areas critical to the stability of the WAIS, from the Pine Island and Thwaites Glacier systems to the Ross Ice Shelf (Fig. 5c). Notably, El Niño events have historically

FIG. 5. Regression maps of seasonal surface melt anomalies onto the (a) SAM and (b) PSA-1 indices and the (c) inverted SOI for the period 1979–2017 (days per standard deviation). For the SAM, highly similar results are obtained using the Marshall (2003) index. White contours enclose areas where the correlation is significant at the 95% confidence level.

tended to coincide with a $-SAM$ (i.e., all except for 2015/16), as seen in maps of Z_{700} regressed onto the inverted SOI (not shown). While this may reflect tropical forcing of the SAM, the increase in coastal Pacific-sector surface melt during El Niño years is clearly driven by the $+PSA-1$ teleconnection (Figs. 5b,c). The opposing temperature and melt response to intensification of the SAM and PSA-1 (Figs. 3, 5) in the Ross sector provides additional evidence that the January 2016 melt event (Fig. 2a) was likely mitigated by the prevailing $+SAM$, as suggested by Nicolas et al. (2017). Similarly, our results also suggest that the long-term positive trend in the SAM (Fig. S4) has helped to protect the WAIS from surface melting.

Our Antarctic summer synoptic climatology is displayed in Fig. 6. Consistent with the preceding analysis and previous studies (e.g., Fogt et al. 2011), $+SAM$ circulations typically coincide with a deep ASL (patterns 1–4 and 6), whereas blocking highs are most pronounced under a $-SAM$ (patterns 5 and 7–9). Patterns 2–4 (8–9) correlate with La Niña (El Niño) conditions in the tropical Pacific Ocean (Table 1). Pronounced opposite phases of the PSA-1 appear in patterns 3 and 9. Table 2 lists the normalized melt index for various regions.

4. Physical mechanisms linking synoptic forcing to ice shelf and ice sheet surface melt

To diagnose atmospheric drivers of surface melt occurrence in West Antarctica, Figs. 7–9 present surface melt anomalies along with composite anomalies of T_{2m} , 10-m winds, cloud cover, and downwelling longwave (LW) and

shortwave (SW) fluxes at the surface for each synoptic pattern. Composite anomaly sea ice concentration fields, overlaid with 10-m winds, are shown in Fig. 10.

Pattern 1 has a $+SAM$ and a deep low over the Ross Sea (Fig. 6), which favors advection of marine air to the Ross–Amundsen sector. From Thwaites Glacier to the Sulzberger Ice Shelf, regionally enhanced melt is associated with positive cloud and downwelling LW flux anomalies. Locally reduced melt on Abbott Ice Shelf is accompanied by contrastingly cold, dry, clear skies. Southwesterly nonlinear föhn winds drive melt along the western Larsen C Ice Shelf (LCIS; Elvidge et al. 2016). The composite SAM and PSA-2 indices, along with Figs. 4a and 4c, suggest that this pattern may be forced by deep convection in the South Pacific convergence zone [supplemental Fig. S2 of Bromwich et al. (2013)].

Pattern 2 has the strongest $+SAM$ and is often present during La Niña events (Table 1). A deep low over the Bellingshausen Sea induces outflow of continental polar air (Nicolas and Bromwich 2011), favoring extreme cold temperatures and low melt occurrence (Table 2) around the WAIS. Along the coastal Pacific sector, negative melt anomalies are associated with excessive (deficient) incoming SW (LW) radiation. Melt on the LCIS, by contrast, is driven by linear föhn winds aided by cloud clearing and enhanced SW radiation (Luckman et al. 2014; Elvidge et al. 2016).

Pattern 3 has a weak $+SAM$, strong $-PSA-1$, and is favored by La Niña forcing. Along coastal Ellsworth Land, regionally enhanced surface melt is linked to advective increases in T_{2m} , cloud cover, and downwelling LW radiation. A föhn effect favors warming on upper Pine

FIG. 6. Antarctic summer synoptic climatology for the period DJ 1979–2017. Each panel shows a Z_{700} anomaly cluster centroid derived from ERA-Interim. At the bottom right, each panel lists the long-term occurrence frequency followed by composite indices of the SAM and PSA modes 1 and 2. All composite indices are distinct from zero ($p < 0.05$) except for the PSA-2 index of pattern 8.

Island Glacier and the southern Ross Ice Shelf. Interestingly, this warming is accompanied by enhanced cloud cover and downwelling LW radiation. On the LCIS, melt is driven by linear föhn winds and SW radiation (Elvidge et al. 2016).

Pattern 4, also correlated with La Niña, has a moderate +SAM. Low T_{2m} anomalies are widespread throughout West Antarctica. Weak föhn warming occurs on the Filchner Ice Shelf in response to cyclonic inflow of marine air from the Weddell Sea. Along the

TABLE 1. Synoptic pattern occurrence frequency correlations with tropical Pacific and high-latitude climate indices for the period 1979–2017. Correlations significant at the 95% (99%) confidence level are highlighted in bold (bold italic) font.

	SOI	ESOI	Niño-3.4	Niño-3	Niño-4	SAM	PSA-1	PSA-2
Pattern 1	0.29	0.23	−0.16	−0.18	−0.13	0.78	−0.11	0.33
Pattern 2	0.36	0.36	−0.34	−0.32	−0.36	0.80	−0.31	−0.05
Pattern 3	0.36	0.34	−0.39	−0.39	−0.34	0.25	−0.68	0.38
Pattern 4	0.34	0.34	−0.32	−0.22	−0.36	0.45	−0.08	0.38
Pattern 5	−0.15	−0.15	0.17	0.09	0.23	−0.15	−0.39	−0.35
Pattern 6	0.13	0.13	0.02	−0.02	0.09	0.21	0.09	0.09
Pattern 7	−0.20	−0.19	0.25	0.24	0.31	−0.39	0.36	0.33
Pattern 8	−0.43	−0.40	0.25	0.28	0.14	−0.80	0.03	−0.21
Pattern 9	−0.34	−0.34	0.27	0.27	0.22	−0.56	0.66	−0.46

coastal Ross–Amundsen sector, regionally enhanced melt coincides with enhanced cloud cover and downwelling LW radiation.

Pattern 5 shows weak −SAM and strong −PSA-2 variability. A northerly influx of marine air drives enhanced melting on the Ronne–Filchner Ice Shelf associated with positive T_{2m} , cloud cover, and downwelling LW flux anomalies. Maritime föhn winds drive positive melt anomalies on the George VI and Filchner Ice Shelves. In contrast, continental föhn winds produce minimal surface melt along the coastal Pacific sector.

Pattern 6 has a +SAM and is the most frequent pattern during the study period. The Antarctic Peninsula experiences warming via direct northerly advection of marine air from off the subtropical coast of South America. While previous studies emphasize northwesterly föhn winds as the primary driver of surface melt on eastern Antarctic Peninsula ice shelves (e.g., [Elvidge et al. 2016](#); [King et al. 2017](#)), this scenario drives the highest melt occurrence of any pattern with a +SAM.

Of the five +SAM patterns (1–4 and 6), only 3 and 6 are capable of driving temperatures in West Antarctica above mean background summer conditions. Warming is primarily found on the Antarctic Peninsula and Ellsworth Land. Consistent with the recent Antarctic Peninsula temperature trends described by [Turner et al.](#)

(2016), these patterns increased in frequency to a peak in the late 1990s and declined thereafter (Fig. S3).

Pattern 7 generates extreme warming and extensive surface melting over Siple Coast and the Ross Ice Shelf. With −SAM and +PSA forcing, a blocked low pressure system drives strong meridional advection of heat and moisture into western West Antarctica. Positive anomalies of T_{2m} and cloud cover favor widespread enhancement of the downwelling LW radiation at the surface ([Nicolas et al. 2017](#); [Scott et al. 2017](#)). Föhn winds in the lee of the Edward VII Peninsula (~750 m tall) and high terrain in Marie Byrd Land promote adiabatic warming and efficient turbulent mixing of sensible heat to the surface. Upslope coastal precipitation and latent heating likely add energy to the intruding air mass. Together with drawdown of potentially dry air from aloft, this tends to reduce cloudiness and cloud optical thickness on leeward slopes (e.g., Fig. S1). Notably, this pattern characterizes the onset of the January 2016 and 2017 melt events (Fig. 2). Composite atmospheric anomalies during the onset/expansion of all major melt events in the satellite record closely resemble pattern 7, confirming it as a major historical driver of surface melting in the Ross sector (not shown). On the Antarctic Peninsula and Abbott Ice Shelf, enhanced melting is associated with warm temperatures, anomalously clear skies, and enhanced incoming SW radiation.

TABLE 2. Normalized melt index (km^2) in different regions for each synoptic pattern shown in Fig. 6. The Ross sector includes the Siple Coast, Ross Ice Shelf, and Sulzberger Ice Shelf as in [Nicolas et al. \(2017\)](#). The Pacific sector encompasses the coastal region from the Abbott Ice Shelf and ASE to the Getz Ice Shelf.

	West Antarctica	Pacific sector	Ross sector	Antarctic Peninsula
Pattern 1	175 510	17 855	17 192	140 463
Pattern 2	166 736	13 102	2057	151 577
Pattern 3	233 775	32 276	10 149	191 350
Pattern 4	196 374	25 747	24 667	145 980
Pattern 5	209 564	22 367	8449	178 748
Pattern 6	266 854	39 270	16 846	210 738
Pattern 7	308 041	57 023	52 766	198 252
Pattern 8	334 080	63 205	49 492	221 383
Pattern 9	268 319	41 743	35 692	190 884

FIG. 7. Satellite-derived West Antarctic surface melt anomalies, ERA-Interim composite T_{2m} and 10-m wind anomalies, and APP-x composite cloud cover and downwelling LW and SW surface radiative flux anomalies associated with synoptic patterns 1–3 in Fig. 6. Each row corresponds to a large-scale atmospheric circulation pattern identified by k -means cluster analysis in Fig. 6.

Pattern 8 has the strongest $-SAM$ and is correlated with the inverted SOI (Table 1), consistent with El Niño–induced weakening of the circumpolar westerlies (Ding et al. 2012; Schneider et al. 2012). Extreme warming and extensive surface melting affect much of West Antarctica. Along with weak $-PSA-1$ forcing, ridging centers over the Antarctic Peninsula and Ross Sea promote advection of marine air toward Ellsworth Land and the Ross Ice Shelf, respectively. Enhanced coastal melt coincides with positive T_{2m} and downwelling LW flux anomalies. Föhn winds induce warming and melting on upper Pine Island Glacier and the western Ronne Ice Shelf, in the lee of the southern Antarctic Peninsula. Consistent with the long-term positive trend in the SAM (Fig. S4), this pattern has decreased ($p < 0.05$) in frequency since 1979.

Pattern 9 has a moderate $-SAM$ and strong $+PSA-1$ (Fig. 6), consistent with El Niño forcing (Table 1; Figs. 3–4). Along the Ross Ice Shelf and coastal Marie Byrd Land, onshore flow from an area of anomalous open water in the Ross Sea (Fig. 10) drives enhanced melting associated with enhanced T_{2m} , cloud cover, and downwelling LW radiation. The increased cloud cover also favors strong reductions in incoming SW radiation. Interestingly, this pattern has increased ($p < 0.05$) in frequency since the late 1990s.

Anomalous open water conditions tend to be collocated or situated to the west of anomalous high pressure zones (Figs. 6, 10). Thus, atmospheric heat and moisture transport events that drive melting on ice shelves also serve as an important driver of regional sea ice loss, in part by enhancing the downwelling LW radiation (figure omitted; e.g., Tjernström et al. 2015). However, sea ice is also influenced by processes in the upper ocean. Less sea ice enables ocean heat/moisture release into the lower troposphere, which may, in turn, influence the structure of the marine boundary layer, low-cloud formation, and the surface energy balance on ice shelves downwind. Patterns with the least surface melting on Pacific-sector ice shelves have strong positive coastal sea ice concentration anomalies (patterns 1–2). In contrast, patterns with enhanced ice shelf surface melting show strong negative sea ice concentration anomalies upwind (e.g., patterns 7–9).

5. Amundsen Sea blocking index

The preceding analysis shows that West Antarctica experiences amplified summer temperature extremes for low- versus high-index patterns for which the SAM and PSA-1 tend to be mutually out of phase. That is,

FIG. 8. As in Fig. 7, but for synoptic patterns 4–6.

negative T_{2m} and surface melt anomalies occur for low-index patterns (1–3) with a deep ASL, characterized by a +SAM and –PSA-1 or by strong +SAM and weak +PSA-1 (pattern 1). In contrast, positive T_{2m} and surface melt anomalies are found for high-index patterns (7–9) exhibiting a –SAM and +PSA-1 or exhibiting strong –SAM and weak –PSA-1 (pattern 8).

Expanding on the preceding analysis, we next examine variability and trends in blocking and geopotential height, and their relationship with WAIS melt conditions, by defining an Amundsen Sea blocking index (ASBI). We define ASBI as the standardized area-weighted mean Z_{700} anomaly over the Amundsen Sea (AS) across 55° – 70° S and 230° – 260° E. This index captures concurrent variability in the PSA-1 ($r = 0.87$, $p < 0.01$) and SAM ($r = -0.72$, $p < 0.01$), and is significantly correlated ($p < 0.01$) with the occurrence frequency of synoptic patterns 7 ($r = 0.51$) and 9 ($r = 0.75$). This is notably analogous to the Greenland blocking index used to assess atmospheric circulation and surface melt conditions in Greenland (Hanna et al. 2013). Positive values indicate anomalously high domain-wide Z_{700} and anticyclonic flow, conducive to warm temperatures along coastal West Antarctica. Daily and seasonal variations in ASBI are shown in Fig. 11.

Coastal Ross–Amundsen-sector surface melt is often triggered by +ASBI events (cf. Fig. 11 with Fig. S5), a prominent example being the 1991/92 season having the

largest Ross sector MI on record (Fig. S6). In mid-December 1991, a persistent anticyclone over the AS (Fig. 11a) induced meridional advection of marine air and caused concentrated melting along Marie Byrd Land and the Ross Ice Shelf. The melt area persisted through mid-January and refroze as the anticyclone decayed. Prominent blocking is also seen from 10 to 13 January 2016, when a rapid increase in melt extent occurred on the Ross Ice Shelf.

Opposite extremes of ASBI tend to be associated with opposite phases of the ENSO cycle, with strong positive (negative) spikes found during El Niño (La Niña) years (Fig. 11b; Table 3). For example, 1979/80, 1982/83, 1987/88, 1991/92, 1997/98, and 2015/16 all correspond to El Niño episodes with strong +ASBI and enhanced melting in West Antarctica (Fig. S5). Similarly, 1988/89, 1998/99, 2001/02, and 2011/12 correspond to La Niña years having a deep ASL and +SAM. Early +ASBI spikes prior to the positive-to-negative IPO shift in the late 1990s (Turner et al. 2016; Meehl et al. 2016a) reflect concurrent –SAM and +PSA-1 conditions. For approximately a decade following the IPO shift, the atmospheric circulation over the AS region was dominated by –ASBI conditions. In contrast, in more recent years +ASBI spikes reflect amplified +PSA-1 forcing.

The seasonal ASBI time series shows an insignificant negative trend from 1979 into the late 1990s, followed

FIG. 9. As in Fig. 7, but for synoptic patterns 7–9.

by a significant ($p < 0.05$) positive trend attributable to a sharp increase in blocking activity in the latest decade, reflecting amplification of the PSA-1 mode (Fig. 11b; Fig. S4). Motivated by this observation and recent studies of twenty-first century Antarctic climate change (Turner et al. 2016; Meehl et al. 2016a), in the following section, we examine trends in regional climate conditions in West Antarctica during two periods, selected for consistency with the latter studies, referred to as period 1 from 1979/80 to 1998/99, and period 2 from 1998/99 to 2016/17. Notably, our conclusions are largely insensitive to the midpoint used in the trend calculations, as confirmed by perturbing it by ± 3 seasons.

6. Twenty-first century West Antarctic summer climate trends

Figures 12–14 show linear trends in the large-scale atmospheric circulation, West Antarctic surface melt, and sea ice concentration during both periods. During period 1, the SAM intensified ($p < 0.05$; Fig. S4). Satellites observed rapid increases in surface melt on the Antarctic Peninsula in response to increasing northwesterly to northerly flow, as exemplified by the increasing frequency of synoptic patterns 3 and 6 (Fig. S3). At the same time, sea ice concentrations declined around the Antarctic Peninsula, with especially strong losses upwind, west of the peninsula (Fig. 14a). An

insignificant decrease in surface melt occurrence was observed along the coastal Ross–Amundsen sector (Fig. 12b). An overall decline in melt index, associated with intensification of the SAM, was punctuated by several warm, high-melt-index El Niño years (Fig. S6).

During period 2, consistent with the positive ASBI trend shown in Fig. 11b, Z_{700} increased over the Amundsen–Bellingshausen Seas (Fig. 12b), causing an anticyclonic advective influx of marine air toward coastal West Antarctica. Satellite T_b data reveal increasing surface energy input and melt occurrence on ice shelves and ice streams critical to the stability of the WAIS from the Pine Island and Thwaites Glacier systems to the eastern Ross Ice Shelf (Fig. 13b). Especially rapid increases in surface melt are seen on the Sulzberger Ice Shelf. At the same time, sea ice cover declined upwind in the coastal Ross–Amundsen Seas (Fig. 14b), suggesting a common atmospheric forcing and amplification of ice shelf surface melt due to increasing (e.g., Taylor et al. 2018) turbulent heat loss from the ocean into the lower troposphere. This, in turn, may have enhanced the formation and abundance of low-level liquid-containing clouds, which are common in coastal West Antarctica during summer, especially during periods of onshore flow (Scott and Lubin 2014; Scott et al. 2017). Such clouds have also previously been implicated in causing and prolonging advective episodes of surface

FIG. 10. Composite anomalies of West Antarctic SIC and 10-m vector wind for each synoptic pattern in Fig. 6.

melting in the Arctic (Bennartz et al. 2013; Tjernström et al. 2015; Van Tricht et al. 2016).

Consistent with cooling of the Antarctic Peninsula since the late 1990s described by Turner et al. (2016), Z_{700}

decreased over the Weddell Sea during period 2 (Fig. 12b), favoring cold southeasterly flow and compaction of sea ice against the peninsula (Fig. 14b). As sea ice concentrations increased upwind, now east of the peninsula, satellites

FIG. 11. (a) Daily and (b) seasonal mean time series of the ASBI from 1979 to 2017. The year corresponds to January (e.g., 80 represents the 1979/80 melt season).

observed decreasing ice shelf surface melt (Fig. 13b) consistent with a decreasing ocean influence on the regional climate.

Interestingly, aside from the 2015/16 El Niño, the recent increase in AS blocking activity does not appear to be explained by tropical forcing. Unprecedented +ASBI and moderate −SAM conditions prevailed in 2016/17,

when pattern 9 characterized 55% of the circulation, inconsistent with concurrent weak La Niña forcing. Thus, some other mechanism is likely required to explain these changes, such as changes in SST and/or sea ice conditions offshore or rising global temperatures. We suggest that persistent +SST anomalies in the AS in excess of 1.5°C (e.g., Stuecker et al. 2017), through

TABLE 3. Correlations among indices of Amundsen Sea atmospheric blocking activity, West Antarctic surface melt, and tropical Pacific and high-latitude climate variability. Correlations significant at the 95% (99%) confidence level are highlighted in bold (bold italic) font.

	SOI	ESOI	Niño-3.4	Niño-3	Niño-4	ASBI	SAM	PSA-1	PSA-2
ASBI	<i>−0.51</i>	<i>−0.50</i>	<i>0.50</i>	<i>0.49</i>	<i>0.45</i>	<i>1</i>	<i>−0.72</i>	<i>0.87</i>	0.31
Ross sector MI	<i>−0.61</i>	<i>−0.61</i>	<i>0.55</i>	<i>0.56</i>	<i>0.42</i>	<i>0.54</i>	<i>−0.41</i>	<i>0.41</i>	0.18
Pacific sector MI	<i>−0.39</i>	<i>−0.43</i>	<i>0.35</i>	<i>0.39</i>	0.27	<i>0.43</i>	−0.3	<i>0.42</i>	0.06
Pine Island to Getz Ice Shelf MI	<i>−0.45</i>	<i>−0.48</i>	<i>0.42</i>	<i>0.46</i>	<i>0.34</i>	<i>0.53</i>	<i>−0.38</i>	<i>0.50</i>	0.08
Abbott Ice Shelf MI	−0.28	<i>−0.33</i>	0.25	0.28	0.17	<i>0.53</i>	<i>−0.26</i>	<i>0.33</i>	0.06

FIG. 12. Linear trends in the large-scale atmospheric circulation (Z_{700} ; gpm yr^{-1}) during the austral summer melt season (DJF) during (a) period 1 and (b) period 2 from ERA-Interim. Gray contours enclose areas with a trend significant at $p < 0.05$.

diabatic heating of the lower troposphere, may have helped maintain the strong 2016/17 blocking (e.g., Fig. 3b). Unprecedented sea ice loss in 2016 may have also preconditioned the atmosphere for extensive

surface melting in January 2017 (Fig. 2b). Notably, many seasons with strong blocking and enhanced melting in West Antarctica (e.g., 1991/92, 2012/13; Fig. S5) also exhibit +SST anomalies offshore (not shown).

FIG. 13. Linear trends in West Antarctic ice shelf and ice sheet surface melt occurrence during austral summer during (a) period 1 and (b) period 2 from passive microwave T_b data. White contours enclose regions with a trend significant at $p < 0.1$ assessed using a Mann-Kendall test.

FIG. 14. Linear trends in West Antarctic SIC during austral summer during (a) period 1 and (b) period 2. White contours enclose regions with a trend significant at $p < 0.05$ assessed using a Mann-Kendall test.

7. Summary and conclusions

Observations of atmospheric warming events and the physical processes that drive surface melting in West Antarctica are extremely rare, being limited to sporadic AWS measurements and the AWARE observations made in January 2016. To address this gap, we combined multidecadal atmospheric reanalysis and satellite data to diagnose large-scale climate and local meteorological processes responsible for melting of the WAIS and to shed light on its historical variability.

Surface melting in West Antarctica is primarily driven by intrusions of warm, moist marine air. Positive and regionally enhanced melt anomalies are typically found in conjunction with enhanced cloud cover, enhanced downwelling LW radiation, reduced downwelling SW radiation, downslope winds having maritime origins, and reduced sea ice cover offshore. Advective enhancement of the lower-tropospheric temperature and cloud cover imparts an infrared (LW) radiative heating of the snow/ice surface. Downslope flows having warm maritime origins favor adiabatic warming and turbulent deposition of sensible heat into the surface but tend to reduce cloudiness and cloud optical thickness through subsidence. Föhn warming is pronounced over Siple Coast and the Ross Ice Shelf (pattern 7), as well as on Pine Island Glacier (patterns 3 and 8). Classic föhn melt

conditions associated with clear skies and enhanced SW radiation are especially frequent on Antarctic Peninsula ice shelves. Low sea ice concentrations offshore favor surface melting on ice shelves downwind by enabling heat/moisture release from the ocean into the lower troposphere, potentially favoring low-cloud formation (Scott et al. 2017).

On the large scale, marine air intrusions are favored by synoptic blocking events over the AS region, which are often forced by Rossby waves excited by tropical convection during El Niño events. Here we presented observational evidence that the El Niño + PSA-1 teleconnection drives significant increases in surface melting on Pacific-sector coastal ice shelves and unstable, fast-flowing glaciers that drain into the ASE, as well as the Ross Ice Shelf. Our results add to a growing body of evidence suggesting that the projected increasing frequency of extreme El Niño events (Cai et al. 2014; Wang et al. 2017), and a return to positive IPO conditions (Meehl et al. 2016b), will increase the risk of WAIS disintegration along the Ross-Amundsen sector (Nicolas et al. 2017; Deb et al. 2018; Paolo et al. 2018). Modulation of this effect, as the WAIS is exposed to increasing +PSA-1 conditions, will depend on the competing tropical and radiative influences on the SAM. Enhanced surface melting is expected if the positive SAM trend relaxes or reverses polarity.

Since the late 1990s, the coastal Ross–Amundsen sector of the WAIS has very likely warmed during the summer melt season, as reflected by several consistent and independent lines of evidence. Satellites reveal increasing surface melt occurrence along the coast from the Pine Island and Thwaites Glacier systems to the northeastern Ross Ice Shelf. Sea ice concentrations also declined in the coastal Ross–Amundsen Seas, enabling increased ocean heat/moisture release into the lower troposphere, potentially exposing the ice shelves to additional stress from incoming ocean swell (Massom et al. 2018). We link these changes to amplification of the +PSA-1 mode within the last decade, which suggests a possible atmospheric component to the acceleration of WAIS mass loss during the same period (Shepherd et al. 2018).

During December–January (DJ) 2012/13, GPS units deployed on the Pine Island Glacier ice shelf observed an abrupt 0.2–0.3-m drop in surface elevation following a period of warm temperatures (1°–5°C) accompanied by surface melting and rainfall (Shean et al. 2017). Landsat imagery also reveals melt-pond formation and growth on Pine Island Glacier during DJ 2013/14 (Kingslake et al. 2017, extended data Fig. 3 therein). Both seasons had strong blocking highs offshore (Fig. 11b), conducive to long-range transport of marine air and warm conditions in the ASE region. Although recent melt index levels do not appear entirely unusual (Fig. S6), the satellite observations used herein provide no information regarding changes in surface melt intensity (magnitude) or melt rate. Nonetheless, Landsat imagery suggests that melt ponding on Pine Island Glacier has increased since the 1990s, being especially frequent in recent years (Kingslake et al. 2017, extended data Fig. 4 and Table 2 therein).

To better constrain the role of atmospheric forcing in WAIS mass loss in the future (DeConto and Pollard 2016), it is critical that coupled climate and ice sheet models accurately represent decadal variability in the Pacific Ocean and associated teleconnection patterns; cloud microphysical processes, surface radiative effects, and boundary layer meteorology over WAIS; sea ice conditions in the coastal ocean; and the effects of surface meltwater on ice dynamics. While our study examined relationships between meteorological conditions and surface melt occurrence, future efforts should investigate relationships between meteorological conditions and meltwater fluxes pertinent to crevasse infiltration, firn air depletion, and melt-pond development. Additional field measurements, regional atmospheric modeling, and satellite active microwave studies are needed to understand finescale melt features and the relative importance of clouds, radiation, and turbulence in

critical areas such as the ASE and Ross Ice Shelf. Nonetheless, our study provides critical insight to the processes governing surface melting in West Antarctica, including its recent evolution and expected response to future tropical and polar climate forcing.

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