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Rapid Changes in Outlet Glaciers on the Pacific Coast of East Antarctica Driven by Climate

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Observations of ocean-terminating outlet glaciers in Greenland and West Antarctica[1-6] indicate that their sea level contribution is accelerating due to increased velocity, thinning and retreat[7-11]. Thinning has also been reported along the margin of the much larger East Antarctic Ice Sheet[1] (EAIS), but whether glaciers are advancing or retreating there is largely unknown, and there has been no attempt to place such changes in the context of localised mass loss[7,9] or climatic/oceanic forcing. Here we present multi-decadal trends in the terminus position of 175 ocean-terminating outlet glaciers along 5,400 km of the EAIS margin and reveal widespread and synchronous changes. Despite large fluctuations between glaciers - linked to their size – three epochal patterns emerged: 63% of glaciers retreated from 1974 to 1990, 72% advanced from 1990 to 2000, and 58% advanced from 2000 to 2010. These trends were most pronounced along the warmer Pacific coast, whereas glaciers along the cooler Ross Sea coast experienced no significant changes. We find that glacier change

along the Pacific coast is consistent with a rapid and coherent response to air temperature and sea-ice trends, linked through the dominant mode of atmospheric variability (the Southern Annular Mode). It is concluded that parts of the world's largest ice sheet may be more vulnerable to external forcing than previously recognised.

Ice sheets lose mass through melting (surface or basal) and dynamic changes (e.g. acceleration and retreat of outlet glaciers). For the Greenland Ice Sheet (GrIS), these two components have made an approximately equal contribution to its recent negative mass balance[12]. In Antarctica, surface melt is much less significant, but the West Antarctic Ice Sheet (WAIS) is thought to be vulnerable to oceanic warming because large parts of its bed lie below sea level[13]. Recent estimates have also confirmed its negative mass balance[9-11]. In contrast, the mass balance of the much larger East Antarctic Ice Sheet (EAIS) is closer to equilibrium or slightly positive[7,9-11], but recent thinning (2003-2007) has been detected on several major outlet glaciers[1], resulting in negative imbalances in some catchments[7,9]. Similar thinning of outlet glaciers in the GrIS, WAIS and the Antarctic Peninsula (AP) over the last two decades has been associated with glacier acceleration and changes at their termini [2,6,8,14], predominantly retreat and the thinning/collapse of ice shelves[5,6]. However, unlike the GrIS [2,17], WAIS[4], and AP[16], there has been no comprehensive analysis of glacier terminus positions in East Antarctica. Measurements on a small number of glaciers (<20) revealed cyclic behaviour with no obvious trend or a reduction in their floating area since the 1950s[17,18].

Here we use ~300 satellite images (spanning 1963 to 2012) to map the terminus position of a comprehensive set of 175 glaciers along 5,400 km of the EAIS, stretching from Queen Mary Land (90°E) to Victoria Land (170°E) (see Methods Summary and Supplementary Table 1). This region represents about a third of the EAIS margin and was selected because: (i) it encompasses two regions of pronounced mass loss (Wilkes and Victoria Land)[7,9], (ii) large parts are grounded below sea level[19], which may enhance its vulnerability to oceanic forcing, and (iii) the absence of large ice shelves makes individual glacier termini readily identifiable. Glaciers in this region encompass a range of widths (0.65 to ~57 km) and flow speeds (~155 to ~1,400 m a^{-1}) and all calve into the ocean, with most (~90%) possessing floating extensions, and many (~84%) unconstrained by lateral boundaries (e.g. fjord walls) at their terminus. To minimise the influence of short-term inter-annual variations and major (potentially stochastic) calving events that are known to occur[17,18], we focus on large numbers of glaciers at approximately decadal time-steps (1974, 1990, 2000 and 2010), but the measurement years were dictated by the availability of imagery when most glaciers (n >130) could be mapped.

A small set of glaciers (n = 38) measured in 1963 and 2010 show an overall pattern of retreat (median terminus position change: –12.9 m a^{-1}, mean: –61.2 m a^{-1}) (Table 1). However, a larger set (n = 132) measured in 1974 and 2010, show very little overall change (median: 0.7 m a^{-1}, mean: –2.7 m a^{-1}), but there are clear phases of advance and retreat within this period (Fig. 1). Specifically, 1974 to 1990 was characterised by retreat (63% of glaciers) at a median rate of –12.5 m a^{-1} (mean: –43.3 m a^{-1}). From 1990 to 2000, however, this trend was reversed, when 72% of glaciers advanced at a median rate of 19.7 m a^{-1} (mean: 43.1 m a^{-1}). During the most recent period, 2000 to 2010, the number of advancing glaciers fell to 58% and the median decreased to 8.4 m a^{-1} (mean: –17.9 m a^{-1}).

The magnitude of advance or retreat experienced by different glaciers varies considerably (Fig. 2) and is linked to their width, which is correlated with glacier speed (Supplementary Fig. 1). Thus, large glaciers with higher flow speeds tend to undergo the largest changes, in both advance and retreat phases. Several large glaciers (e.g. those >15 km wide) experienced major calving events that caused retreats of tens of kilometres followed by re-advance, indicating cyclic behaviour potentially unrelated to external forcing (Supplementary Fig.'s 2 and 3). This process might introduce considerable variability and obscure any trends. However, the inclusion/exclusion of large glaciers appears to have little influence: the switch from retreat (1974-1990) to advance (1990-2000) is very highly significant (P-value < 0.0005) irrespective of whether large glaciers are included (Fig. 2a, b; Supplementary Table 2). Significant differences ($P < 0.05$) are also found between the latter two epochs, due to an increased number of glaciers undergoing retreat from 2000-2010 compared to 1990-2000. However, the significance levels are lower because of the more even mix of advance and retreat in the most recent epoch (Supplementary Table 3).

These trends in terminus retreat/advance are most pronounced along the western South Pacific coast (Fig. 2c), where the changes from retreat (1974-1990) to advance (1990-2000) and back to retreat (2000-2010) are significant (Supplementary Tables 2 and 3). In contrast, those facing the Ross Sea (Fig. 2d) show no significant differences between any epochal divisions. Thus, there is a regional difference between Pacific-facing glaciers, which generally lie along the Antarctic circle (66° 33′), and those further south that face the Ross Sea (Fig. 1), suggesting a potential link to climate forcing.

Mean annual and mean winter (June, July August) air temperatures at three stations along the Pacific coast (Dumont d'Urville, Casey and Mirny: Fig. 1) are around 9 °C and 12 °C warmer, respectively, than at Scott Station along the Ross Sea coast (Supplementary Figure 4). Annual/winter data show no clear trends at any station. However, the 1974-1990 mean austral summer temperature was significantly warmer (~1° C) than the 1990-2000 mean at all Pacific stations, but not at Scott station (Fig. 3; Supplementary Table 4). The long-term warming before 1990 is most pronounced at Casey (0.22 °C per decade) and Dumont d'Urville (0.15 °C per decade), where daily summer temperatures are close to and occasionally climb above 0°C, but the Ross Sea trend shows a cooling over the same period (1963-1990). The most recent period (2000-2010) was slightly warmer (~0.5° C) than the 1990-2000 period at all four stations, but the differences are not statistically significant and temperatures were not as high compared with the 1974-1990 epoch.

Significant changes in air temperature along the Pacific coastline are therefore consistent with significant changes in terminus position in that region (Fig. 3), with the relatively warm period in the 1970s/1980s associated with glacier retreat, and subsequent cooling during the 1990s coinciding with advance. Warming in the first half of the 2000s might also explain the larger number of glaciers that retreated in the 2000 to 2010 period, compared with 1990 to 2000 (Fig 3), but both warming and retreat are shorter-term than before 1990 and, since 2005, there has been a return to cooling. This is consistent with the larger range in terminus position change and the weaker, but still significant differences. In contrast, there are no significant trends in air temperatures or glacier behaviour in the colder Ross Sea region.

These patterns hint at the possibility that the response of outlet glaciers along the Pacific Coast is related to the degree of surface melting. Indeed, meltwater ponds are identifiable on glaciers along this coast (Supplementary Fig. 2), and January temperatures at Casey (1974 to 1990) were, on average, only 0.7°C cooler than at Faraday (AP), where glacier retreat has been linked to atmospheric warming[16]. Increased surface melt during warmer than average summers has the potential to enhance the opening of crevasses close to the glacier terminus, and hence calving, through hydraulic-fracturing[20], as suggested for ice shelf break-up in the AP[21]. This may partly explain the relationship between austral summer temperatures and terminus change, and this hypothesis is supported by the lack of significant trends for glaciers located in the much colder Ross Sea region (Fig. 2 and 3).

While it is appealing to invoke this relationship between terminus change and air temperatures, it is unlikely that they are the only or most important forcing. Trends in air temperature are connected to synchronous changes in the ocean-atmosphere system through the dominant mode of atmospheric variability known as the Southern Annular Mode (SAM), which influences wind speed and direction, sea-ice concentrations, sea-surface temperatures, and coastal ocean upwelling[22-26]. Positive phases of the SAM index, increasingly common during the last two decades (Fig. 3), and linked to both increased greenhouse gas concentrations and ozone depletion[23,26], are associated with cooler temperatures over East Antarctica, increased sea-ice concentrations, and enhanced westerly airflows[22,23,25]. Above-average fast-ice extent along the Pacific coast has also been noted in the study region in the 1990s and related to a change in wind direction from predominantly offshore to more along-shore[24]. Indeed, several studies report increasing sea-ice concentrations in the study region from ~1980 to 2010[22,23,25,28,29], which is consistent with the predominance of glacier advance since 1990, when above average sea/fast-ice concentrations could have suppressed calving by increasing back-pressure on glacier termini[27]. In contrast, reduced sea-ice concentrations from the 1950s to mid-1970s[28] are consistent with glacier retreat during the 1960s and 1970s, when air temperatures were also increasing along the Pacific coast (Fig. 3). A complicating factor is that positive phases of the SAM are associated with increased coastal upwelling of warmer Circumpolar Deep Water (CDW)[22,25]. Intrusion of this water onto the continental shelf could result in increased basal melting and weakening of ice tongues/shelves[14,18], but there are few deep submarine troughs within the study area[14], and it would appear from our data that this process is yet to exert a major influence. Rather, despite the limitations imposed by our decadal measurements, we highlight tentative correlations between terminus position change and both air temperatures and the SAM index, which suggests that a ~1°C change in mean summer temperature is manifest as a median terminus position change of 0.5 km per decade (Supplementary Figs 5 and 6).

Finally, glacier thinning has recently occurred along the Pacific coast in Wilkes (DB12/13) and Victoria Land (DB14/15)[1,9]. Elsewhere in Antarctica, similar rates of thinning have been linked to retreat and a reduction in buttressing, causing flow acceleration[4-6], but similar accelerations have not been reported in our study area[7]. The region of most pronounced mass loss (DB13)[1,7,9,] is the only drainage basin to show a significant return to retreat from 2000 to 2010 (Supplementary Table 6), but a wider comparison indicates that while glaciers that are thickening exhibit very little terminus change, those that are thinning are associated with both retreat and substantial advance (Supplementary Fig. 7). This indicates a more complex coupling between glacier discharge (e.g. velocity and elevation change) and terminus position than has been observed in the GIS, WAIS and AP, because the floating extension of most glacier termini in our study area are unconstrained and they do not exert any substantial buttressing. It may be that any future warming, perhaps driven by oceanic warming, or ozone recovery that results in a more negative SAM index[23,26], will thin or remove unconstrained ice tongues/shelves along the Pacific coast, such that terminus retreat has greater potential to induce dynamic mass loss, as observed elsewhere around Antarctica[5,14]. However, while we detect a previously unrecognised widespread, rapid and synchronous response to large-scale atmospheric/oceanic variability, there is a clear requirement to understand the precise drivers of glacier dynamics in order to interpret and predict near-future mass loss from the EAIS. In particular, our results imply that the vulnerability of large parts of the EAIS margin requires urgent reassessment.

METHODS SUMMARY

We used optical satellite imagery to map the terminus position of 175 neighbouring outlet glaciers. To remove intra- and inter-annual variability at short time-scales, termini were mapped at the end of the austral summer at approximately decadal time-steps. Measurements were made on ~300 Landsat satellite images. The requirement for a comprehensive sample of glaciers spanning 5,400 km of coastline meant that only four main time-steps allowed cloud-free mapping of the majority of glacier termini in the study area: 1974, 1990, 2000 and 2010 (Supplementary Table 1). A sub-sample of glaciers (38) were mapped with ARGON imagery from 1963, but few of these could be re-measured in 1974 and they were widely spread geographically, which is why we exclude this epoch from detailed analysis. The accuracy of the mapping was dictated by co-registration of imagery and is ±75 to ±210 m for Landsat imagery and up to ± 420 m for some ARGON imagery. Overall, 85% of measurements have an error below ±180 m, comparable to a study from the Antarctic Peninsula[16] and sufficient for extracting decadal trends. To account for uneven changes along the calving front, termini were digitised within a reference box that delineated the sides of the glacier[2]. The mean retreat distance was calculated as the area change between each measurement, divided by glacier width. For comparison to elevation change measurements (2003-2007)[1], we mapped a sample of glaciers in austral summer 2006/2007 (Supplementary Fig. 7). Monthly mean surface air temperatures (Fig. 1) were extracted from the SCAR Met reader project (http://www.antarctica.ac.uk/met/READER/) and monthly values of the Southern Annular Mode (SAM) index were obtained from http://www.nerc-bas.ac.uk/icd/gjma/sam.html. To test for significance differences in terminus change and air temperatures between epochs, we used the Student's t-test, the Wilcoxon's Signed-Rank test, and the Wilcoxon Ranked-Sum test, where appropriate.

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Supplementary Information is available.

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Author contributions:

C.R.S and A.V. conceived the research. B.W.J.M. designed and undertook the mapping and data collection, and led the climate analysis. N.J.C. led the statistical analysis and all authors contributed to the analysis and interpretation of the results. C.R.S. wrote the first draft of the paper and all authors contributed to the writing.

Table:

Table 1: Changes in glacier terminus position during different epochs from 1963 to 2010. Negative values denote mean/median retreat (red) and positive denote advance (blue). Data include all glacier measurements available at each time-step (Fig. 1) but, for comparability, values in parentheses are for 128 glaciers measured at every time-step, which reveal near-identical trends. Mean values are sensitive to extreme events (i.e. calving of major ice tongues), suggesting that median values are more robust.

Dates	**1963-2010**	**1974-2010**	**1974-1990**	**1990-2000**	**2000-2010**
Number of glaciers	38	132	131 (128)	168 (128)	171(128)
Advanced (%)	32	53	37 (36)	72 (72)	58 (63)
Retreated (%)	68	47	63 (64)	28 (28)	42 (37)
Mean terminus change (m a^{-1})	**-61.2**	**-2.7**	**-43.3 (-44.9)**	**43.1 (30.9)**	**-17.9 (30.6)**
Median terminus change (m a^{-1})	**-12.9**	**0.7**	**-12.5 (-12.8)**	**19.7 (14.5)**	**8.4 (13.7)**

Figure legends:

Figure 1: Spatial and temporal variations in glacier terminus position in East Antarctica from all glacier measurements in 1974, 1990, 2000 and 2010. The rate of terminus position change (m a^{-1}) for each glacier and period is given by circles (see legend for sign and magnitude). Pie-charts show the percentage of glaciers advancing (blue) and retreating (red) in each major drainage basin (DB 12-16, from ref. *9, 11, etc.*). Climate stations referred to in this study (Fig. 3) are located by stars and location map shows surface flow speed over Antarctica[30] with fast flow zones (e.g. >500 m a^{-1}) in red to yellow.

Figure 2: Changes in glacier terminus position for each epoch for different sets of glaciers. Data for all glacier measurements are shown (A), alongside sub-samples of glaciers <15 km wide (B), those facing the western South Pacific (C), and those facing the Ross Sea (D) (Fig. 1). Glacier data are shaded by width (km), and box-and-whisker plots show the median (horizontal line), 25 and 75th percentiles (box), and the 5 and 95th percentile (whisker ends) on a cube root scale (y-axis). Significant differences between the 1974-1990 and 1990-2000 epochs, and 1990-2000 and 2000-2010 epochs are found for all samples of glaciers (A-C), apart from those facing the Ross Sea (D) (see Supplementary Tables 2 and 3).

Figure 3: Time series of the Southern Annular Mode (SAM) and summer air temperature data alongside changes in glacier terminus positions. The December-May

SAM Index is shown in (A), and mean summer air temperature trends from the three Pacific Stations and one Ross Sea station are shown in (B) (see Fig. 1), alongside corresponding changes in glacier terminus position (C). Box-and-whisker plots show the median (horizontal line) and the 25 and 75th percentiles (box) and the 5 and 95th percentiles (whisker ends) on a cube root scale (y-axis). Mean summer temperatures are calculated from mean monthly values of December, January and February, i.e. 1974 data are from December 1974, and January and February 1975).

METHODS

Data sources and glacier terminus mapping

We use optical satellite imagery to map the terminus position of 175 neighbouring outlet glaciers along the coast of East Antarctica. To remove intra- and inter-annual variability in glacier terminus positions over short time-scales, we mapped glacier change at the end of the austral summer and at approximately decadal time-steps spanning the last five decades. Our primary source of data were ~300 Landsat satellite images and, ideally, it would have been possible to pre-select the years of measurement. However, our requirement for a comprehensive sample of glaciers spanning 5,400 km of coastline meant that only four main time-steps allowed cloud-free mapping of the vast majority of their termini: 1974, 1990, 2000 and 2010. A small sub-sample of glaciers (38) were also mapped with declassified ARGON imagery from 1963 (Supplementary Table 1), but few of these could be measured in 1974 and they were widely spread geographically, which (together with the lower resolution of the imagery in 1963) is why we exclude this epoch from more detailed analysis.

The absolute positional accuracy of the mapping was limited by co-registration of imagery from different sources and is measured at ±75 to ±210 m for Landsat imagery and up to ± 420 m for some ARGON imagery. Overall, 85% of measurements have an error below ±180 m, comparable to a similar study from the Antarctic Peninsula[16], and more than sufficient for extracting the decadal trends we present (Supplementary Table 1). To account for uneven changes along the calving front, glacier termini were digitised within a reference box that approximately delineated the sides of the glacier[2]. The mean retreat distance was calculated as the area change at each time-step, divided by the glacier width, which was obtained from the reference box.

Extraction of glacier flow speed and elevation change from published sources

We compare our data on glacier terminus change and width with recent measurements of their mean flow speed[30,32] and elevation changes[1] (see Supplementary Figure 1). To guide the extraction of flow speeds and elevation changes, we used a map of grounding line positions using differential satellite synthetic-aperture radar interferometry (DInSAR) data[31]. Ice velocity data were obtained from a high resolution digital mosaic of ice motion in Antarctica[30,32], assembled from multiple satellite interferometric synthetic-aperture radar data acquired during the International Polar Year 2007 to 2009. This dataset was used to extract a mean flow speed near the glacier terminus by digitising an approximately square polygon that covered the width of the glacier and a similar distance in the along flow direction (typically producing a box a few kilometres long and wide). The mean velocity was then extracted using the 'spatial analyst' tool in ArcGIS. Given the strong correlation between glacier velocity both up-ice and down-ice from the grounding line (r^2 = 0.85), and the fact that grounding line data were missing from some glaciers, all measurements were taken close to the calving front. The glacier change data are suited to presentation on a cube root scale in Figure's 2 and 3, which allows informative display of long-tailed distributions, including both large positive and large negative values, and is consistent with display of median, quartiles and 5% and 95% percentiles.

For comparison with recent elevation change measurements (2003-2007)[1], we also mapped a sample of glaciers in austral summer 2006/2007 (see Fig. 4, Supplementary Information, and Supplementary Fig. 7). Data on ice elevation changes (thickening/thinning) were obtained from previously published ICESat laser altimetry[1] along the entire grounded margins of the Antarctic ice sheet between 2003 and 2007. Polygons were digitised immediately up-ice from the grounding line of those glaciers where data were available and this permitted the extraction of elevation change data for 24% of glaciers (see Supplementary Figure 7a).

Climate Data and Statistical Tests

Monthly mean surface air temperature records from four research stations in our study region (Scott, Dumonth d'Urville, Casey and Mirny: Fig. 1) were extracted from the SCAR Met reader project (http://www.antarctica.ac.uk/met/READER/). All stations have complete monthly records that coincide with our glacier measurements between 1963 and 2010, apart from at Scott, which has some data missing in 1994. Monthly values of the Southern Annular Mode (SAM) index (Fig. 3) were obtained from http://www.nerc-bas.ac.uk/icd/gjma/sam.html.

We determined whether the trends in glacier terminus position from the different epochs were statistically significant. The key issue is whether any observed differences between two epochs (e.g. 1974-1990 versus 1990-2000) are consistent with random variation at each epoch or whether they represent genuine differences between epochs. When data are normally distributed, this can be determined using a Student's *t*-test, which calculates the probability (P-value) that differences as large as or larger than that observed could occur if the two sets being compared are not different. We follow the common conventions that a P-value <0.05 indicates a 'significant' difference, one <0.01 a 'highly significant' difference (99% confidence) and one <0.001 'very highly significant'.

Glacier data within each epoch are positively skewed towards a few very high values. Although the *t*-test is generally thought to be insensitive to violations of normality[34], especially with large sample sizes, and is unlikely to lead to a type 1 error (i.e. find a significant difference that does not exist); it is prudent to use a non-parametric alternative: Wilcoxon's test, which does not assume normality. We performed two tests on data from each epoch: (i) a 'paired' test, using only data from glaciers measured in both epochs (the Wilcoxon Signed-Rank test); and (ii), an 'unpaired' test, where data were included even if the glacier was only measured in one of the epochs (the Wilcoxon Ranked-Sum test or Mann-Whitney U test). In unpaired *t*-tests we follow standard procedure and allow unequal variances (heteroscedasticity). Results are presented in Supplementary Tables 2, 3, 5 and 6.

We also determined whether there were significant differences in mean austral summer temperatures (December, January, February) between the 1974-1990 and 1991-2000 epochs, and the 1991-2000 and 2001-2010 epochs. In this case, normality holds to a good approximation and so *t*-tests were performed on unpaired samples but allowed unequal variances. Results are presented in Supplementary Table 4.

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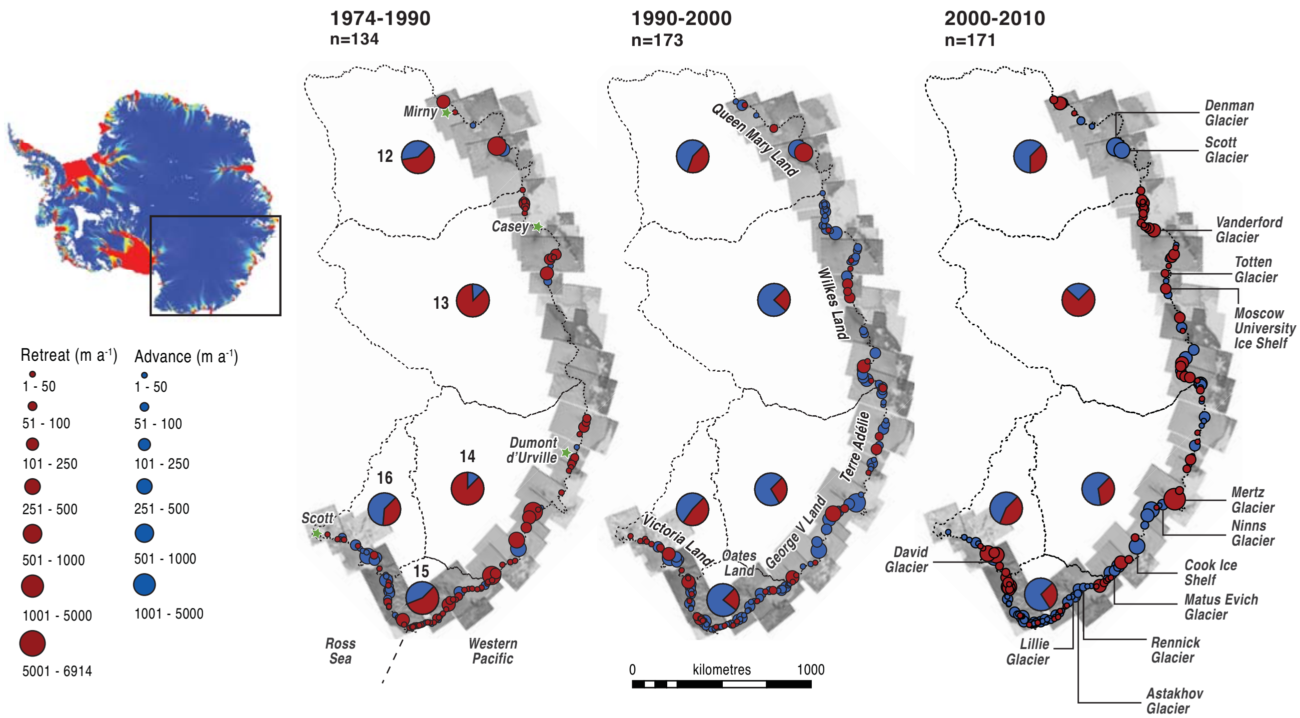
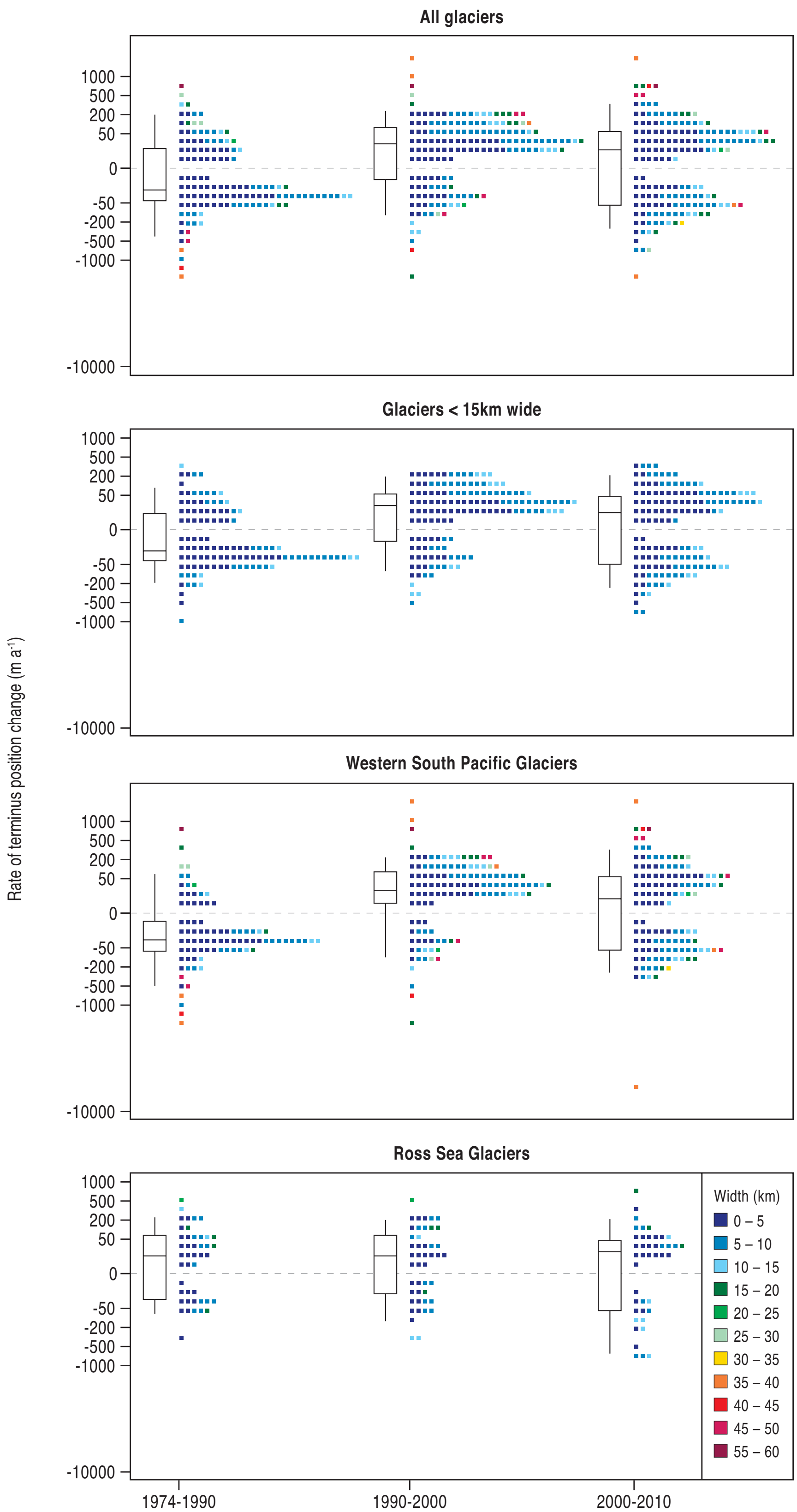
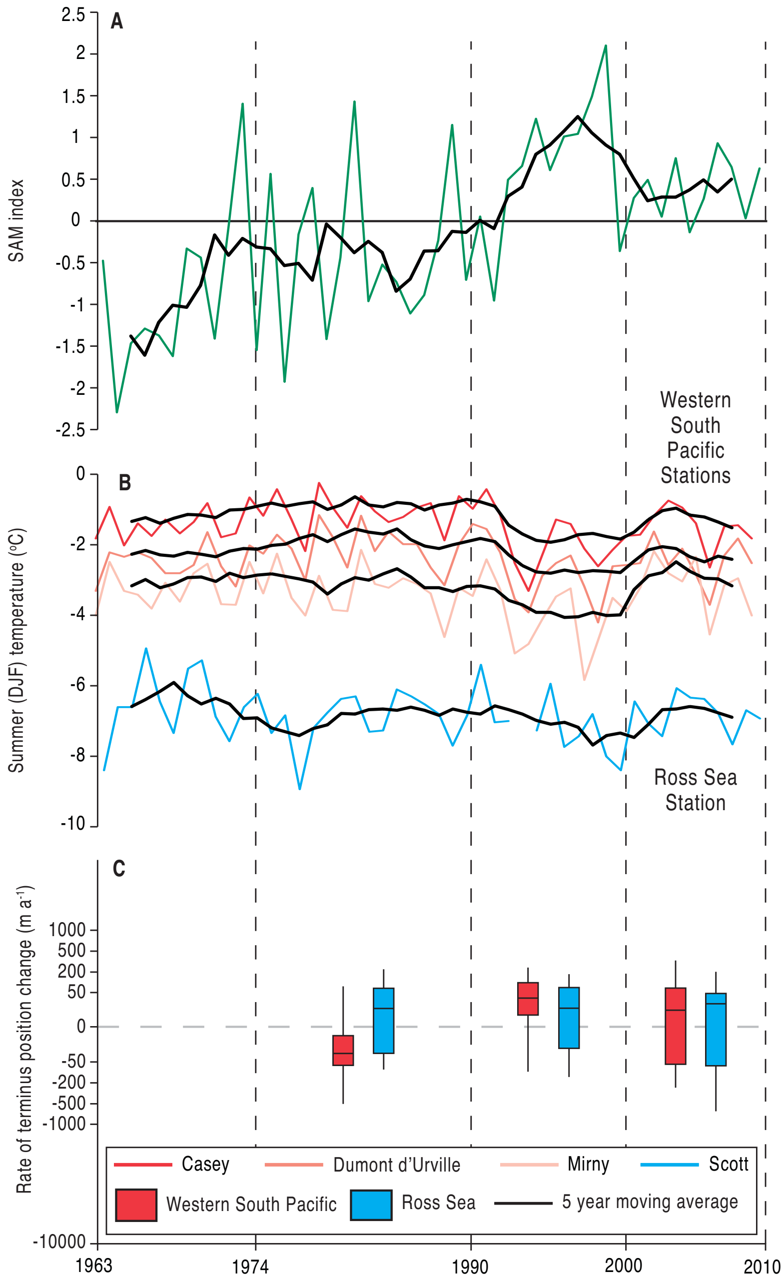


1974-1990
n=134
1990-2000
n=173
2000-2010
n=171
Retreat (m a-1)
1 - 50
51 - 100
101 - 250
251 - 500
501 - 1000
1001 - 5000
5001 - 6914
Advance (m a-1)
1 - 50
51 - 100
101 - 250
251 - 500
501 - 1000
1001 - 5000
Mirny
Casey
Dumont d'Urville
Scott
12
13
14
15
16
Ross Sea
Western Pacific
Queen Mary Land
Wilkes Land
Terre Adélie
George V Land
Oates Land
Victoria Land
0
kilometres
1000
Denman Glacier
Scott Glacier
Vanderford Glacier
Totten Glacier
Moscow University Ice Shelf
Mertz Glacier
Ninns Glacier
Cook Ice Shelf
Matus Evich Glacier
Rennick Glacier
Astakhov Glacier
Lillie Glacier
David Glacier


All glaciers
Glaciers < 15km wide
Western South Pacific Glaciers
Ross Sea Glaciers
Rate of terminus position change (m a-1)
1000
500
200
50
0
-50
-200
-500
-1000
-10000
1974-1990
1990-2000
2000-2010
Width (km)
0 – 5
5 – 10
10 – 15
15 – 20
20 – 25
25 – 30
30 – 35
35 – 40
40 – 45
45 – 50
55 – 60



A
SAM index
B
Western South Pacific Stations
Summer (DJF) temperature (°C)
Ross Sea Station
C
Rate of terminus position change (m a⁻¹)
Casey
Dumont d'Urville
Mirny
Scott
Western South Pacific
Ross Sea
5 year moving average
1963
1974
1990
2000
2010