Change and Variability in Antarctic Coastal Exposure, 1979-2020

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Abstract

Increased exposure of Antarctica's coastal environment to ocean waves due to loss of a protective sea-ice "buffer" has important ramifications for ice-shelf stability, coastal erosion, important ice-ocean-atmosphere interactions and shallow benthic ecosystems. Here, we introduce an important new climate and environmental metric based on the ongoing long-term satellite sea-ice concentration record, namely Coastal Exposure Length or CEL. This is a daily measure of (change and variability in) the length and incidence of Antarctic coastline lacking any protective sea-ice buffer offshore i.e., connected directly to the open ocean. On average and for 1979-2020, ~50% of Antarctica's ~17,850-km coastline is fully exposed at mean annual maximum exposure each February (austral summer) with minimal exposure in winter. Regional contributions vary from 45% (Amundsen-Bellingshausen seas) to 58% (Indian Ocean and Ross Sea), with overall (circumpolar) annual exposure ranging from 38% (2019) to 63% (1993). The northern Antarctic Peninsula is the only region with year-round coastal exposure. The annual maximum length of Antarctic coastline exposed to fully open-ocean conditions decreased by ~30 km (or ~0.32%) per year for 1979-2020, but this slight negative trend is composed of distinct regional and seasonal contributions. The new findings provide previously-unavailable information on change around Antarctica's vulnerable coastal margins, to aid improved modelling and prediction of the likely trajectory of the coastal system in coming decades in response to climate change (including a projected increase in Southern Ocean wave energy).

Introduction

Sea-ice concentration, extent and seasonality (timings of advance and retreat and resultant coverage duration) are well characterised from satellite data¹⁻³ and form the basis of major assessments of polar sea-ice change and variability since the late-1970s e.g., for the Intergovernmental Panel on Climate Change^{4,5}. An important additional climate and environmental factor neglected to date, however, is change and variability in the exposure of the Antarctic coastline to fully open-ocean conditions (including potentially-destructive ocean waves) as a result of loss/gain of a protective sea-ice "buffer" offshore. Circumpolar patterns of Antarctic coastal exposure, and where and how they are varying and/or changing, have been unknown and unreported.

Here, we introduce a major new climate and environmental metric, namely "coastal exposure length" (CEL). This is derived from the continuous daily satellite passive-microwave sea-ice concentration record dating back to 1979 (mapped to 25-km resolution), using a new custom-developed algorithm (details given in Methods). Coastal exposure is here defined as a total lack of sea-ice coverage offshore from any given point on the coast i.e., uninterrupted exposure of the coastal margin to the open Southern Ocean. In this sense, the coastline is not taken to be "exposed" if there is any sea ice offshore (even if the coast has open water adjacent to it in the form of leads or polynyas (persistent and recurrent areas of open water/thin ice that occur in various coastal locations around Antarctica⁶). "Sea ice" refers here to moving pack ice plus the narrower envelope of stationary consolidated landfast sea ice (fast ice) that is affixed to

extensive stretches of Antarctica's coastline⁷. While fast ice alone is not resolved by the CEL algorithm, it is strongly impacted by coastal exposure due to its susceptibility to breakup by ocean waves in the absence of a pack-ice buffer⁸.

There is strong motivation to routinely and consistently measure and monitor change and variability in Antarctic coastal exposure in space and time. This is underpinned by an increasing urgency to identify, understand and accurately model the nature and drivers of environmental change around Antarctica's vast and dynamic coastal periphery, and to more robustly predict the coastal system's likely response to changing climate and the effects (local through global) of coastal change⁵. When and where present, sea ice that covers between ~ 3 million km² and ~ 19 million km² of the Southern Ocean surface (depending on season³) plays an important though poorly-quantified role in buffering (protecting) Antarctica's vulnerable floating ice-sheet margins and coastal environment from potentially-destructive ocean waves. This is due to the capacity of pack ice floes to efficiently damp and dissipate the energy of incoming waves before they can interact with coastal margins⁹. Because of this, any increase (decrease) in coastal exposure due to pack-ice loss (gain) has important ramifications for: (i) the stability of certain ice shelves and iceberg calving rates^{10,11}; (ii) the persistence and distribution of fast ice that is an important element of Antarctica's coastal environment and cryosphere^{7,12}; (iii) coastal erosion¹³; and (iv) the structure of benthic ecosystems¹⁴.

Notably, recent work¹¹ has implicated a regional change to increased sea ice-free conditions offshore from the western and north-eastern Antarctic Peninsula after the late-1980s in abrupt and catastrophic disintegration events of the Larsen A and B and Wilkins ice shelves since 1995^{15,16}. The new paradigm¹¹ is that this sea-ice loss exposed the ice-shelf fronts directly to the high-energy Southern Ocean, and enabled destructive ocean swell waves to reach and interact with the ice-shelf fronts over prolonged periods. Persistent wave-imposed flexure (cyclical bending) of the outer ice shelves then enlarged existing systems of rifts (through-cutting fractures) there to the point of extensive and spontaneous outer-margin calving in the form of multiple elongated icebergs. This triggered the large-scale rapid runaway disintegration of ice-shelf interior regions that had been substantially weakened by decades of warming, thinning, melt-related hydrofracture (surface meltwater enlargement of crevasses) and glaciological perturbations (see Fig. 1 and references in¹¹). This rapid loss of ice-shelf buttressing capacity¹⁷ led in turn to an abrupt increase in the regional discharge of grounded ice-sheet mass into the ocean via feeder glaciers¹⁸, to contribute to an observed acceleration in mass loss from the Antarctic Ice Sheet^{19,20}. In this way, increased coastal exposure contributed to sea-level rise¹¹.

Here, we first provide previously-unknown baseline information on the mean state (climatological pattern) of circum-Antarctic coastal exposure, in terms of both its spatial extent and duration and its regional and seasonal patterns and contrasts. We then highlight strong variability and trends that exist in the exposure record and reveal distinct and differing regional and seasonal contributions. Important wide-ranging implications of change in coastal exposure for ice-sheet processes and sea-level rise, coastal ecosystems and operations are evaluated in the Summary section.

Climatological Patterns Of Antarctic Coastal Exposure

The new time series reveals distinctive large-scale patterns in the long-term daily means (for 1979–2020) of both coastal exposure spatial length and timing around Antarctica (Figs. 1 and 2). Average net circum-Antarctic CEL attains its maximum in late February (late austral summer), at $\sim 8,950 \pm 1,210$ km or about 50% of the entire Antarctic coastal perimeter of $\sim 17,850$ km (Fig. 1a; Extended Data Table 1). The climatological maximum (peak) in CEL sits within a roughly symmetrical annual cycle of 6 months increase in exposure and 6 months retreat. Particularly rapid rates of first increase then decrease in exposure length occur over roughly 2-month phases from mid-December through mid-February (summer) and March through April (autumn), respectively. The remaining 8 months are characterised by a long tail of low CEL (less than $\sim 11\%$ or ~ 2000 km) that tapers to a small late-winter climatological minimum CEL (of only ~ 33 km) in late August i.e., late winter (Fig. 1a).

The climatological circum-Antarctic CEL cycle (Fig. 1a) differs substantially from the mean annual cycle of overall sea-ice coverage (extent) in its timing and rates of seasonal change. The net sea-ice cycle is strongly asymmetric around advance and retreat seasons that run for approximately 7.5 months (mid-February through late September or late summer through early spring) and 4.5 months respectively^{3,21}.

The net annual CEL cycle (Fig. 1a) is in fact made up of distinctly-differing regional contributions (Fig. 1b-f), with average annual maximum exposure (expressed as a percentage of total coastline length) ranging from $\sim 45\%$ for the Amundsen-Bellinghshausen seas (ABS) to $\sim 58\%$ for the Ross Sea and Indian Ocean sectors (Extended Data Table 1). Of the five sectors, only the ABS and Weddell Sea have some year-round coastal exposure (on average). Of these, the ABS is notable for both its broad exposure decrease phase extending through winter and its relatively high interannual variability (with one standard deviation at peak annual exposure being $> 50\%$ of the average value), while the mean annual cycle in the Weddell Sea resembles the net circum-Antarctic cycle.

In contrast and for the East Antarctic (Indian and W Pacific Ocean) and Ross Sea sectors, the mean annual window of coastal exposure is confined to late November through late April-early May (late austral spring through mid-autumn). Moreover, the mean annual exposure cycle across East Antarctica is characterized by a longer increase compared to decrease phase i.e., by ~ 1 month in the Indian Ocean and ~ 1.5 months in the W Pacific. In the Ross Sea on the other hand, coastal exposure length exhibits a particularly sharp seasonal decline of $\sim 70\%$ in only two weeks from late February through early March, after an annual peak that occurs ~ 2 weeks prior to those in the East Antarctic and ABS sectors but near-coincident with that in the Weddell Sea.

Strong regional dependence is also apparent in the mean duration of annual exposure and the timing of the annual exposure window as a function of longitude (Fig. 2) – together with complex intra-regional patterns of variability. Exposure duration covers a wide range, from low (< 2 days) in parts of the W Weddell Sea, eastern Ross Sea and W Pacific Ocean sectors (as well as multiple more localised coastal tracts of the Indian and W Pacific oceans) to very high (~ 290 days) towards the northern tip of the

Antarctic Peninsula (Fig. 2a). Elsewhere, mean annual exposure duration is generally ≤ 50 days, with a broader zone of shorter (< 20 day) exposure across the ABS sector that ramps up towards the Antarctic Peninsula. Broadly-speaking, zonally-extensive regions of low and zero exposure duration (Fig. 2a) and frequency of occurrence (Fig. 2b) centred on $\sim 150^\circ\text{E}$, 110°W and 50°W align with well-documented areas of perennial sea-ice coverage offshore²¹.

Regional contrasts and intra-regional variability are also a feature of the mean timings of annual exposure onset and cessation, the resultant seasonal window of exposure duration and the frequency of occurrence as a function of longitude (Fig. 2b). This again shows the Antarctic Peninsula to be a standout region in terms of the near year-round exposure along much of its western and north-eastern flanks. Elsewhere around Antarctica, the mean timing of annual exposure onset varies by about two months – from mid-November in the East Antarctic sector at $\sim 140\text{--}150^\circ\text{E}$ (George V Land coast) to mid-January in western parts of the Indian Ocean and the Amundsen Sea. The anomalously-early onset in George V Land is likely linked to the recurrent Mertz Glacier Polynya, which has been shown in previous work²² to play an important role in driving an unusually early and rapid seasonal meltback of sea ice to the coast in that region. By comparison and in autumn, the timing of mean annual cessation of exposure again varies regionally over ~ 2 months, from early March (Ross Sea) to early May (Enderby Land in the western Indian Ocean).

The East and West Antarctic sectors in fact differ substantially in terms of their respective zonal patterns of mean coastal exposure occurrence timings (Fig. 2b). For East Antarctica from $\sim 0^\circ$ to 160°E , mean exposure-window duration is relatively uniform at about 4 ± 0.5 months, but displays a broad wave-like configuration that comprises alternating zones of apparent eastward and westward propagation over time for both exposure onset and subsequent cessation. For example, the timing of the exposure window propagates from west to east in the eastern limb of the Weddell Gyre ($0\text{--}40^\circ\text{E}$) over a > 1 month period, but this pattern reverses along much of the adjacent Indian Ocean coast.

The broad wave-like pattern transitions eastwards from the eastern Indian Ocean into a zone of more variable timings and generally lower frequency of occurrence across the W Pacific Ocean. This changes to a narrower (approximately 3-month) and more uniform coastal-exposure window across the central Ross Sea. Moving into the ABS sector, the exposure window is initially fairly narrow (2–3 months), occurs later and is more variable (than the Ross Sea), and also has a substantially lower frequency of occurrence. Exposure duration broadens towards the Antarctic Peninsula, where there is a high frequency of exposure occurrence throughout the year. This is in stark contrast to the adjacent area of zero exposure occurrence in the W/SW Weddell Sea due to the perennial occurrence of sea-ice coverage there. Finally, and from the central Weddell Sea through the Greenwich Meridian, the exposure occurrence window broadens back to ~ 4 to > 5 months, with the timing of exposure onset remaining uniform but cessation timing increasing with distance towards the meridian. These distinct zonal patterns are further depicted in a map of the annual-mean duration of coastal exposure for 1979–2020 for all coastal-adjointing pixels (Fig. 2c).

Variability In Antarctic Coastal Exposure

Previously-unseen patterns of variability are also revealed in the daily time series of net overall CEL for 1979–2020, with annual maximum exposure ranging from 38% (~ 6,850 km) in 2019 to 63% (11,180 km) in 1993 and interannual variability spanning apparent quasi 4- to 6-year cycles (Fig. 3a). This net circum-Antarctic picture is again made up of distinct regional contributions (Fig. 3b-f), with each of the five sectors displaying different and at times contrasting patterns of interannual variability in both annual maximum and (for the Weddell and ABS) annual minimum exposure. Net annual maximum CEL is most highly correlated to the Weddell Sea and least correlated to the ABS (Extended Data Fig. 7), despite the ABS being the greatest regional contributor to the total Antarctic coastline length. Annual maximum CEL for the Indian Ocean is most highly correlated to the Weddell Sea, and not correlated at all to other sectors. CEL in the ABS is anti-correlated to all other sectors, implying that processes involved in coastal exposure in this sector are different from those elsewhere.

Particularly prominent is an abrupt change in the ABS sector from consistently low CEL values (of largely < 2,000 km) prior to 1989 to substantially higher values and greater interannual variability after that date (Fig. 3f). In contrast, the earlier parts of the records for the Weddell and Ross seas and the Indian and W Pacific oceans (prior to 1989) are characterised by relatively high values of CEL (Fig. 3b-e). Very low values of summer-time (maximum) exposure are noted in certain years after 2002, in: the Weddell Sea in 2014 (1,020 km) and 2015 (1,160 km, both versus a mean of 2,130 km [Extended Data Table 1]); the Indian Ocean in 2008 (750 km) and 2014 (570 km v 1,920 km); the W Pacific Ocean in 2013 (590 km v 1,670 km); the Ross Sea in 2003 (180 km) and 2008 (480 km v 1,520 km); the ABS sector in 2005 (1,130 km v a mean of 2,190 km). Moreover, the circumpolar time series contains anomalous years of relatively-extensive annual CEL minima (Fig. 3a), with the net mean-winter CEL remaining positive only in the winters of 1983 (99 km), 1989 (particularly prominent at 392 km), 2001 (268 km), 2004 (318 km) and 2008 (294 km). This comprises positive mean-winter contributions from the Weddell Sea (only in 2004) and the ABS sector (in 1983, 1989 and 2008).

Trends In Antarctic Coastal Exposure

The annual maximum length of Antarctic coastline exposed to fully open-ocean conditions decreased by ~ 30 km (or ~ 0.32%) per year for 1979–2020, but this slight negative trend is composed of distinct regional and seasonal contributions. There are four distinct seasonal contributions (as marked on Fig. 4a):

1. Late-December through April (early-austral summer through mid-autumn) – decreasing net coastal exposure by as much as about 30 to 40 km year⁻¹;
2. May through July (late-autumn through mid-winter) – a switch to increased CEL by up to about + 20 km year⁻¹;
3. August through September (late-winter through early-spring) - a two-month period of near-zero change in net coastal exposure; and

4. October-December (mid-spring through early-summer) - a return to increasing coastal exposure, by up to approximately $+10 \text{ km year}^{-1}$.

There are again differing regional contributions to the overall trend in net circum-Antarctic CEL (Fig. 4b-f), with the ABS being the only sector recording a significant positive (increasing) trend – apart from short and intermittent periods of small positive significant trends of up to $+5 \text{ km year}^{-1}$ in the Weddell Sea from mid-April through mid-December. The increasing trend in the ABS occurs throughout much of the year (apart from near-zero change in late winter-early spring [August-September]), and peaks at $+44 \text{ km year}^{-1}$ in late February. Significant trends in the other four sectors are largely negative or close to zero, with the negative net trends (of about -20 km year^{-1}) being confined to late-spring through mid-autumn i.e., December through April in both the Weddell and Ross seas, and November through May across the East Antarctic sectors.

Analysis of trends in coastal-exposure duration as a function of longitude and season (Fig. 5) again highlights the prominent trend to increasing exposure in the ABS sector – ranging from about approximately $+0.5$ to $+3 \text{ days year}^{-1}$. This occurs through much of the year, but most prominently in December through July and along the western Antarctic Peninsula, and is most extensive westwards in January through April (mid-summer through mid-autumn). Elsewhere, increasing exposure is confined to smaller coastal tracts and over shorter periods in summer in both the Amundsen Sea (during February) and the western part of the W Pacific Ocean (mid-December through mid-January).

In contrast, relatively extensive tracts of decreasing trend in coastal exposure (to $-2 \text{ days year}^{-1}$) occur in late-spring through mid-autumn across the eastern Weddell Sea (January through March), Indian Ocean (late-December through April), eastern part of the W Pacific Ocean (November through April) and western Ross Sea (late-December through March). Intervening areas of zero trend in the eastern Ross and western Weddell seas (Fig. 5a) relate to the perennial presence of pack ice there²¹. The localised zero trend at $\sim 140^\circ\text{E}$ is associated with the build-up of persistent sea-ice coverage to the east of assemblages of grounded icebergs near of the Mertz Glacier tongue, within the westward-flowing Antarctic Coastal Current²³.

Also of note is that the negative trends in the Indian Ocean, eastern W Pacific Ocean and western Ross sectors migrate westward by approximately 20° of longitude in autumn (March through May) (Fig. 5b). The positive trend in the West Antarctic Peninsula region undergoes a similar but earlier westward migration in summer (December through February), before reversing to an apparent eastward migration from in autumn-winter (March through July). The reason for these regional trend propagation patterns is currently unknown. Figure 5c further shows that in some regions, such as around the West Ice Shelf ($\sim 85^\circ\text{E}$), there are trends of opposite sign at adjacent grid points, a complexity not resolved in the Hovmöller-style diagram of Fig. 5b.

Summary And Implications Of Change In Antarctic Coastal Exposure

The new coastal exposure index introduced in this study represents an important and previously-unavailable large-scale climate variable and metric against which to detect, gauge, monitor and assess change and variability in Antarctica's unique and immensely influential yet vulnerable coastal environment on a daily basis (and every other day prior to July 1987). The ongoing CEL time series is also highly-complementary and value adds to the existing time series of sea-ice concentration, extent, area and seasonality, as derived from the same satellite data source dating back to 1978. As such, it will continue to provide important parallel information on the state of the Antarctic (coastal) environment over coming decades.

This analysis has revealed previously-unknown patterns of strong spatial and temporal variability and change in coastal exposure to fully open-ocean conditions around Antarctica. It shows that the net annual exposure cycle is symmetrical around a late-February maximum with an annual minimum in late August; differs markedly from the asymmetric annual sea-ice advance and retreat cycle; and comprises highly-distinct regional contributions in terms of exposure spatial extent, timings of annual onset and cessation, duration and frequency of occurrence. Contrasting patterns of long-term mean exposure in East versus West Antarctica occur within an austral summer-through-autumn window, while the northern Antarctic Peninsula is the only region where exposure occurs year round.

In large part, the trend in Antarctic coastal exposure for 1979–2020 is towards negative exposure (by as much as -20 km year^{-1} and $-2 \text{ days year}^{-1}$) in austral summer through autumn and across all sectors apart from the Amundsen-Bellingshausen seas. There, spatial and temporal trends are positive and up to $+44 \text{ km year}^{-1}$ and $+3 \text{ days year}^{-1}$, respectively, and extend from mid-spring through winter. The ABS region has previously been identified as a “hot spot” for decreasing annual sea-ice duration¹, a different climate and environmental metric to CEL.

There are multiple wide-ranging implications of both positive and negative changes in patterns of coastal exposure shown here, for both current and future epochs - with each warranting further investigation beyond this study. For example and based on recent findings^{10,11}, it is speculated that increased (decreased) exposure could potentially diminish (increase/maintain) the stability and buttressing capacity of certain remaining ice shelves (depending on additional ice shelf-specific glaciological factors and regional setting) – by increasing (decreasing) areal loss from certain ice shelves through interaction of their outer margins with potentially-destructive ocean swells¹¹. This would in turn increase (decrease) the rate of the Antarctic Ice Sheet's contribution to sea-level rise.

Change to increased (decreased) incidence of coastal exposure also increases (decreases) the likelihood of swell-induced breakup of consolidated landfast sea ice (fast ice) attached to certain floating ice-sheet margins^{11,24}. This would in turn reduce/remove (maintain) the key role of fast ice as a regulator of outlet glacier discharge rates²⁵ and as a mechanical “buttress” and bonding and stabilising agent that can minimise/delay iceberg calving^{10,26–28}. Indeed, major disintegration events of the Wilkins Ice Shelf in

2008 and 2009 only occurred after the breakup and removal of adjacent (attached) fast ice, which followed loss of a wider regional pack-ice buffer offshore¹¹.

It is further anticipated that change towards increased (decreased) coastal exposure and associated fast-ice loss could not only increase (decrease) iceberg calving and the number of icebergs in the coastal zone¹⁰. It would also decrease (increase) the residence time of ungrounded icebergs that are usually held in place by fast ice²⁹ – to increase (decrease) their rates of breakup and melt and freshwater and nutrient input into the ocean³⁰ as they drift into lower latitudes. This increase (decrease) in the number and drift of icebergs would also increase (decrease) iceberg scouring of the seabed and its destructive effect on shallow near-shore benthic ecosystems³¹. Change to increased (decreased) coastal exposure could also increase (decrease) wave-related turbulence, the deposition of biogenic material, and light availability for photosynthesis and heating. Shallow coastal benthic ecosystems are particularly vulnerable to such environmental change involving loss of sea ice^{14,32}.

It is expected that the new findings presented here will, in concert with emerging studies highlighting the regional effects of changing coastal exposure¹¹, motivate representation of (change in) circumpolar Antarctic coastal exposure in improved ice-sheet models and next-generation Earth-system models. This will contribute to the development of more accurate and robust predictive capability regarding the fate of the vulnerable Antarctic coastal environment and remaining ice shelves under a changing climate, which is crucial to projecting Antarctica's future contribution to sea-level rise. It is further anticipated that such an advance will also provide additional new information towards coastal-exposure forecasting in support of safe and efficient shipping³³. Such developments are timely and crucial, given that the effects of coastal exposure are likely to be heightened in future by predicted increases in wind speed and wave height in the high-latitude Southern Ocean^{34,35}.

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Declarations

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Figures

Figure 1

Plots of the average (1979-2020) coastal exposure length for each day (kms). (a) Total Antarctic coastline, (b) Weddell Sea, (c) Indian Ocean, (d) W Pacific Ocean, (e) Ross Sea, and (f) ABS. Shaded blue lines represent ± 1 standard deviation above and below the mean value.

Figure 2

Climatology (1979-2020) of coastal exposure events based on coastal exposure length. (a) Annual exposure duration for each longitude (days year⁻¹); (b) coastal exposure occurrence expressed as a percentage of frequency for each day and longitude (%); and (c) annual exposure for each grid point (days year⁻¹). Shaded blue lines in (a) represent the variability (maximum and minimum) for each

longitude. Grid points in (c) are arranged such that those with higher lengths of exposure are plotted over those with lower lengths.

Figure 3

Time series plots of monthly-mean coastal exposure length (in kms) for 1979-2020. (a) Total Antarctic coastline, (b) Weddell Sea, (c) Indian Ocean, (d) W Pacific Ocean, (e) Ross Sea, and (f) ABS.

Figure 4

Plots of the trends (1979-2020) in coastal exposure length for each day (kms year⁻¹). (a) Total Antarctic coastline, (b) Weddell Sea, (c) Indian Ocean, (d) W Pacific Ocean, (e) Ross Sea, and (f) ABS. Statistically-significant values (>95% confidence) are highlighted in blue.

Figure 5

Trends (1979-2020) of annual coastal exposure events based on coastal exposure length. (a) Each longitude (days year⁻¹), (b) each longitude and day (occurrence per decade), and (c) each coastal grid point (days year⁻¹). Statistically-significant values (>95% confidence) for (a) are highlighted in blue. Only statistically-significant values (>95% confidence) are plotted on (b) and (c). For (c), grid points with higher magnitude of trends are plotted over those with lower magnitude.

Supplementary Files

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- [AntarcticcoastalexposuresupplementarynaturecommsJune2021.docx](#)