East Antarctic Landfast Sea Ice Distribution and Variability, 2000–08

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ABSTRACT

This study presents the first continuous, high spatiotemporal resolution time series of landfast sea ice extent along the East Antarctic coast for the period March 2000–December 2008. The time series was derived from consecutive 20-day cloud-free Moderate Resolution Imaging Spectroradiometer (MODIS) composite images. Fast ice extent across the East Antarctic coast shows a statistically significant (1.43% ± 0.30% yr⁻¹) increase. Regionally, there is a strong increase in the Indian Ocean sector (20°–90°E, 4.07% ± 0.42% yr⁻¹), and a nonsignificant decrease in the western Pacific Ocean sector (90°–160°E, −0.40% ± 0.37% yr⁻¹). An apparent shift from a negative to a positive extent trend is observed in the Indian Ocean sector from 2004. This shift also coincides with a greater amount of interannual variability. No such shift in apparent trend is observed in the western Pacific Ocean sector, where fast ice extent is typically higher and variability lower than the Indian Ocean sector. The limit to the maximum fast ice areal extent imposed by the location of grounded icebergs modulates the shape of the mean annual fast ice extent cycle to give a broad maximum and an abrupt, relatively transient minimum. Ten distinct fast ice regimes are identified, related to variations in bathymetry and coastal configuration. Fast ice is observed to form in bays, on the windward side of large grounded icebergs, between groups of smaller grounded icebergs, between promontories, and upwind of coastal features (e.g., glacier tongues). Analysis of the timing of fast ice maxima and minima is also presented and compared with overall sea ice maxima/minima timing.

1. Introduction

Landfast sea ice (fast ice) is sea ice that is held stationary (fast) by being attached to coastal features (e.g., the shoreline, glacier tongues, and ice shelves), grounded icebergs, or grounded over shoals (Massom et al. 2001; World Meteorological Organization 1970). It is a preeminent feature of the Antarctic coastal zone and an important interface between the ice sheet and pack ice/ocean. The reliance of fast ice upon these coastal features as anchor points means that it tends to form in narrow bands of widely varying widths but rarely exceeding 150 km around East Antarctica (Giles et al. 2008). There are strong hemispheric contrasts in fast ice extent and persistence. In the Arctic, a lack of grounded icebergs means fast ice typically grounds itself in shallow waters, with the seaward fast ice edge often located around...
the 20–30-m isobath (Mahoney et al. 2007a; Lieser 2004). By contrast, Antarctic icebergs often ground in water depths of 400–500 m (Massom et al. 2001) and act as fast ice anchor points, giving much larger fast ice extents. Such shoals also occur some distance offshore.

Variability in fast ice extent is important for a number of reasons. It is likely a sensitive indicator of climate change (Heil et al. 2006; Mahoney et al. 2007a; Murphy et al. 1995) and is also closely associated with coastal polynyas. Coastal polynyas have far-reaching consequences in terms of Antarctic Bottom Water formation and hence global thermohaline circulation (Massom et al. 1998; Rintoul 1998; Tamura et al. 2008; Williams et al. 2008). A recent study (Massom et al. 2010) has shown that fast ice acts to mechanically stabilize fragile glacier tongues and ice shelves, delaying calving and ultimately affecting ice sheet mass balance, as well as prolonging the residence times of ungrounded icebergs (Massom 2003). Despite the physical significance of fast ice, it is currently not represented in global climate circulation models or coupled ice–ocean–atmosphere models. Fast ice also has several important biological functions at various trophic levels. It forms a habitat for microorganisms (e.g., McMinn et al. 2000) and plays a crucial role in the life cycle of Emperor penguins and Weddell seals (Massom et al. 2009; Kooymann and Burns 1999). Antarctic fast ice also affects logistical operations, acting to both facilitate and impede navigation and base resupply.

To date, research has focused on overall sea ice extent without discriminating between pack ice and fast ice (e.g., Comiso 2009; Comiso and Nishio 2008; Cavalieri and Parkinson 2008; Lemke et al. 2007; Zwally et al. 2002). Relatively little is known about larger-scale aspects of Antarctic fast ice distribution and its spatiotemporal variability. In particular, little is known about the atmospheric and oceanic controls on the growth and breakout of fast ice around the Antarctic coast. Much of the research has largely focused on the acquisition and analysis of measurements of physical or biological aspects of fast ice localized close to bases—for example, Heil (2006), Kawamura et al. (1997), Lei et al. (2010), Ohshima et al. (2000), Purdie et al. (2006), Smith et al. (2001), Tang et al. (2007), and Uto et al. (2006). Several regional-scale studies of Antarctic fast ice have been conducted using remote sensing techniques, but none have combined large-scale coverage, long time series, and high spatiotemporal resolution. Kozlovsky et al. (1977) studied East Antarctic fast ice on a broad spatial scale (0°–160°E), but sampling was sparse and sporadic and did not resolve fast ice formation or decay.

Giles et al. (2008) presented two snapshots of East Antarctic (88°–170°E) fast ice extent from November 1997 and 1999, derived using image cross-correlation techniques applied to Synthetic Aperture Radar (SAR) image pairs. Massom et al. (2009) created a time series of fast ice extent off the Adélie Land coast from 134°–143°E using cloud-free National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution (AVHRR) data from 1992 to 1998. Several other studies have used remote sensing techniques to obtain regional-scale information on fast ice formation and breakout, primarily in and around Lützow-Holm Bay (Enomoto et al. 2002; Mae et al. 1987; Ushio 2006, 2008) and the western Ross Sea (Brunt et al. 2006). While detailed studies of Arctic fast ice formation, breakout, and extent have taken place on regional scales (e.g., Mahoney et al. 2007a), there has been no similar Antarctic study providing large-scale information on fast ice distribution and its spatiotemporal variability.

The East Antarctic coast has persistent cloud cover, averaging 93% in October compared with a global average of 70% (Spinhirne et al. 2005). Thus, a major challenge when using visible–thermal infrared (TIR) time series (which are heavily affected by cloud)—such as the National Aeronautics and Space Administration (NASA) Aqua and Terra Moderate Resolution Imaging Spectroradiometer (MODIS) instruments—is to derive high-quality imagery of the surface (i.e., the sea ice zone) by appropriate treatment of cloud cover. Fraser et al. (2009) presented an algorithm to effectively produce cloud-free composite imagery of the East Antarctic sea ice zone on a temporal scale suitable for studying large-scale fast ice formation–breakout events. Fraser et al. (2010) used these MODIS composite images, along with 6.25-km resolution NASA Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) AMSR-E passive microwave sea ice concentration composite images, to develop methods for retrieval of fast ice extent along the East Antarctic coast. The work presented in this paper directly builds upon these earlier works (Fraser et al. 2009, 2010), to retrieve the first high spatiotemporal resolution (2 km, 20 day) maps of East Antarctic fast ice, during the period from March 2000 to December 2008, providing information on the seasonality of fast ice occurrence. A further major aim is to provide large-scale fast ice information in support of detailed but localized data acquired within the newly-established Antarctic Fast Ice Network (AFIN) (Heil et al. 2011). The MODIS dataset was chosen because it combines excellent polar synoptic coverage (a 2330-km-wide swath) with moderate resolution (1 km in TIR bands) and is readily available. This dataset also has broad and regular coverage of the narrow but zonally extensive fast ice zone—a zone that cannot easily be covered and monitored by satellite SAR data and remains largely unresolved in lower-resolution
2. Datasets and methods

We create a series of 159 consecutive 2-km, 20-day resolution cloud-free MODIS composite images, from March 2000 to December 2008, of the East Antarctic fast ice zone (63.5°–72°S, 10°W–172°E, see dashed box in Fig. 1), using the methods outlined in Fraser et al. (2009) and Fraser et al. (2010). The method is summarized as follows.

(i) Assess the cloud content of each granule prior to downloading MODIS imagery, using a modified MOD35 cloud mask product (Ackerman et al. 2006; Fraser et al. 2009), and discard the cloudiest half to reduce processing requirements. Over the 8.8-yr study period, around 150 000 MODIS granules were used to produce the 159 composite images, totaling over 12 terabytes of data (reduced from a possible 300 000 granules and 25 terabytes).

(ii) Acquire 20 days of MODIS granules of the East Antarctic coast.

(iii) Perform cloud masking using a modified MODIS cloud mask.

(iv) Reproject masked granules to a common grid.

(v) Finally, average the reprojected images to form cloud-free composite images of the surface. Visible composite images were produced during the summer and early autumn–late spring, and TIR composites were produced when solar illumination was lacking.

AMSR-E sea ice concentration composite images (6.25-km resolution, Spreen et al. 2008) were also constructed over identical 20-day windows. The MODIS composite images were then analyzed (in conjunction with the AMSR-E composites during times of persistent cloud cover or otherwise low-quality portions in the MODIS composite image) to determine pixels with fast ice cover. These fast ice maps form the basis of the time series presented here. Fraser et al. (2010) conducted an error analysis of this method of fast ice detection and identified two error regimes:

(i) error regime 1 represents a higher level of confidence (1σ error of ±1.5%), where ≥90% of the fast ice in the image was classified from a single MODIS composite; and

(ii) error regime 2 (1σ error of ±4.38%) where the equivalent AMSR-E or previous–next MODIS composite was used to classify >10% of the fast ice.

The Antarctic continent was masked using the Mosaic of Antarctica (MOA) coastline product (Scambos et al. 2007). European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis data (Berrisford et al. 2009) from 1989 to 2008 [Mean Sea Level Pressure (MSLP), 10-m wind vectors, and 2-m surface temperatures on a 1.5°grid] were formed into 20-day and annual climatologies to assist in interpretation of fast ice variability. Moreover, 20-day sea ice concentration composite images were also created from the combined Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) dataset (Comiso 1999), to compare overall sea ice extent/area with fast ice extent. This product uses the Bootstrap algorithm, and a threshold of 15% was used to compute sea ice area. These data are available from http://nsidc.org/data/nsidc-0079.html. Bathymetric information was obtained from the Smith and Sandwell (1997) dataset (version 11.1, updated in 2008; available at http://topex.ucsd.edu/WWW_html/mar_topo.html).

The evaluation of trend significance for the fast ice extent time series closely follows that used by Cavalieri and Parkinson (2008), with the metric of a continuous R value (the ratio of the linear trend to the standard deviation) used to indicate the significance of a particular trend. This R value was converted to a confidence interval by assuming a two-tailed Student’s t distribution and using a lookup table with the appropriate number of degrees of freedom (DOF). Following Cavalieri and...
Parkinson (2008), the number of DOFs is set to the number of years of data—two (i.e., the number of DOFs is reduced by two when fitting a linear trend, so here, with approximately 9 years of data, we use DOF = 7). It is important to note that the use of null hypothesis significance testing has been criticized because of the arbitrary nature of significance levels, the effect of sample size on significance levels, and the difficulty of correctly interpreting the result when rejecting or accepting the null hypothesis (e.g., Nicholls 2001). These criticisms are overcome to some extent by using and reporting the R value (thus providing a continuum of significance). Here, we perform trend analyses on the previously defined (Zwally et al. 1983) Indian Ocean (IO; 20°–90°E) and western Pacific Ocean (WPO; 90°–160°E) sectors.

3. Results and discussion

This section first presents a discussion of regional differences in fast ice distribution and morphology around the East Antarctic coast, and then presents the 8.8-year time series of fast ice extent. This includes a regional analysis, and comparison with pack-ice area/extent within those regions.

a. Location and persistence of fast ice features

Figure 2 shows a map of the average percentage of time with fast ice cover throughout the 8.8-yr study period (e.g., a value of 50% likely indicates that fast ice is present for half of each year on average) and the bathymetry for the study region (Smith and Sandwell 1997). Ten distinct regions of fast ice cover were identified from visual inspection of Fig. 2, with the assistance of a SAR image mosaic of Antarctica, the RADARSAT-1 Antarctic Mapping Project (RAMP) (Jezek 2002). These regions were identified to both document and distinguish regional differences in fast ice formation regimes around the East Antarctic coast. The SAR mosaic was compared with the bathymetric map to determine the approximate location of zones of grounded icebergs, that is, in waters shallower that 400 to 500 m. In SAR imagery, icebergs appear as consistently bright (i.e., high backscatter) targets under freezing conditions, compared with the typically lower backscatter values from sea ice (Williams et al. 1999; Gladstone and Bigg 2002). From west to east, these regions are classified as follows.

(i) 10°W–35°E (Haakon VII Sea Coast)—This region is characterized by low fast ice extents, with little to no multiyear fast ice. This is a possible consequence of the continental shelf break being very close (~20 km) to the coast, leading to few grounded icebergs to act as anchor points for fast ice. Localized exceptions are at 11° and 15°E where the shallow continental shelf region is wider (i.e., ~50 km), allowing a number of small icebergs to ground and provide anchors for fast ice. A thin (up to 30 km) strip of seasonally recurring fast ice is also found at 27°–35°E, again where icebergs ground in shallow regions.

(ii) 35°–40°E (Lützow–Holm Bay)—A region of extensive multiyear fast ice surrounds Syowa base. Despite relatively deep bathymetry in the center of the bay (up to ~900 m), groups of icebergs grounded to the west of Riiser–Larsenhalvøya (~69°S, 34°E) and to the north of Syowa station (at ~69°S, 39.5°E) anchor fast ice formations. These icebergs naturally reinforce the sheltering effect of Lützow–Holm Bay, maintaining the frequently extensive fast ice. Additionally, relatively calm atmospheric conditions are often encountered in the bay during December and January; that is, during the fast ice breakout season, according to ECMWF Interim Reanalysis data (see Fig. 3). This may reduce the occurrence of wind-driven fast ice breakout. Fast ice formed under such quiescent conditions is mainly thermodynamically formed and can attain considerable thickness (Ushio 2006).

(iii) 40°–50°E (Enderby Land Coast)—A seasonally recurring, approximately 50-km-wide strip of fast ice is found along this coastline, of which little is multiyear fast ice. Several thousand small grounded icebergs, clustered along several NW–SE-aligned bathymetric ridges, act to anchor the fast ice between the coast and the 400–500-m isobath.

(iv) 50°–57°E (Amundsen Bay to Cape Boothby)—Fast ice rarely forms extensively in this region, despite the fact that the shallow bathymetry permits a line of grounded icebergs about 40 km from the coast. Few grounded icebergs exist between this line and the coast. It is possible that this distance is too wide for fast ice to span in the absence of suitable onshore atmospheric/oceanic forcing. Also, the continental shelf is very narrow here, possibly allowing warmer waters from the divergence of the Weddell Gyre and the Antarctic Circumpolar Current to penetrate more easily onto the continental shelf (Meijers et al. 2010), which could explain the reduced fast ice extent here.

(v) 57°–68°E (Mawson Coast)—Small grounded icebergs closely follow the contour of undersea ridges, leading to recurring and distinctively shaped fast ice features extending ~50 km from the coast in this area. Fast ice is present for much of the year, particularly in the 57°–62°E section. Multiyear fast
ice is found only in the most sheltered bays (e.g., Edward VIII Gulf, ~57°E).

(vi) 68°–71°E (Cape Darnley)—A line of small grounded icebergs extends northeast from Cape Darnley, leading to extensive and frequent (though not typically multiyear) fast ice coverage. This fast ice feature frequently extends to the western edge of the Amery Ice Shelf.

(vii) 71°–74°E (north face of Amery Ice Shelf terminus)—No significant fast ice forms in this dynamic polynya region, likely due to the deep bathymetry (600–700 m) in Prydz Bay. The depth here precludes iceberg grounding, leading to a lack of fast ice anchor points.

(viii) 74°–81°E (Ingrid Christensen Coast)—A narrow strip of fast ice often covers this coast, forming along the eastern margin of the Amery Ice Shelf, the Polar Record Glacier, and hundreds of small grounded icebergs. Multiyear fast ice is found at the eastern edge of the Amery Ice Shelf. Further offshore (~100 km), a large, seasonally-recurring region of offshore fast ice exists, of which the main body is present for around half of each season. This is anchored around a group of small
grounded icebergs (centered on approximately 67°S, 78.5°E).

(ix) 81°–152°E (West Ice Shelf to Cook Ice Shelf)—This zonally extensive region is characterized by several coastal features that are north–south aligned, for example, iceberg tongues, glacier tongues, ice shelves, coastal promontories, and groups of smaller grounded icebergs. Irregular-shaped fast ice regions are located on the eastern (windward) side of these coastal features (as opposed to the majority of fast ice features found from 10°W to 81°E, which typically run parallel to the coast). Latent heat polynyas (driven by katabatic winds) are typically found on the western (ice) side of the features (Barber and Massom 2007). Several extensive (a few 1000 km² in area) regions of multiyear fast ice are encountered in this region. Every major north–south protrusion (i.e., the West Ice Shelf, Shackleton Ice Shelf, line of grounded icebergs north of Vincennes Bay, Dalton Iceberg Tongue, Dibble Iceberg Tongue, and Mertz Glacier Tongue) has a latent heat polynya on its western side (Massom et al. 1998; Tamura et al. 2008) and a fast ice feature on its eastern side.

(x) 152°–172°E (Cook Ice Shelf to Cape Adare)—This final region is characterized by a relatively narrow (≈50 km) strip of fast ice which is oriented parallel to the coast, similar to the fast ice morphology found in the aforementioned Enderby Land Coast and Mawson Coast regions (regions iii and v). The strip of fast ice is more extensive in the western half of this region. Multiyear fast ice is found between Lauritzen and Slava Bays (154°–156°E) and also off the coast of the closed Russian Leningradskaya Station (≈159.5°E). Very few grounded icebergs are present in this region. The recurring fast ice feature to the east of this region likely forms in the oceanic lee of Cape Adare. Wind speeds in the region, as shown in ECMWF ERA-Interim reanalyses (Berrisford et al. 2009, not shown here), are typically relatively low, which precludes the formation of a significant latent heat polynya from the Cape. There is no evidence to support the presence of the ocean ridge, reportedly centered at 68.5°S, 157°E (Smith and Sandwell 1997, see Fig. 2d), as there appear to be no grounded icebergs at this location. The ridge is also not present in other more recent bathymetry products, e.g., Timmermann et al. (2010).

It is suggested that these regimes can be combined into two larger regions with broadly similar fast ice conditions:
Fast ice formation regime 1

Fast ice formation regime 2

Fig. 4. Conceptual schematic diagrams of two East Antarctic fast ice formation regimes, with a similar color scale to Fig. 2. The continent and coastal protrusions are shown in white, and the ocean–pack ice–polynyas are shown in black. (top) Fast ice formation regime in the vicinity of a protrusion into the Antarctic Coastal Current. Multiyear fast ice (shown here in red) is frequently observed attached to the upstream side of the coastal protrusion. We hypothesize that fast ice growth is achieved via dynamic interception of pack ice (shown here in yellow and green) for coastal configurations such as this, leading to the characteristic sawtooth shape of fast ice features. (bottom) Fast ice formation regime in the vicinity of several small grounded icebergs some distance offshore. Note the lack of multiyear fast ice. A strip of first-year fast ice, often ~50 km wide, forms when fast ice extends to the farthest grounded icebergs.

characteristics: 1) between 81° and 155°E, a region characterized by a large number of coastal protrusions; and 2) west of 81°E, plus the small region from 155°~172°E, where relatively few coastal protrusions exist. These two formation regimes are shown schematically in Fig. 4. Regime 1, representative of region (vi) and the extensive region (ix), occurs when a N–S-aligned protrusion into the (westward) Antarctic Coastal Current (ACoC) exists. This protrusion can be in the form of a coastal promontory, one or more large tabular grounded icebergs, or a near-contiguous group of smaller grounded icebergs. This regime is characterized by extensive fast ice formation on the upstream side of the protrusion (multiyear fast ice in many cases) and a coastal polynya in the oceanic ice of the protrusion. The ACoC generally advects pack ice into the protrusion, resulting in dynamically formed fast ice frequently extending over 100 km from the shore (e.g., region ix in particular). The location of the fast ice edge thus progresses toward the east during the growth season as more advected pack ice is held fast against pre-existing fast ice.

Regime 2, representative of regions (iii), (v), (viii), and (x), typically occurs where small icebergs ground some distance from the coast, at a depth of 400–500 m (Beaman and Harris 2005). Initial fast ice growth can occur abruptly between the coast and the closest grounded icebergs, or alternatively, fast ice can form between closely spaced grounded icebergs some distance offshore. Subsequent growth then occurs between existing fast ice features and other grounded icebergs. Little multiyear fast ice is observed under this formation regime. The proportion of thermodynamically formed fast ice may be higher under this regime than for regime 1 because this regime does not rely on pack ice advection for formation to occur. The distance from the shore to the fast ice edge during maximum extent is typically shorter under this formation regime than regime 2. Under this regime, the shape of the fast ice feature at maximum extent broadly resembles the 400–500-m bathymetry contour.

b. Fast ice time series trend analysis and overall trend analysis

The time series of fast ice extent for the entire region (10°W–172°E) is shown in Fig. 5, with the mean annual cycle given in Fig. 5b. The 8.8-yr mean annual cycle begins each year by steadily declining to the fast ice minimum of ~120 000 km² at around Day of Year (DOY)
61–80 (early mid-March). This is followed by a period of rapid fast ice growth to a relatively broad maximum of \(388 \times 10^4\) km\(^2\) (persisting from \(\sim\) DOY 141 to 300, or mid-May to late October). Following DOY 300, the fast ice extent declines until the end of the year. In contrast, the shape of the overall sea ice extent and area cycles is more sinusoidal, with fairly slow seasonal formation (from mid-March to late September) being followed by relatively rapid retreat, typically from mid-October to early February (Gloersen et al. 1992).

**Fig. 5.** (a) Fast ice time series (thick line) for the East Antarctic coast (10°W–172°E), showing a statistically significant (99% confidence level) increase of \(4012 \pm 830\) km\(^2\) yr\(^{-1}\). Note the major impact of extraordinarily extensive fast ice along the Enderby Land and Mawson coasts from 2006 to 2008. (b) The shape of the annual fast ice cycle, produced from the 8.8-yr dataset. This cycle is also shown as a thin line in (a). (c) Solid line: Fast ice extent anomaly (differences between the observed fast ice extent and the 8.8-yr mean for that time period). Dashed line: Linear trend for the 8.8-yr period.

**Fig. 6.** As in Fig. 5, but for the Indian Ocean sector (thick line), showing a statistically significant increase of \(4444 \pm 457\) km\(^2\) yr\(^{-1}\). (b) Note the smooth annual cycle, possibly reflecting the relatively high portion of thermodynamically formed fast ice in this region.
The annual cycle is more sinusoidal in the IO sector (Fig. 6b) than the WPO sector (Fig. 7b), though it is still substantially broader around the maximum than the minimum. This possibly reflects the different formation regimes in each region (see Fig. 4). The proportion of thermodynamically rather than dynamically formed fast ice in the IO sector is likely higher than that in the WPO sector because of the greater number of north–south coastal promontories in the latter sector. These features act to intercept pack ice that is drifting westward around the coast within the ACoC, leading to more dynamically formed fast ice (Giles et al. 2008; Jezek 2002). Maps of fast ice in Giles et al. (2008) show higher radar backscatter (indicating rougher ice on the scale of the radar wavelength, or \( \sim 5 \) cm in this case) for fast ice on the upstream side of these coastal promontories. Similarly, the SAR mosaic of Antarctica (Jezek 2002) shows low backscatter for fast ice along the Mawson and Enderby land coasts, both of which are regions with no significant N–S-aligned promontories of protrusions. It is hypothesized here that the dynamic fast ice formation leads to the jagged shape of the mean annual cycle in regions containing a high proportion of dynamically formed fast ice. Significant fast ice breakout also typically begins to occur earlier in the WPO sector than the IO sector (see Figs. 6b and 7b) and continues at a steady rate throughout the summer breakout season. This suggests that dynamically formed fast ice may be mechanically weaker than thermodynamically formed fast ice, leading to episodic breakout, which may occur at the interfaces between existing fast ice and newer dynamically formed fast ice. This result showing the more transient nature of dynamically formed fast ice in Antarctica, characterized by series of breakouts and reformations, has also been observed in the Arctic by Mahoney et al. (2007b).

There is a pronounced peak in the mean annual fast ice extent cycle in the WPO sector at DOY 261–280. Initially, it was suspected that an anomalously high fast ice maximum extent in 2006 was solely contributing to this peak. This anomalous maximum fast ice extent was caused by advection of pack ice against the coast, driven by strong easterly winds (see section 3c and Fig. 8 for a detailed description of this event). The contribution of this event to the peak in the annual cycle was evaluated by calculating a truncated mean (whereby the maximum and minimum values were removed from the mean calculation). The truncated mean annual cycle also exhibited a peak at DOY 261–280, indicating that the timing of the fast ice maximum extent occurs within this period.

Table 1. Table of fast ice extent trend results by region. The \( R \) value represents the ratio of trend slope to its standard deviation. An \( R \) value greater than 3.499 indicates a statistically significant trend with greater than 99% confidence and is shown here in a bold font.

<table>
<thead>
<tr>
<th>Sector</th>
<th>( \text{km}^2 \text{yr}^{-1} )</th>
<th>( % \text{yr}^{-1} )</th>
<th>( R ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Antarctica (10°W–172°E)</td>
<td>4012 ±830</td>
<td>1.43 ±0.30</td>
<td>4.84</td>
</tr>
<tr>
<td>Indian Ocean (20°–90°E)</td>
<td>4444 ±457</td>
<td>4.07 ±0.42</td>
<td>9.73</td>
</tr>
<tr>
<td>Western Pacific Ocean (90°–160°E)</td>
<td>−579 ±525</td>
<td>−0.40 ±0.37</td>
<td>−1.10</td>
</tr>
</tbody>
</table>
We also performed a regional analysis on the fast ice time series, comparing the IO and WPO sectors. Table 1 summarizes the results of the trend analyses, and Table 2 shows the value of the fast ice minimum/maximum areal extent in each year.

For the entire East Antarctic coast and from 2000 to 2008, a positive trend (increase) in fast ice extent of 4012 ± 830 km² yr⁻¹ is observed. Though this trend is statistically significant (at the 99% confidence level), the time series is too short to determine whether it is part of a longer-term positive trend. The observed increase is concentrated mainly in the IO sector (see Fig. 6), with a trend of 4444 ± 457 km² yr⁻¹. Interannual variability in areal extent in this region is relatively large, especially in fast ice minima. As with the entire East Antarctic coast, annual minima in the IO sector seem to have little relation to previous or subsequent maxima. Fast ice maxima in this region appear to follow a bimodal distribution, with the 2000–05 maxima falling near the 8.8-yr mean cycle value, while the 2006–08 maxima are considerably

### Table 2: Table of fast ice (FI) maximum and minimum extents (km²) for East Antarctic coast, Indian Ocean, and western Pacific Ocean sectors.

<table>
<thead>
<tr>
<th>Year</th>
<th>East Antarctica (10°W–172°E)</th>
<th>Indian Ocean sector (20°–90°E)</th>
<th>Western Pacific Ocean (90°–160°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>2000</td>
<td>392 000</td>
<td>144 000</td>
<td>140 000</td>
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<td>2001</td>
<td>375 000</td>
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<td>137 000</td>
</tr>
<tr>
<td>2008</td>
<td>407 000</td>
<td>173 000</td>
<td>134 000</td>
</tr>
<tr>
<td>Mean</td>
<td>388 000</td>
<td>153 000</td>
<td>131 000</td>
</tr>
</tbody>
</table>

![Prevailing wind diagram and wind difference plot](image-url)
higher than that of the previous 6 years. In contrast, there is no significant trend in fast ice extent for the WPO sector (−579 ±525 km² yr⁻¹).

An apparent change in fast ice extent trend is observed in the IO sector from ~2004 onward (Fig. 6). Prior to 2004, a slightly negative trend is observed, and interannual variability is relatively small. From 2004 onward, the trend becomes strongly positive and variability increases. This change in trend in the IO sector contributes strongly to the trend observed for the entire East Antarctic coast. In the IO sector, minima range from ~9000 km² (2004) to ~92 000 km² (2008), while maxima range from ~137 000 km² (2004) to ~179 000 km² (2006). No such change is observed in the WPO sector (Fig. 7), where there is relatively little interannual variability (but values still span quite a large range), and the negative trend continues throughout the 8.8-yr record. In this sector, minima range from ~51 000 km² (2002) to ~87 000 km² (2001), while maxima range from ~184 000 km² (2004) to ~238 000 km² (2006).

The relationship between each year’s fast ice maximum and the subsequent minimum was also analyzed. Anomalously low minima are observed in 2002 (~96 000 km²), 2004 (~83,000 km²), and 2006 (~104 000 km², compared with the mean of ~120 000 km²). Of these years, only the 2004 maximum was anomalously low (~341 000 km² compared with the mean maximum extent of ~388 000 km²). In fact, the 2006 maximum was anomalously high (~447 000 km²). The only anomalously high minimum (~191 000 km²) was encountered in 2008, which was followed by an anomalously high maximum (~407 000 km²). It appears that there is little correlation between maxima and subsequent minima, except from 2006 to 2008 in the IO sector, which recorded strongly positive extent anomalies for almost the entire 3-yr period.

c. Fast ice extent climatology and annual minimum-to-minimum averages

The fast ice extent by time of year, averaged over the 8.8-yr time series, is shown in Figs. 9 and 10. These figures represent a fast ice climatology. Comparison between these figures and Fig. 2 reaffirms the close links between bathymetry, iceberg grounding, and fast ice extent discussed in previous sections. In many regions, and particularly where minimal coastal protrusions are present, fast ice reaches its maximum extent early in the season and is unable to grow past this because of a lack of grounded icebergs in waters deeper than approximately 400–500 m. It is suggested that these regions (e.g., the Mawson and Enderby Land coasts) may have a higher fraction of thermodynamically formed fast ice. This is in contrast to regions where the presence of shallow bathymetry allows large numbers of icebergs to ground, leading to dynamic fast ice growth via interception of pack ice (e.g., to the east of iceberg B-9B, at ~150°E).

Annually averaged (annual minimum to subsequent annual minimum) fast ice conditions are shown in Fig. 11 (except for the image labeled “2008,” where no data from 2009 were analyzed and hence the 2009 minimum was unavailable, making this image more biased toward greater fast ice coverage). This figure clearly shows the origin of the positive trend in the IO sector (20°–90°E, see Fig. 6), especially over the period 2006–08. In particular, much more of the fast ice along the Enderby Land and Mawson coasts (40° ~ 50°E and 57° ~ 68°E, respectively) survives the summertime melt during 2007 and 2008, contributing to the progressively higher minimum fast ice extents during these years. Additionally, more fast ice forms north of the region from Amundsen Bay to Cape Boothby (50°–57°E) during the maxima of 2006, 2007, and 2008, contributing to the higher maximum extent observed in the IO sector during these years.

In the WPO sector, the main contribution to the origin of the anomalously high maximum extent in 2006 (DOY 261–280) can be traced to an extensive fast ice feature to the east of iceberg B-9B [until recently (Young et al. 2010), centered at approximately 67°20′S, 148°23′E]. Here, the westward-flowing ACoC advects pack ice into the region between B-9B and the coast, often forming heavily consolidated pack ice which can temporarily form fast ice (Massom et al. 2001; Barber and Massom 2007). Dense clusters of small grounded icebergs, that is, those to the north of B-9B, act in a similar fashion to individual large grounded icebergs (Massom et al. 2001; Barber and Massom 2007). In this way, fast ice can extend across waters deeper than the maximum depth of iceberg grounding (~450 m) and be present more than 200 km offshore. The 2006 maximum is possibly an extreme manifestation of this phenomenon, and an in-depth investigation into this event is planned. Examination of ECMWF Interim reanalysis data for this period shows anomalously strong easterly winds (see Fig. 8). This provides evidence for pack ice advection being an important contributor to fast ice growth in this region. Ocean currents are also likely to be an important factor in this region, but data are lacking.

Analysis of the fast ice climatology (Figs. 9 and 10) reiterates the important differences in the nature of fast ice formation and breakout in each sector, as described in section 3a. Fast ice growth and breakout along the Enderby Land and Mawson coasts, and also the region to the east of the Cook Ice Shelf (~152°E), both occur first between the coast and the closest grounded icebergs, before progressing to nearby grounded icebergs.
eventually forming a strip (typically <50 km wide) of fast ice across the coast. This is in contrast to much of the fast ice in the WPO sector. As previously mentioned, in this region, several coastal protrusions allow fast ice to form windward (upstream) of these features. As the season progresses, the fast ice grows more in an eastward direction as more pack ice is intercepted by the preexisting fast ice. Fast ice retreat in this sector then occurs by recession of the fast ice largely from east to west in spring–summer.

The length of the fast ice coverage per year at a given location, that is, the seasonality or fast ice season duration, is an important parameter, responding to both oceanic and atmospheric forcing (Heil 2006; Heil et al. 2006; Mahoney et al. 2005). Because of the large spatial scale of this dataset, detailed analysis of fast ice seasonality is outside of the scope of this work.

d. Comparison between fast ice extent and overall regional sea ice extent and area

The relationship between fast ice extent and overall sea ice extent was examined using SSM/I passive microwave sea ice concentration 20-day composite images generated over the same time period. Comparisons for the whole coast, the IO sector, and the WPO sector are shown in Figs. 12, 13, and 14, respectively. Note the difference in overall sea ice extent and area between the IO and WPO sectors, a consequence of the greater pack ice extent in the IO sector, relating to the location of the eastern part of the Weddell Gyre and the southern
boundary of the Antarctic Circumpolar Current (Gloersen et al. 1992). Across the East Antarctic coast and both subregions, pack ice area/extent maxima are uncorrelated with fast ice maxima, with correlation coefficients \( R \) of 0.22, 0.14, and 0.2 for the entire coast, IO, and WPO sectors, respectively. However, the minima are strongly correlated (correlation coefficients of 0.93, 0.94, and 0.81, respectively). This is not necessarily an indication that fast ice extent and overall sea ice extent share a common forcing; rather the relative fraction of fast ice comprising overall sea ice increases (i.e., the ratio of sea ice to fast ice decreases to a minimum) during the summertime sea ice minimum (see Table 2, Fig. 15). Additionally, fast ice is highly vulnerable to ocean waves (Crocker and Wadhams 1988, 1989; Langhorne et al. 2001), and it may be that pack ice acts as a protective buffer to their destructive effect, leading to larger fast ice minimum extents during years when more extensive pack ice is present.

This fast ice time series mirrors the longer-term trends in overall sea ice extent/area in the region (dating back to 1978). For example, both Comiso (2009) and Cavalieri and Parkinson (2008) show a larger increase in sea ice extent in the IO sector \((\sim 1.9 \pm 1.4\% \text{ decade}^{-1})\) than the WPO sector \((\sim 1.4 \pm 1.9\% \text{ decade}^{-1})\), though neither trend is significant at the 95% confidence level (Cavalieri and Parkinson 2008).

d. Variability in timing of fast ice maxima and minima

Fast ice extent is thought to respond to atmospheric and oceanic forcing in a complex manner (e.g., Heil 2006; Mahoney et al. 2007a; Massom et al. 2009). It is, however, outside the scope of this paper to carry out a
A detailed analysis of the effects of atmospheric and oceanic variability and change on the observed variability in timing of fast ice maxima/minima and spatiotemporal behavior. Such work is planned for the future, using the time series presented here.

Timing of maximum and minimum fast ice extent are important fast ice parameters that are sensitive to changes in climate (Heil et al. 2006; Mahoney et al. 2005). The minimum fast ice extent, averaged across the entire region, typically occurs during DOY 61–80 (early–mid-March), with a mean value of $\sim 120\,000\,km^2$. Maximum typically occurs during DOY 261–280 (mid–late September), with a mean value of $\sim 388\,000\,km^2$ (see Table 3)—that is, the ratio of maximum to minimum fast ice extent is typically $\sim 3.2$ to 1. This compares with mean regional minimum and maximum overall sea ice extents over the same time period (2000–08) of $\sim 770\,000$ and $\sim 9\,300\,000\,km^2$, respectively (Comiso 1999), that is, a ratio of $\sim 12$ to 1 for overall sea ice to fast ice. The fast ice minimum almost always occurs later than the overall sea ice minimum, a likely consequence of the pack ice protecting the fast ice from swell-induced breakout.

The timing of fast ice minimum extent is observed to occur progressively earlier in the IO sector (on the order of 5 days yr$^{-1}$) throughout the 8.8-yr time series (see Table 3). No obvious trend is observed in the timing of the overall sea ice extent in the IO sector. In general, the timing of maximum/minimum fast ice extent displays higher variability than the corresponding timing of overall sea ice maximum/minimum extent, reflecting
both the lower fast ice extent compared to overall sea ice, and the complex controls that limit fast ice extent (e.g., grounded icebergs acting as anchor points).

f. Percentage of fast ice comprising overall sea ice extent/area

The percentage of fast ice area comprising overall sea ice area throughout the 8.8-yr time series for the East Antarctic coast is shown in Fig. 15. The percentage of fast ice extent comprising overall sea ice extent is also shown in this figure. Minimum, maximum, and mean values for each year are shown in Table 4. We assume here that fast ice concentration is 100%; hence, fast ice extent is equivalent to fast ice area. This is a reasonable assumption based on field observations.

A strong seasonal cycle is observed in the fraction of overall sea ice area/extent, which is fast ice. Following the maximum fast ice percentage early in the season (around DOY 41–60, late February), the fast ice extent (area) percentage slowly decreases to a broad minimum, with a mean value of 3.77% (4.51%). A rapid increase in the fast ice percentage is observed from around DOY 341–365 (mid-December), with maximum percentage occurring during DOY 41–60 in most years, except 2003 and 2005, when the maximum fast ice extent percentage occurred during DOY 21–40. The value of the maximum (minimum) extent percentage varies between 16.0% and 21.0% (3.2% to 4.2%), with the maximum (minimum) area percentage showing similar variability.

Note that the largest variability in this quantity occurs during the summer sea ice/fast ice minimum, where the relative variability of both sea ice and fast ice is greater.

4. Summary and further work

The new time series presented in this paper entails the most comprehensive and detailed information on variability in the distribution of Antarctic fast ice to date and represents an important new climatic baseline against which to gauge future change and variability along the entire coastal and near-coastal East Antarctic environment in a warming climate. This is by virtue of the sensitivity of fast ice to change/variability in atmospheric and oceanic circulation and temperature, ocean

During winter, the variability of fast ice extent is much lower than the summer, a consequence of the limit placed upon maximum fast ice extent due to the location of grounded icebergs (see section 3e).

FIG. 12. Time series comparison between overall sea ice extent–area and fast ice extent along the entire East Antarctic coast (10°W–172°E). The scale for overall sea ice extent and area is on the left. Fast ice extent has been scaled by a factor of 10 for inter-comparison purposes, and uses the scale on the right.

FIG. 13. As in Fig. 12, but for the Indian Ocean sector (20°–90°E).

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waves/storms, and the larger-scale pack ice realm. The new dataset also provides an important means of spatially extending detailed (though geographically limited) point measurements of fast ice formation and break-up processes at sites close to Antarctic bases within the AFIN program (Heil et al. 2011).

Although the time series is currently short, that is, ~9 years, certain spatiotemporal patterns are apparent that highlight broad regional differences in factors relating to fast ice formation, persistence, and seasonality. In terms of overall extent across the entire East Antarctic region (from 10°W to 172°E), there has been a statistically significant increase (at the 99% confidence level) of 1.43 ±0.3% yr⁻¹. This pattern is in fact dominated by the signal from the IO sector, where an increase in fast ice extent of 4.07 ±0.42% yr⁻¹ is observed. In contrast, the 9-yr trend in the adjacent WPO sector is of a (non-significant) decrease of −0.40 ±0.37% yr⁻¹. Nested within these linear trends are major contrasts in the degree of interannual variability, however. In the IO sector, the period 2000–03 is characterized by low variability and a slight decreasing trend, while an abrupt upward trend combined with much higher interannual variability occurs in the subsequent period (2004–08). This latter part of the record, which both determines and dominates the upward 9-yr trend, is attributed to the anomalous persistence of extensive fast ice off the Mawson and Enderby Land coasts, both in summer and winter (and to a lesser extent during the shoulder seasons of spring and autumn). Atmospheric factors influencing this variability are currently unknown but are under investigation.

By comparison, the concomitant lower variability and lack of a similar abrupt change around 2004/05 in the WPO sector is attributed to differences in the physical setting (given that different atmospheric forcing patterns may also play a key role). In this broad sector, extensive north–south-oriented coastal promontories and grounded iceberg assemblages are more of a factor than they are in the IO sector. These lead to generally greater persistence in the WPO sector of more dynamically formed fast ice masses that also extend further offshore. More work is necessary, however, to tie down the processes and regional mechanisms involved (in both sectors). With this in mind, research is underway to investigate links between coastal configuration and spatiotemporal characteristics of fast ice coverage. Additional information on fast ice type (and process of formation) as a function of region.

![Graph](image_url)
can be derived from backscatter characteristics related to fast ice roughness/deformation using satellite SAR data (Giles et al. 2008). In addition, a SAR-based algorithm has been developed that will provide higher spatial and temporal resolution maps of fast ice coverage in regions-of-interest (Giles et al. 2011), to complement the broader-scale coverage of the MODIS product and better resolve breakout/formation events related to the passage of storms. Combination of the two datasets should enable improved understanding of processes and mechanisms responsible for the strong inter- and intraregional differences noted in this study, particularly when merged with meteorological analysis.

The broader physical and biological implications of the observed change/variability in East Antarctic fast ice coverage from 2000 to 2008 are currently unknown but may be significant and are under investigation. Plans are in place to apply the new dataset to a temporal extension of the regional study of Massom et al. (2009), which showed an apparent linkage between fast ice extent and wind-driven variability in intraseasonal fast ice breakout frequency and extent in the Adélie Land coastal sector of East Antarctica and the annual breeding success of the Emperor penguin population at Dumont d’Urville for the period 1992–99 (based on AVHRR data analysis).

In particular, the new fast ice data will be compared with improved penguin demographic information to investigate possible relationships between fast ice coverage and penguin mortality, for example. Moreover, spatio-temporal variability in fast ice coverage has recently been implicated in the breeding success and ecology of Adélie penguins at Béchevaise Island in East Antarctica (Emmerson and Southwell 2008), and the new dataset will allow a more detailed analysis and assessment of the linkages. In addition, a linkage has recently been proposed between fast ice and the stability of floating ice sheet margins, that is, the Mertz Glacier Tongue prior to its calving in 2010 (Massom et al. 2010). This study suggests that changes in fast ice coverage may have important ramifications for ice loss from the vulnerable ice sheet margins that are under increasing threat from oceanic warming; the new dataset will enable wider

| Table 3. Table of the timing of fast ice and overall sea ice minimum and maximum extent, shown in DOY range format for the period March 2000–December 2008. Bold entries indicate which event occurred earlier (overall sea ice minimum extent or fast ice minimum extent). |
|---|---|---|---|
| **East Antarctica** | **Indian Ocean** | **Western Pacific** |
| Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
| Fast ice | Sea ice | Fast ice | Sea ice | Fast ice | Sea ice | Fast ice | Sea ice | Fast ice | Sea ice |

| Table 4. Table of maximum and minimum percentage of overall sea ice extent/area which is fast ice (see Fig. 15). |
|---|---|---|
| **East Antarctica (10°W–172°E)** | **Minimum fast ice percentage compared to:** | **Overall sea ice extent (%)** |
| **Overall sea ice area (%)** | **Minimum fast ice percentage compared to:** | **Overall sea ice area (%)** |
| 2000 | 21.0 | 34.0 | 3.9 | 4.8 |
| 2001 | 19.4 | 34.1 | 4.0 | 4.8 |
| 2002 | 17.9 | 25.9 | 3.7 | 4.4 |
| 2003 | 20.7 | 33.9 | 3.2 | 3.7 |
| 2004 | 19.6 | 35.1 | 3.3 | 4.1 |
| 2005 | 20.6 | 32.2 | 3.6 | 4.3 |
| 2006 | 16.4 | 26.6 | 4.1 | 4.7 |
| 2007 | 16.0 | 24.1 | 4.0 | 4.9 |
| 2008 | 19.0 | 30.7 | 3.8 | 4.5 |
| **Mean** | | | |
assessment of this potentially important role of fast ice in a changing climate. In all cases, a better understanding is required of the role of change/variability in large-scale patterns (modes) of atmospheric circulation in driving the observed regional change/variability in fast ice coverage across East Antarctica, and this is once again the focus of current research.

Although based on a temporally limited dataset, the current study confirms an intimate though complex association between fast ice variability and that of the surrounding regional pack ice. This implies that projected changes in Antarctic pack ice (e.g., Bracegirdle et al. 2008) may significantly impact fast ice distribution. On the broadest scale, the regional short-term trends in fast ice extent shown in this study broadly agree with longer-term (1979–2008) trend in overall sea ice (comprising both pack ice and fast ice) extent/area (e.g., Cavalieri and Parkinson 2008; Comiso 2009). However, East Antarctic fast ice extent displays greater variability than overall sea ice extent/area on monthly through seasonal to interannual time scales. This is likely due to the often abrupt transitions that typically occur between fast ice breakout and growth. In general, fast ice maxima are uncorrelated with sea ice extent (and area) maxima, while the opposite is true for the respective minima. This relationship is thought to be indicative of the effect of pack ice as a protective buffer against ocean swell/wave-induced fast ice breakout (Langhorne et al. 2001). This linkage is further suggested by the fact that the fast ice minimum typically occurs after the overall sea ice minimum. However, fast ice minima (maxima) are generally uncorrelated with subsequent maxima (minima). Significant interannual variability is also observed in the timing of fast ice minima and maxima, although the latter is difficult to determine accurately given the broad nature of the peak in the annual cycle. The minimum extent of fast ice is observed to occur progressively earlier in the IO sector, despite there being no corresponding trend in the timing of minimum overall sea ice extent. Further analysis is necessary to determine possible causes.

The mean annual growth and decay cycle differs for fast ice compared to overall sea ice in that it is characterized by a temporally broad maximum and an abrupt, relatively short minimum. By comparison, the seasonal cycle of Antarctic pack ice is characterized by a relatively long expansion phase (typically from February through August–October) followed by a rapid decay from November through December (Gloersen et al. 1992). The shape of the annual fast ice cycle itself (in particular the broad maximum, and the relatively short growing season compared to that for overall sea ice) is thought to reflect the link between fast ice presence and shallow bathymetry: 400–500 m is the maximum depth at which icebergs ground (Beaman and Harris 2005). In most regions, this forms an upper limit on maximum extent of fast ice coverage offshore, given that grounded iceberg assemblages for anchor points for fast ice growth by both thermodynamic and dynamic processes, a finding that is in line with other studies, for example, Giles et al. (2008) and Massom et al. (2009). Further fast ice growth past this physical boundary is achieved only in the most sheltered regions (e.g., Lützow–Holm Bay) or regions where pack ice is continually advected into other protruding coastal features, for example, near 150°E (Massom et al. 2001).

Given the wide-ranging importance of improved estimation of fast ice coverage, we plan to use the same technique to extend the time series both forward and back in time, the latter using NOAA AVHRR data from pre-2000 (where and when available). Future fast ice extent derivations will exploit imagery from MODIS and the Ocean Land Color Instrument (OCLI) onboard the European Space Agency Sentinel-3 satellite (due for launch in 2013, http://www.eoportal.org/directory/pressGMESSentinel3Mission.html). Further plans are to extend Antarctic coverage to circumpolar and to apply the technique to mapping regional Arctic fast ice. Work is underway to semi-automate the algorithm, an important step given the large volume of data involved and the need for routine coverage, to create a gap-free climatic dataset that is equivalent to the important satellite passive microwave–derived pack ice time series that dates back to 1979 (Comiso 2009).

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