Antarctic sea-ice velocity as derived from SSM/I imagery

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ABSTRACT. Sea-ice velocities derived from remotely sensed microwave imagery of the Special Sensor Microwave/Imager (SSM/I) have been analyzed for changes over time in Antarctic sea-ice velocity, for the period 1988–2004. Year-to-year variability in mean Antarctic annual SSM/I-derived ice speed is small (17 year standard deviation (SD) = 0.008 m s^{-1}), with greater interannual variability in the zonal (eastward positive) velocity components (17 year SD = 0.016 m s^{-1}). Seasonally, minimum ice speed is encountered during summer, when nearly all Antarctic sea ice is within the marginal ice zone. Ice motion peaks during winter and spring, due to high velocities encountered in the outer pack of the seasonal sea-ice zone. The correlation (R^2 = 0.47) between winter Southern Annular Mode (SAM) and mean winter ice speed highlights the importance of atmospheric forcing on sea-ice dynamics. The spatial pattern of the correlation of the standardized SAM index with the June–November ice speed exhibits a wave-3 pattern, which matches the sea-level pressure distribution. Sea-ice speed in the upstream regions of quasi-stationary centres of low sea-level pressure is likely to increase (decrease) during high (low) SAM years, and the opposite for sea-ice speed in the downstream regions of the centres.

INTRODUCTION

Climate research, including that of polar regions, rapidly produces new hypotheses and provides interpretations of observational and modelled data. Interannual to decadal atmospheric variability in the southern polar region may be quantified by the Southern Annular Mode (SAM) index (Thompson and Wallace, 2000) or the Antarctic Oscillation (AAO; Gong and Wang, 1999). Gong and Wang (1999) interpreted this phenomenon as the exchange of mass between the mid- and higher latitudes due to the air-pressure gradient between 40° S and 65° S.

In the Southern Ocean, changes in SAM index can be thought to cause significant sea-ice and ocean circulation anomalies by way of stronger westerly winds, and thus increased Ekman transport of sea ice northwards and also eastwards, with strongest signals in the Pacific sector (Hall and Visbeck, 2002). The index was low during the 1960s and into the 1970s, but from the early to mid-1970s it increased (Hurrell and Van Loon, 1994; Meehl and others, 1998; Gong and Wang 1999). Thompson and Solomon (2002) interpreted large-scale atmospheric changes south of 20° S as a consequence of changing strength of the polar vortex. They suggest that the change in sign of the SAM is in response to ozone depletion. This is in agreement with Marshall and others (2004), who suggest that increases in greenhouse gases also are a contributing factor.

Consequent to these findings, we need to explore if there are any traceable changes in the state of the Antarctic sea ice. Sea ice is an integral part of the polar climate system, that interacts with ocean and atmosphere on various timescales. The evolution of sea ice is determined by environmental factors, chiefly by atmospheric temperature, winds and incoming solar radiation near the surface, oceanic currents including tidal and inertial forcing, and the heat content within the upper ocean (e.g. Hibler, 1979). While, on seasonal scales, sea-ice concentration and extent are largely driven by the thermal budget at the ocean–atmosphere interface, interannual changes are generally due to dynamic variability within the patterns of atmospheric and oceanic circulation. Sea-ice motion depends largely on the integrated effect of oceanic and atmospheric momentum transfer but is also influenced by internal ice properties, which in turn are affected by thermodynamic processes. Sea-ice dynamics is important, as it redistributes the pack, hence influences ice extent, concentration and thickness distribution. Via these processes, sea ice interacts with other components of the climate system, such as surface albedo, or heat and moisture exchange at the ocean–atmosphere interface, and also the Southern Ocean biota. To fully assess the state of the sea ice, information on sea-ice velocity is required covering those temporal and spatial scales relevant to climate processes.

Few data are available on the past state of sea ice. Remote-sensing instruments such as the Scanning Multichannel Microwave Radiometer (SMMR; 1979–87) and the Special Sensor Microwave/Imager (SSM/I; 1987–present) provide bidaily and daily, respectively, composites of sea-ice concentration. Using data from 1979 to 1998, Zwally and others (2002) determined that the total Antarctic sea-ice extent (for concentrations above 15%) has increased by (0.98 ± 0.37)% decade^{-1}, and that the total sea-ice area has increased by (1.26 ± 0.43)% decade^{-1}. Regional differences are apparent: ice extent has increased in the Weddell Sea, the Pacific Ocean sector and the Ross Sea, while a slight decrease in the Indian Ocean sector and a stronger decrease in the Bellingshausen and Amundsen Seas sector have been recorded. See Liu and others (2004) or Parkinson (2004) for details.

Emery and others (1997) have previously presented mean sea-ice motion derived from SSM/I data for 1988–94. They reported strong, coherent patterns of ice motion consistent

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with wind directions. Their study did not assess the interannual variability in sea-ice motion. Liu and others (2004) analyzed changes in the state of Antarctic sea ice (including ice velocity) using SMMR and SSM/I data and related those to changes in atmospheric forcing.

In this study, we extend the SSM/I-derived ice-motion time series to cover the interval 1988–2004 but exclude SMMR-derived ice motion, as our analysis showed that the time series are not compatible. Reprocessing and validation of the SMMR-derived motion data is currently underway. We examine the SSM/I-derived data for temporal changes in ice motion as well as the regional nature of change; the modes of variability in the motion data and the potential for these modes to be related to atmospheric phenomena; and interpret the findings with regard to temporal changes in sea-ice extent and concentration.

SEA-ICE MOTION FROM PASSIVE MICROWAVE IMAGERY

The broad-scale features of sea-ice drift can be derived effectively using consecutive satellite imagery together with the maximum cross-correlation method (e.g. Fowler, 1995; Emery and others, 1997). This yields a composite product of sea-ice motion on an Eulerian grid with global coverage where passive microwave data are available. Prior to satellite techniques, sea-ice motion was measured by Lagrangian methods (e.g. with ice-moored vessels or drifting buoys). Spatial accuracy and temporal resolution of in situ measurements (e.g. drifting buoys) are superior to measurements derived from passive microwave imagery, but the latter is extremely valuable as it covers most of both polar sea-ice zones and is available daily.

The gridded horizontal resolution of the SSM/I 85.5 GHz (37 GHz) data is 12.5 km by 12.5 km (25.0 km by 25.0 km). The maximum cross-correlation method (e.g. Emery and Thompson, 1998) was applied to derive sea-ice velocity as a temporal function of the spatial translation of features within the imagery. A search window of 125 km by 125 km was selected with a search range of 90 km. The derived velocity product using combined data from the 85.5 and 37 GHz channels has a resolution of 25 km by 25 km. Using the daily SSM/I time series, a continuous range from –1.04 to 1.04 m s^{-1} may be detected in both horizontal ice-motion components. This range envelopes all ice motion within the physically plausible range of sea-ice velocities.

In a previous study, daily buoy-derived sea-ice motion was compared with daily composites of SMMR- and SSM/I-derived ice motion off East Antarctica (Heil and others, 2001). Large-scale patterns in sea-ice drift compared well, while the comparison along the buoy trajectory showed that satellite-derived ice motion is up to 40% less than that derived from buoy data. Thus, in this study, the satellite-derived data have been calculated using a larger search area (see previous paragraph), as suggested by Heil and others (2001), to allow the detection of high ice speeds in this dataset.

We assess the revised satellite-derived ice-velocity data by comparison with direct observations of sea-ice motion. In situ ice-motion data have been obtained from the International Programme on Antarctic Buoys (IPAB) for the years 1995–2000. Buoy data, available for most regions around the Antarctic and covering all seasons, have been used here. The drift trajectories of daily buoy motion have been traced in the daily composites derived from the passive microwave imagery. For the circum-Antarctic average, the IPAB ice-drift speeds exceed those derived from SSM/I passive microwave imagery by about 30%. The root-mean-square error of daily SSM/I composites compared to buoys is about 0.096 m s^{-1}, with the bias below 0.025 m s^{-1}. This discrepancy might be due to non-coincident observations, as the SSM/I data have been taken over a 24 hour interval centred at the buoy's 00:00 UT observation, or due to the difference in spatial footprint of the velocity data: buoy observations are effectively point data, while SSM/I velocities are given on a 25 km by 25 km grid. For further comparison of sea-ice velocities, see Heil and others (2001).

THE SPATIAL PATTERN OF ANTARCTIC ICE MOTION

As with the ice extent and ice concentration, there are regional differences in the sea-ice velocity. The sea ice responds to atmospheric and oceanic forcing, which vary both spatially and temporally. We present the spatial pattern of mean June–November ice velocity for each year (Fig. 1). June–November mean data have been chosen to cover the time when the Antarctic sea ice is at or near its maximum equatorward extent. It is worth noting that during June–November the effect of atmospheric moisture on the 85.5 GHz SSM/I channel is considerably less than during summer (Gloersen and Cavalieri, 1986), hence avoiding significant loss in accuracy of the combined 85.5 and 37 GHz ice-velocity product.

While the general pattern of sea-ice velocities around the Antarctic repeats from year to year, Figure 1 indicates that June–November ice velocities for 1990, 2003 and 2004 are lower than those in other years. During those years, ice velocities are low in the East Antarctic and to a certain degree also in the large Antarctic gyres. Those years coincide with low circum-Antarctic ice extent (e.g. Parkinson, 2004). This implies that there is less sea ice along the outer pack, where one generally encounters high ice velocities, this being the reason for overall slower ice speed. During most other years, higher ice speeds were identified in individual regions, often near the outer ice edge in the eastward limb of the Weddell, Ross or Amundsen Sea, and occasionally also near the outer edge of sea ice north of Prydz Bay and in the northward limb of the Ross Sea Gyre.

The mean June–November sea-ice velocity for 1988–2004 is shown in Figure 2a to explore the pattern of Antarctic ice velocity over that interval. The net eastward motion in the outer pack dominates the zonal component. There is a near-continuous band of eastward ice motion, which is only disrupted in the region 115–145° E. The latter region is identified as an area of minimum thickness in the circumpolar band of Antarctic sea ice. The northward ice extent in this region is generally around 450 km or less, considerably less than the average northward ice extent of about 620 km around Antarctica. The eastward flow of sea ice is strongest from 180° E to 290° E north of the Ross and Bellinghausen and Amundsen Seas. The Ross Sea region also has the fastest northward movement of Antarctic sea ice. Net movement north and east of sea ice in this sector may pertain to the decrease in ice extent (Zwally and others, 2002) and also in annual duration of sea-ice cover (Parkinson, 2004) observed in the Bellinghausen and Amundsen Seas region.

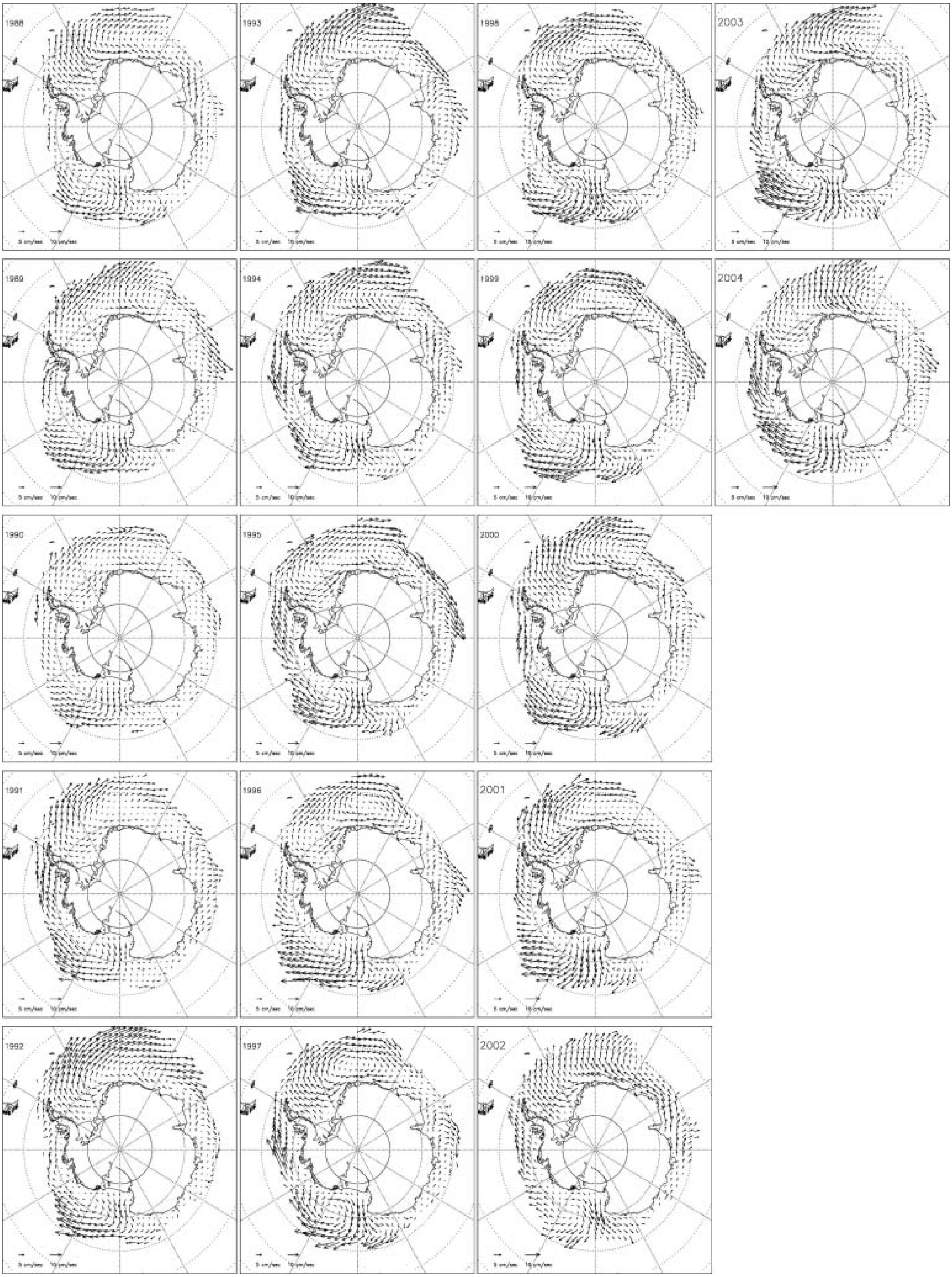

Fig. 1. Mean June–November sea-ice drift derived from SSM/I imagery for 1988–2004. For clarity, only every eighth vector is shown.

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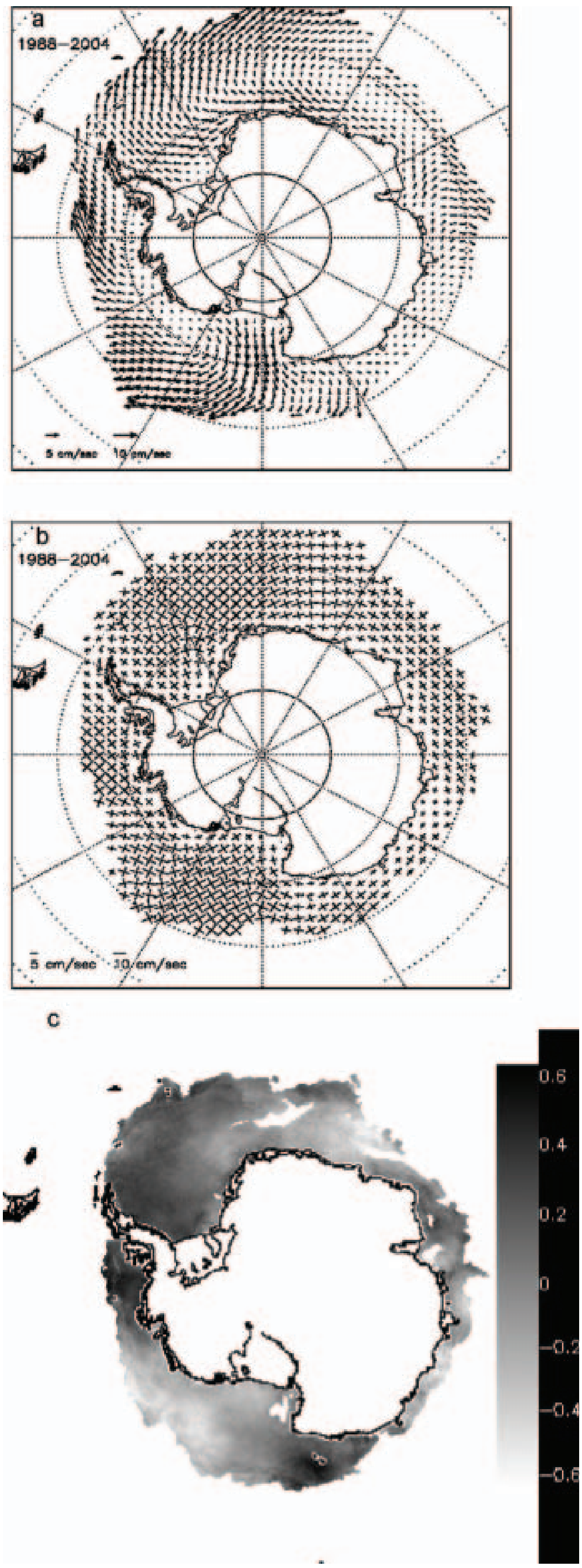

Fig. 2. (a, b) Mean sea-ice speed derived from SSM/I imagery for June–November 1988–2004 (a) (for clarity, only every sixth vector is shown) and its standard deviations (b) (both in m s^{-1}). (c) Correlation coefficient of mean sea-ice speed with SAM index for June–November 1988–2004. A minimum of 20 independent pairs of passive microwave imagery are required for any gridcell to be included in this representation.

There is also strong northward movement in the outer Weddell Sea, but in this region the north- and eastward motion of ice seems to be balanced by the westward drift of sea ice into the Weddell Sea Gyre from the East Antarctic coast. Westward ice motion peaks in the region from 15° W to 45° E, where the coastal current is steered to the south by bathymetric features, such as the Riiser-Larsen Ridge. We should note here that due to masking effects the passive-microwave-derived ice velocity data do not extend all the way to land but stop about 75 km short of the coast.

Figure 2b depicts the interannual variability in sea-ice motion for the axes, along which the largest change occurred. The variability in ice motion is largest in the eastern Ross Sea and northern Weddell Sea. There the variability for both velocity components is of similar magnitude. Off East Antarctica, interannual variability in the zonal velocity component exceeds that of the meridional component, and the opposite in the Bellingshausen Sea. The magnitude in the standard deviation is controlled dynamically.

The correlation between the standardized (to 1 SD) SAM index and the mean June–November ice speed (Fig. 2c) exhibits a wave-3 pattern. For 1988–2004, sea-ice speed and standardized SAM index exhibit negative correlation in the eastern Ross Sea and Amundsen Sea, along 10° W to 45° E, along 100–140° E and also in the eastern limb of the Prydz Bay Gyre. Positive correlations are found in large parts of the Weddell Sea and to a lesser degree in the Bellingshausen Sea, along 45–70° E and 145–165° E. This wave-3 pattern projects onto the surface-pressure distribution (e.g. Hurrell and Van Loon, 1994) as well as the density distribution of Antarctic cyclone centres (e.g. Simmonds and Keay, 2000): centres of low surface pressure and also peaks in winter cyclone activity are found over the southern Ross Sea, southeastern Weddell Sea and southern Prydz Bay. Our analysis consistently reveals positive correlations between ice speed and standardized SAM index in each of the upstream regions of the low-pressure centres, and negative correlations in the downstream regions of the low-pressure centres. This indicates that changes in the atmospheric pressure field modify the Antarctic sea-ice speed bifold: in regions upstream of low-pressure centres ice speed increases with increasing SAM index, but in downstream regions the ice speed decreases with increasing SAM index. This dichotomy is likely to be associated with the strengthened clockwise rotation of low-pressure centres during high SAM, which induces northward (southward) deflection in the upstream (downstream) pack, and hence a translation of the pack into regions of higher (lower) ice speed.

ANTARCTIC SEA-ICE MOTION, 1988–2004

The long-term average Antarctic SSM/I-derived ice speed is about 0.095 m s^{-1}. During 1988–2004, interannual variability in circum-Antarctic mean annual ice speed is as large as 28% of its overall magnitude. There was a slight net rise of 0.001 m s^{-1} a^{-1} (significant at the 90% confidence interval; Kreyszig, 1988) in the mean annual ice speed from 1988 to 2000 (Fig. 3a). In 2003 and 2004, ice speed dropped back to its lowest values for the 1988–2004 record (Fig. 3, triangles). The analysis of circumpolar net ice speed derives that the trend of the 1988–2004 annual mean is not significant at the 90% confidence interval.

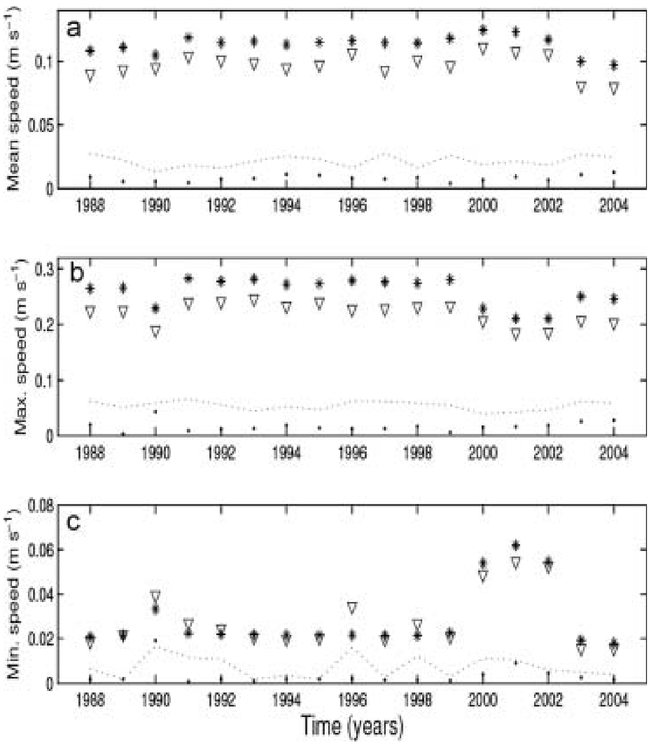

Fig. 3. Annual (triangles) and mean June–November (stars) mean (a), maximum (b) and minimum (c) ice speed for all of the Antarctic sea-ice zone. Standard deviations are shown as dotted line (annual) and dot points (mean June–November).

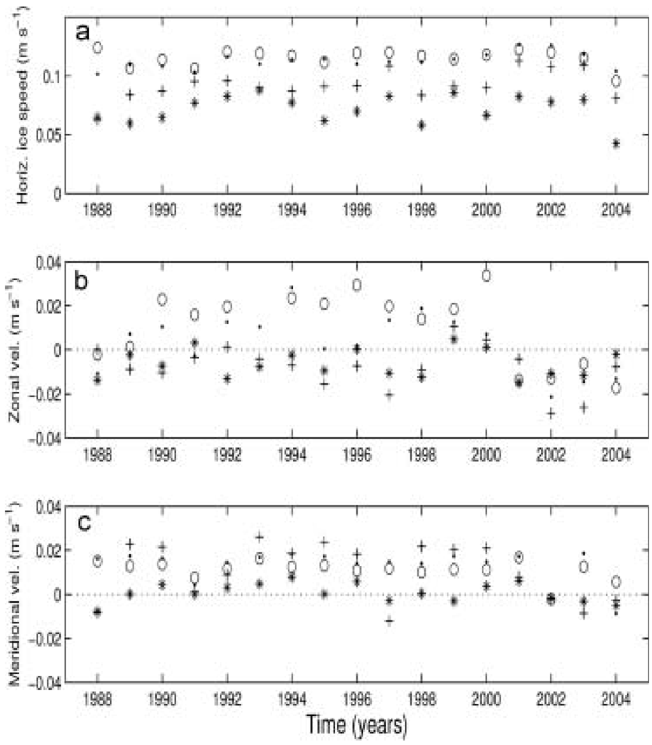

Fig. 4. Seasonal mean horizontal ice speed (a), zonal (b) and meridional velocity (c) for December–February (stars), March–May (crosses), June–August (dots) and September–November (circles).

The mean June–November ice speed for 1988–2004 is 0.113 m s^{-1}, with an interannual pattern of change similar to the mean annual pattern. For all years, the mean and maximum June–November ice speed (Fig. 3, stars) exceeds the annual mean and maximum, respectively. Due to the extreme northern position of Antarctic ice extent during winter and spring, at these times ice drift is affected by the oceanic and atmospheric regimes in the heart of the Southern Ocean, including the strong eastward flow of the surface ocean along the southern edge of the Antarctic Circumpolar Current.

The analysis of seasonal ice velocities (Fig. 4a) confirms that circum-Antarctic mean ice velocity is lowest during summer (December–February), and that ice speed increases in autumn (March–May) and reaches maximum speed during winter (June–August) and spring (September–November). Mean horizontal velocities during winter and spring are generally of similar magnitude for each year. The magnitude of the interseasonal changes (summer to winter) is more than twice that of the interannual variability within each seasonal component. Zonal (Fig. 4b) and meridional (Fig. 4c) velocities exhibit significant interannual variability within each season. This year-to-year variability of the seasonal velocity components includes reversal of the flow direction, especially for the zonal velocity: Summer and autumn zonal ice motion is mostly net westward from 1988 to 2004. Winter and spring zonal ice motion is net eastward from 1989 to 2000 and net westward before and after those years. The net westward ice motion during summer and autumn agrees with observations of the sea-ice distribution, with most of the sea-ice-covered area to the south of the Antarctic Divergence, where the flow is westward with the Antarctic coastal current (e.g. Orsi and others, 1995). Net southward ice motion (Fig. 4c) is rarely observed for any season. For the few summer and autumn seasons to exhibit net southward ice motion, comparison with spatial distributions of sea-ice concentration (courtesy US National Snow and Ice Data Center (NSIDC)) shows that during these seasons the pack ice was largely limited to the large cyclonic embayments.

Fourier analysis of the 17 years of circum-Antarctic SSM/I ice-velocity data reveals that major changes in the horizontal ice speed and the zonal and meridional ice velocities take place at annual and semiannual periods. The Fourier analysis also indicates an 8.2 year periodicity in the mean horizontal ice speed and the zonal ice velocity. Changes in sea-ice velocity at this period might be interpreted as consequences of a circum-Antarctic wave-2 or wave-3 pattern (White and Peterson, 1996) or stationary oscillations (Kienzle, 2000; Yuan and Martinson, 2001). The longer periodicity identified here should, however, be treated with caution, as the current SSM/I time series is only long enough to resolve periodicities up to 8.5 years.

CONCLUSIONS

We have presented an analysis of Antarctic sea-ice velocity derived from passive microwave data from the SSM/I sensor for 1988–2004. There is little evidence for a net change in annual or winter ice speed during the SSM/I record, although interannual variability is close to 30% of the velocity magnitude. Ice speeds are seasonally stratified, with lowest speeds during summer, increasing during autumn and peaking during winter and spring. For the 1998–2004 SSM/I record, June–November ice speed exceeds the annual mean speed by about 20%. Interannual variability is of similar magnitude. No net trend has been derived over the 17 year record, although Fourier analysis indicated that mean ice speeds wax and wane with an 8.2 year period

Changes in the regional distribution of sea-ice velocity pertain to changes in the pattern of ice concentration, extent and duration, and relate to changes in the external forcing mechanisms. The regional response to changes in the atmospheric forcing, as expressed by the SAM index, appears to depend on the sea-level pressure distribution, with the ice speeding up (slowing down) on the upstream (downstream) side of the three quasi-stationary Antarctic low-pressure centres. This hypothesis may be tested by extending the SSM/I ice-motion dataset back in time. In support of this, SMMR ice-motion data are currently being reprocessed.

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