"Popular Summary" for the paper "Trends in the length of the Southern Ocean sea ice season, 1979-1999" by C. L. Parkinson, submitted to the *Annals of Glaciology*:

Satellite data can be used to observe the sea ice distribution around the continent of Antarctica on a daily basis and hence to determine how many days a year have sea ice at each location. This has been done for each of the 21 years 1979-1999. Mapping the trends in these data over the 21-year period reveals a detailed pattern of changes in the length of the sea ice season around Antarctica. Most of the Ross Sea ice cover has undergone a lengthening of the sea ice season, whereas most of the Amundsen Sea ice cover and almost the entire Bellingshausen Sea ice cover have undergone a shortening of the sea ice season. Results around the rest of the continent, including in the Weddell Sea, are more mixed, but overall, more of the Southern Ocean experienced a lengthening of the sea ice season than a shortening. For instance, the area experiencing a lengthening of the sea ice season by at least 1 day per year is 5.8×10^6 km^2, whereas the area experiencing a shortening of the sea ice season by at least 1 day per year is less than half that, at 2.8×10^6 km^2. This contrasts sharply with what's happened over the same period in the Arctic, where, overall, there has been some depletion of the ice cover, including shortened sea ice seasons and decreased ice extents.

Trends in the Length of the Southern Ocean Sea Ice Season, 1979-1999

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Abstract. Satellite passive-microwave data have been used to calculate and map the length of the sea ice season throughout the Southern Ocean for each year 1979-1999. Mapping the slopes of the lines of linear least squares fit through the 21 years of resulting season-length data reveals a detailed pattern of trends in the length of the sea ice season around the Antarctic continent. Specifically, most of the Ross Sea ice cover has, on average over the 21 years, undergone a lengthening of the sea ice season, whereas most of the Amundsen Sea ice cover and almost the entire Bellingshausen Sea ice cover have undergone a shortening of the sea ice season. Results for the Weddell Sea are mixed, with the northwestern portion of the sea having experienced a shortening of the sea ice season but a substantial area in the central portion of the sea having experienced a lengthening of the ice season. Overall, the area of the Southern Ocean experiencing a lengthening of the sea ice season by at least 1 day per year over the period 1979-1999 is 5.8×10^6 km^2, whereas the area experiencing a shortening of the sea ice season by at least 1 day per year is less than half that, at 2.8×10^6 km^2.

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Introduction

The Southern Ocean (Fig. 1) sea ice cover extends over a vast area, approximately 18 x 10^6 km^2, in the austral winter and experiences an enormous annual decay each spring and summer, with its coverage at the summer minimum typically reduced to under 4 x 10^6 km^2 (Zwally and others, 2001). The ice cover has a substantial impact on regional climate, most prominently by restricting exchanges of heat, mass, and momentum between the ocean and the atmosphere and by reflecting most of the solar radiation incident on it. It also has a substantial impact on the biology of the Southern Ocean, for instance housing many species of microorganisms, serving as a platform for penguins, seals, and other animals, insulating marine life below the ice from the atmosphere, and reducing light penetration into the ocean. The reader is referred to Bentley (1984), Drewry and others (1992), and Worby and others (1996) for more on the climatological impacts of the ice and to Massom (1988), Drewry and others (1992), and Smith and others (1995) for more on the biological impacts of the ice, including the impacts on primary productivity, phytoplankton blooms, krill, and breeding success in seabirds.

Until the 1970s, data sets regarding the Southern Ocean sea ice cover tended to be sparse both temporally and spatially, due in large part to the vast area, the remoteness to most human habitations, and the harshness of the in situ conditions. Fortunately, the ease of obtaining data on the ice cover changed dramatically with the advent of satellite technology, with satellite passive-microwave instrumentation in particular allowing the fairly routine monitoring of the Southern Ocean sea ice cover since the late 1970s. In fact, the ease with which ice and water can be distinguished in passive-microwave data, due to the sharp contrast in ice and water emissivities at many microwave wavelengths, makes sea ice coverage now amongst the most readily observed of all climate variables.

This paper takes advantage of satellite passive-microwave data sets over the 21-year period 1979-1999 to report on changes in the length of the sea ice season, defined as the number of days per year with sea ice coverage, throughout the Southern Ocean. Changes in the length of the sea ice season not only affect the regional climate and ecology, in ways alluded to above, but also can serve as indicators of change within the broader climate system. The length of the sea ice season was first examined and mapped for the Southern Ocean in Parkinson (1994), where results were presented for the eight-year period 1979-1986. It has subsequently been examined for the seven-year period 1988-1994 by Parkinson (1998) and for the two eight-year periods 1979-1986 and 1989-1996 by Watkins and Simmonds (2000).

Data and Methodology

This study uses data from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imagers (SSMIs). The SMMR instrument collected data on an every-other-day basis for most of the period October 26, 1978 – August 20, 1987, and the SSMIs have collected data on a daily basis for most of the period since July 9, 1987. The two data sets have been used by Cavalieri and others (1999) to create a consistent set of sea ice concentrations (areal percentages of sea ice) using an algorithm commonly termed the NASA Team algorithm. This algorithm is based on the assumption of three surface types (two ice types plus liquid water), polarization and gradient ratios calculated from three channels of the satellite data, and a weather filter. The algorithm is described in detail in Gloersen and others (1992), and the procedures for matching the SMMR and SSMI data sets are described in Cavalieri and others (1999). The ice concentrations have spatial resolutions of approximately 55 km and are gridded to a consistent grid with grid cell size approximately 25 km x 25 km (NSIDC, 1992).

The sea ice concentration data are used here to determine the length of the sea ice season in each year at each grid point, by counting the number of days with ice coverage of at least 15%. Alternative ice-concentration cutoffs of 30% and 50% have also been used, with similar patterns resulting irrespective of which cutoff is selected (e.g., next section and Parkinson, 1994). The 15% cutoff is used for the main results in this paper both because it is the standard cutoff used for the ice extent results from the same data set (e.g., Zwally and others, 2001) and because comparison of the ice concentrations from the NASA Team algorithm with those derived from other algorithms yield a close match in distributions of ice coverage of at least 15% but some substantial differences in distributions of ice of higher concentrations (e.g., Comiso and others, 1997; Hanna, 1999; Markus and Cavalieri, 2000). The 15% results are thus considered the most robust.

The trend in the length of the sea ice season is calculated at each ocean grid point as the slope of the line of linear least squares fit through the 21 years of season-length data. The calculations are done through matrix manipulations on the 21 annual matrices of the length of the sea ice season for the 15% cutoff, and are then repeated for the 30% and 50% cutoffs. For the trend calculations, each year's season lengths are linearly scaled to equivalents for a 365-day year.

Results

Season Lengths

Figure 2 presents maps of the length of the sea ice season for the beginning and ending years of the data set and for the 21-year average over the period 1979-1999. All three sets of results are presented for an ice-concentration cutoff of 15%, and the 21-year averages are also presented for an ice-concentration cutoff of 50%. The 1979 and 1999 maps show some similarities apparent in all the yearly maps, plus clear contrasts between the two years. Similarities include the perennial ice in the far western Weddell Sea, the tendency for season lengths to decrease outward from the coast, and the anomalously short ice seasons in the southwestern Ross Sea compared to other locations of similarly high latitudes (Fig. 2a and 2b). Differences include the substantially greater area of perennial ice in the Amundsen and especially the Bellingshausen Sea in 1979 than in 1999, contrasted by the substantially lesser area of perennial ice in the Ross Sea in 1979 than in 1999. Differences also include the prominent arm of long ice seasons extending northeastward in the western Weddell Sea in 1979 but not in 1999, and the much shorter ice seasons in the western Ross Sea in 1979 than in 1999 (Fig. 2a and 2b). The 21-year averages (Fig. 2c) indicate that for the latter phenomenon, the 1999 case was more typical than the 1979 case. Also, the prominent arm of long ice seasons in the western Weddell Sea in 1979 (Fig. 2a), which can be explained on the basis of the cyclonic gyre often apparent in the Weddell Sea (e.g., Gordon, 1978), does not appear in the 21-year averages (Fig. 2c), and in fact shows up prominently only in years 1979, 1980, and 1992, with less prominent appearances in 1984, 1991, 1996, and 1998 (visible in the individual yearly data, not shown here except for the years 1979 and 1999).

The 21-year averages are presented both for a 15% ice-concentration cutoff and for a 50% ice-concentration cutoff to verify that the basic patterns remain the same irrespective of which cutoff is used (Fig. 2c and 2d). Naturally, with a stronger criterion for ice coverage, the 50% cutoff yields season lengths that are generally less and never more than those for the 15% cutoff (Fig. 2c and 2d). For instance, immediately off the Ross Ice Shelf, all grid cells have at least 255 days with ice of concentration at least 15% (Fig. 2c), whereas some pixels have fewer than 195 days with ice of concentration at least 50% (Fig. 2d). This is an extreme case, brought about by the polynyas (areas of open water within an ice pack) that commonly form immediately off the Ross Ice Shelf.

Still, despite the few large numerical differences between the 15% and 50% cases, the spatial patterns are quite similar throughout the images (Fig. 2c and 2d).

Trends

Trends in the length of the sea ice season over the 21 years are presented in Figure 3a for an ice-concentration cutoff of 15% and in Figure 3b for an ice-concentration cutoff of 50%. The marked similarity of these two images illustrates the robustness of the results with respect to the choice of the specific ice-concentration cutoff used. In spite of the fact that some locations have much shorter seasons with ≥ 50% ice coverage than with ≥ 15% ice coverage (Fig. 2d versus Fig. 2c), either cutoff yields a very similar pattern of trends (Fig. 3a and 3b).

Linear least squares trends for the 21-year period show an overall lengthening of the sea ice season throughout most of the Ross Sea, around the coast of much of East Antarctica, and in a portion of the south-central Weddell Sea (Fig. 3a). They show an overall shortening of the sea ice season in almost the entire Bellingshausen Sea, most of the Amundsen Sea, the far western Weddell Sea, the northwestern Weddell Sea, non-coastal regions off East Antarctica at about 15°-35°E and about 85°-110°E, and the immediate coastal area from 25°W to 30°E (Fig. 3a). In general, the regions of positive and negative trends are fairly coherent and identifiable, with little speckling of the colors that might simply reflect small motions within the ice pack.

Although the strongest trends indicated in Figure 3 are negative trends within the Bellingshausen Sea, overall the area covered by positive trends exceeds that covered by negative trends. Specifically, for the case using a 15% ice-concentration cutoff (Fig. 3a), the area covered by positive trends of at least 0.5 days/yr is 8.6 x 10^6 km^2, whereas the area covered by negative trends of at least 0.5 days/yr is 5.3 x 10^6 km^2, making the area covered by positive trends of that magnitude 62% greater than that covered by negative trends (Fig. 4). The contrast is even stronger when considering trends of magnitude at least 1.5 days/yr, for which positive trends cover an area of 3.9 x 10^6 km^2 and negative trends cover 1.6 x 10^6 km^2, making the area covered by positive trends 136% greater than the area covered by negative trends (Fig. 4). The positive trends greater than 1.5 days/yr come predominantly from the Ross Sea region, while the negative trends greater than 2.5 days/yr are overwhelmingly from the Bellingshausen and Amundsen Seas (Figs. 3-4). For a whole-number division, the area experiencing a least-squares-fit lengthening of the ice season of at least one day per year is 5.8 x 10^6 km^2, while the area experiencing a least-squares-fit shortening of at least one day per year is 2.8 x 10^6 km^2.

Comparisons with Earlier Studies

When examined for the eight years 1979-1986, the first eight years of the 21-year data set used here, the length of the sea ice season was found to have shortened in the northern portions of the Bellingshausen and Amundsen seas, the northern Weddell Sea, the eastern Weddell Sea, and the very near-coastal regions around East Antarctica (Parkinson, 1994; Watkins and Simmonds, 2000). Lengthening of the sea ice season occurred throughout most of the Ross Sea, in the south-central Weddell Sea, and around much of East Antarctica away from the near-coastal region (Parkinson, 1994; Watkins and Simmonds, 2000). So for both the 8-year and the 21-year records, the ice season predominantly shortened in the Bellingshausen, Amundsen, and northwestern Weddell seas, predominantly lengthened in the Ross Sea and south-central Weddell Sea, and had a more mixed pattern around the rest of the continent. However, in the sizable areas where the signs of the trends match, the magnitudes tend to be larger in the shorter, 1979-1986 record than in the 21-year record, reflecting some reversals in the trends since 1986. Indeed, both Parkinson (1998) and Watkins and Simmonds (2000) note such reversals for the periods 1988-1994 and 1989-1996, respectively, versus 1979-1986.

In view of the trend reversals, it is particularly important not to over-interpret the results of Figure 3. This figure gives a clear visualization of the overall changes in the length of the sea ice season for the 21-year period 1979-1999, but it incorporates fluctuations within the record, likely related to various oscillations within the climate system (e.g., Gloersen, 1995; White and Peterson, 1996), and its values should not be projected into the future.

Summary and Discussion

Satellite passive-microwave data have been used to determine and map the length of the sea ice season in each year 1979-1999, with results showing season lengths generally decreasing outward from the coast except in regions of coastal polynyas, perennial ice cover consistently in the far-western Weddell Sea and more selectively elsewhere around the continent, and decidedly short ice seasons (for the high latitudes involved) off the Ross Ice Shelf (Fig. 2). Trends in the season lengths show that most of the Ross Sea underwent a lengthening of the sea ice season, most of the Amundsen Sea and almost the entire Bellingshausen Sea underwent a shortening of the sea ice season, the Weddell Sea had a shortening of the sea ice season in the northwest but mostly a lengthening of the season in the central sea, and around much of East Antarctica the near coastal region experienced a lengthening of the season while further from the coast, there was a more even mixture of areas experiencing season shortenings and those experiencing season lengthenings (Fig. 3). Integrating spatially, a much larger area of the Southern Ocean experienced an overall lengthening of the sea ice season over the 21 years 1979-1999 than experienced a shortening (Fig. 4).

These results complement results on trends in the Southern Ocean ice extent (defined as the area having sea ice concentrations of at least 15%) found from the SMMR and SSMI record. Analyses of the regional and hemispheric ice extents for the 16-year period 1979-1994 by Stammerjohn and Smith (1997) and for the 20.2-year period from November 1978 through December 1998 by Zwally and others (2001) find positive ice-extent trends for the

Weddell Sea, the Indian Ocean, the Western Pacific Ocean, the Ross Sea, and the Southern Ocean as a whole and negative ice-extent trends for the Bellingshausen and Amundsen seas. The mapped results on the trends in the length of the sea ice season (Fig. 3) provide a far more detailed spatial picture of the 21-year changes in the Southern Ocean than is possible when examining the ice extents, but at the same time, they provide a far less detailed temporal picture. Together, the ice-extent and season-length results show an overall increasing Southern Ocean ice cover, with the Bellingshausen and Amundsen seas and the far-western Weddell Sea showing instead ice cover decreases. These results are consistent with reports of notable warming over the Antarctic Peninsula from 1978 to 1996 (King and Harangozo, 1998; Skvarca and others, 1998; both studies also include years prior to 1978) and with a tendency for air temperature anomalies in the Peninsula region to be opposite in sign to those predominating over much of the rest of the Antarctic (Rogers, 1983; Stammerjohn and Smith, 1997).

The satellite-derived Southern Ocean sea ice results, with lengthening sea ice seasons (Fig. 3) and increasing ice extents (Stammerjohn and Smith, 1997; Zwally and others, 2001) overall, provide a sharp contrast with the widely publicized overall ice-cover decreases in the Arctic occurring over the same period. Many uncertainties remain, but one certainty is that the ice covers of the two hemispheres have not been fluctuating in sync over the past two decades.

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Figure Captions

Figure 1. Location map, including the boundaries of the five sectors into which the Southern Ocean is divided for analysis. The boundaries are along the longitude lines at 20°E, 90°E, 160°E, 130°W, and 60°W.

Figure 2. (a) Length of the sea ice season for 1979, using a 15% ice-concentration cutoff, i.e., considering a location to have sea ice if the ice-concentration calculations show at least 15% ice coverage. (b) Length of the sea ice season for 1999, using a 15% ice-concentration cutoff. (c) Average length of the sea ice season for the 21 years 1979-1999, using a 15% ice-concentration cutoff. (d) Average length of the sea ice season for the 21 years 1979-1999, using a 50% ice-concentration cutoff.

Figure 3. Trends in the length of the sea ice season over the 21 years 1979-1999, using (a) a 15% ice-concentration cutoff, and (b) a 50% ice-concentration cutoff.

Figure 4. Histogram showing the area of the Southern Ocean experiencing various levels of trends in the length of the sea ice season over the 21 years 1979-1999, with bar segmentation to identify the contributions from each of the five sectors of the Southern Ocean identified in Figure 1. The histogram corresponds to Figure 3a, i.e., using a 15% ice-concentration cutoff and the same trend categories as in Figure 3. The 0 category extends from values of –0.5 days/yr to +0.5 days/yr and covers an area of 32.6 x 10^6 km^2, largely from the region outside the ice cover.

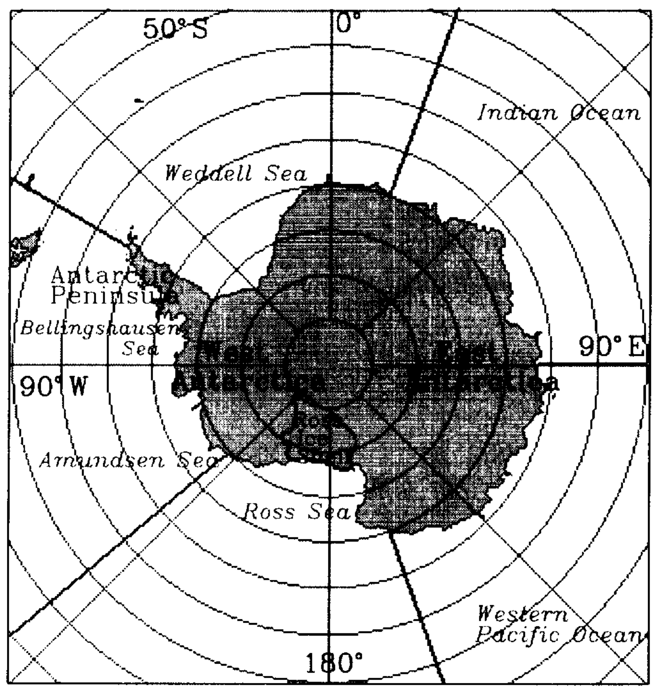

50°S
0°
Indian Ocean
Weddell Sea
Antarctic
Peninsula
Bellingshausen
Sea
90°E
90°W
Amundsen Sea
Ross Sea
Western
Pacific Ocean
180°

Figure 1

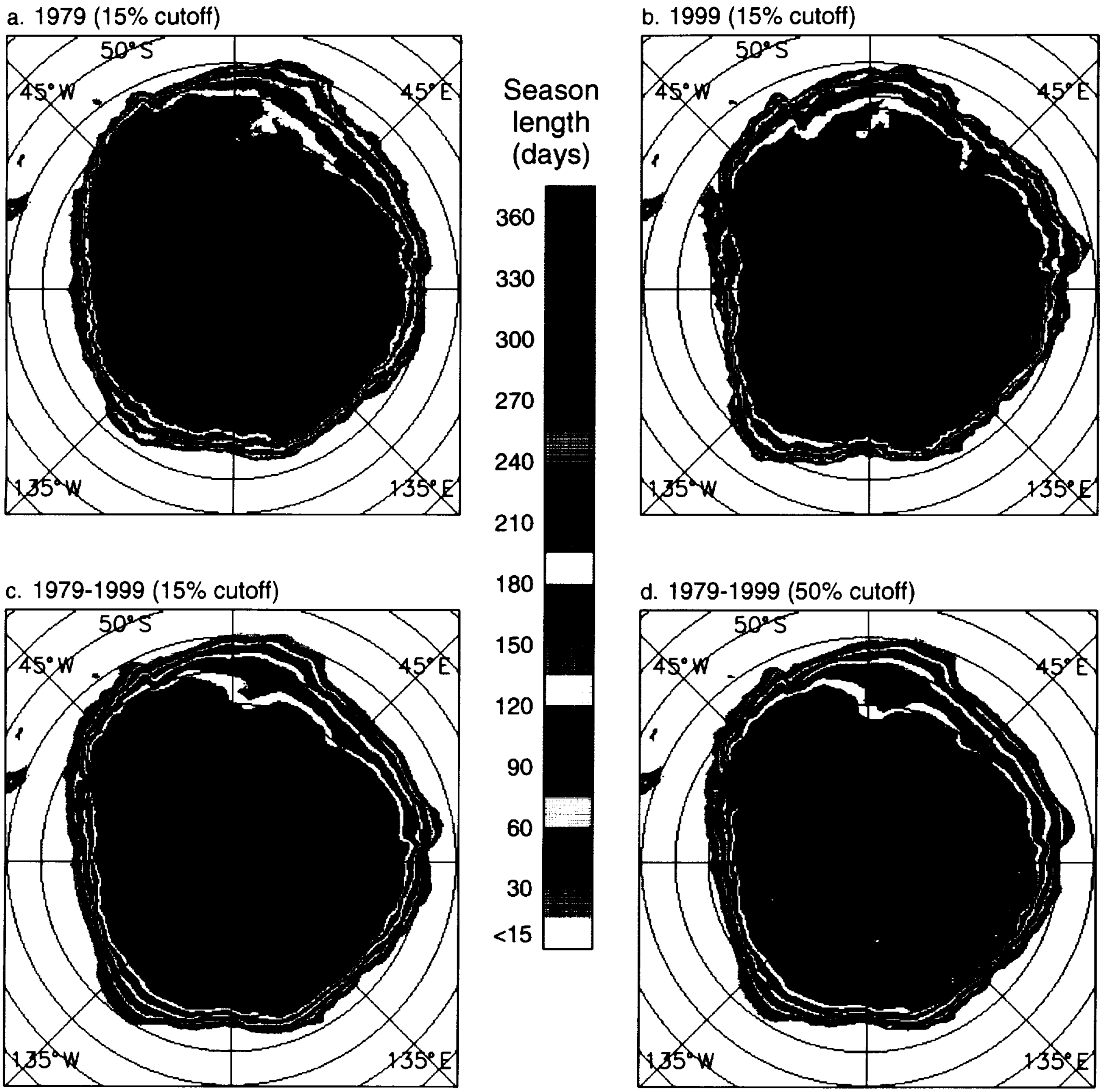

a. 1979 (15% cutoff)
b. 1999 (15% cutoff)
c. 1979-1999 (15% cutoff)
d. 1979-1999 (50% cutoff)
50°S
45°W
45°E
135°W
135°E
Season length (days)
360
330
300
270
240
210
180
150
120
90
60
30
<15

Figure 2

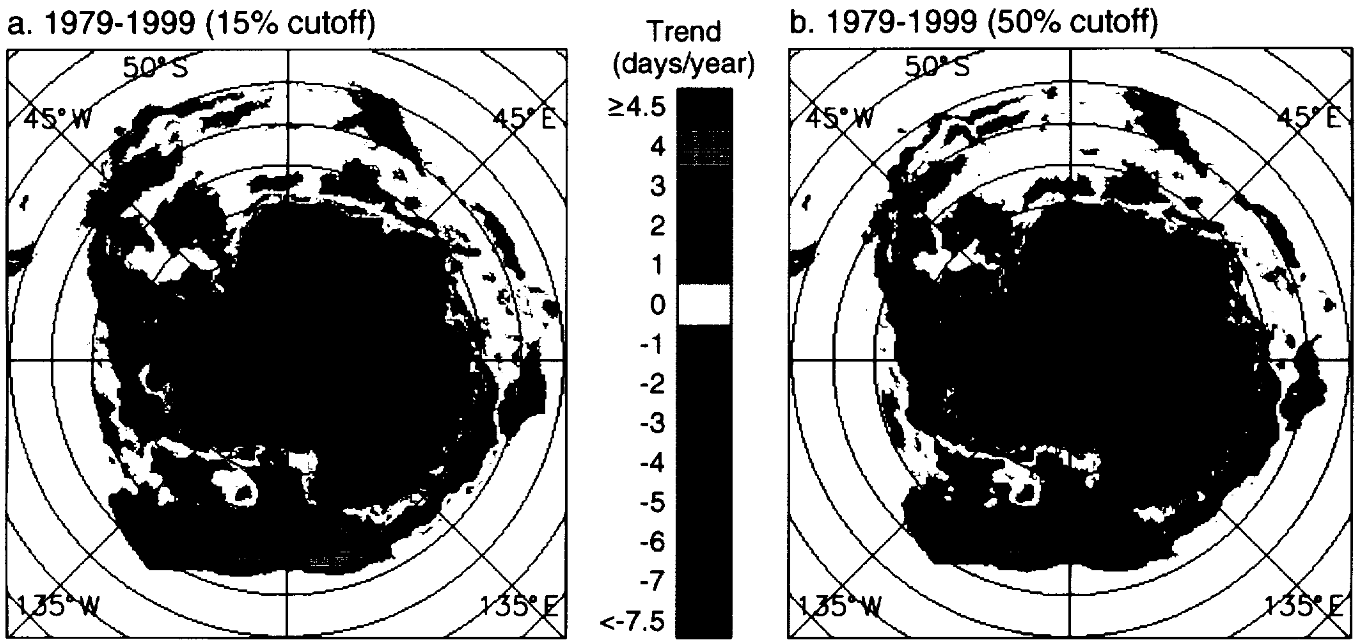
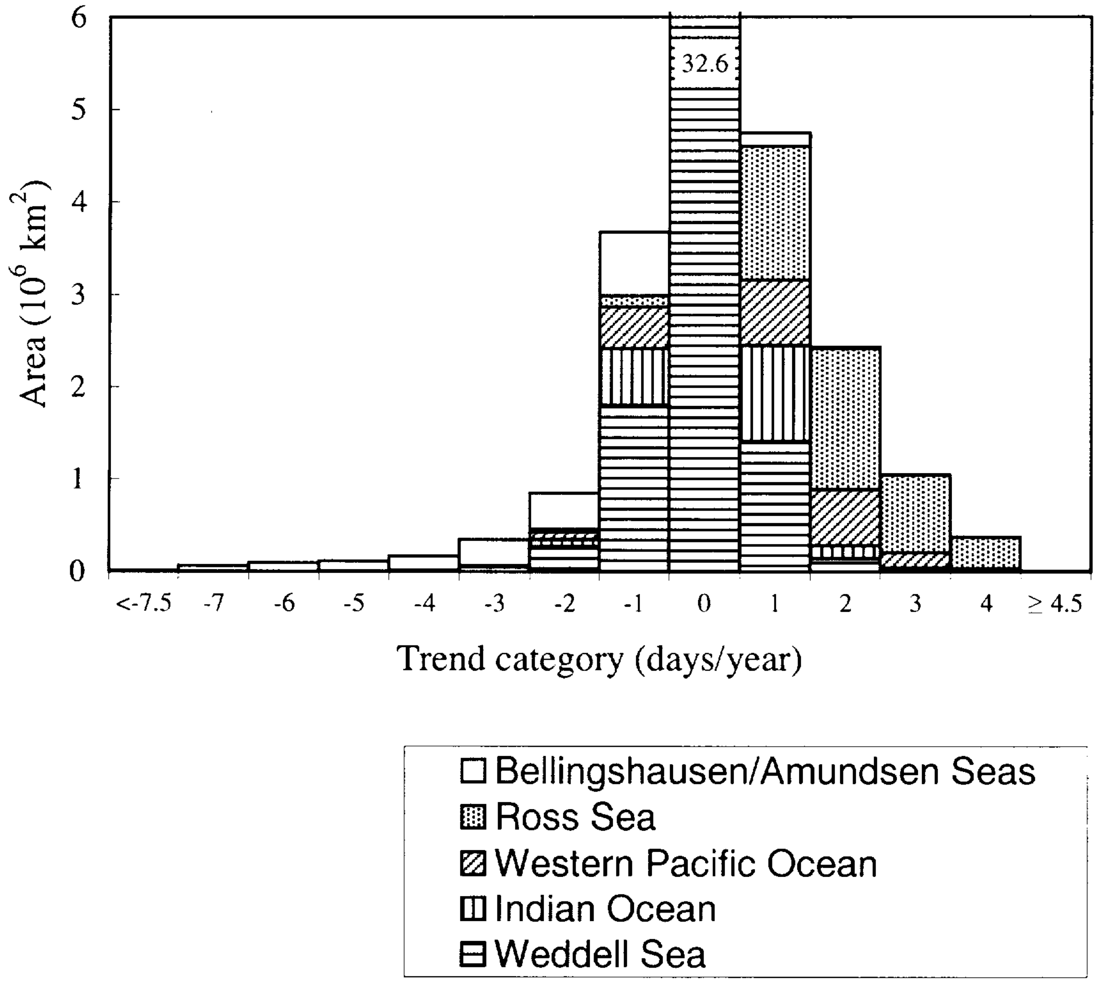

a. 1979-1999 (15% cutoff)
b. 1979-1999 (50% cutoff)
Trend
(days/year)
≥4.5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
<-7.5
50°S
45°W
45°E
135°W
135°E

Figure 3



6
5
4
3
2
1
0
Area (10^6 km^2)
32.6
<-7.5
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
≥ 4.5
Trend category (days/year)
Bellingshausen/Amundsen Seas
Ross Sea
Western Pacific Ocean
Indian Ocean
Weddell Sea

Figure 4