Mapping of Antarctic sea ice in the depletion phase: an indicator of climatic change?

G. Sreenivasan[1] and T. J. Majumdar[2,*]

[1]Regional Remote Sensing Service Centre, Nagpur 440 010, India
[2]Space Applications Centre, Indian Space Research Organization, Ahmedabad 380 015, India

The mapping and monitoring of the sea ice variability in the polar regions is of prime importance for global climate modelling. Apart from sea ice, spatial snow cover variability and depth estimates are needed for accurate assessment of many climate parameters required in the ice-ocean models. Mapping and analysing the spatial and temporal variability of Antarctic sea ice and snow cover are therefore highly important for polar ice-pack studies in the global climate cycle. The present study has been carried out mainly for sea ice mapping surrounding Antarctica using Special Sensor Microwave Imager (SSM/I) passive microwave data during its depletion phase (November 2001 to January 2002). Sea ice concentrations and snow depths over the Antarctic sea ice have been calculated and their temporal variation patterns studied. The overall extents under all ice concentration categories during different months over the study period have decreased in the order of 1 to 3 million km^2 in comparison to the sea ice concentration categories during 1978–87 period. The thermal conductivity of snow is about an order of magnitude less than the sea ice. Hence the presence of small amount of snow on sea ice can greatly affect the heat flux between the sea surface and atmosphere. Depletion in snow depths over sea ice (from 1988–94 to 2001–02) could be observed particularly in December, though not much change has been observed in November and January. These changes (shrinking ice covers/depletion in sea ice concentration) can be attributed to some locally changing weather patterns in the Antarctic continent as well as due to regional phenomenon like global warming.

Keywords: Antarctica, areal extent, climatic change, depletion phase, sea ice concentration.

ANTARCTICA is the fifth largest continent on the Earth (area approximately 14 million km^2), located in the South Pole. It is almost totally covered by ice, devoid of any permanent human population. Ice-covered region over Antarctica constitutes almost 4.5% of the Earth's surface area. It is also the coldest continent with ambient air temperatures much below the freezing point of water (–80 to –30°C) throughout the year. Thickness of ice at places is beyond 4500 m and the average thickness is approximately 2100 m (ref. 1). Sea ice and snow are among the most dynamic and ephemeral geophysical features on the Earth's surface. Together with land ice, they exert a profound influence on local and global climatic and oceanic regimes. Moreover, polar ice masses, and the ice sheets in particular, are sensitive indicators of climate change, which, it is feared, may result from an increase in atmospheric 'greenhouse gases' such as methane and CO_2, the latter caused by burning of fossil fuels[2]. The large expanse (~ 30 × 10^6 km^2) of sea ice greatly reduces the exchange of heat, mass and momentum between ocean and atmosphere, and decreases the amount of solar radiation absorbed at the surface[3]. Knowledge of the spatial and temporal variability of the distribution of Antarctic sea ice cover is essential for understanding the role of ice-pack in modifying atmosphere–ocean interactions and exchanges of heat, mass and momentum, their influences on the ocean and climate variability from the local to global scale and the biological productivity of the ice and ocean[4]. Information of the distribution of snow thickness on sea ice is vital to understanding the overall heat exchange in the polar regions. Snow depth and accumulation rate are also important variables in the fresh water budget of the oceans[4–6] and for estimation of precipitation minus evaporation, needed in the coupled ice-ocean models[7].

With temperatures rising in parts of Antarctica in recent years, melt water seems to be penetrating deeper and deeper into ice crevices, weakening immense and seemingly impregnable formations that have developed over thousands of years. As a result, huge glaciers in Antarctica are thinning and ice shelves are either disintegrating or retreating which are all possible indications of global warming. In view of the importance of the sea ice and snow cover in the polar regions for the global climatic studies, the present study was taken up for mapping of Antarctic sea ice/snow cover along with sea ice concentration and snow cover depths using SSM/I passive microwave data during its depletion phase (November 2001–January 2002).

The Special Sensor Microwave Imager (SSM/I) sensor on-board Defense Meteorological Satellite Program (DMSP) is a passive microwave radiometer which provides near real time data for operational use for specific research areas like sea ice. To understand the features of microwave images, it is important to know the approximate depths from which the radiation emanates. Passive microwave observations of the polar oceans have been very useful in delineating/classifying sea ice and in estimating the concentrations of sea ice by virtue of the large contrast between the microwave emissivity of open water (around 0.4 at 10 GHz) and of sea ice (0.7–0.9) (refs 2, 8, 9).

The location and sector maps of Antarctica and its surrounding oceans are given in Figure 1 *a* and *b*. For the sea ice-snow study of the Antarctic, SSM/I passive microwave data at 19.35 GHz (H&V) and 37.0 GHz V from 1 November 2001 to 30 January 2002 have been used.

*For correspondence. (e-mail: tjmajumdar@sac.isro.gov.in)

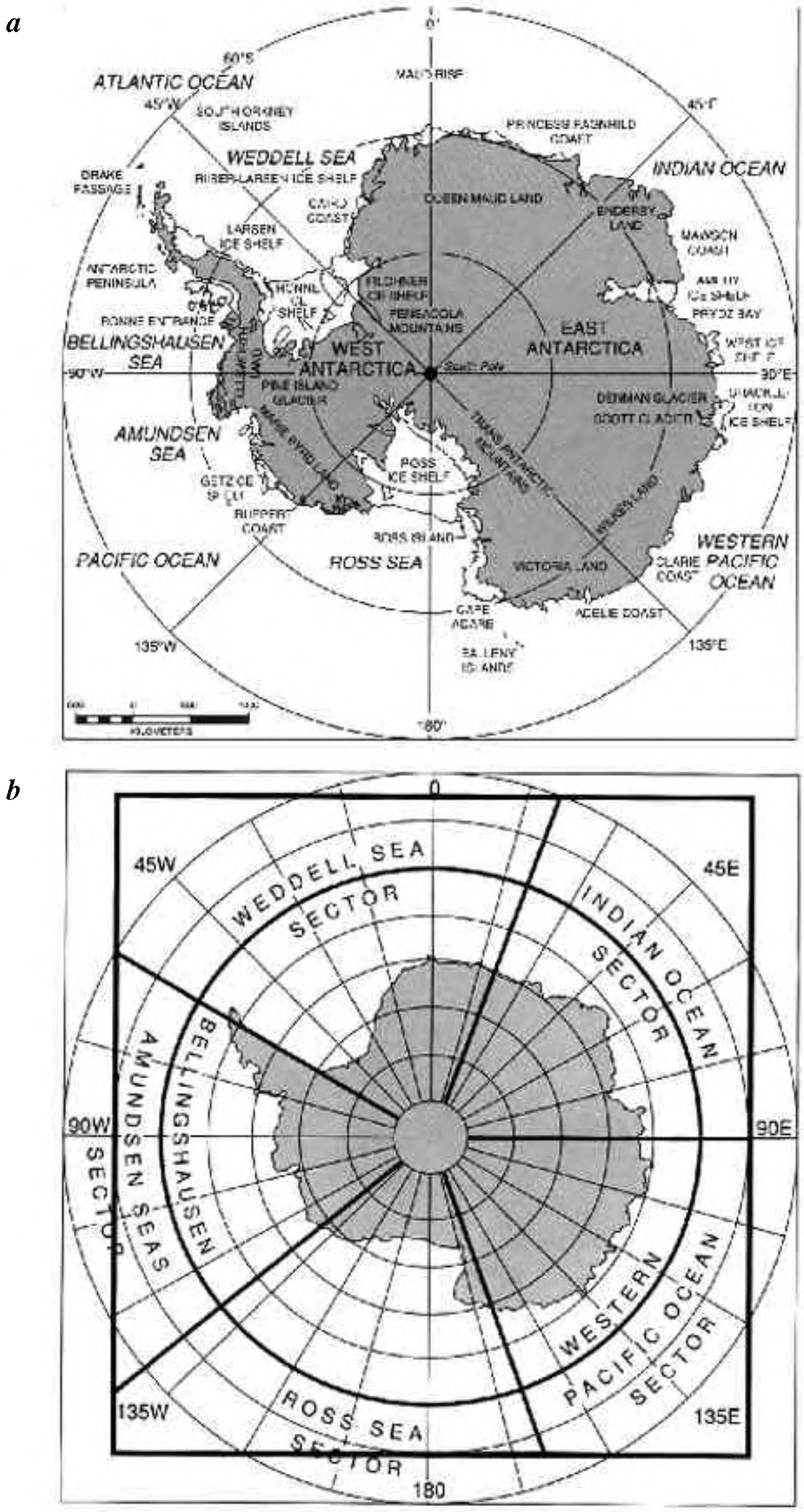

Figure 1. Study area. ***a***, Antarctic location map; ***b***, Antarctic sector map (after Gloersen *et al.*[3]).

The SSM/I data are provided by the National Snow Ice Data Center's Distributed Active Archive Center, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, USA which are available in the form of Calibrated Brightness Temperatures daily gridded averages[10] at 25 km ground resolution for the 19, 22, 37 GHz and at 12.5 km ground resolution for the 85 GHz frequency channel.

The present work carried out consists of four parts, viz. first, studying the spatial and temporal variations in the Antarctic sea ice cover in its depletion phase; second, calculation of sea ice concentrations and studying their spatial and temporal variations; third, snow depth modelling for estimation of snow cover depth over the Antarctic sea ice and finally, comparison of our results with earlier studies.

The sea ice extents have been derived using 19 GHz horizontal polarization data sets only. The reason for this is that at this frequency brightness temperature (T_B) differences are greatest for the ice/water contrast in comparison to the 37 and 85 GHz frequency channels[8,11].

The dominant factor affecting the observed brightness temperature (T_B) of the ocean surface in polar regions is the fraction of ice cover within the observed area, which is called sea ice concentration. Development of algorithms to extract ice concentration values are based on the linear interpolation between the radiance of ice-free ocean water and that of fully consolidated sea ice cover[12,13]. In the present study, the NASA Team Algorithm for sea ice concentration calculations has been used, initially developed for sea ice concentration derivation from SMMR data[14,15], for SSM/I data (19 GHz H and V polarized channels and 37 GHz V polarized channel) with modified tie-points and coefficients[5,16].

In view of the weather interference in the calculation of sea ice concentration[17], the sea ice concentrations obtained by applying the NASA Team algorithm have been calibrated by using the weather filter. Cavalieri *et al.*[16] considered a weather filter with upper limit of GR as 0.05. In the present study, it was observed that the weather filter '>0.05 GR' is not effective in completely removing the spurious ice concentration values due to weather effects. Therefore, a new weather filter with GR upper limit value of 0.045 has been applied.

The Antarctic snow cover on the sea ice is highly heterogeneous and variable, and snow depths can vary greatly on spatial scales as small as few centimeters to a meter[6]. The thermal conductivity of snow is about an order of magnitude less than the sea ice. Hence the presence of small amount of snow on sea ice can greatly affect the heat flux between the sea surface and atmosphere[5]. The development of snow depth model considers the regression coefficients obtained from the regression of *in situ* snow depths with the SSM/I T_B. The *in situ* snow depths for calculation of the regression coefficients were obtained from various expeditions to the Weddell, Bellingshausen and Amundsen Seas surrounding Antarctic continent[5]. In this algorithm, the gradient ratios (GR) of 19 and 37 GHz channels have been used, because the calculated parameters will then be independent of the physical temperature variability of the sea ice. Vertical polarization channels have been used as the studies conducted earlier by Markus and Cavalieri[5] have shown high correlation of the *in situ* snow depths with the vertically polarized gradient ratios than the horizontally polarized gradient ratios. Vertical polarization is also expected to be less sensitive to layering in the snow[18].

Weekly sea ice extents have been mapped for the depletion phase covering months of November–December, 2001 and January, 2002 for every 1st, 8th, 15th, 23rd and 30th day of each month. Figure 2 shows the sea ice extents for this period and Table 1 gives the sea ice areal extents and depletion statistics. The total sea ice extents vary from 17.494 to 16.314 million km^2, during the first fortnight of November, from 14.227 to 11.314 million km^2, during the first fortnight of December, and from 7.686 to 4.517 million km^2, during 1 to 30 January. The depletions in sea ice cover in November, December and January are 16.45, 34.47 and 21.26%, respectively. The maximum depletion is in December 2001, which is almost double that in November 2001 and January 2002, indicating that December could have been the peak summer in Antarctica. The total depletion of sea ice from 1 November to 30 January is 13.527 million km^2, amounting to 77.32% of the maximum sea ice extent on 1 November 2001. The overall rate of depletion of sea ice in Antarctic for the study period is 139,428 km^2/day.

During January, the Antarctic sea ice retreats to the coast along approximately 50% of the coastline including almost total Indian Ocean sector and Western Pacific Ocean sectors and part of eastern Weddell and eastern Ross Sea sectors. The reason for this retreat is that, in the Indian Ocean sector and Western Pacific Ocean sectors, the Antarctic continent extends much farther from the South pole leading to higher sea surface temperatures in this region[3]. Another interesting observation is the gradual opening up of the Ross Ice Shelf starting from the end of November. Gloersen *et al.*[3] have attributed this phenomenon to the influence of cyclonic circulations in the Ross Sea sector.

Fortnightly sea ice concentration calculations have been done starting 1 November 2001 to 30 January 2002. Comparison of the results from both the weather filters (GR > 0.5 and GR > 0.45) has shown that both of them eliminate the spurious ice concentrations in the open water area, but the elimination is better with the GR > 0.045, which removes the spurious ice concentrations up to 99% (Figure 3). Also, the snow depth modelling over the Antarctic sea ice has been done fortnightly only for those areas where the total sea ice concentration is more than 20% (Figure 4).

Comparison of the results obtained in the present study has been made with those of Gloersen *et al.*[3] which have

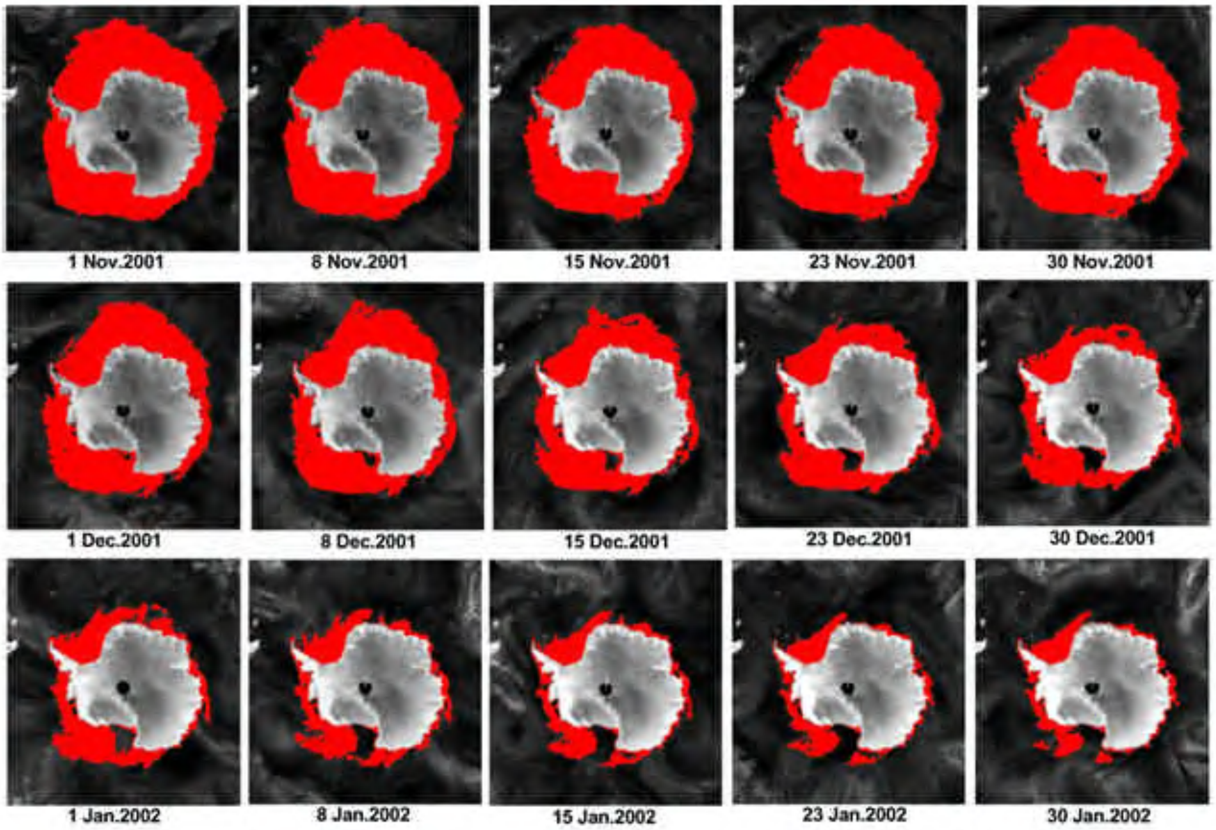

Figure 2. Weekly areal extents of Antarctic sea ice during 1 November 2001 to 30 January 2002 showing their temporal variation.

Table 1. Sea ice areal extents and depletion statistics

Month/year	Day	Area of sea ice depletion (million km^2)	Weekly depletion (million km^2)	Average weekly rate of depletion (km^2/day)	Total monthly depletion (million km^2)	Average monthly rate of depletion (km^2/day)
November 2001	1	17.494	–		2.878	81661
	8	16.814	0.680	97143		
	15	16.314	0.050	7143		
	23	15.182	1.132	141500		
	30	14.616	0.566	80857		
December 2001	1	14.227	–		6.036	206817
	8	12.903	1.324	189143		
	15	11.314	1.589	227000		
	23	9.353	1.961	245125		
	30	8.191	1.162	166000		
January 2002	1	7.686	–		3.719	129808
	8	6.183	1.503	214714		
	15	5.023	1.160	165714		
	23	4.348	0.675	84375		
	30	4.517	0.381	54429		

been carried out during 1978 to 1987 using SMMR. The results indicate that the average sea ice extents in November range from 15 to 17 million km^2 (Figure 5); in December, sea ice extents vary from 10 to 12.5 million km^2 and in January, from 5 to 6 million km^2. It has been observed that there is a marginal decrease in the sea ice extents under different ice concentration categories in comparison to the 1978–87 periods. There is a decrease in the extents of higher ice concentration categories and increase in the extents of lower ice concentrations. The overall extents under

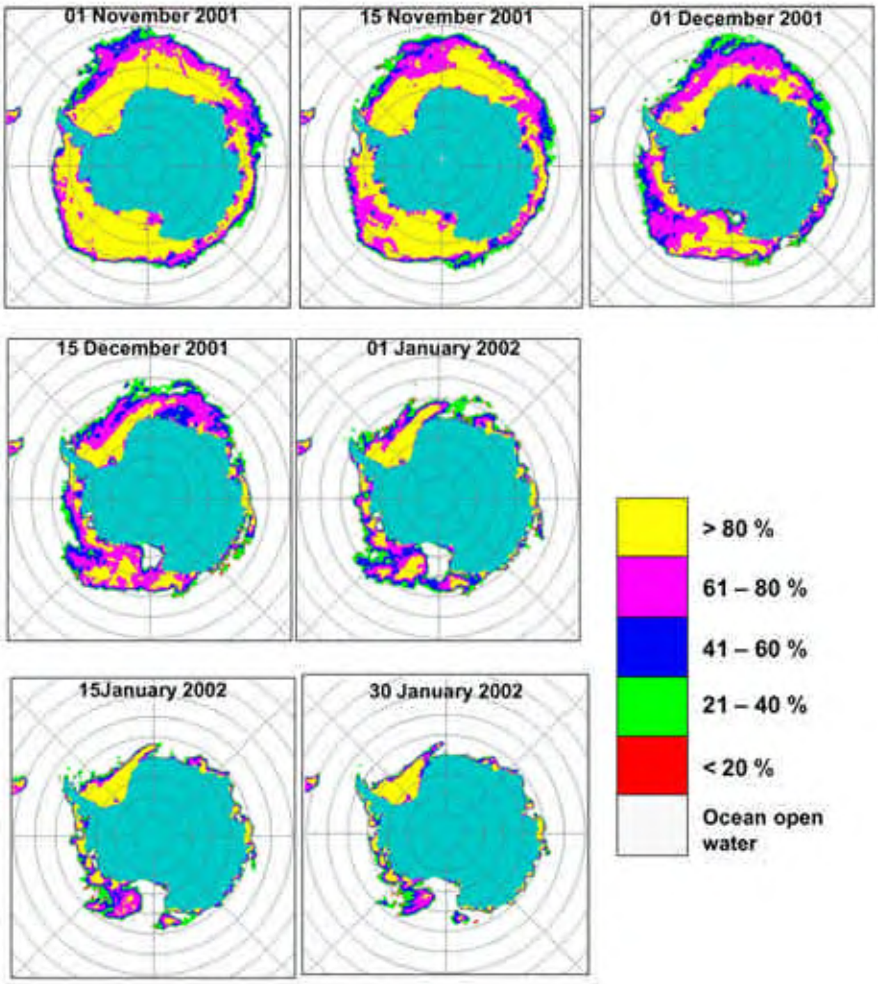

Figure 3. Fortnightly sea ice concentrations from 1 November 2001 to 30 January 2002 derived after applying GR > 0.045 weather filter.

all ice concentration categories during different months have decreased in the order of 1 to 3 million km^2 in comparison to the 1978–87 period. This change may be indicative of the fast changing weather patterns in the Antarctica due to local as well as regional phenomena.

The snow depth modelling over the Antarctic sea ice has been done fortnightly only for those areas where the total sea ice concentration is more than 20% (Figure 4). The snow depth maps show that the deepest snow cover is found in the Ross Sea sector followed by Weddell Sea sector and Bellingshausen–Amundsen Sea sector. The results obtained here are consistent with those of Eicken *et al.*[19] and Jeffries *et al.*[20] who also reported greater snow depths in the western Weddell and Bellingshausen Seas than in other regions. Compared to Ross Sea, Weddell Sea and Bellingshausen–Amundsen Sea sectors, the snow depth in the Indian Ocean and Western Pacific Ocean sectors is very low. Most parts of these sectors have snow depths in the range of 1–10 cm and at very few places of the order of 11–20 cm. This is in agreement with the average *in situ* snow depth measurements and earlier estimations (Figure 5)[5,21]. Comparison of the results has also been made with the results of Markus and Cavalieri[5]. The mean monthly snow depth maps (1988–1994) for November, December and January from their studies are given in Figure 5. The snow depth patterns obtained in the present study for different sectors of the Southern Ocean tally with the earlier results[5,19–23]. However, depletion in snow depths over sea ice (from 1988–94 to 2001–02) could be observed particularly in December, though not much change has been observed in November and January (Figures 4 and 5).

The mapping of Antarctic sea ice and snow cover has been carried out using SSM/I passive microwave data during its depletion phase (1 November 2001 to 30 January 2002). The spatial and temporal changes in the sea ice extents have been mapped, sea ice concentrations have been derived using the available algorithms and finally the snow cover depths over the sea ice have been estimated. The following are the main conclusions drawn from the study:

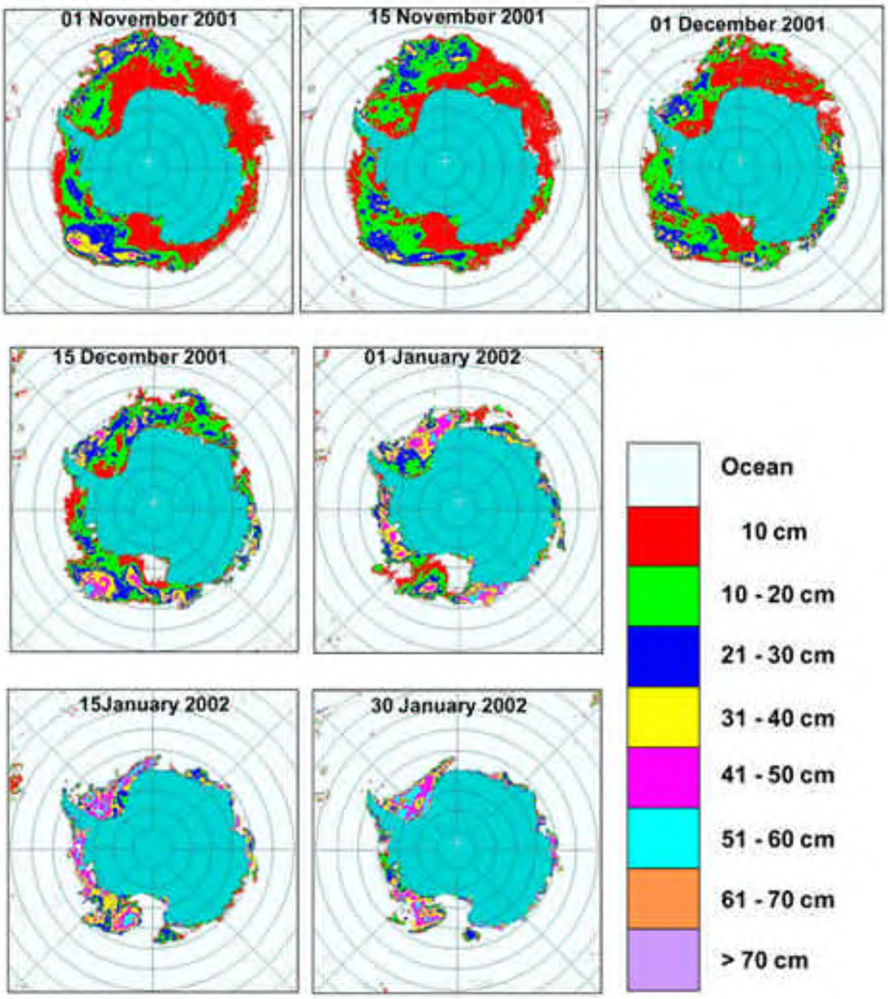

Figure 4. Fortnightly snow depth patterns over Antarctic sea ice from 1 November 2001 to 30 January 2002.

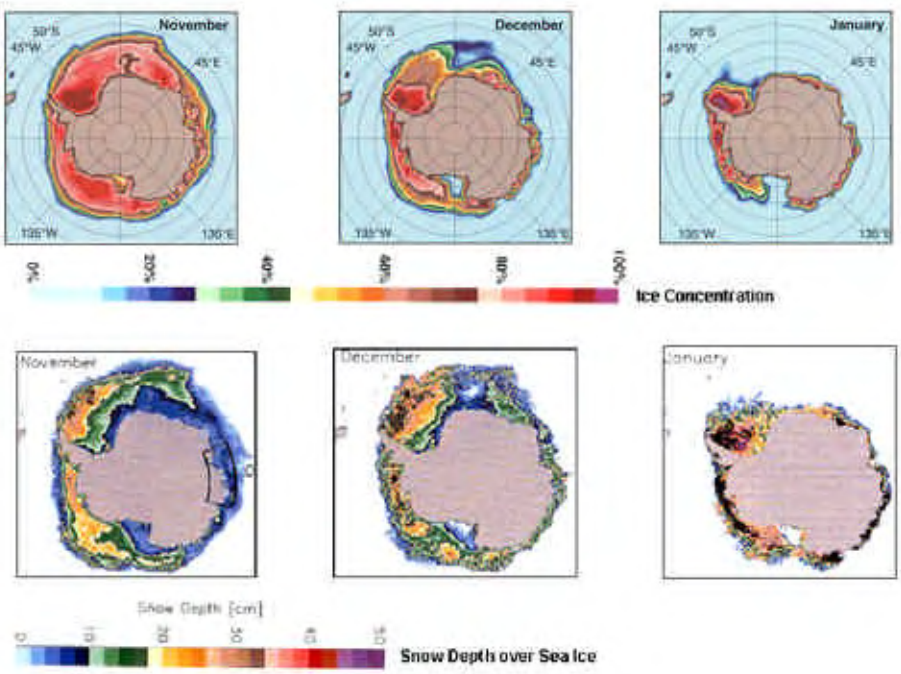

Figure 5. Average sea ice concentration for the period 1978–87 derived by Gloersen *et al.*[3] and average snow depths over sea ice for the period 1988–1994 derived by Markus and Cavalieri[5] for November, December and January.

- The overall rate of depletion in Antarctic sea ice for the study period (1 November 2001 to 30 January 2002) is 139,428 km^2/day.
- The sea ice concentration calculated using NASA team algorithm, after processing through a new weather filter (GR > 0.045) was found useful in eliminating most of the spurious ice concentrations in open water.
- The overall extents under all ice concentration categories during different months over the study period have decreased in the order of 1 to 3 million km^2 in comparison to the sea ice concentration categories during 1978–87 period. These changes (shrinking ice covers/depletion in sea ice concentration) can be attributed to some locally changing weather patterns in the Antarctic continent as well due to regional phenomenon like global warming.
- Depletion in snow depth over sea ice could be observed particularly in December, though not many changes have been observed in November and January. The snow depth modelling over the Antarctic sea ice cover estimates snow depth of the order of 10 to 70 cm in different sectors of the Southern Ocean. Results tally well with *in situ* snow depth measurements and also with those calculated earlier.

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