GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 10, PAGES 1553-1556, SEPTEMBER 1990

SEASONAL AND INTER-ANNUAL VARIATIONS IN ANTARCTIC SEA ICE EXTENT AS MAPPED BY RADAR ALTIMETRY

Seymour Laxon

University College London, Mullard Space Science Laboratory, Dorking, Surrey RH56NT, United Kingdom.

Abstract. Previous work has shown that inter-annual variations in total sea ice extent may provide a sensitive indicator of global climate change. Data from passive microwave instruments have allowed mapping of global sea ice extents from 1973-76 and from 1978 up to September 1987, [Gloerson and Campbell, 1988]. In this paper data from another microwave instrument, the Geosat radar altimeter, have been used to map the Antarctic sea ice extent for the period November 1986 to January 1989. Comparison with total Antarctic sea ice extents derived from the Scanning Multichannel Microwave Radiometer (SMMR) show excellent agreement during the freeze up period but show significant differences during the late part of the melt period.

Introduction

The monitoring of sea ice extent on a global scale has attracted much attention in recent years since it may provide a sensitive indicator of climate change. A temperature rise in the polar regions would be amplified through the ice/albedo positive feedback mechanism [Mitchell, 1989] resulting in a decrease in average sea ice extent by as much as 2.5° in latitude for each 1°C rise in global surface temperature [Budd, 1975]. Zwally et al. [1983] suggest that the response may not be of quite such a large magnitude, but will still be considerable. Kukla and Gavin [1981] discuss changes in the extent of Antarctic sea ice extent for the period 1973-1980. Their results are derived from charts produced by the US Navy-NOAA Joint Ice Center (JIC) using satellite visible, infra-red and uncalibrated passive microwave observations. However the visible and infra red data are limited by darkness and cloud cover. Zwally et al [1983] show that differences exist between Navy-NOAA maps and calibrated passive microwave observations of global sea ice extent raising doubts about the reliability of the ice charts. More recently Gloerson and Campbell [1988] have presented results of global variations in sea ice extent, sea ice area and open water coverage within the pack based solely on passive microwave observations. They define the sea ice extent as the total area for which sea ice concentrations are greater than 15%. The sea ice area is defined as the product of the ice concentration and area for each passive microwave pixel summed over the entire region. The open water percentage is the difference between the sea ice extent and the sea ice area. They conclude that a significant downward trend in global sea ice extent occurred during the period 1978-1987 although no corresponding decrease in sea ice area was observed.

In this paper we present sea ice extent data derived from another satellite-borne microwave instrument, the radar altimeter on board the US Navy's Geosat satellite. The altimeter is designed primarily for operation over the open ocean where it records a series of radar echoes plus measurements of range, ocean wave height and return echo strength as it progresses along its ground track. The presence of sea ice within the altimeter footprint causes distinct changes in the strength and shape of the return echo from the surface [Dwyer and Godin, 1980; Robin et al, 1983, Ulander, 1987]. Changes in pulse shape disturb the operation of the on board tracker used to maintain lock on the leading edge of the return echo [Rapley, et al, 1983] resulting in increased noise on the height values computed on-board.

An operational sea ice product has been produced since 1986 by the US Navy [Hawkins and Lybanon, 1989] using a method similar to that suggested by Dwyer and Godin. The product consists of an ice index based on a suitable combination of parameters derived from the echo waveform intensity and shape. Work is currently underway to understand better the relationship between the altimeter echoes and sea ice characteristics by comparing near co-incident imagery from the Advanced Very High Resolution Radiometer and Geosat data [Laxon, 1989]. For a compact ice edge, a rapid change in both returned power and waveform shape is observed close to the ice/ocean boundary visible in the AVHRR image. A transition over a diffuse ice edge causes a less marked, although still significant change in return echo strength and shape, even at low ice concentrations. The exact relationship between ice concentration and the altimeter is not clear and almost certainly depends on the prevailing wind and wave conditions. However, given the high sensitivity of the altimeter to a change in surface roughness over even a small fraction of the surface [Robin et al., 1983], it is likely that a significant change in the altimeter return occurs at ice concentrations of only a few percent. Given the need for ongoing effort to establish means of extracting quantitative estimates of ice concentration and characteristics, from the echo data, and the large volumes of data involved for global processing, it is worth evaluating what might be deduced about sea ice from the reduced data set of on-board estimates of height, 'waveheight' and echo strength. Thus in this paper altimeter parameters contained within the Geosat Geophysical Data Records are used to map Antarctic sea ice extent over a period of 28 months between October 1986 and February 1989.

Data Sets

After completing a classified mission the Geosat satellite was placed in a so called 'Exact Repeat Mission' (ERM) orbit repeating coverage of the same ground track every 17.05 days. In this analysis we map the total sea ice extent for intervals corresponding to the exact repeat period. During each 17 day period about 500 Antarctic sea ice boundary crossings occur giving a mean longitudinal spacing of around 40km at 60°S. The resolution in longitude is therefore similar to the SMMR although the altimeter along-track resolution is potentially 7km, which is considerably better than the SMMR. It should be noted, though, that the altimeter observations are restricted to the ground track (i.e. reduced spatial sampling) and are collected over a 17 day period during which the sea ice extent may undergo considerable (100's km) changes.

Paper number 90GL01883
0094-8276/90/90GL-01883$03.00

Data from the Geosat altimeter are created in several different formats :

(i) The Sensor Data Record (SDR) - consisting of telemetred samples of surface range and Automatic Gain Control (AGC) at 10 Hz, satellite pointing used in the computation of the Geosat ice index (sensitive to changes in pulse shape), instrument status and quality words.
(ii) The Waveform Data Record (WDR) - consisting of return echo profiles at 10 Hz.
(iii) The Geophysical Data Record (GDR) - consisting of surface elevation at 10 Hz, AGC and Significant Wave Height (SWH) at 1 Hz, Standard deviation of surface elevation AGC and SWH plus Quality flags.

Data contained within the GDR are further split into 'Ocean' and 'Land/Ice' data sets depending on the status of various quality flags [Cheney, et al. 1987]. The data employed here come from the 'Oceans' GDR and they are often intermittent over sea ice areas, where the Navy processing algorithm has identified waveforms as being 'Land/Ice'. Future work will involve the acquisition and merging of the 'Land/Ice' GDR's to allow complete coverage. Ideally to map sea ice boundaries individual return echo profiles and associated parameters (contained within the SDR and WDR) should be analysed. This involves the merging and processing of very large quantities of data (e.g. approximately one tape per day). However, the Geosat GDR contain parameters which provide indications of the presence of sea ice as described below and provide data in a much more compact form.

Figure 1 shows the Geosat GDR coverage from ERM cycle 1. The sparsity of data points near the continent indicates the presence of sea ice which is causing much of the data to be incorporated into the 'Land/Ice' GDR's. Coverage over the Larsen, Shackleton and West ice shelves is more dense than over the surrounding sea ice, reflecting the fact that return echos from ice shelves resemble those from the open ocean more frequently than echos from sea ice. A further problem with the use of Geosat data for sea ice mapping is that coverage is limited to areas north of 72.05°S, the latitudinal limit of the orbit. Fortunately, the majority of the Antarctic sea ice boundary lies north of this latitude throughout the year with a few exceptions such as regions of the Weddell and Bellinghausen seas. As explained in the next section, in cases where the sea ice boundary lies south of 72°, all data between the latitudinal limit and the coast is classified as "unknown".

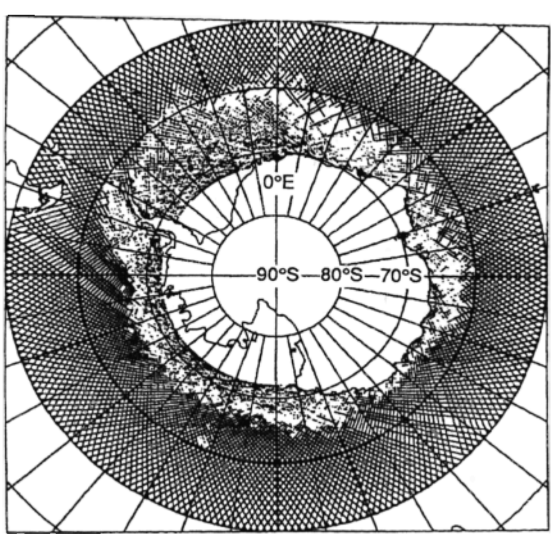

Figure 1. Geosat Ocean GDR coverage during ERM cycle 1 (November 1986). The presence of sea ice results in data gaps where the GDR processing algorithm have classified echoes as "Land/Ice".

Data Processing

To overcome the problem of the intermittency of the "oceans" data set, data were averaged into geographical cells. Since the Antarctic sea ice boundary, on average, lies East-West it is preferable to have cells which have a finer North-South than East-West resolution. After some trial and error, the final size of geographical cells chosen was 2° in longitude x 0.4° in latitude. The latitude size was chosen to be comparable to the resolution of the SMMR (40km) and the longitude size was chosen so that at least two or three altimeter tracks pass through each cell. One point to bear in mind is that cells containing multiple tracks of valid data are classified as "sea ice" even if the data from only one of the tracks indicates the presence of sea ice. The total sea ice extent will generally, therefore, be biased towards the maximum for any 17 day period rather than the mean. The three parameters used in the analysis were as follows :

(i) SDH - the standard deviation of 10 surface height values recorded during each one second averaging period. Over the ocean this is relatively insensitive to variations in waveheight and windspeed. Over the sea ice, the presence of bright targets off-nadir causes some disruption of the tracker, resulting in a significant increase in SDH.
(ii) AGC - a measure of the return echo strength. Over the ocean this depends on the wind speed. Over discontinuous sea ice, near the margin, very high values of AGC occur.
(iii) SWH - over the open ocean the SWH provides a measure of the ocean wave height. Over sea ice the increased tracker noise disrupts the on-board computation of the SWH parameter, resulting in large erroneous values.

Figure 2 shows average values in geographical bins of these three parameters : (a) SDH, (b) AGC and (c) SWH. All three parameters show increases in regions where the presence of sea ice is likely. The SDH values are less variable over the open ocean than either AGC or SWH, both of which vary due to changes in ocean wave height and wind speed. Histograms of the three parameters are also shown for geographical bins lying south of 60°S. Values of SDH show the narrowest distribution over the ocean and so this parameter was selected as the primary indicator of sea ice, with AGC and SWH used as secondary indicators. Since the ocean data exhibit very narrow distributions of the parameters compared with ice or land the methodology adopted was to identify ocean cells, unambiguously from the data first. This was achieved using the following criteria : (i) SDH $<$ 0.1 metres, (ii) SWH $<$ 20 metres, (iii) AGC $<$ 35 dB.

Cells which failed any of the three inequalities given above were then classified as either (i) land, (ii) sea ice or (iii) unknown. Data cells were classified as 'land' according to a land mask derived from a coastline provided by the Scott Polar Research Institute in Cambridge [Drewry, 1983]. Cells containing no GDR data were classified as ocean if the neighbouring cell lying immediately northward was classified as ocean. Otherwise a cell containing no GDR data and lying immediately south of a cell classified as sea ice was classified as sea ice. Cells lying within the latitudinal limit and bounded by an

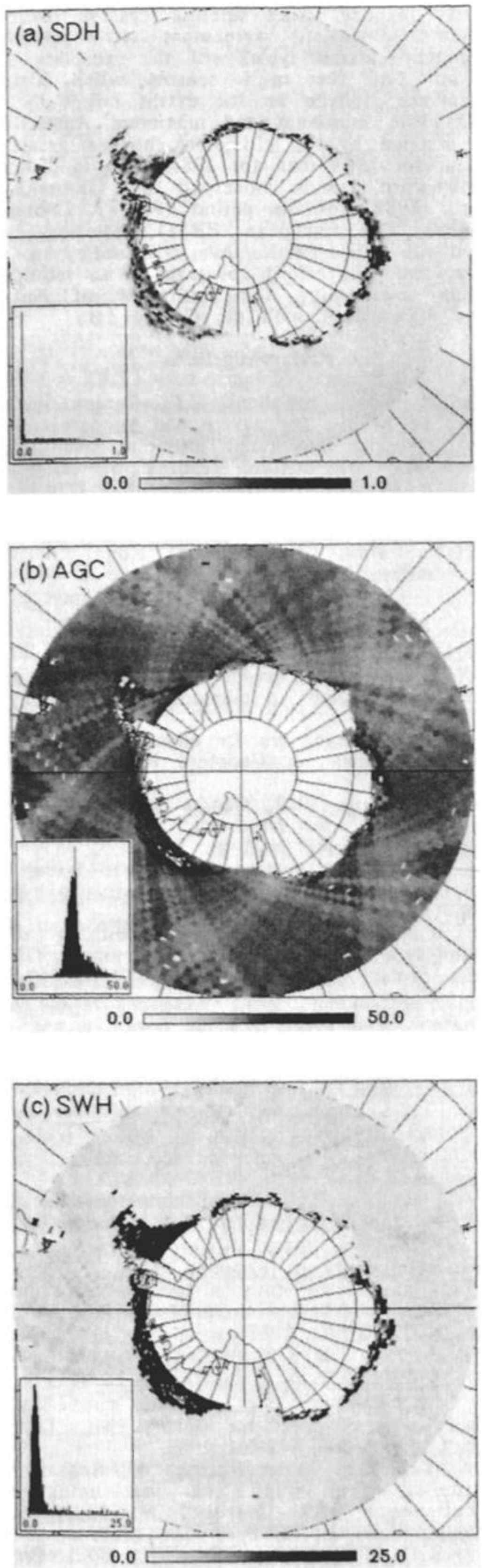

Figure 2. Geosat altimeter parameters averaged in geographical bins for ERM cycle 8 (March 1987) with histograms of parameter values for bins lying south of 60°S.

"ocean" cell at the latitude limit were classified as "unknown". All remaining cells not classified as ocean, land or unknown, were classified as sea ice.

Figure 3 shows the classification for data bins from ERM cycle 8. Areas classified as 'unknown' are observed in both the Weddel and Ross seas, although they make up only a small percentage (maximum ~ 0.42 million square kilometres) of the total area. Some cells classified as sea ice but lying well outside the ice edge are also observed. These may be caused, either by coastlines and small islands, which are not resolved by the land mask, or by anomalous surface conditions over the open ocean [Laxon and Rapley, 1987]. Examination of individual plots showed the maximum number of such events to be less than 20, resulting in a maximum additional error of 0.06 million square kilometres.

The total area enclosed by the sea ice boundary for each ERM cycle was calculated using :

$$\text{TOTAL EXTENT} = \sum \text{AREA OF SEA ICE BINS} + \frac{1}{2}\sum \text{AREA OF UNKNOWN BINS}$$

The second term, concerning the "unknown" cells, assumes a 50:50 probability that they are ocean or ice. An error was also assigned to each value based on the following :

$$\text{ERROR} = \frac{1}{2}\sum \text{AREA OF UNKNOWN BINS} + 110^2 * 360 * 0.2 * \text{COS}(65°)$$

The second term in the error calculation assumed an average error of 0.2° in the latitude of the sea ice boundary location for the entire periphery (corresponding to 0.37 million square kilometres), due to the quantisation of the geographical cells. The random error due to the altimeter sampling distance (7km) will be considerably less than this. When comparing the total sea ice extent determined by the altimeter with values derived from passive microwave data it must be noted that the latter refer to the 15% ice concentration boundary, whereas the altimeter boundary almost certainly corresponds to a lower concentration of sea ice. This may account for

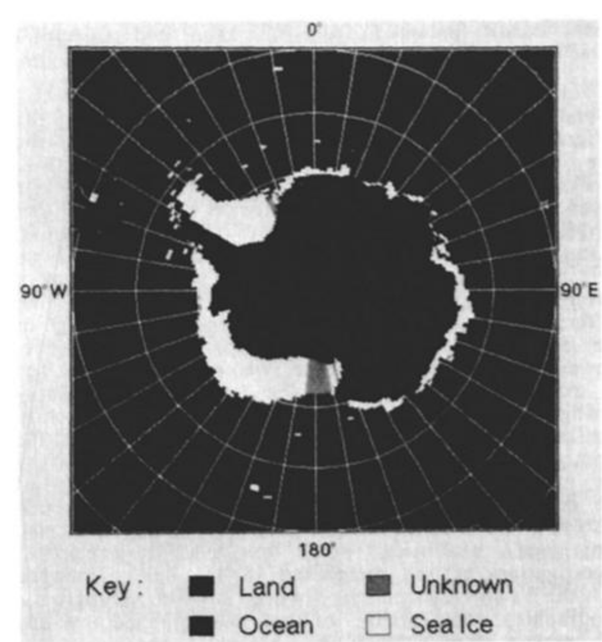

Figure 3. Classification of data bins for ERM cycle 8 (March 1987).

some differences in the estimates of total extent (see next section).

Results And Conclusions

Figure 4 shows the curve representing the total Antarctic sea ice extent computed using the method described above for 48 ERM cycles covering the period November 1986 to January 1989. Also shown is the curve for November 1985 to October 1987 published by Gloerson and Campbell [1988] based on passive microwave data. During the freeze up period the agreement is close, lying well within the uncertainties of the altimeter data. During the latter part of the melt period (Jan-Feb 1987), however, a significant lag is observed in the altimeter sea ice extent, the area derived from the altimeter being greater than that mapped by the SMMR. The difference amounts at most to 1.2 million square kilometres, which exceeds the maximum estimated error of 0.85 million square kilometres. A difference of 1.2 million square kilometres corresponds to a mean latitude difference of the order of 0.6° or about 60km.

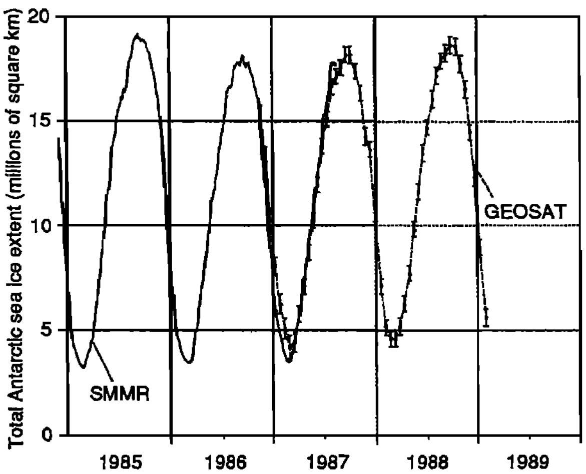

Figure 4. Total Antarctic sea ice extent derived for Geosat altimeter data compared with that derived from SMMR (adapted from Gloerson and Campbell [1988]).

There are several possible explanations for the difference observed in total ice extent during the late part of the melt season. The assumption, necessarily employed in this analysis, that if sea ice cover exists at 72° then sea ice is present on that meridian up to the coast, may not hold in some areas. Examination of sea ice maps provided in Zwally et al. [1983], however shows that this would result in a difference of only a few percent. Alternatively the different temporal and spatial sampling patterns of the two instruments account for the difference. However, if this were the case, we would expect to see a difference throughout the cycle, particularly during times of rapid change, which is apparently not the case. A more likely explanation is that the altimeter exhibits a greater sensitivity to the diffuse ice margin which occurs during the latter part of the melt period and therefore detects sea ice outside the 15% ice concentration boundary which is the limit of visibility for the SMMR. Further investigation of the difference in ice extent mapped by the two instruments work should involve a geographical comparison of sea ice mapped by the two sensors over a least one seasonal cycle.

In conclusion satellite radar altimeter data have, for the first time, been used to provide an independent measure of the total Antarctic sea ice extent previously mapped using satellite passive microwave instruments. Excellent agreement is observed for most of the seasonal cycle, with the exception of the latter part of the melt season when altimeter measurements indicate an ice extent larger by 30%. Note that the minimum and maximum Antarctic ice extent, mapped by the altimeter, show a greater sea ice extent for 1988 than for 1987. This is counter to the downward trends observed by Gloerson and Campbell [1988] for the period 1978-87. Looking to the future, the European ERS-1 satellite, to be launched in late 1990, this will carry a radar altimeter, and will afford coverage up to latitudes of 82° thus overcoming the limitation of Antarctic coverage experienced with the Geosat data.

Acknowledgements

The author wishes to thank C.G. Rapley and N.F. McIntyre, of MSSL, for advice and encouragement in pursuing research into radar altimetry over sea ice and also for the critical reading of this script. Thanks are also due to the Algorithm Development Facility, Earth Observation Data Centre, Farnborough for supplying the data. The author is funded by the Earth Observation Data Centre, Royal Aerospace Establishement, Farnborough.

References

Budd, W.F., 'Antarctic sea-ice variations from satellite sensing in relation to climate', J. Glaciology, 15, 417-427, 1975.

Carsey, F.D., 'Summer sea ice character from Satellite microwave data', J. Geophys. Res., 90, c3, 5015-5034, 1985.

Cheney, R.E., et al, 1987, 'Geosat altimeter Geophysical Data Record user handbook', NOAA Technical memorandum, NOS NGS-46.

Drewry, D.J, 'Antarctica : glaciological and geophysical folio', Scott Polar Research Institute, Cambridge, UK, 1983.

Dwyer, R.E., Godin, R.H., 'Determining sea-ice boundaries and ice roughness using GEOS-3 altimeter data', Nasa contract report CR-156862, 1980.

Gloerson, P., Campbell, W.J., 'Variations in the Arctic, Antarctic, and global sea ice covers during 1978-1987 as observed with the Nimbus 7 Scanning Multichannel Microwave Radiometer', J. Geophys. Res., 93, c9, 10666-10674, 1988.

Hawkins, J., Lybanon, M., 'Geosat altimeter sea ice mapping', IEEE Oceanic. Eng., 14, No.2, 139-148, 1989.

Kukla, G., Gavin, J., 'Summer ice and Carbon Di-Oxide', Science, 214, No. 4520, 497-503, 1981.

Laxon, S., Rapley, C.G., 'Radar altimeter data quality flagging', Adv. Space Res., Vol. 7, No. 11, 315-318, 1987.

Laxon, S., 'Satellite radar altimetry of sea ice', PHd thesis, University of London, 1989.

Rapley, C.G., et al, 'A study of satellite radar altimeter operation over ice covered surfaces', E S A 5182/82/F/CG(SC), 1983.

Mitchell, J.F.B., 'The Greenhouse Effect and climate change', Reviews of Geophys., 27, 1, 115-139, 1989.

Robin, G.Q., Drewry, D.J., Squire, V.A., 'Satellite observations of polar ice fields', Phil. Trans. R. Soc. Lond., A 309, 447-461, 1983.

Ulander, L.M.H., 'Interpretation of Seasat radar altimeter data over sea ice using near-simultaneous SAR imagery', Int. J. of Remote Sensing, vol.8, No.11, 1679-1686, 1987.

Zwally, H.J., Parkinson, C.L., and J.C. Comiso, 'Variability of Antarctic sea ice and changes in Carbon Di-Oxide', Science, 220, 1005-1012, 1983.

(Received June 12th 1989;
Accepted February 12th 1990)