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Assessment of sea ice melting rates in the Antarctic from SSM/I observations

ABHINAV SRIVASTAVA[1], I. M. L. DAS[1,2,3*], SANDIP R. OZA[5], AMITABH MITRA[2], MIHIR KUMAR DASH[4] and N. K. VYAS[5]

[1]*K. Banerjee Centre of Atmospheric & Ocean Studies*

[2]*M. N. Saha Centre of Space Studies*

[3]*Department of Physics, University of Allahabad, Allahabad – 211002, India*

[4]*Centre for Oceans Rivers Atmosphere and Land Sciences, Indian Institute of Technology, Kharagpur – 721302, India*

[5]*Space Applications Centre, Indian Space Research Organisation, Ahmedabad – 380015, India*

***e mail : profimldas@yahoo.com**

सार – महासागर वायुमंडल के दानों ओर के पार समुद्र की बर्फ तापमान, नमी और संवेग के फलक्सों को प्रभावित करती है क्योकि यह पतली होती है अतः समुद्र की बर्फ महसागर में जरा सी हलचल से भी प्रभावित होती है जो कि ध्रुवी हिमाच्छादन की विस्तार और मोटाई को काफी परिवर्तित करती है। अतः समुद्र कर बर्फ जलवायु के परिवर्तन का संकेत देती है। एंटार्कटिक क्षेत्र डी.एम.एस.पी. एस.एस.एम./आई. में अंटार्कटिक मासिक हिम सांद्रण आँकड़ों का उपयोग 1988–2006 के दौरान प्रतिवर्ष मासिक समुद्र हिम विस्तार (अगस्त से फरवरी) का आकलन करने के लिए किया गया है। सौर विकिरण के मौसमी चक्र के आधार पर पिघलन की दर के साथ साथ एस.एस.एम./आई. आँकडों का आकलन किया गया है। सौर विकिरण के मौसमी चक्र के आधार पर पिघलन दर की अपेक्षा एस.एस.एम./आई. आकलित पिघलन दर सितंबर के आरंभ में कम है और दिसबंर के अंत में चरम अवस्था में है। प्रेक्षित की गई पिघलन दर का व्यवहार यह दर्शाता है कि सौर विकिरण के मौसमी चक्र को छोड़कर यह अन्य मकैनिज़्मों द्वारा भी नियंत्रित होता है। इस अध्ययन में 1988–2006 की अवधि में फीडबैक इंपेक्ट कारण प्रतिक्रिया समय पिघलन दर में तेजी आना और धीमी होना का आकलन किया गया है।

ABSTRACT. Sea ice governs the fluxes of heat, moisture and momentum across the ocean-atmosphere interface. Because it is thin, sea ice is vulnerable to small perturbations within the ocean and the atmosphere, which considerably change the extent and thickness of the polar ice cover. Thus, sea ice is a climate change indicator. The DMSP SSM/I monthly ice concentration data over the Antarctic region have used to calculate the monthly sea ice extents (August to February) for each year during 1988-2006. Melting rates based on seasonal cycle of solar irradiance as well as the SSM/I data have been calculated. Compared to the melting rates based on seasonal cycle of solar irradiance, the SSM/I estimated melting rate, is less in the beginning of September and increases to its peak value by the end of December. The observed melting rate behaviour indicates that apart from the seasonal cycle of solar irradiance, it is controlled by other mechanisms also. The present study estimates the feedback impact factor, response time, accelerating and decelerating melting rate duration for the period 1988-2006.

Key words – Antarctica, SSM/I, Sea-ice extent, Melting rate, Ice-albedo feedback.

1. Introduction

The sea-ice cover in the Polar Regions is one of the most expansive and seasonal geophysical parameters on the earth's surface. The polar sea ice plays a key role in the earth's climate system. Sea ice is having a profound effect on the ocean and atmosphere as it modulates the exchange of heat, moisture and momentum between the atmosphere and ocean. It also affects the ocean-atmosphere dynamics through various feedback mechanism.

The most important feedback mechanism is the albedo-temperature feedback: an initial small warming (cooling) implies a decrease (increase) in the sea-ice extent and hence, a smaller (larger) reflection and larger (smaller) absorption of total incident solar energy over the region, which would be conducive to further enhancement of the initial warming (cooling). The mean albedo ($\propto$) of sea-ice ranges roughly from 0.5 to 0.7, compared to 0.05 to 0.15 for the open water [Grenfell and Maykut (1977); Massom and Comiso (1994)]. As a result of the high albedo of ice surfaces, only a small fraction ($1-\propto$) of the energy is absorbed at the surface. Solar heating of the surface during summer results in the increase of snow/ice wetness and development of melt ponds, which in turn, significantly reduce the regionally averaged summer time albedo [Eicken *et al.* (2002)]. This reduction in albedo plays an important role in the Polar Regions. Any perturbation in the surface energy balance resulting in a decrease of ice extent due to warming may spread and amplify Curry *et al.* (1995).

Another feedback mechanism is provided by sea-ice modifying the evaporation rates: a decrease (increase) in the sea-ice compactness through melting (freezing) leads to higher (lower) water-vapour concentration in the lower atmosphere and to an enhancement (inhibition) of the atmospheric longwave radiative absorption, thus supporting further ice ablation (accretion). Because of such feedback effects between the surface and the atmosphere, the climate change signals are expected to be amplified in polar regions Budyko (1966).

The Southern Ocean, variously known as the Great Southern Ocean, the Antarctic Ocean and the South Polar Ocean, comprises the southernmost waters of the World Ocean south of 60° S latitude. Sea ice in the Antarctic Ocean is an important component of the terrestrial cryosphere and plays a very vital role in global climate. The impact of ice-albedo feedback on hemispheric scale sea-ice melting rates in the Antarctic using Multi-frequency Scanning Microwave Radiometer data have been studied by Mitra *et al*. (2008). The Antarctic Sea Ice extent (AnSIE) has been found to have a significant impact on the Indian monsoon also. It is found that AnSIE variation has provided a strong signal to imply that 2002 would be a deficit monsoon year Prabhu *et al*. (2009). The long term impact of the Antarctic Sea Ice Concentration (AnSIC) on the All India Rainfall (AIR) has also been studied using Artificial Neural Network Das and Tripathi (2009). The AnSIC time series lagging by 11 months is found to be strongly correlated with the AIR showing a possible association between the two.

Microwave emission comes from different layers such as snow surface, snow/ice interface and the internal ice layers and depends on the frequency. Open water is reflective in microwave band and emits little energy and has strong polarization. In contrast, first year ice is highly emissive and has weak polarization while the multiyear ice emission falls between that of water and the first year ice. Consequently, the brightness temperature recorded by the passive microwave remote sensor depends on the type of the surface from which the radiation has emanated Mitra *et al*. (2008).

The Special Sensor Microwave Imager (SSM/I) onboard Defense Meteorological Satellite Program (DMSP) satellites F8, F10, F11, F12, and F13 is a seven-channel, four-frequency, orthogonally polarized, passive microwave radiometric system that measures atmospheric, oceanic and terrain microwave brightness temperatures at 19.35, 22.2, 37.0, and 85.5 GHz. Using the Bootstrap algorithm, data is gridded at a resolution of 25 × 25 km since 25 June 1987.

To assess the impact of the ice albedo feedback mechanism on the Antarctic sea ice melting rates, we have used the DMSP SSM/I sea ice monthly concentration data in the Antarctic region with latitudinal variation [39.3649 S to 89.8368 S] and longitudinal variation [000.1651 E to 359.8350 E] during the summer melt season (August-February) for the period 1988-2006.

2. The analysis procedure

The monthly sea ice extents were assumed to correspond to the 15th day of each month. The mid day of the month of August, *i.e.*, 15th August was allocated the time $t = 0$ which has been taken to correspond to the maximum sea ice area during the study period. Then $t = 184$ corresponds to the mid day of the month of February, *i.e.*, 15th February which has been taken to correspond to the minimum sea ice area during the period of our study.

The solar irradiance at given latitude depends on the seasonal variation of the cosine of the solar elevation angle at that latitude during the apparent annual motion of the sun. So, we fit a cosine curve of the form given by equation (1) for the sea-ice extent values against time t in days during the melting phase:

$$y = c + a \cos (\omega t) \tag{1}$$

where y represents the expected sea-ice extent (SIE). Here $\omega = 2\pi/ T$, where $T = 365.24$ days corresponding to a periodicity of 1 year. For all the years varying from 1988 to 2006, the coefficients 'a' and 'c' were determined by using the sea ice extent values on the 15th August ($t = 0$) and 15th February ($t = 184$).

Actual melting rate (in million sq km per day) of SIE observed by SSMI is computed as difference in two SIE observed at two different dates divided by time period in days. The actual melting rate of sea-ice extent for each month was compared with the depletion rate obtained by differentiating Eqn. (1) as shown below

$$- (\mathrm{d}y/\mathrm{d}t) = a\, \omega \sin (\omega t) \tag{2}$$

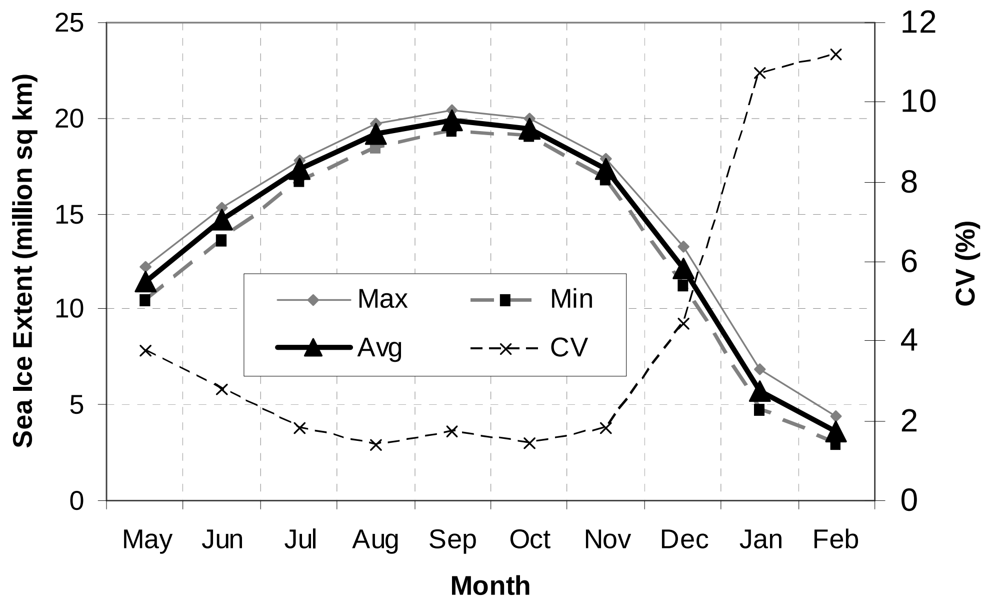
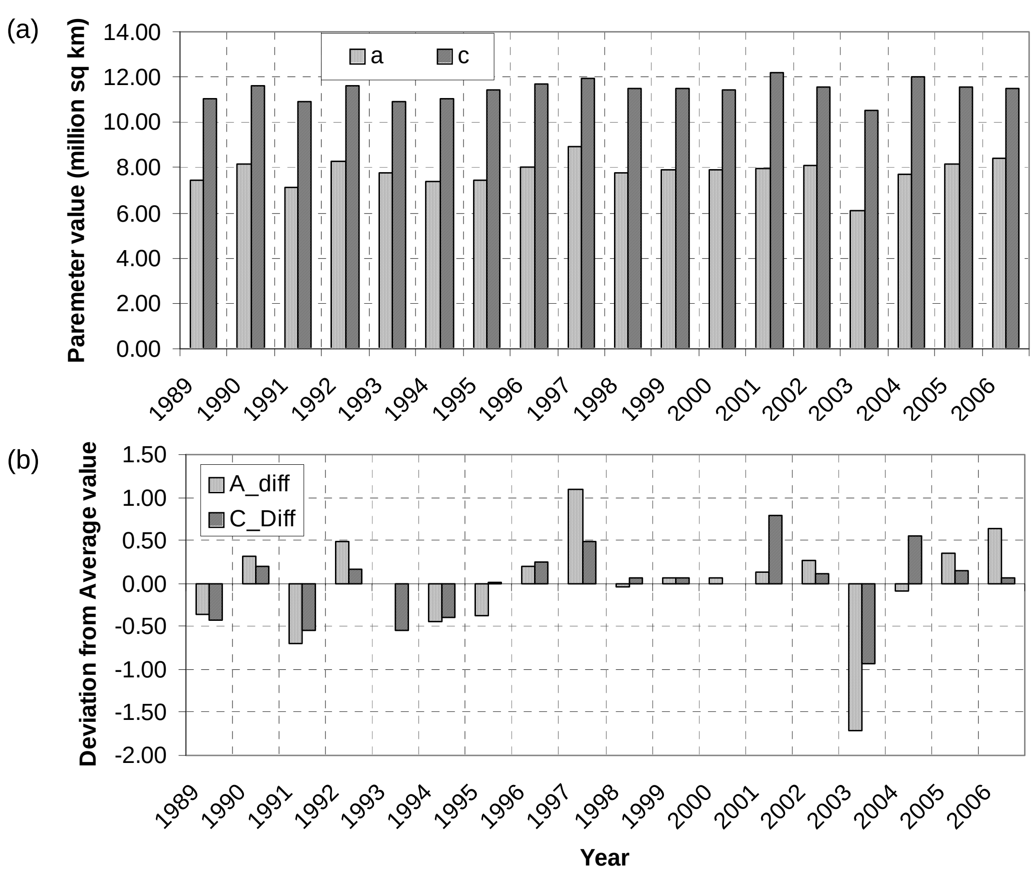
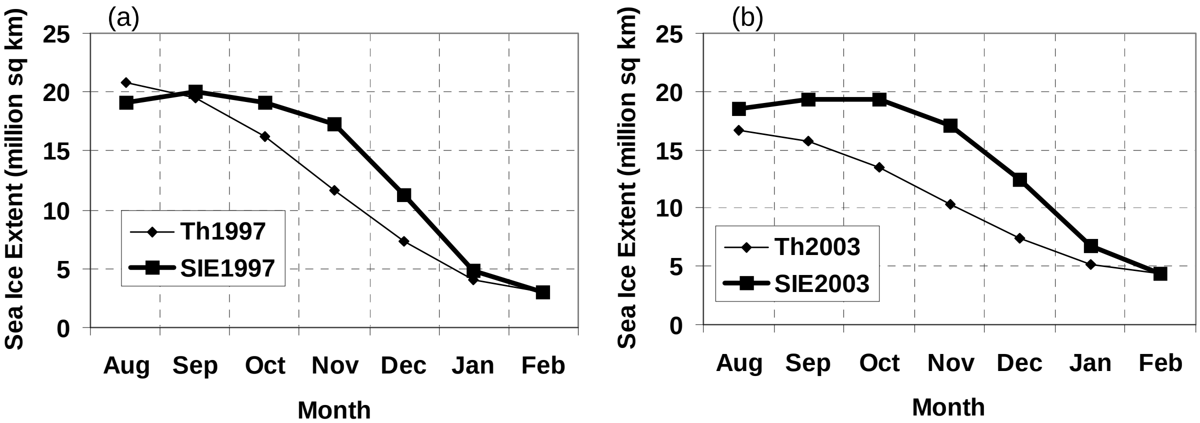


Fig. 1. Maximum (Max), minimum (Min), Average (Avg) and the Coefficient of Variation (CV) of the Sea Ice Extent in the Antarctic observed from SSM/I for the period from 1988-2006



Figs. 2(a&b). Values of the parameters *a* & *c* used in equation (1). (a) Year-wise values and (b) Difference of values in individual year from that of 18-year average of *a* (A_diff) and *c* (C_Diff). Year 1989 indicates the period of August-1988 to February-1989



Figs. 3(a&b). Sea Ice Extent Observed from SSM/I (SIE) and derived from equation (1), denoted as Th. Year 1997 indicates the period from August-1996 to February-1997 and year 2003 indicates the period from August-2002 to February-2003

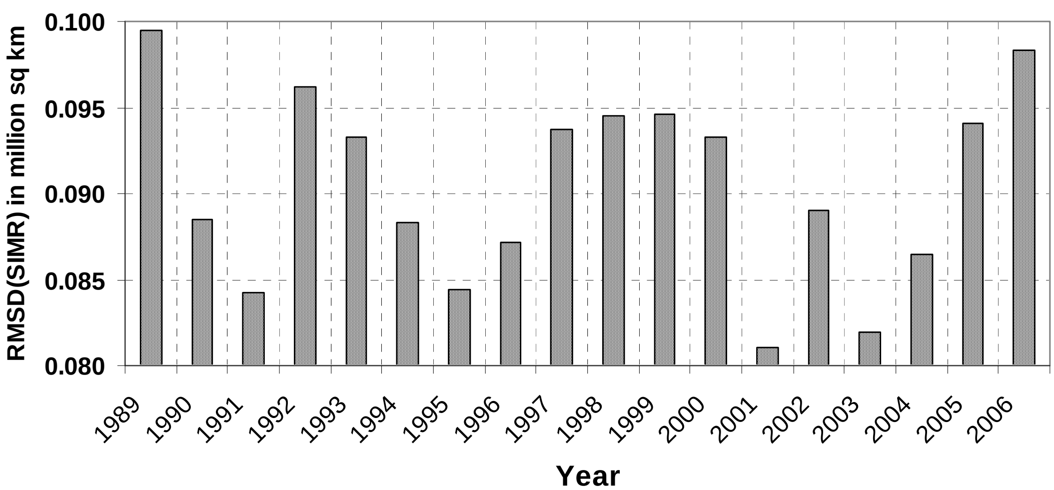
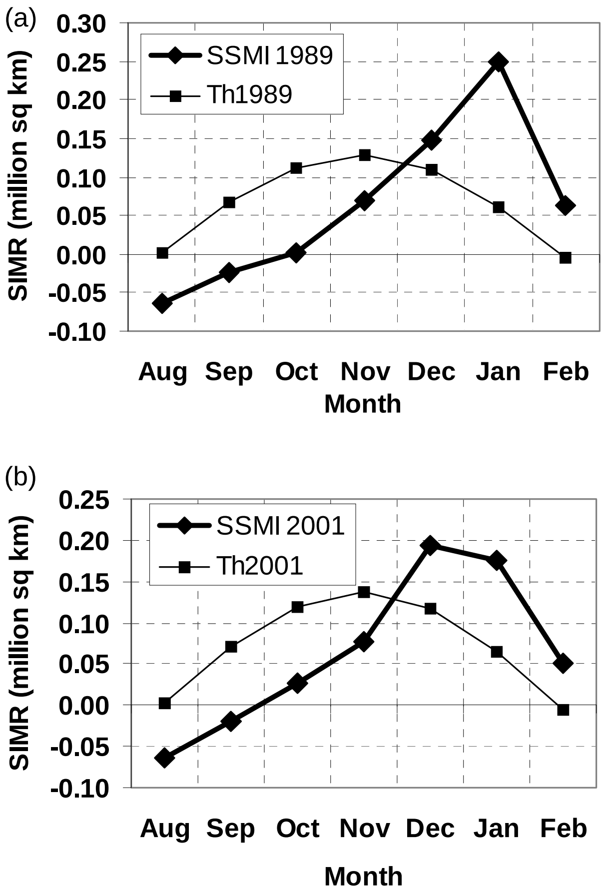


Fig. 4. Root Mean Square Deviation (RMSD) observed between the Sea Ice Melting Rate (SIMR) derived from SSM/I data (actual) and theoretical SIMR derived using equation (2). Year 1989 indicates the period from August-1988 to February-1989

3. Results and discussion

The statistics of Sea Ice Extent (SIE) in the Antarctic region, observed during study years 1988-2006 are shown in Fig. 1. It is observed that average SIE is maximum in September with around 20 million sq km sea ice and it is at its minimum in February with about 2 million sq km sea ice. The higher values of Coefficient of Variation (CV) during the months from November to January indicate the higher inter-annual variability during these months.

The year-wise values of parameters ‘*a*’ and ‘*c*’ of the equation (1) are shown in Fig. 2(a). It is observed that year-to-year variations are higher for the parameter ‘*a*’ as compared to that observed for the parameter ‘*c*’. This indicates that the inter-annual variation in winter maximum SIE are higher than that observed in summer minimum SIE in the Antarctic. Fig. 2(b) shows the deviation of year-wise parameter values of ‘*a*’ and ‘*c*’ from the 18-year average values. The deviations observed for the years 1997 (1996-97) and 2003 (2002-03) indicate that the value of ‘*a*’ in the year 1997 is higher than the



Figs. 5(a&b). Month-wise Sea Ice Melting Rate (SIMR) derived from SSM/I (SSMI) and derived using equation (2), denoted as 'Th'. Year 1997 indicates the period from August-1996 to February-1997 and year 2003 indicates the period from August-2002 to February-2003

18-year average value of 'a' [Fig. 3(a)], where as that in 2003 is lower than the average value [Fig. 3(b)].

The Sea Ice Melting Rate (SIMR) for the study years were computed from SSM/I data (actual) and by using Eqn. (2), theoretical SIMR, for the study years. The root mean squared deviation between actual and theoretical SIMR is shown in Fig. 4. The highest deviation is observed in 1989 (1988-89) and lowest in the year 2001 (2000-01).

The month-wise melting rates for these two years 1988-89 and 2000-01 are shown in Figs. 5(a&b). The higher difference between the theoretical and actual SIMR observed in the months of October and January is the reason for the higher deviation between actual and theoretical SIMR observed in 1988-89 from that observed for 2000-01.

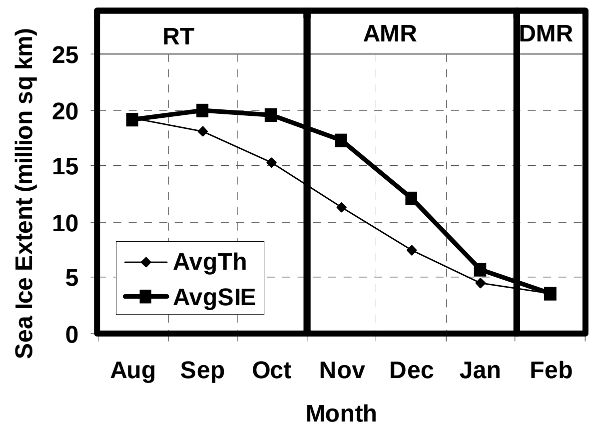


Fig. 6. Average (1988-2006) values of Actual (AvgSIE) and theoretical (AvgTh) sea ice extent. RT is the response time, AMR is accelerating melt rate duration and DMR is decelerating melt rate duration

The melting rate picks up from the August month and reaches its peak during the months of December and January. Then, the sea-ice extent starts decreasing rapidly and reaches its bare minimum in February.

The peak-melting rate derived from the observed SSM/I data lags behind that obtained from Eqn. (2) based on the cycle of solar irradiance by nearly 60 days. This is due to the time taken by the melting process to complete in response to the absorbed solar radiation. It is evident from Fig. 5 that during the melting phase (August-February), the actual rate of depletion of sea-ice extent remains low for a considerable time and then peaks up very fast and subsequently comes down at a steep rate. It deviates from the path expected purely from the cycle of solar irradiance described by Eqn. (2), suggesting the presence of some basic physical feedback processes controlling the extent of sea-ice.

The age and thickness of sea-ice present in different sectors of the Antarctic Ocean also play a role in increasing / decreasing the absorption of solar radiation, as the melting process proceeds with time. These processes need to be further explored and their effects need to be quantified. Similar results were obtained by earlier calculations based on observations obtained from OCEANSAT-1/MSMR data Mitra *et al.* (2008).

To assess the impact of the sea ice feedback processes we further calculated the followings:

(*i*) *Response time* : It is the duration for which the SSM/I melting rate is slow (less than 0.05 million km^2 per day) before attaining the peak melting rate.

TABLE 1

Impact of feedback processes

	Max	Min	Average	Standard deviation
Response time (days)	61	61	61	0
Effective melting phase (days)	123	123	123	0
Peak SSMI melting rate (million sq. km. per day)	0.248629	0.178629	0.210355	± 0.02146
Peak theoretical melting rate (million sq. km. per day)	0.139991	0.121013	0.133521	± 0.00454
Feedback impact factor	1.85	1.33	1.57	± 0.13

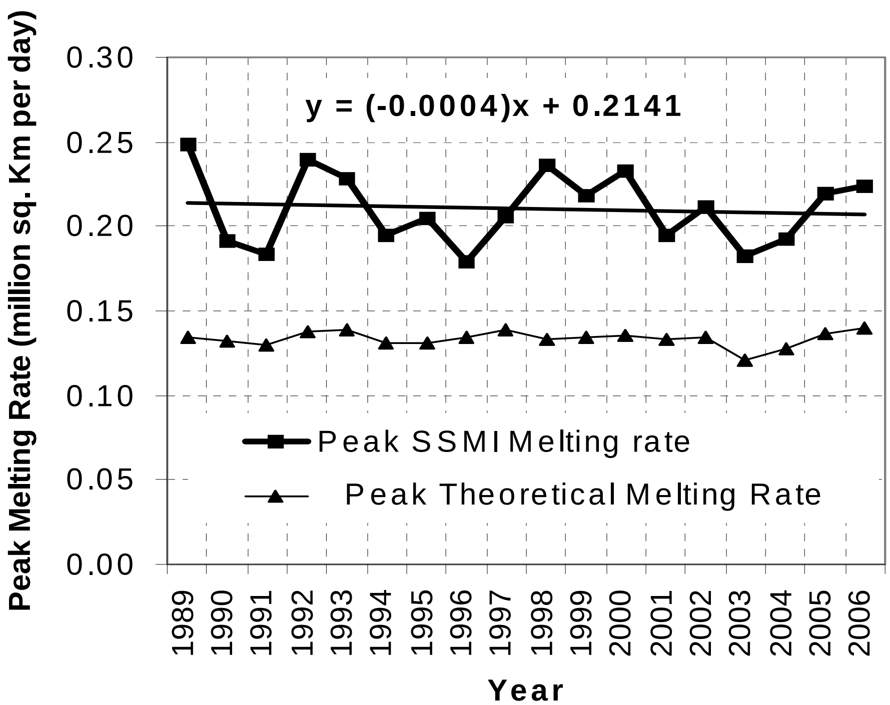


Fig. 7. Peak SSM/I melting rate and peak theoretical melting rate attained in each year for the period from 1988 to 2006. Year 1989 indicates the period from August-1988 to February-1989

(*ii*) *Accelerating melt rate duration in days* : It is the time for which the SSM/I melting rate is greater than 0.05 million km^2 per day but less than the peak melting rate.

(*iii*) *Decelerating melt rate duration in days* : It is the time period between the peak SSM/I melting rate and mid February.

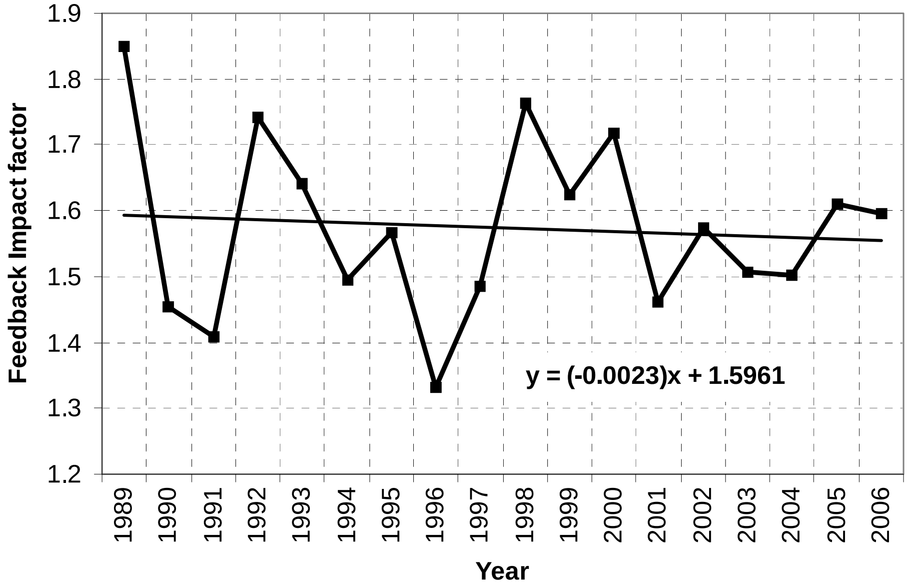


Fig. 8. Feedback impact factor for the period from 1988-2006. Year 1989 indicates the period from August-1988 to February-1989

(*iv*) *Effective melting phase duration in days* : The period during which most of the ice melts *i.e*., sum of (b) and (c).

(*v*) *Peak SSM/I melting rate* : Highest value of the sea ice melting rate in a year, derived from the observed SSM/I data.

(*vi*) *Peak theoretical melting rate* : Highest value of the sea ice melting rate in a year, estimated from Eqn. (2) and

(*vii*) *Feedback impact factor* : Ratio of (e) and (f).

The estimated response time (RT) was found to be 61 days, from mid August to mid October for the period 1988-2006 (Fig. 6). During this period the existing sea-ice increases the local albedo of the region and resists the incoming solar radiation from melting the surface, thus reducing the melting rate in the beginning. Further, the accelerating SSM/I melting rate (AMR) duration was found to be 92 days from mid October to mid January for all the years, except 1994-95 and 2000-01 when the peak melting rate was attained in mid December itself and the duration decreased to 61 days. The calculated decelerating SSM/I melting rate duration (DMR) was 31 days from mid January to mid February for all the years, except 1994-95 and 2000-2001 when this duration increased to 62 days. The effective melting phase duration was of 123 days, from mid October to mid February for the entire period 1988-2006.

Fig. 7 shows the peak SSM/I melting rate and the peak theoretical melting rate attained in each year from 1988 to 2006 during the period mid-August to mid-February. The peak SSM/I melting rate shows an insignificant decreasing linear trend of $Y = -0.0004X + 0.2141$. Further, it is observed that the peak theoretical melting rate is far below than the observed peak SSM/I melting rate possibly due to the presence of some physical albedo feedback processes which raises the melting rate of sea ice. As the sea-ice starts melting, the open water fraction increases. The shortwave radiation over the open water fraction further increases the melt rate, hence the actual melting rate observed by the SSM/I is more than the expected. This behavior clearly illustrates the presence of the sea-ice albedo-temperature feedback process Yao *et al*. (2000).

The feedback impact factor for all the years from 1988-2006 is shown in Fig. 8. It follows an insignificant decreasing linear trend of $Y = -0.0023X + 1.5961$. Table 1 shows the maximum, minimum, average and standard deviation of some of the parameters described above for the years 1988 to 2006 during mid August to mid February. The average value for the feedback impact factor is 1.57, which nearly coincides with the value of 1.5

obtained from an earlier analysis Mitra *et al*. (2008) using OCEANSAT-1/MSMR data for the year 1999-2000.

5. Conclusions

The SSM/I ice concentration data from 1988-2006 was used to assess the impact of the feedback processes. The melting rate obtained from the SSM/I data was compared with the theoretical melting rate obtained by differentiating a theoretical curve, based on the effect of seasonal cycle of solar irradiance. The feedback acts with a response delay of 61 days and increases the sea ice melting rate by 1.57 ± 0.13 times. The amount of sea ice present in the Polar Regions determines the future of Antarctic sea ice variability. The feedback processes should be taken into consideration while modeling the sea ice system in the Polar Regions.

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