JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, C12001, doi:10.1029/2005JC003447, 2006

Observational evidence of a hemispheric-wide ice–ocean albedo feedback effect on Antarctic sea-ice decay

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Received 19 December 2005; revised 26 June 2006; accepted 15 August 2006; published 2 December 2006.

[1] The effect of ice–ocean albedo feedback (a kind of ice-albedo feedback) on sea-ice decay is demonstrated over the Antarctic sea-ice zone from an analysis of satellite-derived hemispheric sea ice concentration and European Centre for Medium-Range Weather Forecasts (ERA-40) atmospheric data for the period 1979–2001. Sea ice concentration in December (time of most active melt) correlates better with the meridional component of the wind-forced ice drift (MID) in November (beginning of the melt season) than the MID in December. This 1 month lagged correlation is observed in most of the Antarctic sea-ice covered ocean. Daily time series of ice concentration show that the ice concentration anomaly increases toward the time of maximum sea-ice melt. These findings can be explained by the following positive feedback effect: once ice concentration decreases (increases) at the beginning of the melt season, solar heating of the upper ocean through the increased (decreased) open water fraction is enhanced (reduced), leading to (suppressing) a further decrease in ice concentration by the oceanic heat. Results obtained from a simple ice–ocean coupled model also support our interpretation of the observational results. This positive feedback mechanism explains in part the large interannual variability of the sea-ice cover in summer.

Citation: Nihashi, S., and D. J. Cavalieri (2006), Observational evidence of a hemispheric-wide ice–ocean albedo feedback effect on Antarctic sea-ice decay, *J. Geophys. Res.*, *111*, C12001, doi:10.1029/2005JC003447.

1. Introduction

[2] The Antarctic sea-ice zone has primarily a seasonal sea-ice cover, and most of the ice surface is covered by snow with a high albedo. In the seasonal and marginal ice zones, the existence of open water with an albedo much lower than that of sea ice results in high solar radiation absorption by the upper ocean during summer [*Maykut and McPhee*, 1995]. This absorption is the dominant heat source for bottom and lateral melting of the ice [*Maykut and Perovich*, 1987]. This process is particularly important for the Antarctic sea-ice covered ocean which has a relatively large open water fraction resulting from the divergent drift of ice.

[3] From the calculated net heat flux in the Arctic and Antarctic Oceans, surface melting of the sea-ice cover and the subsequent formation of meltponds appears to be small in the Antarctic, unlike that for the Arctic [*Andreas and Ackley*, 1982]. Multiple satellite data sets also indicate that areas of surface melting are sparse and short-lived in the Antarctic sea-ice zone [*Drinkwater and Liu*, 2000]. From a heat budget analysis of the Antarctic sea-ice zone, *Nihashi and Ohshima* [2001] showed that net heat input at the water surface from the atmosphere during the time of maximum melt (December) reaches 100–150 W m^{-2} as a result of solar heating, and is one or two orders of magnitude larger than the heat input at the ice surface ($\leq$ 10 W m^{-2}) because of the albedo difference. Further, they showed that the total heat input into the upper ocean through areas of open water is comparable to the latent heat of sea-ice decay for the entire Antarctic sea-ice zone.

[4] The heat input through open water is much larger than the estimated heat entrained from the deeper ocean, another possible heat source. In the Weddell Sea, the heat flux from the deeper ocean during winter was estimated to be about 20–50W m^{-2} due to the underlying warm Circumpolar Deep Water (CDW) [*Gordon and Huber*, 1990; *McPhee et al.*, 1999]. However, in summer, since the oceanic surface layer is strongly stratified both by heating and melting, entrainment of heat from the deeper ocean is suppressed. Further, winter water (WW) exists beneath the surface layer at a temperature near the freezing point and prevents the underlying warm CDW from reaching the surface. Also, from the Gordon and Huber study, the winter ocean heat flux was estimated to be 41 W m^{-2} and the annual value was estimated to be 16 W m^{-2}; thus, the summer value is expected to be small. Based on a heat budget analysis, *Nihashi and Ohshima* [2001] showed that an assumed spatially uniform flux of 10 W m^{-2} from the deeper ocean is less than 25% of the total heat input through open water

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0148-0227/06/2005JC003447$09.00

from the atmosphere during the active melt period (December–January). Ignoring the deeper ocean heat flux appears to be valid during the active melt season as a first-order approximation. Therefore, in the summer Antarctic sea-ice zone, heat input into the ice–upper ocean system mainly occurs over the open water areas and this heat input is the main heat source for sea-ice decay.

[5] If sea ice is primarily melted by heat input into the upper ocean through open water areas within the ice pack, the following positive feedback mechanism is possible in the ice–upper ocean coupled system: once ice concentration decreases (increases) at the beginning of the melt season, heat input into the upper ocean through the increased (decreased) open water fraction is enhanced (reduced), leading to (suppressing) a further decrease in ice concentration through ice melting by the oceanic heat. This effect is regarded as a kind of ‘ice-albedo feedback’, because the difference in surface albedo between ice and water causes the feedback.

[6] The term of ‘ice-albedo feedback’ for sea ice is often used for the following positive feedback mechanism: a decrease in the surface albedo of snow/ice due to surface melt with melt pond formation causes an increase in the solar radiation absorption, and then this causes further surface melt and a further surface albedo decrease [e.g., *Curry et al.*, 1995]. On the other hand, the positive feedback mechanism described in the previous paragraph is caused by the areal albedo change due to a change in open water fraction rather than a change in the surface albedo of snow/ice. In this study, to avoid misunderstanding, we use hereafter the term of ‘ice–ocean albedo feedback’ for the albedo feedback effect caused by a change in open water fraction within the ice pack. Since the surface melting appears to be small in the Antarctic sea-ice zone, the ice-albedo feedback effect caused by a change in the surface albedo of snow/ice is expected to be small.

[7] *Ackley et al.* [2001] applied the ice–ocean albedo feedback mechanism (‘open water–albedo feedback’ in their study) to the Ronne polynya during the 1997/98 summer season; the anomalously large open water area was initiated by an anomalous divergent wind field. They concluded that the open water area was enhanced through this feedback mechanism. A numerical modeling study also supported this idea [*Hunke and Ackley*, 2001]. For the 25–45°E sector, *Ohshima and Nihashi* [2005] demonstrated this feedback effect using a simple two-dimensional ice–ocean coupled model for the case of meridional ice retreat. Since the heat input mainly occurs over open water and this heat input is the main heat source for sea-ice decay, the ice–ocean albedo feedback effect is expected to be particularly prominent for the entire Antarctic sea-ice zone. Although this kind of albedo feedback effect is thought to be important in the Antarctic sea-ice zone, there have been very few studies that show the existence of this feedback mechanism from observational data, except for some specific regions. The objective of this study is to demonstrate through an analysis of observational data sets the ice–ocean albedo feedback effect on sea-ice decay over the entire Antarctic sea-ice zone.

[8] The organization of the paper is as follows. Section 2 describes the data used in the study, our method is explained in section 3, and the results and discussion are presented in section 4. A summary is given in section 5.

2. Data

[9] In this study a 22-year (1979–2001) daily sea ice concentration data set, previously derived from the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite (1979–1987) and the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) F8, F11, and F13 satellites (1987–2001) [*Cavalieri et al.*, 1999] using the NASA Team algorithm [*Cavalieri et al.*, 1984; *Gloersen and Cavalieri*, 1986; *Cavalieri et al.*, 1991, 1995], is employed. The spatial resolution of the ice concentration maps is ~25 km. The ice edge is defined as the 15% ice concentration contour. All late spring periods (November–December) from 1979 through 2001 are used except for 1987 when a 6-week period (December 1987–mid January 1988) of SSM/I data were missing.

[10] Air temperatures at 2 m, dew point temperatures at 2 m, wind at 10 m, and surface sea level pressures (SLP) are obtained from the European Centre for the Medium-Range Weather Forecasts Re-Analysis (ERA-40) data set for the same period as the ice concentration data. The resolution is 1.125° × 1.125°. We use daily data averaged at 0000 UT, 0600 UT, 1200 UT, and 1800 UT. For cloud cover, we use the International Satellite Cloud Climatology Project (ISCCP) D2 data with a resolution of 2.5° × 2.5°. We averaged the monthly cloud cover from 1983 to 2001 to obtain a climatological data set. The cloud data are used for the heat budget calculation in section 4.

[11] We use the monthly mean ice motion data retrieved from the SMMR and SSM/I [*Schmitt et al.*, 2004]. All November data during 1979–1997 except for 1987 are used. The spatial resolution of the ice motion maps is ~100 km. The accuracy of large-scale Antarctic ice motion retrievals from passive microwave data has been determined through quantitative comparisons with drifting buoys [*Kwok et al.*, 1998; *Drinkwater and Liu*, 1999; *Drinkwater et al.*, 1999]. During late spring (December) and summer (January and February), the period we focus on in this study, ice motion retrievals from passive microwave data are unreliable because of the decorrelation of the passive microwave data resulting from rapid sea-ice decay and atmospheric interference [*Kwok et al.*, 1998]. Therefore, we mainly use ice drift derived from SLP in addition to the satellite-retrieved ice drift since sea-ice drift is forced predominantly by the geostrophic wind determined from the SLP pattern [*Kwok et al.*, 1998; *Drinkwater*, 1998; *Drinkwater and Liu*, 1999; *Drinkwater et al.*, 1999]. In this study, the wind-forced ice drift is calculated from the geostrophic wind based on SLP, where the ice drift is assumed to be 1.5% of the wind speed and directed 18° to the left [*Thorndike and Colony*, 1982; *Vihma et al.*, 1996; *Kottmeier and Sellmann*, 1996; *Uotila et al.*, 2000]. In order to check the accuracy of the ice drift derived from SLP, a comparison with the ice drift retrieved from satellite data in November when the ice drift derived from satellites is thought to be relatively reliable is given in Appendix A.