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Summer fast ice evolution off Zhongshan Station, Antarctica

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Abstract Based on the field data acquired in the program of fast ice observation off Zhongshan Station, Prydz Bay, East Antarctica during the austral summer 2005/2006, physical properties evolution of fast ice during the ice ablation season is analyzed in detail. Results show that the annual maximum ice thickness in 2005 occurred in later November, and then ice started to melt, and the ablation duration was 62 days; sea water under the ice became warmer synchronously; corresponding to the warming sea ice temperature, a "relative cold mid-layer" appeared in sea ice; the fast ice marginal line recoiled back to the shore observably, and the recoil distance was 20.9 km from 18 December 2005 through 14 January 2006. In addition, based on the data of sea ice thickness survey along the investigation course of MV *Xuelong* on December 18 of 2005, the ice thickness distribution paten in the marginal ice zone have been described: sea ice thickness increased, but the diversity of floe ice thickness decreased from open water to fast ice zone distinctly.

Key words fast ice, physical characteristic, evolution, Antarctica, austral summer.

1 Introduction

Sea ice is an important component in global coupling climate system and has been recognized as an significant indicator for local and global climate change[1,2]. Growth and decay of sea ice in polar area is probably the most significant seasonal dynamic change on the Earth's surface. Freezing and melting of sea ice in Antarctica are of paramount importance for the formation of deep and bottom waters in the oceans [3] and for the structure and stabilization of marine ecological systems[4,5]. Fast ice in Prydz Bay, East Antarctica, especially off Zhongshan Station, makes a hugest obstacle for the MV *Xuelong* when it approaches to Zhongshan Station for material re-supplying. As being enslaved to abominable polar field environment and measurement techniques, observation about the physical properties of sea ice off Zhongshan Station in the austral summer only has been conducted during the austral summer of 2003 by Tang *et al.* [6,7]. However, owing to the various investigation objectives, they have not given the time series of sea ice property evolution in the ice melting season. Thereby, it is undefined yet that how fast ice physical characteristics evolutes and what is dominating forces during sea ice melting, which further restrict the development of some sea ice research fields in this region, such as interpretation and utilization of sea ice remote sensing datum and development of local numerical model of sea ice, etc.

The time series of temperature at the vertical profile among the bottom layer of atmosphere, sea ice and the mixed layer of ocean water is an intuitionistic representation of the interactions among them, i. e., radiations and turbulent heat exchange between atmosphere and ice, and the heat exchange between ice and water, and the heat flux conduction in sea ice layer. The marginal ice zone (MIZ) is the transitional area between open water and continuous sea ice cover. At the small scale, the MIZ is the region where sea ice receives the most frequent environmental influences from the open ocean, in particular wave-ice interaction, which has become a focus in sea ice dynamics research, especially in sea ice ablation season[8].

In this paper, an exhaustive analysis about the evolution of physical property of fast ice in the ablation season will be made, focusing on the thermodynamic mass balance, sea ice thickness distributing in the MIZ, sea ice temperature profile, according to the field datum drawn during the period from later November, 2005 to later January, 2006. Some generic or local conclusions about physical characteristics of fast ice in ablation season will be present. It will help to set up groundwork for developing local numerical model of sea ice in this region, and to provide significant warranty for making a ship schedule for MV *Xuelong* every year.

2 Fieldworks

2.1 *Investigation location*

Zhongshan Station locates in Larsemann Hills, Prydz Bay alongshore, East Antarctica, (69°22′ S, 76°22′ E, see in Fig. 1(a)). There are tow seasons throughout a year in this area, summer and winter. The period from later November to later February next year is summer, and the period from later November to middle January next year is Polar Day Time. Surface winds at Zhongshan Station are most frequenly from ENE to ESE, and multi-year mean wind direction frequency in this range is 75%[9]. There are multitudinous islets off Zhongshan Station, and the underwater topography in this coastal area is rugged and rough. Therefore, a large numbers of icebergs were broken apart from D? lk Glacier and went away with the wind and ocean current to the west by the canyon, bypassed the topographic obstacle, finally grounded in the inshore area around Zhongshan Station[10]. Just for the presence of a large numbers of icebergs off Zhongshan Station, comparing to the other area, sea water temperature will warm up much more slowly in summer, and also the impact of katabatic wind on the surface of fast ice will be weaken. As a result, fast ice will open up later. Fast sea ice in this area would breakout in summer and refreeze in February or March commonly, but in occasional years it would sustain through summer due to the restriction of islets and grounded icebergs[6].

The fast ice survey areas off Zhongshan Station is in north of Zhongshan station, located in Nala Fjord, named by Ice Station (denoted by IS in Fig. 1(c)).

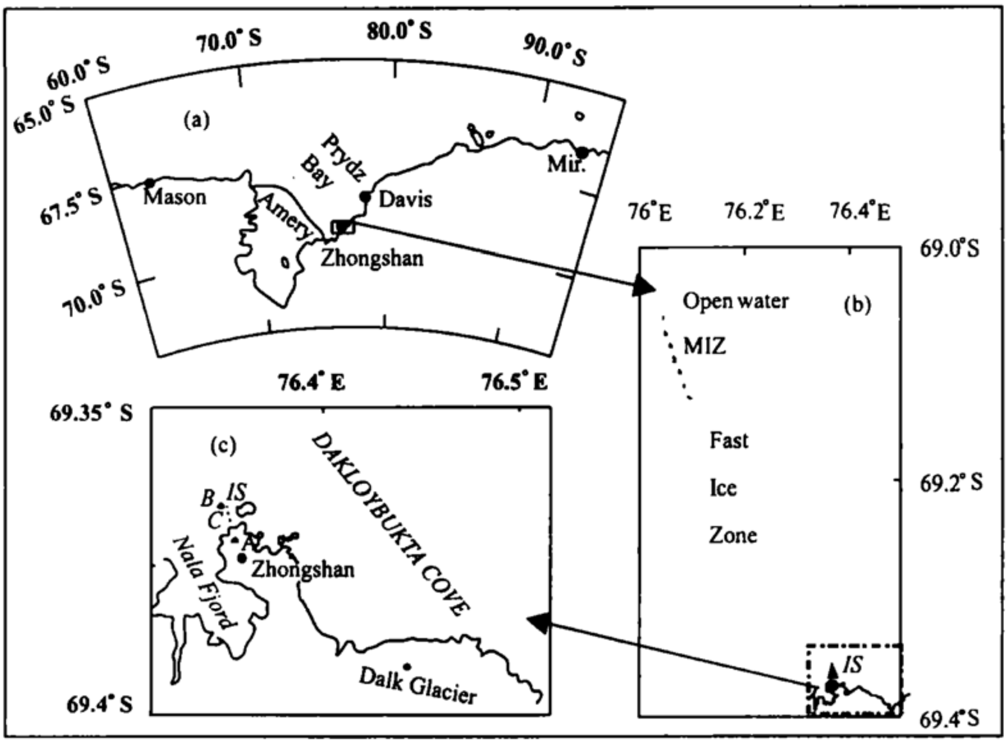

Fig. 1 Location of fast ice survey areas off Zhongshan Station.

2.2 *Observation and Methods*

Sea ice thickness was measured every 1 ~ 4 days by drilling, using a narrow drill with a 0.05 m diameter stainless steel auger, with a precision of 0.5 cm, from 11 November 2005 through 6 January 2006 in Ice Station. The length of ice thickness observation section (denoted by C in Fig. 1(c)) which is perpendicular to the coastline was 200 m. Every time, 4 ~ 20 ice-holes would be drilled and measured, and there were 256 records of ice thickness records in all.

When a ship sails in the sea area covered by ice, the floating ice can be broken up and reversed under the ship, the cross section of the broken ice may come out from water[11,12]. In attempt to collect sea ice thickness distribution in the MIZ, when MV *Xuelong* sailed from open water to the fast ice zone off Zhongshan Station, passing through the MIZ (the course of MV *Xuelong* in the MIZ is denoted by a dash line in Fig. 1(b)) on 18 December 2005, a digital video recorder SONY 18E was fixed on the shipboard of MV *Xuelong* to catch the cross section of broken ice, the collected signals were transmitted to a computer. The position of the ship was recorded by a Garmin 12XL GPS receiver synchronously. To get the absolute value of ice thickness, a red ball of known diameter, d, was hung near the waterline of the ship as a reference; the scene of the video included the cross section of the broken ice and the reference ball (Fig. 2). The method is as follows. First, mark the thickness of the ice cross section and the diameter of the reference ball on the image, as shown in Fig. 2, where AB, $A'B'$ are the ice thickness, and CD is the diameter of the reference ball. The actual sea ice thickness of this floe ice is $AB \cdot d/CD$. The position and the ice thickness can be matched according to the sampling time of the image and GPS receiver record. Then the ice thickness distribution in the MIZ can be plotted.

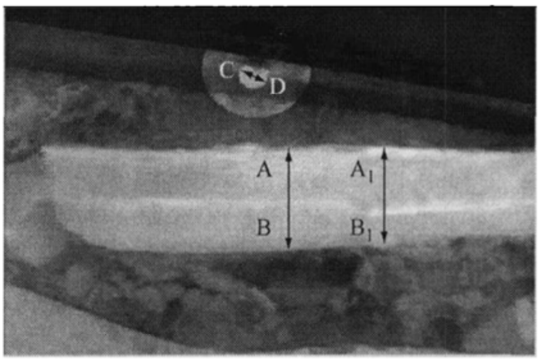

Fig. 2 Image recording ice thickness.

As confined by the abominable polar field environment, fast-ice extent in summer can't be estimated through the extension of fast ice, but through the location evolution of transition zone between open water and fast ice. The location evolution of fast ice marginal line has been surveying through ship-borne and airborne observation during the experiment. Ship-borne observation was performed on 18 December 2005 when MV *Xuelong* sailed approaching to Zhongshan Station. 3 flights of aerial observation were performed in the fast ice zone and the MIZ of South Prydz Bay near Zhongshan Station at approximately weekly intervals. An instrument package was mounted, in a downward-looking orientation, outside the *Zhijiu* helicopter. It consisted of a Canon PowerShot G2 camera equipped with a motor drive, and a data line connecting the camera with a mobile computer inside the helicopter so that the photographs could be stored directly in the computer. Position information of each aerial photo has been recoded automatically by the onboard Garmin 12XL GPS.

A thermistors string has been disposed in north coastal area of Zhongshan Station, site B (69°22.043'S, 76°21.525'E) located in the northern end of section C as shown in Fig. 1(c). Sea ice/water temperature, at the depth of 0、0.06、0.12、0.18、0.24、0.30、0.36、0.42、0.48、0.54、0.60、0.66、0.72、0.78、0.84、0.90、0.96、1.02、1.08、1.14、1.20、1.26、1.32、1.38、1.50、1.70、10、30、53 m, has been measured automatically at the interval of 30 minutes from 20 November through 29 December in 2005. Thermistor sensors, made by Dalian filiale of JUMO Germany, are PT100 sensors at level A. The resolution of the data records was 0.01℃, and the accuracy was 0.1℃.

Shore-based observations of fast ice off Zhongshan Station had been taken every day from November 2005 through January 2006, and ice condition photos would be shot every time.

Meteorological datum used in this investigation was obstained from the meteorological office in Zhongshan Station, located about 1 km from the experiment site (69°22.323'S, 76°21.968'E, denoted by A in Fig. 1(c)).

3 Results and discussions

3.1 Fast ice decay

From the time series of fast ice thickness records, it can be found that the maximal value of sea ice thickness (1.635 m) appeared on 20 November 2005. Comparing with the time at which the maximal sea ice concentration appeared in Prydz Bay, it lagged about 2 months. It is dictated that not only the thickness but also the length of ice season of fast ice is larger than the ice floe so much. In the addition, at the maximum, fast sea ice can make up as much as 14% by area of the East Antarctic sea ice[13]. Thereby, fast sea ice mass can't be neglected when evaluating the role of Antarctic sea ice within the climate system.

The time series of air temperature and ice thickness (the mean value and the standard deviation) from 20 November 2005 through 6 January 2006, and the time series of water temperature at the depth of 1.7m from 20 November through 29 December in 2005 are shown in Fig. 3. As the plot indicates, fast ice began to melt from 26 November onward, as a result of the increasing of air temperature and the ocean heat flux. Based on the evolution of ice melting rate, the experiment period can be divided into 3 periods: the fist one is the ice growth-decay balance period from 20 November through 26 November in 2005; the second one is the mild melting period with a melting rate of 9 mm/d from 26 November through 17 December in 2005; and the third one is the rapidly melting period with a melting rate of 18mm/d from 17 December 2005 through 6 January 2006. Fast ice decay is an outcome of air-ice-sea coupling process, thus its melting rate is controlled by local air temperature and sea water temperature primarily. In the period from 13 through 17 December, ice melting rate was small as air temperature was lower slightly. According to that a lot of dynamic cracks have been appeared in the experiment area after 17 December. The synthetical albedo of ice surface decreased evidently as the albedo of water is only 10% of that of the pure

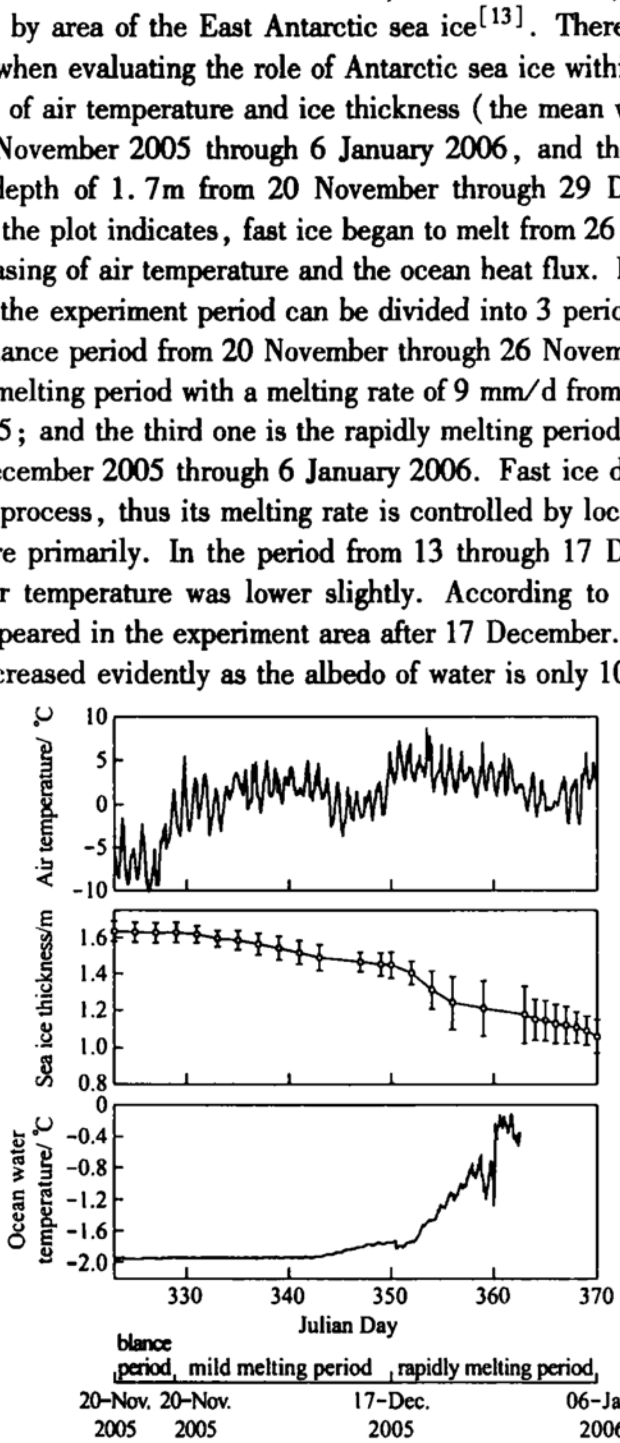

Fig. 3 Variety of air temperature (a), sea ice thickness (b), water temperature (c) in melting period.

sea ice. The solar shot wave radiation which penetrated into ocean water underline sea ice became lager. Thereby the water temperature warmed up fleetly, and the ice melting rate increased remarkable and fast ice fell into the rapidly melting period. The anomalistic jump of water temperature on 27 December can be owed to that the site has melted through the ice thickness where the thermistors string deposed and a thawy hole with a diameter of 0.5m appeared on 26 December.

On account of the strong offshore katabatic winds event, with the maximal wind speed of 23.2m/s, last from mid-night on 27 to early morning on 28 in December of 2006, the experiment area with sea ice concentration of 7 tenths changed into open water in short order. Thereby, the specific value between the length of ice growth season and that of ice decay season is 4.55, which is lager than the specific value, 1.41[14], between the length of Antarctic sea ice extension increasing season and that of Antarctic sea ice extension decreasing season distinctly.

3.2 *Sea ice thickness distribution in the MIZ*

Fig. 4 presents the variations of sea ice thickness in the function of latitude from open water to fast ice zone in the MIZ. It is dictated that the ice thickness increased but its diversity level decreased from open water to fast ice zone stably. The MIZ around Antarctic continent, the transitional area between open water and fast-ice cover, is the area where sea ice receives the most frequent environmental forces from open water, especially wave-ice interaction. The thickness distribution paten illuminated in Fig. 4 maybe due to the energy consumptive effect of the MIZ; in other word, the decreases of kinetic energy result in the decreases of ice melt rate, the increase of ice thickness and the decreases diversity level of ice thickness, from open water to fast ice zone in the MIZ.

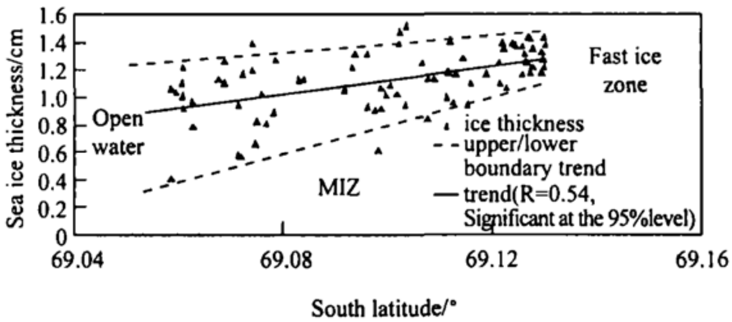

Fig. 4 The variety of sea ice thickness following latitude.

In melting season of fast ice, the environmental forces from open water cause acceleration of the recoil process of fast ice marginal line back to the coastline. In the early melting season, fast ice marginal line is comparatively far away from coastline; thereby, fast ice marginal line was parallel to coastline approximately. In the later melting season, the ice floes drifted to west under the partial eastern wind force. And then more and more floes concentrated in the northwestern region off Zhongshan Station due to the block of islets and grounded icebergs. The width of MIZ in the northwestern region became larger than that in the northeastern region. The recoil rate of fast ice marginal line in the northwestern region is smaller markedly when compared to that in the northeastern region. Table 1 presents the variations of the distance between fast ice marginal line and the coastline in the same longitude as Zhongshan Station, and the recoiling rate of fast-ice marginal line during this experiment. It is indicated that: the distance of fast ice marginal line recoiled back to coastline was 20.9 km during 27 days; the recoiled rate increased initially under the influence of decay of fast ice thickness, the appearance and evolution of melt ponds on the surface of fast ice, the appearance of abundance of fracture and flaw Lead, and so on; but the recoiled rate decreased subsequently due to the block of islets and grounded icebergs.

Table 1. The recoil process of fast-ice marginal line

Time	Location of fast ice marginal line /°S	Distance between fast ice marginal line and coastline / km	Recoiled rate (km/d)	Observation manner
2005-12-18	69.15	24.2		ship borne
2005-12-27	69.18	20.9	0.4	aircraft borne
2006-01-04	69.28	9.8	1.4	aircraft borne
2006-01-14	69.34	3.1	0.7	aircraft borne

As the recoil process of fast ice marginal line back to the coastline, more and more heat flux from open water can be horizontal transmitted to the fast ice zone; and then it would warm up ocean water temperature underline fast ice (see also in Fig. 3) and accelerate fast ice decay at bottom. In reverse, the decrease of fast ice thickness also accelerates the recoil process of fast ice marginal. Thereby it is a positive feedback process.

3.3 The feature of ice temperature

Fig. 5 gives out 5 sea ice temperature profiles measured at 18:00 (local time), on 20 November, 26 November, 1 December, 5 December, and 10 December, 2005. The direction and the magnitude of the conductive heat flux in sea ice layer are dominated by temperature gradients in sea ice layer; simultaneity, the ice melting rate is dominated by the conductive heat flux along with the ocean heat flux[15]. In the sea ice melting season, sea ice temperature increased gradually, yet there was a lag when compared with the warming of air temperature due to the heat reservoir effect of brine pocket in sea ice, furthermore the lag time increased along with the depth increasing. Due to the lag of ice temperature variations at the under layer, the "relative cold mid-layer" appeared after middle November, thereafter thermodynamics conduction direction was no longer identical at the whole depth, the heat flux can be conducted both from ice surface and ice bottom to the middle layer. Sea ice temperature at the upper layer became higher than sea water freezing point in the ice temperature profiles of 5 December and 10 December. The thickness with this characteristic increased rapidly along with time pass; it reached to 0.42m in the profile of 10 December. It was dictated that sea ice freezing process and melting process are irreversible. In principle, sea ice is a multiphase system, including pure ice crystals, liquid brine and solid salt crystals, thus the phase fractions in sea ice would change as ice temperature increasing. At the same time, the ice structure could be disintegrated, and individual brine pockets could be connected, and then desalination would be enhanced remarkably in this state. The fraction of pure ice became larger, thus resulted in sea ice temperature becomes higher than sea water freezing point in the ice decay season.

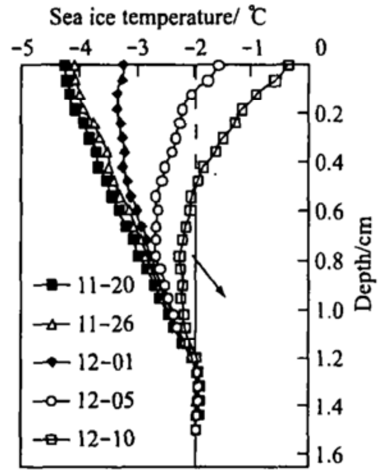

Fig. 5 Variety of sea ice temperature profile in melting period.

4 Conclusions

(1) The period from 20 November through 26 November in 2005 was the growth-decay balance period of fast ice off Zhongshan Station. After that, fast ice in this area began to melt gradually. And 17 December 2005 onward, the melting rate changed greater, fast ice fell into a rapidly melting period. Finally, fast ice in this area opened up completely on 27 January 2006. The ablation duration was 62 days.

(2) Sea ice thickness increased, but the diversity of floe ice thickness decreased from open water to fast ice zone distinctly due to the energy consumptive effect of the MIZ in ice decay season.

(3) During the period from 18 December 2005 to 14 January 2006, the distance of fast-ice marginal line recoiled back to coastline was 20.9 kilometers; the recoiled rate increased initially under the influence of decay of fast ice thickness, the appearance and evolution of melt ponds on the surface of fast ice, the appearance of abundance of fracture and flaw Lead, etc.; but the recoiled rate decreased subsequently due to the block of islets and grounded icebergs.

(4) Sea ice warmed up gradually in melting period, the "relative cold mid-layer" in ice appeared. Sea ice temperature in the up-layer was higher than sea water freezing point in the ice temperature profile of 5 December and 10 December, therefore sea ice freezing process and melting process is irreversible.

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