

# Role of sea ice in air-sea exchange and its relation to sea fog

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**Abstract** Synchronous or quasi-synchronous stereoscopic sea-ice-air comprehensive observation was conducted during the First China Arctic Expedition in summer of 1999. Based on these data, the role of sea ice in sea-air exchange was studied. The study shows that the kinds, distribution and thickness of sea ice and their variation significantly influence the air-sea heat exchange. In floating ice area, the heat momentum transferred from ocean to atmosphere is in form of latent heat; latent heat flux is closely related to floating ice concentration; if floating ice is less, the heat flux would be larger. Latent heat flux is about  $21 - 23.6 \text{ W} \cdot \text{m}^{-2}$ , which is greater than sensible heat flux. On ice field or giant floating ice, heat momentum transferred from atmosphere to sea ice or snow surface is in form of sensible heat. In the floating ice area or polynya, sea-air exchange is the most active, and also the most sensible for climate. Also this area is the most important condition for the creation of Arctic vapor fog. The heat exchange of a large-scale vapor fog process of about  $500000 \text{ km}^2$  on Aug. 21 - 22, 1999 was calculated; the heat momentum transferred from ocean to air was about  $14.8 \times 10^9 \text{ kW}$ . There are various kinds of sea fog, radiation fog, vapor fog and advection fog, forming in the Arctic Ocean in summer. One important cause is the existence of sea ice and its resultant complexity of both underlying surface and sea-air exchange.

**Key words** Arctic sea ice, ice-air-sea interaction, sea-air exchange, Arctic sea fog.

## 1 Introduction

The Arctic Ocean is covered by sea ice all the year; even in summer, there exist both fixed ice sheet and a large-scale sea ice. Sea ice plays an important role in air-sea thermal exchange, which forms a peculiar nature of Arctic climate. It is not too much chance to encounter gale in Arctic summer time without any gale stronger than force 6 during 2 months we expedited in the Arctic. Same in the pole region, the Antarctic climate is different with the Arctic. On the Antarctic continent, it is extremely cold and dry with mainly snowstorm weather and cold katabatic wind, so that it is called as the wind extreme point and cold extreme point of the world. The extreme minimum temperature of the world appeared in the Antarctic but not in the Arctic. The around-pole cyclones and associated gale are usually observed in the periphery of the ice ocean around the Antarctic. We met an average wind speed of  $38 \text{ m/s}$  in the Antarctic Prydz Bay in January 1998 with an instantaneous wind speed of  $100 \text{ m/s}$ . However in the Arctic, only variable sea fog threatens the safety of navigation, aviation and expedition in the sea ice area. The Arctic sea fog is the most difficult problem to forecasting, and also the most serious obstacle for navigation, aviation

and expedition operation on the ice station. Even though study of sea ice is paid high attention in China and abroad, but the observation and study on the Arctic sea fog is still very few due to its highly difficulty.

The principal purposes of this paper are to study the role of the Arctic sea ice in air-sea thermal exchange, to understand physical mechanism of ice-air-sea thermal interaction, and physical mechanism, type and characteristics of its resultant main weather phenomenon — sea fog formation.

## 2 Observation means and equipment

### 2.1 Observation means

Many kinds of methods were used in field observation: shipboard automatic meteorological station associated with artificial field observation; photograph from helicopter; shipboard meteorological satellite receiving-processing system and satellite remote sensing (Zou *et al.* 2000); A comprehensive stereoscopic observation on vessel, small working boat and floating ice station and by satellite for atmosphere, ocean and sea ice elements. Using small boat observation solved ice-air-sea synchronous stereoscopic observation in the ice periphery belt, which is very difficult to realize both in domestic, and abroad.

### 2.2 Instruments-equipment

Many kinds of instruments-equipment were used: 2 sets of shipboard automatic meteorological station made respectively in China and Finland are installed on the “*Xuelong*” vessel; tethered balloon manufactured in Finland is used for atmospheric boundary layer observation; the newest “ship-land dual purpose handy-carried albedo sounding” is first used both in domestic and abroad which solved a technical difficulty of observation balance in high and low height on ship; marine equipment CTD is made in USA: “Shipboard meteorological satellite receiving-processing system” (Xie *et al.* 2000), a new system is developed by us in 1998. This system can process very clear cloud map and ice map, monitor extensive weather system, extensive distribution of cloud, fog and ice. It is difficult to distinguish low cloud area and fog area in the satellite cloud map. However using our system, we can recognize low cloud and fog in situation of less low cloud amount. A comprehensive data has been obtained by use of satellite observation associated with field observation (point-area association method).

## 3 Role of sea ice in air-sea thermal exchange

Most part of Arctic Ocean is covered by fixed ice sheet and floating ice. Sea ice has two physical features. First, sea ice is a bad conductor to separate thermal exchange between ocean and atmosphere. During polar nighttime in winter, ocean is much warmer than atmosphere, but cannot transfer heat momentum to air. Second, albedo of ice-snow surface is high. During polar daytime in summer, sea ice reflects a great number of short wave radiations of sun to space, so that not too much heat momentum can be absorbed and stored by ocean. It is the important cause of very

cold in the Arctic. In floating ice area or ice periphery belt where is the area with ice and water alternatively, air and sea can exchange freely through water area between ices. Heat momentum of sea, which is separated by ice sheet in winter, can be given off through ice crack and transferred to air in summer. Moreover in summer polar daytime, abundant solar radiation is absorbed by sea water, it makes air-sea exchange active. As a result the floating ice area becomes a sensitive area to affect climate. Distribution, thickness and surface condition of sea ice, all gives an impact on air-sea exchange. It makes physical feature of underlying surface complexity; then the resultant atmospheric phenomena, especially sea fog in the Arctic become complexity.

### 3.1 Calculation method of air-sea energy exchange

Using stratification atmosphere dynamic transformation method, the calculation formulas of momentum flux ( $M$ ), sensible heat flux ( $H_s$ ), and latent heat flux ( $H_L$ ) at 10 m height are given as follows:

$$M = \rho C_D U_{10}^2 \quad (1)$$

$$H_s = \rho C_P C_H U_{10} (\theta_0 - \theta_{10}) \quad (2)$$

$$H_L = \rho L C_E U_{10} (q_0 - q_{10}) \quad (3)$$

here,  $\rho$  is air density, a function of air temperature and pressure;  $U_{10}$  is wind speed at 10 m height;  $\theta_0$  and  $\theta_{10}$  are potential temperature;  $q_0$  and  $q_{10}$  are saturated specific humidity;  $\theta_0$  and  $q_0$  are values at sea surface;  $\theta_{10}$  and  $q_{10}$  are field observation values at 10 m height observed by TMT;  $C_P$  is specific heat at constant pressure; evaporation latent heat for water surface  $L_v = (597 - 0.56 T_s) \times 4168.8$  J/kg; sublimation latent heat for ice-snow surface  $L_s = 677.12 \times 4168.8$  J/kg;  $T_s$  are sea surface temperature;  $C_D$ ,  $C_H$  and  $C_E$  are, respectively, drag coefficient, sensible heat exchange coefficient and latent heat exchange coefficient of neutral stratification atmosphere. Based on the whole neutral atmosphere dynamic exchange coefficient and its relation to roughness length of dynamic, thermal and water vapor.  $C_D$ ,  $C_H$  and  $C_E$  can be calculated as follows:

$$C_D = \frac{k^2}{[\ln(10/Z_0)]^2} \quad (4)$$

$$C_H = \frac{\alpha_H k C_D^{1/2}}{k C_D^{-1/2} - \ln(Z_\theta/Z_0)} \quad (5)$$

$$C_E = \frac{\alpha_E k C_D^{1/2}}{k C_D^{-1/2} - \ln(Z_q/Z_0)} \quad (6)$$

here,  $k$  is Von Karman constant (0.4);  $Z_0$ ,  $Z_\theta$ , and  $Z_q$  are dynamic, thermal and water vapor roughness length, respectively. Then,  $C_D$ ,  $C_H$  and  $C_E$  can be calculated by formulas (4) - (6) based on average profile method (which is given by best fitting field observation by tethered balloon TMT, or,  $\theta_0$  is estimated by infrared radiation graph,  $q_0$  is saturated specific humidity of sea surface temperature for ocean).  $Z_\theta/Z_0$  and  $Z_q/Z_0$  are given by Andreas's (Andreas 1987) empirical formula as follows:

$$\ln(Z_s/Z_0) = b_0 + b_1 \ln R^* + b_2 (\ln R^*)^2 \quad (7)$$

here, Reynolds Number  $R^* = u^* z_0 / \nu$ ;  $u^*$ ,  $z_0$  and  $\nu$  are, respectively, friction velocity, dynamic roughness length and kinematics viscosity coefficient; coefficient values of  $b_0$ ,  $b_1$ ,  $b_2$  are seen in Andreas (1987);  $R^*$  is an empirical formula, suitable

to underlying surface of ice, snow, water and floating ice area. For stable and unstable atmosphere,  $C_{DD}$ ,  $C_{HH}$  and  $C_{EE}$  are calculated by formulas:

$$\frac{C_{DD}}{C_D} \approx \frac{C_{HH}}{C_H} \approx \frac{C_{EE}}{C_E} \approx 0.1 + 0.03S + 0.9 \exp(4.8S) \quad (8)$$

$$\frac{C_{DD}}{C_D} \approx 1.0 + 0.47S^{0.5} \quad (9)$$

$$\frac{C_{HH}}{C_H} \approx \frac{C_{EE}}{C_E} \approx 1.0 + 0.63S^{0.5} \quad (10)$$

Here stability parameters  $S$  and  $S_0$  are:

$$S = S_0 \frac{S_0}{S_0 + 0.01} \quad (11)$$

$$S_0 = \frac{T_s - T_a}{U^2 [1.0 + \lg(10/Z)]^2} \quad (12)$$

Due to existence of sea ice in the Arctic, roughness length varies complicatedly. Sea ice restrains variation of sea wave and ocean swell; more floating ice makes less roughness. However on ice sheet, there is larger undulation with larger roughness. In floating ice areas with 2 - 3, 3 - 4, 6 - 7 tenth ice,  $Z_0$  are, respectively 1.0, 0.6 mm, and 0.4 mm. While in Tropical Ocean without restraintment of ice, sea wave undulates largely;  $Z_0$  is also larger, of 5 mm (see Table 1).

Based on field observation on different underlying surface, roughness length  $Z_0$ , friction velocity  $u^*$ , average wind speed at 10 m height  $U_{10}$ , average potential temperature difference  $\Delta\theta$  and average specific humidity difference  $\Delta q$  between surface ground and 10 m height are gotten. Then,  $C_D$ ,  $C_H$  and  $C_E$  for neutral atmosphere are calculated by formulas (4) - (6). Stability parameter  $S$  is calculated by formula (11) - (12).  $C_{DD}$ ,  $C_{HH}$  and  $C_{EE}$  are calculated by formula (8) - (10). Finally, momentum flux  $M$ , sensible heat flux  $H_{ss}$  and latent heat flux  $H_{LL}$  for stratification atmosphere can be calculated by formulas (1) - (3).

Table 1. Dynamic roughness length  $Z_\epsilon$  under impact of sea ice in the Arctic

	State of sea ice in the Arctic							
State of underlying surface	2 - 3 ice	3 - 4 ice	6 - 7 ice	One year ice, small undulation	Multi-year ice, large undulation	Tropical Pacific	Ice sheet of Greenland	Ice sheet of Zhongshan Station
$Z_0$ /mm	1.0	0.6	0.4	0.2	0.3	5.0	0.2 - 0.5*	0.028**

\* Meesters *et al.* 1997; \*\* Qu *et al.* 1997.

### 3.2 Momentum flux from atmosphere to ocean in the Arctic

Momentum flux shows action force of atmosphere to surface ground of unit area, which is an important component of land-air interaction. In polar area, atmospheric momentum flux directly affects on limits and thickness of floating ice, and variation of ice sheet. It is decided by atmospheric dynamic process, thermal process and feature of underlying surface (Qu and Hu 2000). Sensitive experiment shows that, momentum flux from air to land is the most sensitive to wind speed variation, second to atmospheric stability parameter and roughness of underlying surface. Based on field gradient observation of surface atmospheric layer, momentum flux from air to ocean is obviously positive correlation to average wind speed in the

Arctic. During polar daytime in the Arctic, average wind speed at 10 m height is about  $3 \sim 7$  m/s, momentum flux varies between  $(11.4 \sim 91.9) \times 10^{-3} \text{ N} \cdot \text{m}^{-2}$ . It is much larger than in the Antarctic continent (Qu and Hu 2000). It is due to roughness length in the Arctic Sea area much larger than in the Antarctic ice sheet. Momentum flux value is almost same as in the strong convective process in the western Pacific tropical sea area (Qu and Lin 1994), while it is much less than in the westerlies burst process in the western Pacific tropical sea area (Qu and Wang 1996).

During transferring momentum process from atmosphere to ice area in the Arctic, when strong wind suddenly blows off concentrative floating ice, heat moment of ocean should be transferred to atmosphere through ice crack. This is the dynamic effect of vapor fog formation.

### 3.3 *Sensible heat flux of air-sea thermal exchange under state of vapor fog in the Arctic*

In the Arctic, due to underlying surface affected by sea ice, air-sea exchange is very complex. Atmosphere is usually stable stratification on ice sheet of  $9 \sim 10$  tenth ice, while stratification is variable on floating ice area. Inversion layer structure always appears on very large floating ice. But on area with  $2 \sim 7$  tenth ices, stable and unstable stratification will appear alternately or one by one. Therefore, air-sea interaction on floating ice area is very complicated.

#### 3.3.1 *In unstable stratification atmosphere, heat momentum is transferred from ocean to atmosphere in form of sensible heat*

In the Arctic, sea water temperature is generally higher than air temperature. Especially in high latitude region (north of  $73^\circ\text{N}$ ), when cold air comes, air temperature decreases rapidly, but sea water temperature decreases very slowly in floating ice area. In clear area after cold air comes, albedo of sea water is very low, about 5%. Most of solar short wave radiation is absorbed by sea water to raise sea water temperature. As a result, an unstable stratification usually appears in ground layer. In this situation, heat momentum is transferred from ocean to atmosphere in form of sensible heat. Using field observation during vapor fog process on August 21 – 22, 1999 as representative value: air temperature at 10 m height of  $-5.2^\circ\text{C}$ , and sea surface temperature of  $-1.2^\circ\text{C}$ , and using  $C_{\text{HH}}$  of unstable atmosphere to replace  $C_{\text{H}}$  in formula (2), we calculated  $C_{\text{HH}}$  value to be 3.64 based on formula (10). In addition based on field observation, we evaluated density of moist air  $\rho_{\text{w}}$  as  $1.293 \times 10^{-3} \text{ g} \cdot \text{cm}^{-3}$ , specific heat at a constant pressure  $C_{\text{p}}$  as  $1.005 \times 10^{-3} \text{ Jkg}^{-1}$ , average wind speed as 5 m/s, sea surface temperature as  $-1.2^\circ\text{C}$ . Then we calculated sensible heat flux as  $6.6 \text{ W} \cdot \text{m}^{-2}$  based on formula (8). Using spherical area calculation formula, we roughly calculated that vapor fog limits on satellite cloud map were about  $500000 \text{ km}^2$ . Finally total heat momentum transferred from sea to air in form of sensible heat during this process was about  $3.3 \times 10^9 \text{ kW}$ .

#### 3.3.2 *In stable stratification atmosphere, heat momentum is transferred from atmosphere to ocean in form of sensible heat*

On ice sheet or large ice, due to high albedo of ice-snow surface, a lot of solar radiation is reflected to outer space, temperature varies very little. However, the back solar radiation is absorbed by air, especially during cloudy weather. Therefore, inversion usually appears. In the inversion state, temperature is high with height.

As a result, the calculated sensible heat flux is negative value, heat momentum was transferred from atmosphere to ice-snow surface. Based on formula (8), the calculated sensible heat flux was different with different ice concentration, but all were negative values. During polar nighttime, on open water area, 3 - 4 and 6 - 7 tenth ice areas, average sensible heat flux was  $-4.2 \text{ W} \cdot \text{m}^{-2}$ ,  $-6.5 \text{ W} \cdot \text{m}^{-2}$ , and  $-9.1 \text{ W} \cdot \text{m}^{-2}$ , respectively. While on very large floating ice of that year and multi-years, flux values were, respectively,  $-8.7 \text{ W} \cdot \text{m}^{-2}$  and  $-12.5 \text{ W} \cdot \text{m}^{-2}$ .

Excepting being correlated to sensible heat coefficient and wind speed, sensible heat flux may be also obviously correlated to average potential temperature difference between observed heights.

### 3.4 Latent heat flux of sea-ice thermal exchange in the Arctic

#### 3.4.1 In floating ice area, heat momentum is transferred from ocean to atmosphere in form of latent heat

Based on formula (3), latent heat flux is positive value in floating ice area of 2 - 3, 4 - 5, 6 - 7 tenth ice in the Arctic. It is said that, heat momentum is transferred from ocean to atmosphere in form of latent heat. The flux values were, respectively,  $23.6 \text{ W} \cdot \text{m}^{-2}$ ,  $22.3 \text{ W} \cdot \text{m}^{-2}$ , and  $21.6 \text{ W} \cdot \text{m}^{-2}$ , almost the same or very close. It is caused by comprehensive effect of dynamic and thermal processes. There are two main causes: First in floating ice area with alternative ice and water in high latitude north of  $75^\circ\text{N}$ , sea temperature is higher than air temperature. Second in floating ice area of 2 - 7 tenth ices, albedo of sea water is about 5% - 20%, much less than on ice sheet. A lot of solar radiation is absorbed by sea water, and then is transferred to atmosphere again in form of latent heat. In sea area of vapor fog formation on August 21 - 22, the average calculated latent heat flux was  $23 \text{ W} \cdot \text{m}^{-2}$ , and total transferred latent heat momentum in altogether  $500000 \text{ km}^2$  area was  $1.15 \times 10^{10} \text{ kW}$ . Therefore, it can be roughly estimated that, during this vapor fog process, total transferred heat momentum from ocean to atmosphere in form of sensible and latent heat was about  $(0.33 + 1.15) \times 10^{10} \text{ kW}$ , or  $14.8 \times 10^9 \text{ kW}$ . It is corresponding to 1/20 of total heat momentum, about  $300 \times 10^9 \text{ kW}$ , transferred from the North Atlantic to the Arctic through the Norway Sea and Greenland Sea.

#### 3.4.2 On very large floating ice or ice sheet, heat momentum is transferred from atmosphere to ice surface in form of latent heat

On floating ice stations 1 and 2, latent heat flux were, respectively, negative values, about  $-3.9 \text{ W} \cdot \text{m}^{-2}$  and  $-6.6 \text{ W} \cdot \text{m}^{-2}$ . It means that, water vapor and heat momentum are transferred from atmosphere to ice station. It is because these two floating ice was rather small, about  $1 \text{ km}^2$  and  $0.3 \text{ km}^2$ , surrounded by extensive sea water and floating ice, as a result, an inversion layer of temperature and moisture appears in lower layer. Excepting being positive proportion to latent heat exchange coefficient and wind speed, latent heat flux  $H_{\text{LL}}$  is also obviously positive proportion to average specific humidity between observing heights.



## 4 Classification of sea fog in the Arctic

Through field expedition of more than 70 d from July 1 to September 9, we have a good understanding on sea fog in the Arctic including the Bering Sea. Sea fog in the Arctic can be classified in three categories: advection fog, radiation fog, and vapor fog.

### 4.1 *Advection fog*

Generally, advection fog is so-called sea fog. Due to warm, moist air flowing through cold sea surface, the vast vapor condenses to form sea fog. Most of this kind of sea fog is formed in front of cyclone. However in the Bering Sea, even cyclone passes through, sea fog still lasts for a longer time. Sometime, even though without distinct weather system, an extensive sea fog can still appears over ocean surface lasting for several days or even more.

#### 4.1.1 *Sea fog on the Bering Sea*

In July, fog day in the Bering Sea is as more as 60% - 70%. Sea fog is extensive in limits and long in sustained time. It is one of the largest weather disasters for ship navigation, and also the most difficult forecasting problem for disastrous weather phenomena. Fig. 1 shows sea fog received and processed by satellite remote sensing imagery. All the Bering Sea was covered by heavy sea fog, among them, the Aleutian Islands appear or hidden. Limits of sea fog strides across 5600 km from south of 40°N to north of 68°N, and 3000 km in east-west direction with its area of about  $16.8 \times 10^6 \text{ km}^2$ . Sea fog sustained a very long time from July 17 to 24. It was formed under impact of a strong cyclone. In some local sea areas, sea fog disappeared after cyclone passed through, however, it still sustained in other sea areas.

Based on hourly observation of ship-board automatic meteorological station and artificial observation, in 15 d of July 19 - August 2 during expedition of "Xuelong" ship in the Bering Sea, sea fog was almost observed every day excepting 5 d of July 26 - 30. Even in these 5 d, no sea fog is seen only in local sea area of ship site, however in other sea areas, sea fog was still obviously observed in satellite cloud map.

Physical mechanism of formation and dissipation of advection fog in the Bering Sea: Very broad and extensive North Pacific with abundant vapor is located to south of the Bering Sea. Only if southerlies wind blows, it will bring a lot of warm, moist air to the cold Bering Sea surface. It is very easy to be saturated and condensed to form sea fog. Generally, sea fog appears and sustains only in calm or small wind condition. But it is found from field observation in the Bering Sea that, for example, at 06 h of July 19 when SE wind speed was as strong as 11.9 m/s, heavy fog with visibility < 300 m took place and sustained for a long time. This situation is very rarely seen in other sea areas. The main cause is that, here sea area is very broad, once an extensive heavy fog is formed, even strong gale cannot blow heavy fog dissipating. Provided that southerlies wind which always brings warm, moist air current, it is very easy to enlarge fog limits and increase fog strength. Sea fog there can arrive southward to south of 50°N and northward to 70°N, the Arctic. Such kind of extensive sea fog can be easily observed on satellite cloud maps.

Based on field observation and analysis, the full and necessary conditions of



Fig. 1. Satellite image received at 10:00(Beijing Time) July 21.

advection fog formation in the Bering Sea are as follows: (1) Small or moderate wind speed  $< 11$  m/s, high relative humidity  $> 96\%$ , low pressure  $< 1010$  hPa not within high pressure area; (2) Wind direction is an important index. Sustained SE wind for 2 - 3 h or more, will very easily introduce sea fog or heavy fog. Easterlies or ESE wind will maintain sea fog. If it turns to NW wind or westerlies, sea fog will gradually disappear. (3) Advection fog has very small diurnal variation, but it may be related to atmospheric stratification. Stable atmosphere is benefit to formation and maintenance of sea fog, while unstable atmosphere is easy to lift sea fog to change to low cloud.

#### 4. 1. 2 *Advection fog at open sea water area of the south Arctic Ocean or outer periphery band of sea ice area*

Advection fog usually appears at open sea water area of the south Arctic Ocean or outer periphery band of sea ice area. This kind of fog belongs to same category of fog in the Bering Sea. It is of long duration, large concentration and extensive limits but is smaller than fog in the Bering Sea. Formation and disappearance of sea fog are closely related to cyclone impact.

On August 12, "Xuelong" ship entered water channel between North American continent and Arctic ice sheet and navigated to Tuke Port, Canada. Warm, moist air entered the Arctic from Bering Strait, and moved northeastward to push cold air. On August 13, a strong warm front cloud belt was formed near Tuke Port (Fig. 2). Records of shipboard automatic meteorological station can show its variation process. From 10 h to 22 h of the 12th, it was mainly northerlies with wind speed



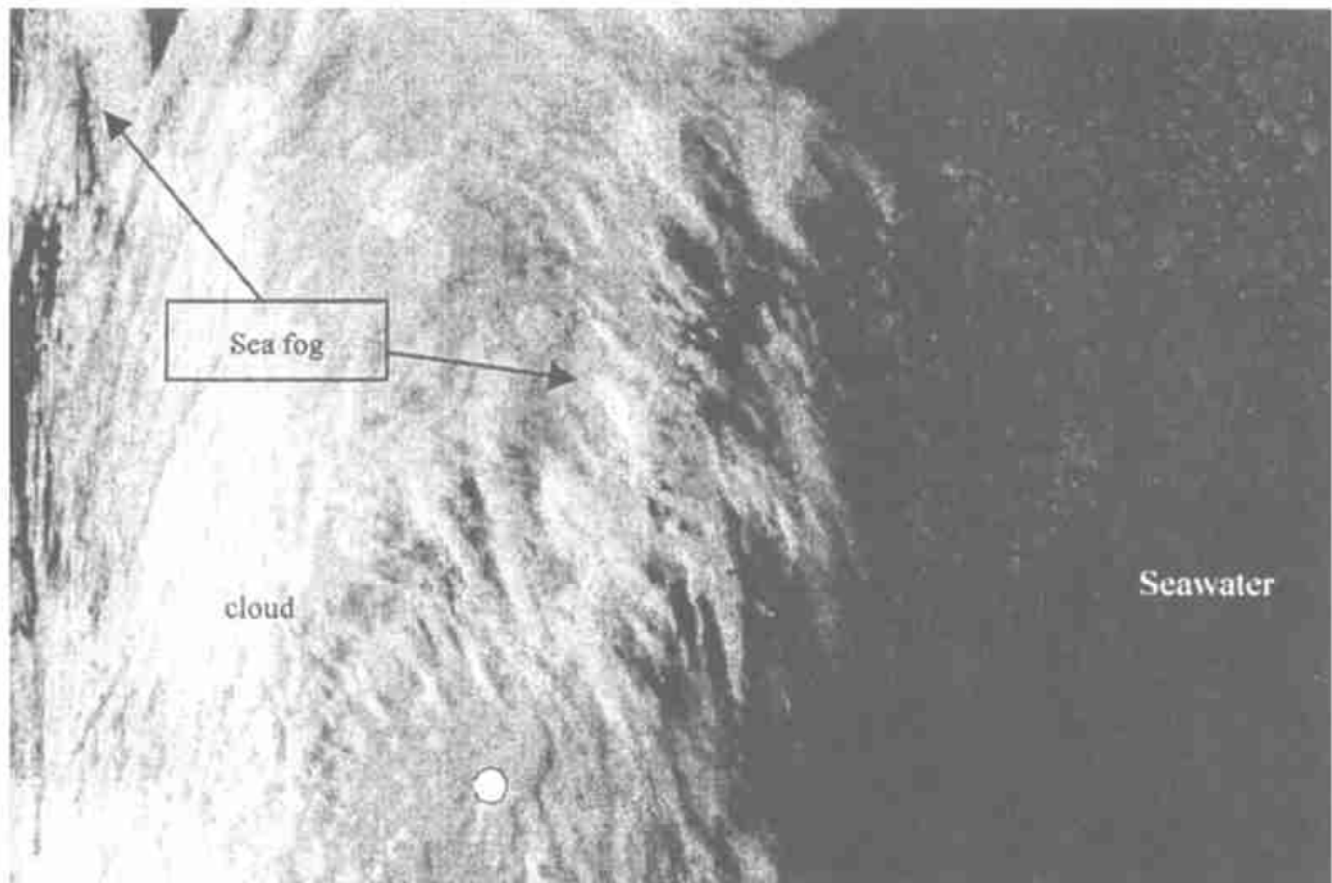


Fig. 2. The satellite image received at Tukttoyaktuk harbour on August 14. The white spot in the image is the anchorage of *Xuelong*:  $69^{\circ}52'N$ ,  $133^{\circ}12'W$ .

$3 - 5.8$  m/s; air temperature was  $3 - 4^{\circ}C$  with the minimum of  $1.8^{\circ}C$ . Relative humidity was  $96\% - 100\%$  with light fog, then temperature gradually increased to the maximum of  $9.8^{\circ}C$  at 04 h of the 13th, wind speed decreased to  $0.5 - 2$  m/s of westerlies. This shows that "*Xuelong*" vessel anchored in warm sector behind warm front. Westerlies blow warm, moist air from warm sector to form sea fog. Therefore, vessel was covered by heavy fog from 22 h of the 12th to 00 h of the 15th. Since 01 h of the 15th, wind direction began to change from westerlies to northerlies with temperature decreasing. Even though relative humidity was still  $100\%$ , but sea fog concentration decreased, visibility began to be better. This case of advection fog formed under impact of warm, moist air current behind warm front was related to wind direction, wind speed, temperature, and humidity and sea temperature.

#### 4.1.3 Advection fog over fixed ice sheet in the Arctic

On the Arctic fixed ice sheet, it is usually covered by two kinds of sea fog: advection fog and radiation fog.

Advection fog over fixed ice sheet is mainly formed by warm, moist air current from its south; especially vapor fog in floating ice area being transported by southerlies. There is always stable atmospheric stratification with inversion layer on ice sheet, which is unfavorable to sea fog to lift and disappear. Therefore, advection fog can last for a long time.

Based on records analysis of automatic meteorological station, the full and necessary conditions of advection fog formation are as follows: (1) Full warm, moist air current transportation; (2) Wind speed  $< 6 - 8$  m/s; (3) Wind direction is favor

to transfer warm, moist air; (4) Relative humidity > 96%; (5) Sea area, floating ice area or sea ice of underlying surface have an enough large area; (6) Sea fog formation and disappearance are not related to diurnal change.

## 4.2 *Vapor fog*

### 4.2.1 *Physical mechanism of vapor fog formation*

Most of sea fog formed in floating ice area in the Arctic to the north of 73°N is vapor fog. Physical mechanism of vapor fog is fully different from advection fog. Formation condition of vapor fog is that, over warmer ocean, air temperature is rather low with large temperature difference between air and sea, so that, water of warmer sea surface evaporates and meets colder air to form vapor fog. Fig. 3 is a typical Arctic vapor fog photo taken from helicopter at about 500 m heights on August 21. Fog layer was rather thin, about 300 m.

During polar daytime in summer, in floating ice area or ice periphery belt, especially when cold air comes, gale blows sea ice scattered to form extensive floating ice belt, the stored oceanic heat energy pushes out from ice crack to atmosphere in form of water vapor to form vapor fog. When sea temperature is higher than air temperature, if temperature difference is larger, vapor fog should develop more vigorously. Vapor fog on August 21 was observed under this condition. The field average sea surface temperature was  $-1.0^{\circ}\text{C}$  –  $-1.2^{\circ}\text{C}$ , and air temperature was  $-5.2^{\circ}\text{C}$  –  $-6.5^{\circ}\text{C}$ . Vapor fog is water vapor evaporated from ice crack; therefore it is of balls and balls, discontinuousness in horizontal direction. There is fog in open water area and no fog in ice area.

The full and necessary conditions of vapor fog formation in the Arctic are determined preliminary as follows:

(1) Vapor fog is formed over floating ice area or polynya. If temperature difference is larger, vapor fog is easier to be formed. In twice typical vapor fog processes we encountered during the First China Arctic Expedition, air temperature was  $-5^{\circ}\text{C}$  –  $-8^{\circ}\text{C}$ , sea surface temperature was  $-1.0^{\circ}\text{C}$  –  $-1.2^{\circ}\text{C}$ , temperature difference was as large as  $4^{\circ}\text{C}$  –  $7^{\circ}\text{C}$  or more.

(2) Wind is not too strong, not stronger than force 4. If there is gale, fog is very easy to be broken.

(3) The most favorable weather situation of vapor fog formation in the Arctic is cold air just passing. Gale of cold air blows and breaks floating ice. It is clear sky, very small wind, and low temperature. However in floating ice area, sea temperature is rather high. It is suitable to vapor fog formation.

### 4.2.2 *Drift and transformation of vapor fog*

If vapor fog in the Arctic is blown by northerlies from floating ice area to southern warmer area, due to decreasing of temperature difference, air temperature increasing, relative humidity decreasing, and air not saturated, vapor fog will disappear. If fog is blown by southerlies to northern fixed ice sheet or very large floating ice, and if there exists inversion layer over ice sheet, it will be more favorable to maintenance of fog. But at this time, sea fog category changes into advection fog.

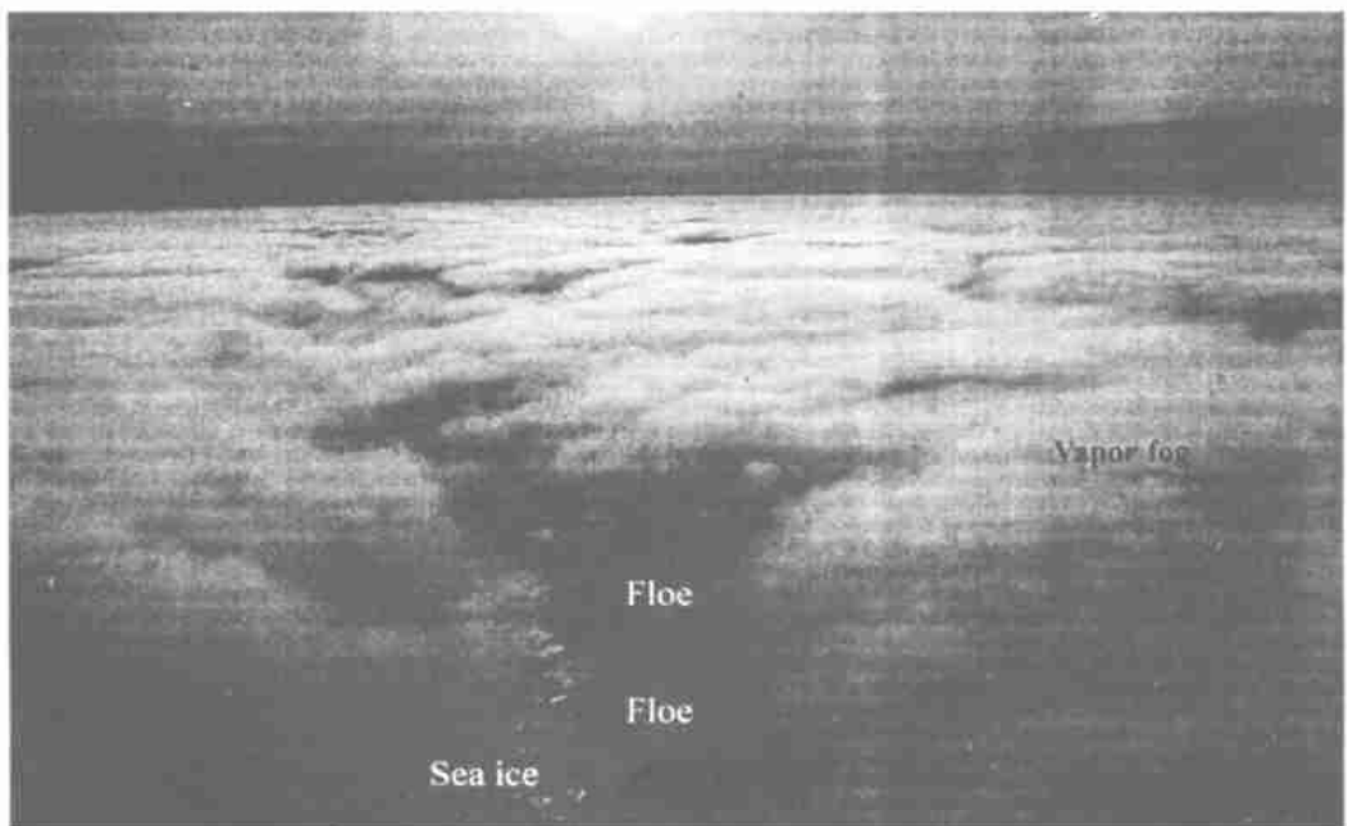
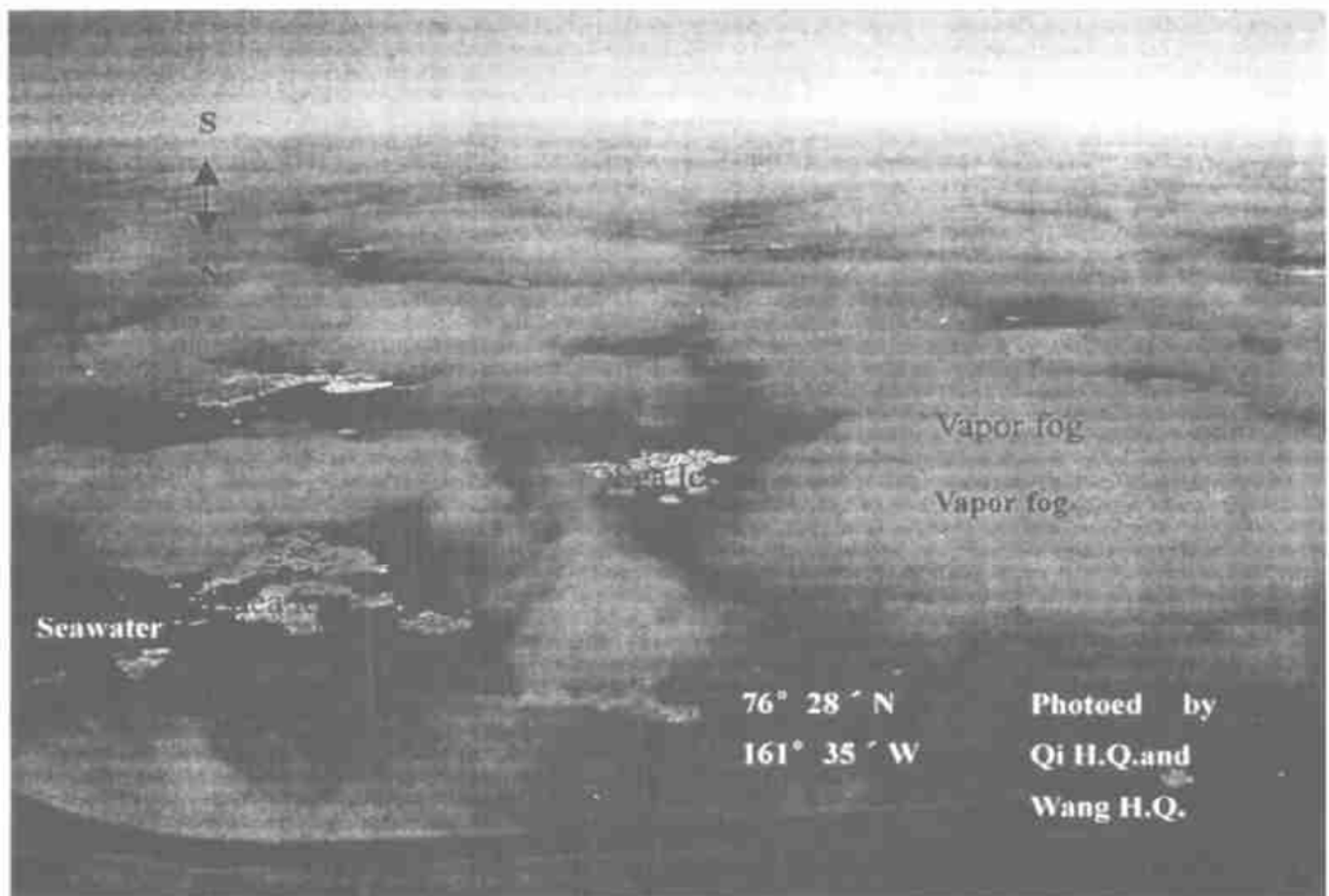


Fig. 3. The picture of vapor fog in the floating ice taken from a helicopter at the height of about 500 m, at 09:00(LT) August 20, on the position of 76°28'N, 161°35'W.

#### 4.3 Radiation fog

The Arctic ice sheet and concentrative floating ice area are usually covered by fog including advection fog and radiation fog. The important cause of radiation fog is very high albedo of ice-snow surface, which reflects 80% of solar radiation to space; therefore, ice-snow surface temperature is not easy to rise. Conversely, atmosphere, especially with cloud, has very strong ability to absorb and reflect solar radiation; its temperature rises rapidly; therefore, it is very easy to form ground inversion layer. Concentration and thickness of sea ice give an important impact on albedo. We used the ship-land dual-purpose handy-carried albedo sounding for observation on vessel, small boat, large floating ice and ice sheet.

Comprehensive ice-air-sea observation were made three times at altogether 12 points by small boat in ice periphery belt. During 2 - 3, 3 - 4, 4 - 5, 5 - 6, and 8 - 9 tenth ice, corresponding albedo observation values are, respectively, 5% - 7%, 10% - 13%, 16%, 18%, and 42%, while albedo in 7 - 9 tenth ice observed on vessel was 43%. Albedo values observed on large floating ice Stations 1, 2, and 3 were different, respectively, 67%, 60% and 80%. All these three ice stations were covered by snow with snow thickness of 0.5 m. These area were, respectively, about 1 km<sup>2</sup>, 0.3 km<sup>2</sup>, and 5 km<sup>2</sup> with ice thickness of, respectively, 3 - 5 m, 4 - 6 m, and 5 - 8 m. Their surface all had several melted water pools. The ice-snow surface had not been some polluted or the least.

Atmospheric stratification was calculated by air temperature, pressure, wind and humidity in ground layer observed by tethered balloon. Thickness of inversion layer is closely related to sea ice concentration, albedo and cloud amount. The thickest inversion layer of about 300 m was observed on Station 1. At this time, albedo was 67%.

Inversion layer usually appears on ice sheet. In nighttime of clear sky, radiation cooling on ice surface is very strong. Air is easy to be saturated status and form fog, which is called as radiation fog. Even though sun rises, temperature of ice-snow surface varies very little due to stable atmosphere and high albedo, which induce inversion layer maintenance. It is not easy to lift sea fog and disappear. Therefore, radiation fog on the Arctic ice sheet can maintain for a long time. This is very different from radiation fog on land, which will disappear after sun rises and temperature increases.

## 5 Discussion and conclusions

### 5.1 Discussion

Due to existence of sea ice, air-sea thermal exchange in the Arctic is greatly different from other ocean without ice. Sea ice is a bad conductor, just like a membrane separated between ocean and atmosphere to block air-sea thermal exchange. Ice-snow surface has a very high albedo for solar radiation, about 80%. During polar day time, sea ice reflects a lot of solar energy to space, and blocks chance of ocean absorbing solar energy. More complex is that, albedo in floating ice area varies greatly under impact of floating ice concentration, thickness, and existence of melted water pool and pollution degree or not, its value varies ranging 5% - 80%. In addition, ocean is under sea ice, it is greatly different from land under ice sheet in the Antarctic continent. Ocean has abundant water with very large

thermal inertia to store number of heat moment in Equatorial-tropical Ocean. Global oceans are connected with each other where temperature, salt, etc. can exchange. Therefore, variation range of sea temperature in the Arctic is not as large as atmosphere. Most of the Arctic is covered by sea ice. Generally sea surface temperature is higher than atmosphere, but it is not able to exchange with atmosphere. Once sea ice breaks, thermal exchange through ice crack would be very vigorous. This is physical mechanism of vapor fog formation in the Arctic. Sea ice has a high albedo, so that even in polar daytime, temperature is not easy to rise. But, atmosphere can absorb much solar short wave radiation and surface long wave radiation, its temperature increases rapidly. Inversion layer is easy to form. This is full and necessary condition of radiation fog formation on ice sheet. In summer of the Arctic, it is ocean with ice and water alternatively, which is very favorable condition of advection fog formation.

As a result, existence of sea ice in the Arctic makes air-sea thermal exchange complicated, its result introduces complex atmospheric phenomena. Sea fog in the Arctic is the result and manifestation of complex air-sea thermal exchange. Sea fog in the Arctic is complete in categories including advection fog usually appearing over the ocean, vapor fog usually occurring over river, lake and wet land, as well as radiation fog usually appearing in mountain-valley. Fog day is more in the Arctic, lasting for several days or even tens days, and undergoing a myriad change in the twinkling of an eye, sometime appearance and sometime disappearance. Shortly, sea fog in the Arctic is very complex both in categories and variation, as well as with its unique features.

## 5.2 Conclusions

(1) Sea ice status and its complexity give a great impact on air-sea thermal exchange. In floating ice area and fixed ice sheet under stable atmospheric stratification, heat momentum was transferred from ocean to atmosphere in form of latent heat and done from atmosphere to ice-snow-surface in form of sensible heat. In floating ice area under unstable atmosphere stratification, heat momentum was transferred from ocean to atmosphere in both forms of sensible and latent heat. Here it is very easy to form vapor fog showing a strong status of air-sea thermal exchange. During an extensive vapor fog process about  $500000 \text{ km}^2$  on August 21 - 22, 1999, total heat momentum transferred from ocean to atmosphere in form of sensible and latent heat was  $14.8 \times 10^9 \text{ kW}$ . This is the important cause of vapor fog formation. It verifies that the floating ice area and polynya is climate variation sensitive region.

(2) Existence and complex status of sea ice make air-sea thermal exchange, also resultant atmospheric phenomena complicated. Sea fog in the Arctic is typical product with all kinds of fog: advection fog, vapor fog, and radiation fog.

(3) In summer, the Arctic is ocean of sea ice and water alternatively. There is a favorable condition to advection fog formation. The common features of advection fog in the Arctic and Bering Sea are long sustained time, large limits and with few relation to diurnal change. However in the Bering Sea, warm, moist air comes from broad and wide Pacific to cold ocean, the sustained time, limits and concentration of fog are more advantageous than in the Arctic.

(4) Vapor fog is formed in floating ice area. Its characteristics are: it comes

very fast, disappears very rapidly. It looks as vapor suddenly sending up from your foot, very different from advection fog moving from other place far away. The necessary condition of formation is in floating ice area, where sea surface temperature is higher than air temperature, water vapor comes out from ice crack. It undergoes large diurnal change. When sun rises, air temperature increases to higher than sea temperature; sea fog is no long formed continuously, but disappears gradually. When vapor fog is blown to cold ice sheet, it changes into advection fog. If an inversion layer exists over ice sheet, the changing advection fog will maintain for a long time. Vapor fog is the strongest manifestation of heat momentum transportation from ocean to atmosphere, which is usually observed in floating ice area and polynya.

(5) Radiation fog is fog formed by radiation cooling on very large floating ice or fixed ice sheet. Its necessary condition is that on ice sheet with existence of inversion layer under stable atmospheric stratification, radiation cooling introduces sea fog formation. It is not related to diurnal change. Ice sheet has a very high albedo to solar radiation, generally 45% - 60% with the maximum more than 80%. That is to say, ice-snow cover can absorb very little solar radiation. It is not easy to increase ice-snow cover temperature to destroy stable stratification, therefore it is not easy to cause sea fog to lift and disappear.

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