

Experiment of near surface layer parameters in ice camp over Arctic Ocean

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Abstract Estimates of near surface layer parameters over 78°N drifting ice in ice camp over the Arctic ocean are made using bulk transfer methods with the data from the experiments operated by the Chinese Arctic Scientific Expedition in August 22–September 3, 2003. The results show that the net radiation received by the snow surface is only 3.6 W/m^2 , among which the main part transported into atmosphere in term of sensible heat and latent heat, which account for 52% and 31% respectively, and less part being transported to deep ice in the conductive process. The bulk transfer coefficient of momentum is about 1.16×10^{-3} in the near neutral layer, which is a little smaller than that obtained over 75°N drifting ice. However, to compare with the results observed over 75°N drifting ice over the Arctic Ocean in 1999, it can be found that the thermodynamic and momentum of interactions between sea and air are significant different with latitudes, concentration and the scale of sea ice. It is very important on considering the effect of sea-air-ice interaction over the Arctic Ocean when studying climate modeling.

Key words Arctic Ocean, Ice camp, Turbulence flux, Heat budget

1 Introduction

Numerous studies show that in the global warming background the Arctic ice layer thinning and the covered area diminishing are being accelerated in summer. Undoubtedly, changes in the underlying surface would affect the local weather/climate and energy budget, thereby exerting remarkable impacts on variations in climate and environment on a global basis including China, and currently the prediction of global climate change, especially in relation to the changing polar region climate, has become a leading problem worldwide. Many advanced climate models produce bigger biases in simulations of the polar climate owing mainly to poorer understanding of interactions between snow cover and atmosphere in the polar region. As a result, it is necessary to make observational study of polar radiation balance, water vapor, momentum transfer as well as energy exchange in conjunction with their parameterizations in order to provide climate models with more suitable atmospheric boundar-

ry layer physical characteristic parameters, with which to improve the relevant parameterization schemes, thereby reasonably evaluate the role of the polar region in global climate change. For this reason, China organized Arctic Scientific Expedition in 1999 and 2003^[1-3]. Since 1997 the United States has launched, jointly with Canada, Japan, Russia and northern-European countries, a 10-yr SAFIRE Project for the Arctic observations, including SHEBA (Arctic Surface Heat Equilibrium Observation), ARM (Arctic Atmospheric Radiation Observation) and FIRE (international cloud climate regional experiment). Duynkerke and Roode (2001)^[4] discussed the structures and features of Arctic ice-surface heat equilibrium components based on the SHEBA data, indicating that although the monthly mean turbulent flux near ice surface layer is small, the diurnal variation is remarkable. It was required to using suitable parameterization schemes for momentum, heat and water vapor exchange for studying the Arctic Ocean sea/ice/air interactions. Jordan (1999)^[5] investigated the exchange of energy and mass between snow-ice surface and atmosphere, with the ice-snow measures and meteorological data from 31 Arctic pack ice observation stations, and established improved one-dimensional models of mass and energy balance. Lack of Arctic data led to fewer researches on applications of the boundary-layer parameters and variations to climate models. Qu *et al.* (2002)^[6] and Bian *et al.* (2003)^[7] made estimation of near surface layer parameters over a range of drifting ice. Since global warming and the thickness and area of sea ice of the Arctic Ocean are decreased greatly from year to year, yet the calculating methods of turbulent exchange and heat balance differ greatly between in ice-free and in ice regions. It is concluded that by Li *et al.* (2005)^[8] the bulk transfer method is one of the best methods for studying parameterization of sea/ice/air interactions over the Arctic, after they analyzed the turbulent fluxes of the Arctic Ocean ice pack regions based on boundary layer similarity theory by using the measured meteorological elements gradient derived from the drifting ice observations over the Arctic Ocean. Following above conclusion, this article analyses the exchange parameters of heat and momentum and their variations in the near surface layer over a representative drifting ice by using measured radiation, turbulence and snow temperature profiles around the ice camp near 78°N during the 2003 expedition, which furnished experimental results for constructing parameterization schemes and models.

2 Observation instruments and data

The Second Chinese National Arctic Research Expedition was carried out onboard “*Xuelong*” research vessel. It set off on July 15, 2003 from Dalian, crossed the Bering Sea into the drifting ice regions of the Arctic Ocean and arrived at the adjacent region of 78°N on August 20, where a relative flat multiyear-ice (2~3 m thick and the area about 300 km²) was selected by helicopter reconnaissance, whereon a camp was established for joint observation. From August 22 to September 23 Chinese and Finnish scientists made a two week observation experiment of ocean/sea ice/atmosphere interactions, with a 6 m meteorological tower elected over a pack ice with thickness about 2 m, on which all necessary devices were mounted: temperature and humidity probes (Model Hmp-35D, Vaisala) and wind direction/speed sensors (Models Cpe-3 d, China and 05106 monitor, Ma Young USA) at 0.5, 3.0 and 6.0 m above surface; a 3D ultrasonic turbulent flux observing sys-

tem (Model SA-4 and M100 App Tec Inc., USA) and up- and downward long- and short-wave radiation sensors (PSP and PIR, Eppley) at 2 m, ice temperature sensors (PT100) at a range of depth of the pack ice along with ice-surface pressure sensor (PTB100 Vaisala) and an ice-surface infrared temperature transducer (KT19 & HE-IRONICS). All the transducers were connected with the data sampler (Dataaker-600 TEC) for automatic recording with 1 min sampling frequency and a set of data recorded at 10 min intervals. All the sensors were calibrated at CMA (Chinese Meteorological Administration) before setting off for the mission. Under the effects of wind and ocean circulation the camp ice drifted from west to east (from 148°W, 78.3°N to 143°W, 78.7°N) during the observation^[9].

This paper used the data of temperature, humidity, wind profile and radiation balance components near-ice-surface layer along with other relevant data calculated and analyzed the boundary layer parameters in near ice surface layer by means of bulk transfer method with the results compared to those obtained from in situ observations during the First Chinese National Arctic Expedition.

3 Methods

The ice surface energy balance can be expressed as

$$R_n = S_t - S_g + L_a - L_g \quad (1)$$

$$R_n = H + LE + G + M \quad (2)$$

where R_n is net radiation, S_t and S_g are incoming and reflected shortwave radiation fluxes, L_a and L_g are incoming and emitted longwave radiation fluxes. All of these terms are of in situ measurements. H and LE are the turbulent fluxes of sensible and latent heat, which evaluated at the surface by bulk transfer method, and G is the subsurface conductive heat flux, as well as M is the heat flux absorbed/released in surface melting/freezing. According to the known boundary layer parameters, making use of the average of wind speed, temperature and humidity derived from the near surface and a layer of certain height above the surface, turbulent characteristics were calculated by using the bulk transfer method as follows

$$\tau = \rho C_d U^2 \quad (3)$$

$$H = \rho C_T U (\theta_0 - \theta) \quad (4)$$

$$LE = \rho L_v C_E U (q_0 - q) \quad (5)$$

$$C_d = (u_* / U)^2 = \left| \frac{k}{\ln(Z/Z_0) - \Psi_m(Z/L) + \Psi_m(Z_0/L)} \right|^2 \quad (6)$$

$$C_T = \left| \frac{u_* T_*}{U(\theta - \theta_0)} \right|^2 = \left| \frac{k^2}{R(\ln(Z/Z_r) - \Psi_m(Z/L) + \Psi_h(Z_T/L))(\ln(Z/Z_T) - \Psi_h(Z/L) + \Psi(Z_T/L))} \right| \quad (7)$$

where C_d , C_T and C_E is bulk transfer coefficient for momentum, sensible heat and water vapor respectively, and assumed $C_E = C_T$ during the calculating process. θ_0 and q_0 are potential temperature and specific humidity over the pack ice, U , θ and q are wind speed, potential temperature and specific humidity at the reference height respectively, Z_0 , Z_T and Z_q

are roughness (strength) form on entum, sensible heat and moisture, generally assumed $Z_0 = Z_T = Z_q = 0$ initially. It was approximately considered as near neutral stratification when the bulk Richardson Number $|R_B| \leq 0.025$. According to neutral stratification, wind profile $U = ku_* \ln(Z/Z_0)$, then $Z_0 = 1.526 \times 10^{-4}$ m was obtained by using least squares method. q_0 is specific humidity over the ice surface and can be computed by the formula $q_0 = RH_{0.5} \times q_{sat}^{[10]}$, where $q_{sat} = 0.622 \times \frac{e_{sat}}{p - 0.378e_{sat}}$ and $e_{sat} = 6.11 \times 10^{9.5t_1/(t_1 + 265.5)}$ are saturation specific humidity and saturation water vapor pressure at the drifting ice respectively, t_1 (°C) is the temperature at Z_0 height here taken for the drifting ice surface temperature t_0 , and $RH_{0.5}$ is relative humidity at 0.5 m. The stability functions Ψ_m and Ψ_h in (6) and (7) adopted the formula that Li *et al.* (2005)^[8] selected from Holtslag *et al.* (1988)^[11] expressions

4 Radiation parameters

In Fig 1 temporal series of hourly up- and downward radiation fluxes and albedo at snow surface August 22 to September 3 are illustrated. In Fig 1a it is indicated that remarkable interdiurnal and diurnal variations of total and reflected radiation occurred, with total radiation higher in fine days than in overcast weather. The maximum flux at noon in a fine day was as much as 600 W m^{-2} , in contrast to $< 200 \text{ W m}^{-2}$ in a cloudy sky. It showed that the radiation fluxes are related to the cloud cover. The mean daily total radiation over the period reached 110 W m^{-2} approximately, with daily amplitude range over $80 \sim 182 \text{ W m}^{-2}$. The maximum of daily reflected radiation flux was 435 W m^{-2} , with the total daily mean 95 W m^{-2} and daily amplitude range over $71 \sim 147 \text{ W m}^{-2}$. The total and reflected radiation values in fine days were more than twice as great as that in cloudy days. The albedo (A) represented significant daily variation (Fig 1c) with mean reaching 0.85. The ratio of reflected to total radiation was rather high when the solar altitude angle was maximum, leading to the greatest (smallest) reflectivity of 0.95 (0.5). The albedo became small as ice melted, when the ice structure was changed due to the fact that the thawing water infiltrated through ice. It also declined during a snowing day. Comparison shows that the 2003 observed reflectivity was obviously greater relatively to the instantaneous measurements obtained in 1999 at $75^\circ\text{N}^{[7]}$, and the greater albedo was associated with a clean snow cover which thickness was about 7 cm and with no depositing pollutants on its surface practically, on the 78°N pack ice, in comparison to the multiyear snow-free ice surface in the 1999 case that was grayish on account of sea water erosion and atmospheric contaminants that led to absorbed radiation increased, responsible for reduced reflectivity. That the Arctic ice reflectivity increase depends on increasing latitude and distance from human activity is of particular significance to the parameterization scheme of climate models.

With temporal series of snow surface emitted and atmospheric long-wave radiation absorbed in Fig 1b it can be seen that the diurnal variation was very small but its interdiurnal variation was remarkable, both varying insignificantly only during snow fall. The snow cover emitted long-wave radiation had its interdiurnal range over $294 \sim 317 \text{ W m}^{-2}$, with the maximal daily total slightly smaller than 320 W m^{-2} at 75°N (in 1999). It showed that the snow

surface long-wave radiation intensity was related to snow temperature, indicating its dependence upon latitude. The daily amplitude of atmospheric radiation ranged over 287

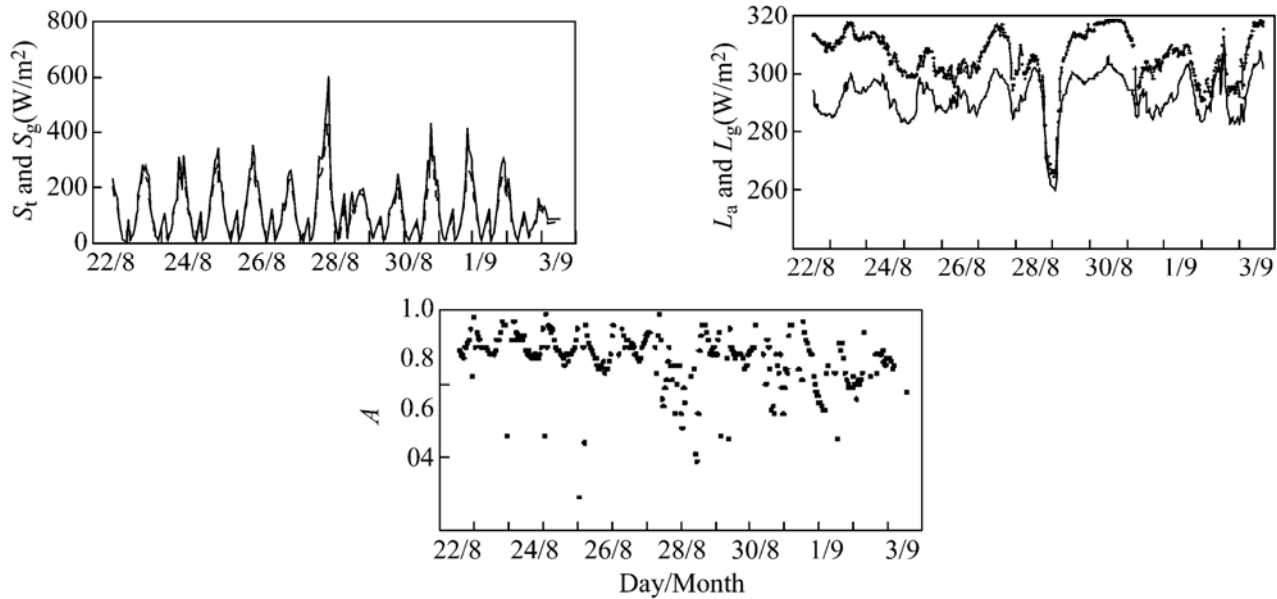


Fig 1 Time series of 30m mean fluxes of global (S_t , solid line) and reflected radiation (S_g , dashed line), incoming (L_a , solid line) and outgoing (L_g , dashed line) longwave radiation, and ice surface albedo (A) on August 22-September 3, 2003

$\sim 300 \text{ W m}^{-2}$. For the interdiurnal amplitude, evidently, atmospheric net long-wave radiation was greater at 78°N than that at 75°N , because it related in ice concentration and weather conditions. As for 75°N the ice concentration was relatively lower so that stronger ocean-air interactions occurred in contrast to the 78°N case where ice-air interplays dominated because of higher ice concentration, leading to a quick change in atmospheric temperature and humidity in the near surface layer such that the longwave radiation varied more greatly. As shown in Fig 1b, during nighttime of 28 to the early morning of 29 August, the minimum temperature and longwave radiation of snow and air were observed, which was obviously consequent on the intense radiation cooling in a cloudless sky near surface in association with the incursion of the cold airmass.

5 Parameters of turbulence

The diurnal mean variations of sensible heat (H) and latent heat fluxes (LE) over the snow cover calculated by formulas (3) and (4), snow-ice heat conductivity fluxes (G) acquired from the observed snow-ice temperature profile and computed by the scheme of Duynkerke (2001)^[4] are presents in Fig 2, as well as (1)-given net radiation flux (R_n). The positive (negative) H and LE denote heat transfer into the air (snow cover); positive G indicates the downward transfer of heat inside the cover, for upward transport vice versa; positive (negative) R_n designates snow-ice surface absorbed (released) net energy. Limited effective radiation taken by the ice surface resulted in rather weak turbulent exchange between snow cover and air. As indicated in Fig 2, the turbulent heat flux showed a significant diurnal variation. For 0600 to 1700 LST, net radiation energy absorbed by snow cover was emitted into air in the form of sensible and latent heat, part of heat conducted into dee-

per layers of the snow-ice and all components of the heat balance were negative for the rest of time intervals. Due to the radiation cooling the snow cover received energy from the atmosphere as sensible and latent heat, with the energy lost from the ice cover compensated for partly by heat from the layers of greater depth. Around the noon solar radiation became maximum, leading to the strongest turbulent fluxes, with the diurnal amplitude of sensible (latent) heat fluxes ranging over -5 to 13 (-5 to 2) Wm^{-2} , ice conductive heat flux over -8 to 12Wm^{-2} , and net radiation flux over -15 to 33Wm^{-2} . Fig 3 depicts the time series of ice surface sensible (latent) heat fluxes H (LE), snow conductive heat flux G , and net radiation flux (R_n) for August 22~ September 3, 2003, indicating that all terms of the energy balance show more remarkable interdiurnal variations. In fine and partly cloudy weather snow cover absorbed net radiation was greater such that the heat and vapor fluxes exchange were stronger between the snow-ice and atmosphere, and vice versa in overcast and snow fall weather.

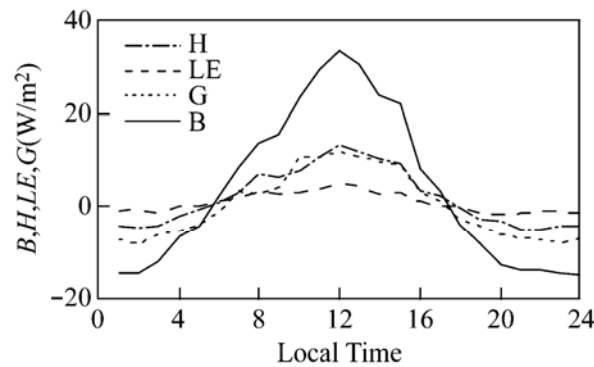


Fig 2 Mean diurnal variation of fluxes sensible heat flux (H) and latent heat flux (LE), sea-ice conductivity heat flux (G) and net radiation flux (R_n).

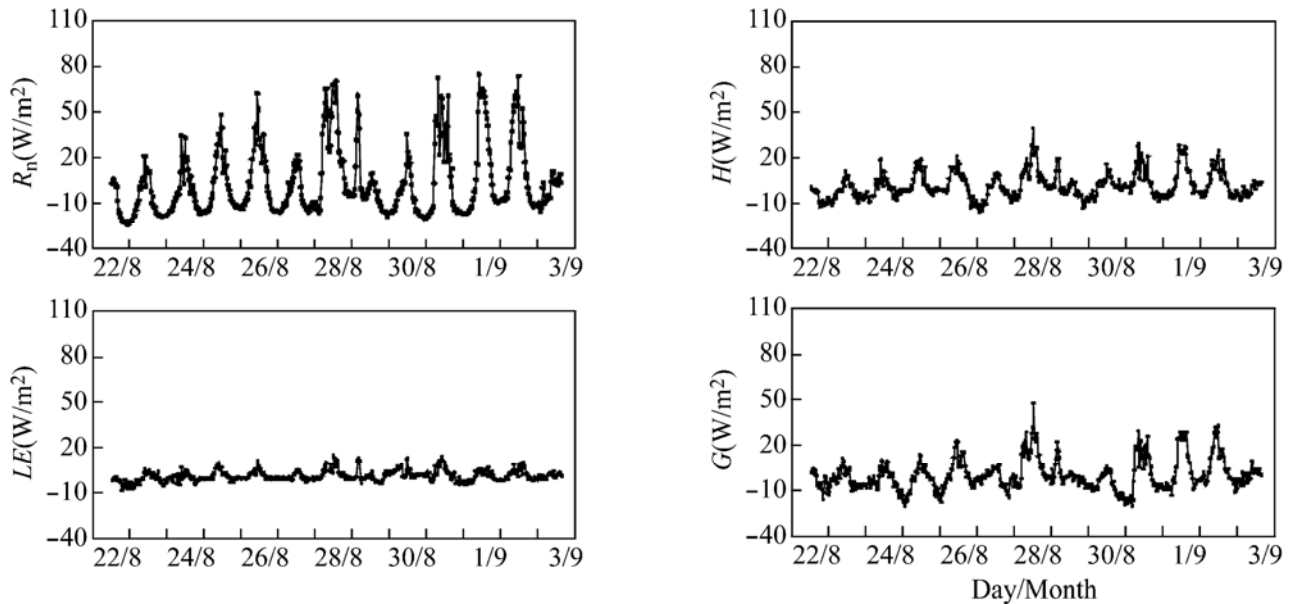


Fig 3 Time series of hourly net radiation flux (R_n), sensible (H) and latent (LE) heat flux, sea-ice conductive heat flux (G) in August 22-September 3, 2003

6 Parameter of momentum

Atmospheric momentum parameter in the near surface layer is often denoted by the drag coefficient C_d , which is one of the most important parameters to boundary-layer mod-

els. Owing to lack of observations for the Arctic Ocean most of such models take the drag coefficient of $2 \sim 3 \times 10^{-3}$ over the ice surface for near neutral stratification. To further understand the characteristics of drag coefficient with the variations of latitude and drifting ice concentration, in this context the calculation of the atmospheric stability z/L and drag coefficient C_d was completed by means of ice-surface gradient observations and similarity theory. The results showed that a few of the absolute values of z/L were greater than 0.1, but most of them were less than 0.1 or close to zero (61% of total samples), and 3% were smaller than -0.1, and the rest exceeding 0.1. This implies that the stability of the atmosphere ($-0.1 < z/L < 0.1$) in the near surface layer over the Arctic Ocean is neutral or near neutral and has quite weak convection event (unstable stratification) during the observation. The relationship between drag coefficient C_d , which calculated by the formula (6), and wind speed (U) is as given in Fig 4. It indicates that C_d is larger with smaller wind speed and it approaches a steady value with wind speed in excess of 5 m/s. A fitted linear relation between C_d and wind speed (U) is obtained as the form of $C_d \times 10^{-3} = 1.383 - 0.026U$. The relationship between C_d and z/L under neutral or near neutral stratification is presented in Fig 5, and the drag coefficients are variable in the near neutral condition with a range of $0.5 \sim 3 \times 10^{-3}$. Therefore the mean value of $C_{dn} \approx 1.16 \times 10^{-3}$ for near neutral stratification ($z/L \approx 0$) over the ice surface were calculated. This value is greater than $C_{dn} \approx 1 \times 10^{-3}$ in open sea (Gao *et al.* 2000)^[12], but slightly smaller than the value of 1.24×10^{-3} obtained in the 1999 Expedition at 75°N Arctic pack ice for neutral stratification^[7]. Thus it can be seen that the observation during 2003 Expedition is representative of the momentum features over the high-latitude Arctic flat ice surface in summer. Compared with the value at 75°N, the C_{dn} was smaller at 78°N where drifting ices covered a larger portion of the sea with more flat snow cover and its insignificant roughness.

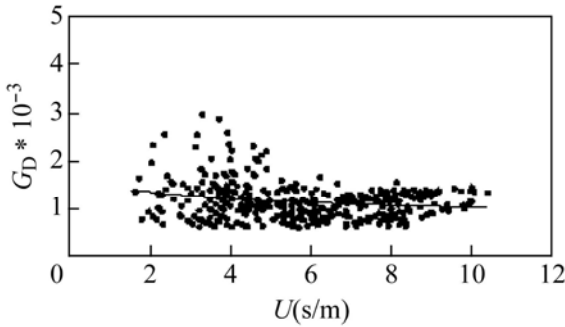


Fig 4 Relationship between drag coefficient (C_d) and wind speed (U).

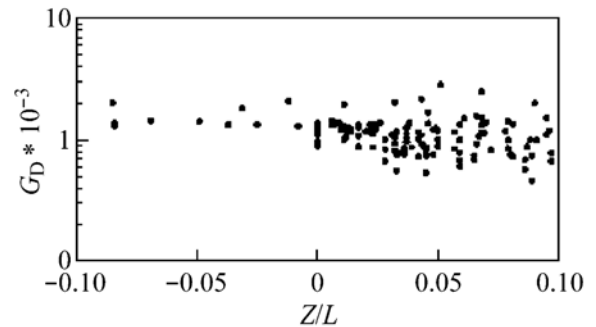


Fig 5 Relationship between drag coefficient (C_d) and atmospheric stability (z/L).

7 Analysis of the energy closure error

The estimation of closure error of the energy balance with which to improve turbulent flux calculation technique is significance to the parameterization of the boundary layer. The closure error of the energy budget equation over ice can be given as $[(R_n - H + LE + G) / R_n] \times 100$, where R_n is the measured net radiation with a higher accuracy and the other terms are the mean fluxes of the heat balance components calculated by similarity theory. Temperature higher than 0 degree observed multiple times around the ice camp at 75°N in 1999, suggesting significant ice melting that the melting-consumed heat was taken into con-

sideration, but during the 2003 Expedition, temperature was relatively lower and temperatures $> 0^{\circ}\text{C}$ hardly occurred there, thus ignoring the term of ice melting. Table 1 indicates that the closure error of the heat balance in 2003 was 8%, a figure that is reasonable enough to show high precision of observations and calculations with comparison to the 1999 value of 12%^[7]. The difference maybe arose mainly due to the complicated sea-ice-atmosphere interactions at 75°N in 1999 and especially due to the melting process and the camp closeness to open waters in addition to instruments errors, thus suggesting the 2003 measurements at 78°N displayed a representative of ice and air interactions at high-latitude. Mean fluxes in Table 1 showed that the net radiation absorbed by snow surface was transferred mainly to air as sensible and latent heat, accounting for 52% and 31% respectively, and the rest transported into the sea of great depth. As a result, sensible heat and latent heat over snow cover were important terms in the heat budget.

Table 1 Components fluxes of the snow-surface heat balance in summer at 78°N (Wm^{-2})

R_n	H	LE	G
3.6	1.9	1.1	0.3

8 Conclusions and discussion

From the foregoing analysis of the near surface radiation and turbulent fluxes over the Arctic Ocean at 78°N , $144^{\circ}\sim 148^{\circ}\text{W}$ during August 22~ September 3, 2003, further understanding of the thermal and dynamic processes of ice-air interactions was established. It is found that the use of bulk transfer scheme for turbulent parameter has higher precision, reaching closure error of the energy balance as low as 8%.

During the observation period the near surface atmosphere over the sea-ice is almost in a neutral or near neutral stratification. Weakly unstable or stable stratification only developed for a short time. The fitted relationship between C_d and U is given as $C_d \times 10^{-3} = 1.383 - 0.026U$. It approaches a steady value with wind speed in excess of 5 m/s , and the mean drag C_{dn} is 1.16×10^{-3} under near neutral stratification conditions. This value is slightly smaller relative to the value of 1.24×10^{-3} obtained at the 1999 Expedition at 75°N Arctic pack ice for neutral stratification. The mean albedo of the snow cover is 0.85 during the observation. Owing to so great albedo snow-cover absorbed net radiation is only 3.6 Wm^{-2} , it was transferred to air mainly as sensible and latent heat, which accounts for about 52% and 31% respectively, and the rest transported to deep water by conductive process. By the comparison to 1999 measurements it is seen that due to the differences in latitude, sea-ice concentration and scale of the drifting ice where the camp is located, there arises considerable difference in dynamic and thermodynamics of interactions between sea-ice and atmosphere in the higher-ice-concentration area and that in open waters. The pack ices in the regions to the south of 75°N are of low concentration and present obvious melting, and ice there is grayish because of sea water erosion and deposited pollutants, leading to reduced reflectivity and more energy absorbed. That is the answer for the fact that the melting and sensible heat fluxes become the important terms of the heat budget. Consequently, ice-surface lost heat exceeds absorbed net radiation that is compensated for by heat from the

depth of the ice. In comparison, the ice-absorbed radiation at 78°N is only $1/3$ of that at 75°N , so that only a small amount of heat is transferred into depth of the ice and hence sensible heat flux acts as the important term of the heat budget. Therefore, it is necessary to consider further ice density, scale of drift ice and albedo as the significant factors affecting near-surface layer parameterization in preparing the parameterization schemes of thermodynamic and dynamic processes in the boundary layer for interactions between high-concentration ice region and air as well as between open water and atmosphere in the Arctic Ocean.

The observation over the ice camp during 2003 Expedition was more extended than that during 1999 Expedition with an optimized calculation scheme of turbulence adopted, but the results in this paper remain preliminary, should be followed by further observational studies. In order to discover the evolution of some physical parameters for the sea ice-atmosphere interaction, a longer time series required.

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