

# Analyses of structure of planetary boundary layer in ice camp over Arctic ocean

Bian Lingen(卞林根)<sup>1</sup>, Lu Longhua(陆龙骅)<sup>1</sup>, Zhang Zhanhai(张占海)<sup>2</sup>, Cheng Bin(程斌)<sup>3</sup> and Lu Changgui(逯昌贵)<sup>1</sup>

*1 Chinese Academy of Meteorological Sciences, Beijing 100081, China*

*2 Polar Research Institute of China, Shanghai 200136, China*

*3 Finnish Institute of Marine Research, Helsinki FIN-00931, Finland*

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**Abstract** The vertical structure of Planetary boundary layer over Arctic floating ice is presented by using about 50 atmospheric profiles and relevant data sounded at an ice station over Arctic Ocean from 22 August to 3 September, 2003. It shows that the height of the convective boundary layer in day is greater than that of the stability boundary layer in night. The boundary layer can be described as vertical structures of stability, instability and multiplying. The interaction between relative warm and wet down draft air from up level and cool air of surface layer is significant, which causes stronger wind shear, temperature and humidity inversion with typical wind shear of 10 m/s/100 m, intensity of temperature inversion of 8 °C/100 m. While the larger pack ice is broken by such process, new ice free area in the high latitudes of arctic ocean. The interactions between air/ice/water are enhanced. The fact helps to understanding characteristics of atmospheric boundary layer and its effect in Arctic floating ice region.

**Key words** Arctic Ocean, atmospheric profile sounding, boundary layer structure

## 1 Introduction

It is one of the goals of Chinese National Arctic Research Expedition (CHINARE) to investigate the exchange of energy and interaction among ocean/ice and sea/air in the Arctic region, for more understanding the role of the Arctic in changing global climate and environment along with its relation to climate over China<sup>[1,2]</sup>. The extreme scarcity of atmospheric soundings over the Arctic leads to relatively less research into the structure and variation of the planetary boundary layer (PBL) as well as its impacts upon global climate. A 10a SAFIRE program for the purpose was carried out, started from 1997 under the cooperation of the United States, Canada, Japan, Russia and northern European countries, including the Arctic Surface Heat Equilibrium Observation (SHEBA), Atmospheric Radiation Program (ARM) and International Cloud program of Regional Climate Experiment (FIRE). Zou *et al.* (2001)<sup>[3]</sup> examined the atmospheric structure and vertical distribution of ozone in the Chukchi Sea by means of soundings obtained during the first CHINARE. Qu

*et al.* (2002)<sup>[4]</sup> illustrated the near-surface atmospheric structure over a range of floe-ice areas by use of soundings from the tethered balloon, indicating the 73~75°N strong inversion of the atmospheric structure, turbulent strength as well as their possible effect. Liu *et al.* (2002)<sup>[5]</sup> analyzed diurnal variation of the Arctic inversion layer. The dramatic decrease in the ice area and depth of the Arctic Ocean is triggered by global warming, producing vast differences in turbulent exchange and energy balance between open sea and floe ice<sup>[6,7]</sup>, which exert significant impacts on atmospheric circulations over the Arctic and mid-latitudes. A problem that has caused great attention of the scientific community.

Based on the experience of first CHINARE in 1999<sup>[8]</sup>, second CHINARE was made from July 14 to September 25, 2003. The observations of relevant atmospheric/oceanic elements were implemented on the R/V *Xuelong* in its journey supported by advanced instruments and powerful logistics assistance. The ice station was set up around 78°N, 143–148°W for conducting an observational experiment on interactions between ocean, sea ice and atmosphere, acquiring a set of valuable data. In this paper, the high-latitude PBL structure and feature over the Arctic are presented by using the data of vertical profiles of temperature, humidity, wind speed/direction and other related data. Effects of ice/snow surface temperatures and radiation upon the PBL will be dealt with in the following.

## 2 Description of observation and data

The second CHINARE mission was carried R/V *Xuelong* onboard that traveled from Dalian to the Arctic Ocean, crossing the Bering Seas and reaching the selected area of the Arctic Ocean on August 20. A large slab of the sea-ice 2–3 m deep and about 300 km<sup>2</sup> in area was chosen for the ice station of PBL experiment by helicopter reconnaissance. Under the influence of winds and oceanic currents, the station moved roughly from west to east, i.e., from 78.3°N, 148°W to 78.7°N, 143°W (Fig. 1).

A 2-weekly experiment was conducted on interactions between sea ice and air, recorded data including 3D turbulent heat fluxes, 3-level gradient of meteorological elements (6 m, 3 m and 0.5 m), radiation balance components, snow surface temperature, ice temperatures at different depth and vertical profiles from August 22 to September 3. The atmospheric profile sounding system is consisted of a tethered balloon and a set of receiver as well as the processing software produced by USAir Company. The technical indices are listed in Table 1 for sensors measured atmospheric elements. The sensors were calibrated against the standards in the Metering Station under the Chinese Meteorological Administration. The accuracy of the measurements is shown in Table 1 with elements involving temperature, humidity, pressure, and wind velocity/direction.

The atmospheric profiles are sounded in 55 times and associated with data from different weather processes during the observation. In the observational period complicated weather phenomena often occurred, there were noticeable interactions among ocean/air/sea ice which happened around the station. From August 22 to September 3 the station was experienced weather process from low to high-pressure systems (Fig. 2). The highest pressure occurred on August 29 with a clear day and the lowest temperature. It was dominated by windy/snowy and heavily foggy weather in the rest time. As the station was near about 2 km

from the open sea, it was under the influence of warm / wet air from the sea, resulting in

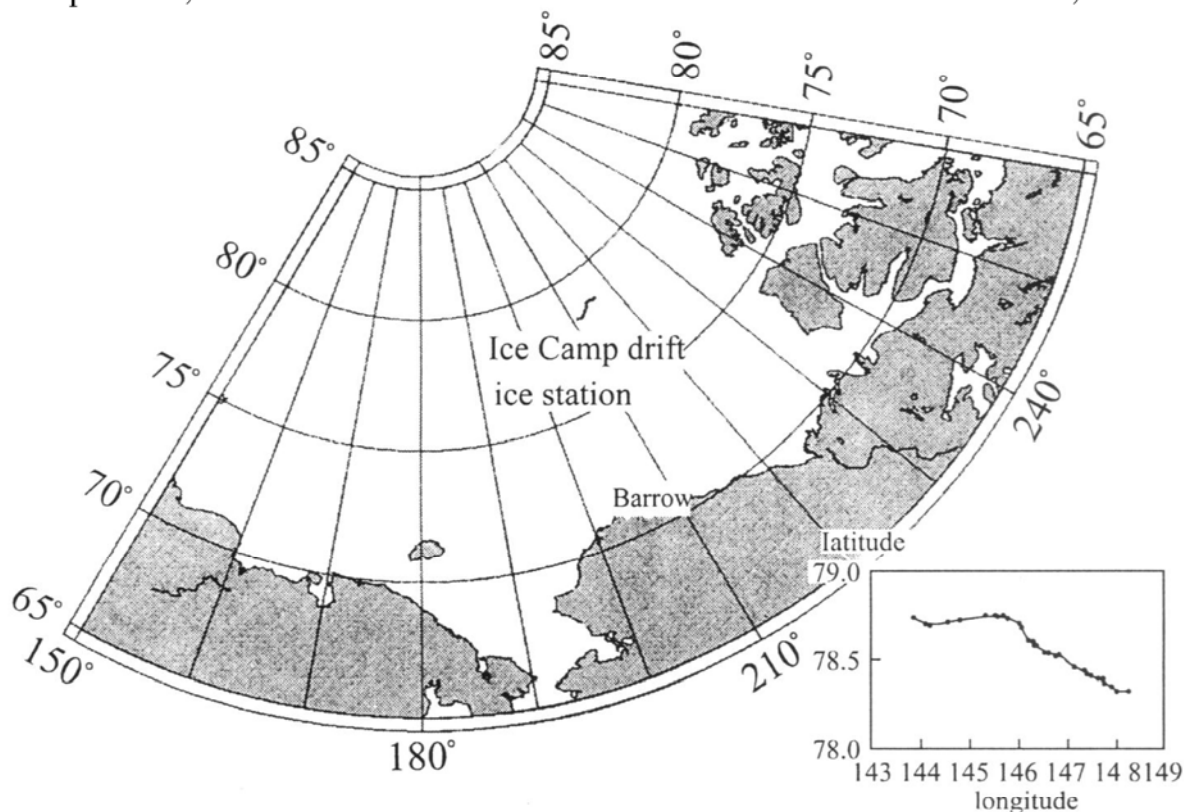


Fig 1 Ice camp drift trajectory from Aug 22 to Sep 3 2003 measured by GPS

Table 1. Specification of tethered sounding atmospheric elements

Atmospheric elements	Measuring range	Precise
Air temperature	- 40~ 50 °C	$\pm 0.3$ °C
Relative humidity	0~ 100%	$\pm 3\%$
Pressure	600~ 1050 hPa	$\pm 0.3$ hPa
Wind speed	0~ 25 m/s	$\pm 0.3$ m/s
Wind direction	0~ 360°	$\pm 5^\circ$

> 90% relative humidity except its slight drop at weaker winds, and in this case tempera-

can be seen that the sounding height could arrive at > 1000 m in the condition of weak winds, and lower 600 m and even lowest of 210 m when winds were stronger

### 3 PBL structure over sea ice

It is of major scientific interests to research PBL structure with its evolution and to determine the PBL parameterization scheme for sea ice/ocean/air interactions over the Arctic Ocean. The great differences exist in absorbing solar radiations between ice-free and snow-ice cover different surfaces, thereby making the Arctic PBL structure to differ vastly from those in other regions of the earth. The PBL structure is also dependent on the density and

depth of floe ice. As shown in Qu *et al.* (2002)<sup>[4]</sup>, inversions of temperature and humidity

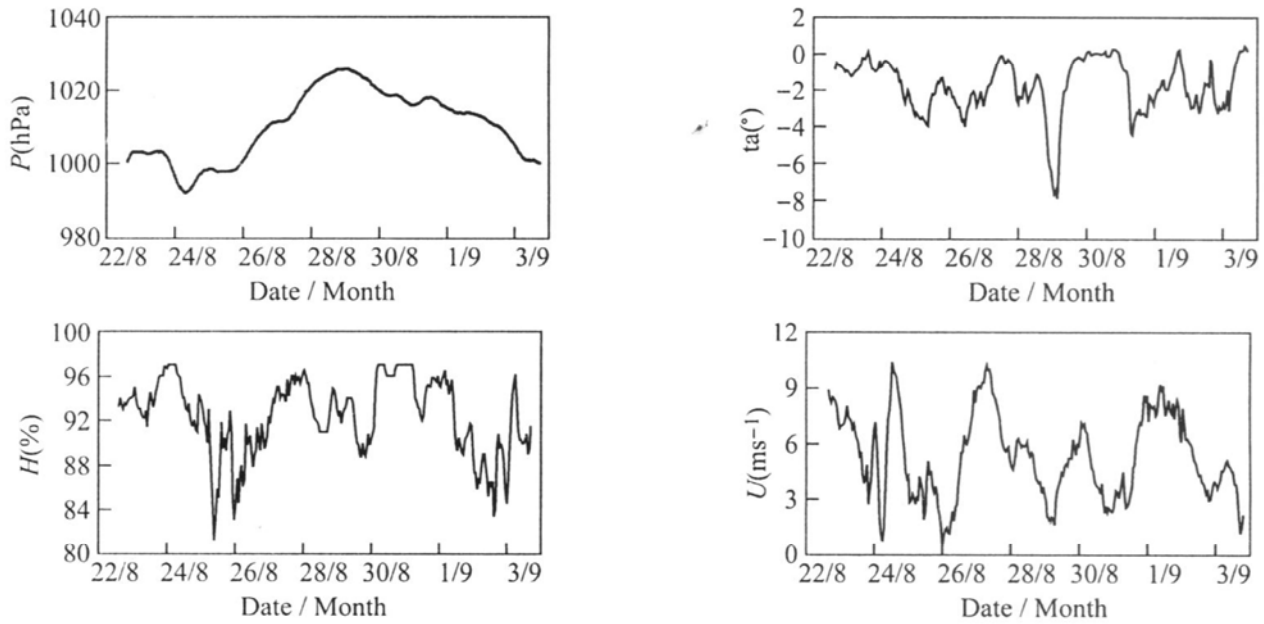


Fig 2 Time series of pressure( $P$ ), air temperature( $ta$ ), humidity( $H$ ) and Wind speed( $U$ ) observed in ice camp from August 22, 2003 to September 3, 2003

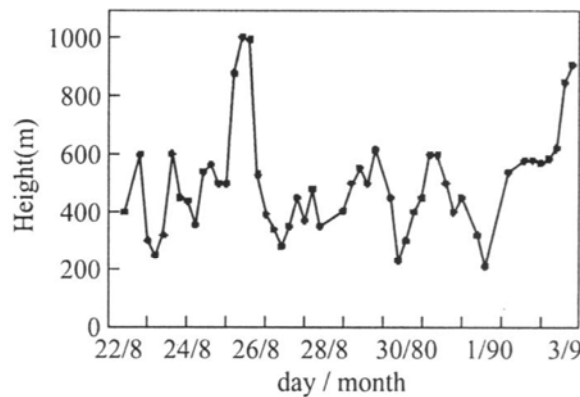


Fig 3 The series of heights of tether sonde sounding in ice camp over the Arctic Ocean from August 23, 2003 to September 3, 2003

inside the PBL observed in 1999 were related to different distributions of sea ice. In the 2003 mission Chinese meteorologists obtained atmospheric profiles over a  $\sim 300 \text{ km}^2$  ice sheet around  $78^\circ\text{N}$  that was of larger-scale representativeness compared to the 1999 counterparts.

### 3.1 Diurnal Variation of Temperature, Humidity and Wind Speed in Vertical

Sounding number of atmospheric profiles each day was different as impacted by strong winds in the ice station. To obtain typical diurnal variation features of atmospheric vertical structure, profile data on 29 August was selected with controlled by a high pressure (Fig 2) and all the most fine day to analyze the variations. Figure 4 presents the profile variations of temperature, humidity and wind velocity at different time (10:00, 12:00, 18:00 and 22:00 LT.).

As given in Figure 4a, the vertical structure of temperature profile is of typical pattern

on diurnal variation of the floe ice in high latitude over the Arctic Ocean. Temperature on the surface is higher than that in the near-surface layer at the noontime owing to solar heating. A mixed layer is below 100 m level and above the level temperature increases with height that is the level of temperature inversion at intensity of  $1^{\circ}\text{C}/100\text{m}$ . The mixed layer disappears after 16:00 LT and a new mixed layer emerges above 200 m level with its lower portion for inversion at intensity of  $2^{\circ}\text{C}/100\text{m}$ . The PBL becomes steady at nighttime (after 18:00 LT) with a mixed layer above 100 m level where temperature was about  $0^{\circ}\text{C}$ , while the effect of irradiative cooling in clear sky before sun rising the inversion strength reaches maximum of near  $\sim 6^{\circ}\text{C}/100\text{m}$ . An observational fact was similar to those in the other parts except lower intensity. In general, the variation of profiles showed that temperature at 400–600 m level was higher than the surface and there is thermally steady stratification in most cases as air temperature increases with height.

The diurnal variations of humidity, wind velocity and direction in vertical synchronously with above temperature profile show as figure 4b, 4c, 4d. At daytime there is a mixed layer of humidity below 50 m level indicating that humidity varies little with height. Above the level humidity rises noticeably with increasing height and an inversion layer of humidity exist. In the afternoon (16:00 LT) the inversion layer reaches its maximum intensity and went up above 150 m level. From evening till night the mixed layer at  $< 50\text{m}$  level turns into an inversion layer of humidity, and above 50 m level becomes mixed layer. The vertical structures of wind direction/velocity were sufficiently simple. The velocity increased versus height with peaking at the 100 m level at daytime. The wind gradient was maximal around noontime about  $4\text{m s}^{-1}/100\text{m}$ . From the evening till the night the height of the speed increasing with the height was limited to 50 m above surface and the gradient reduced to the order of  $3\text{m s}^{-1}/100\text{m}$ . As to the change in wind direction in the vertical it was quite similar to the velocity, i.e., it changed more greatly with height in the near-surface layer and smaller variation above 100 m level. In general southeast wind at surface changes to steady southerly winds as the height increased.

The above description of the diurnal variations in vertical structures of the four elements indicates that the depths of temperature and humidity inversions as well as the height of wind shear above near surface layer are of remarkable pattern of the diurnal variations on August 29, 2003. The altitude of convective boundary layer in daytime is higher than that of stable boundary layer in nighttime. The altitude for both averaging is 200 m, which is 100 m lower compared to the first CHINARE measurement around  $73^{\circ}\text{N}$ .

### 3.2 Mean Characteristics of PBL Vertical Structures

The vertical structures of PBL parameters are different by the influence of different weather processes in the ice station. To get the PBL mean feature the profile data of temperature, humidity and winds sounded 50 times are treated and statisticly analyzed. It is indicated that the PBL over  $78^{\circ}\text{N}$ ,  $144^{\circ}\text{--}148^{\circ}\text{W}$  area could be broadly classified as the structures of stable, unstable and multi-layered, with their mean profiles presented in figure 5. It can be seen that from figure 5a air temperature rises vertically with height, the snow surface temperature is  $-4.9^{\circ}\text{C}$  and  $-0.58^{\circ}\text{C}$  at 100 m level. It means that the intensity of

temperature inversion reached  $4.3^{\circ}\text{C}$ . Then temperature goes up gradually with a mixed

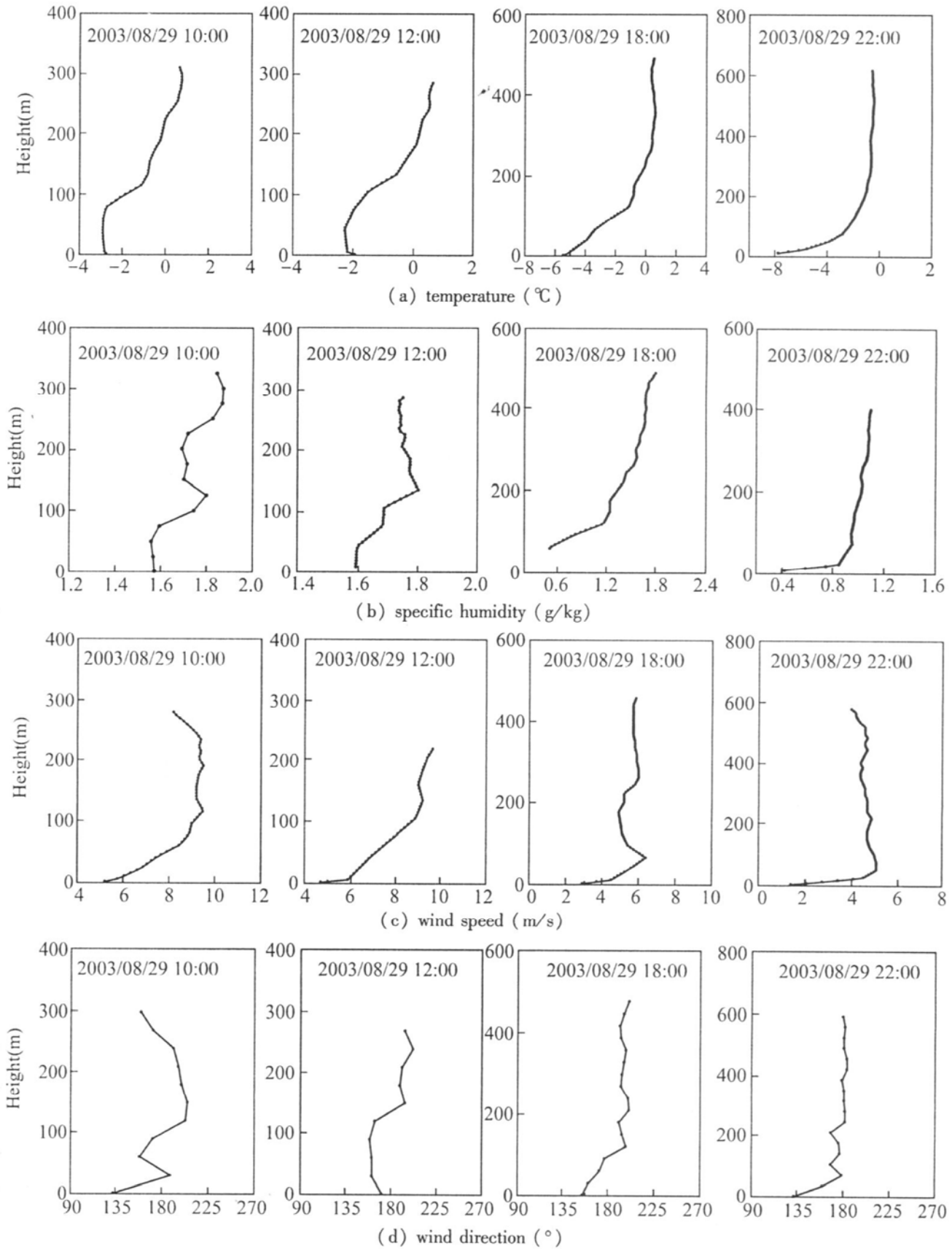


Fig 4 Diurnal variation of temperature( a), humidity( b), wind speed( C) and wind direction( d) profiles sounded in the ice camp in September 29, 2003

layer above 250 m. This typical structure of stable PBL happened at the frequency of near 20%. From soundings the temperature of mixed layer was higher than that of near-surface layer in association dominantly with upper-air warm advection as dynamic effects. The fea-

tures of average profile of wind speed and humidity for stable stratification are of gradients

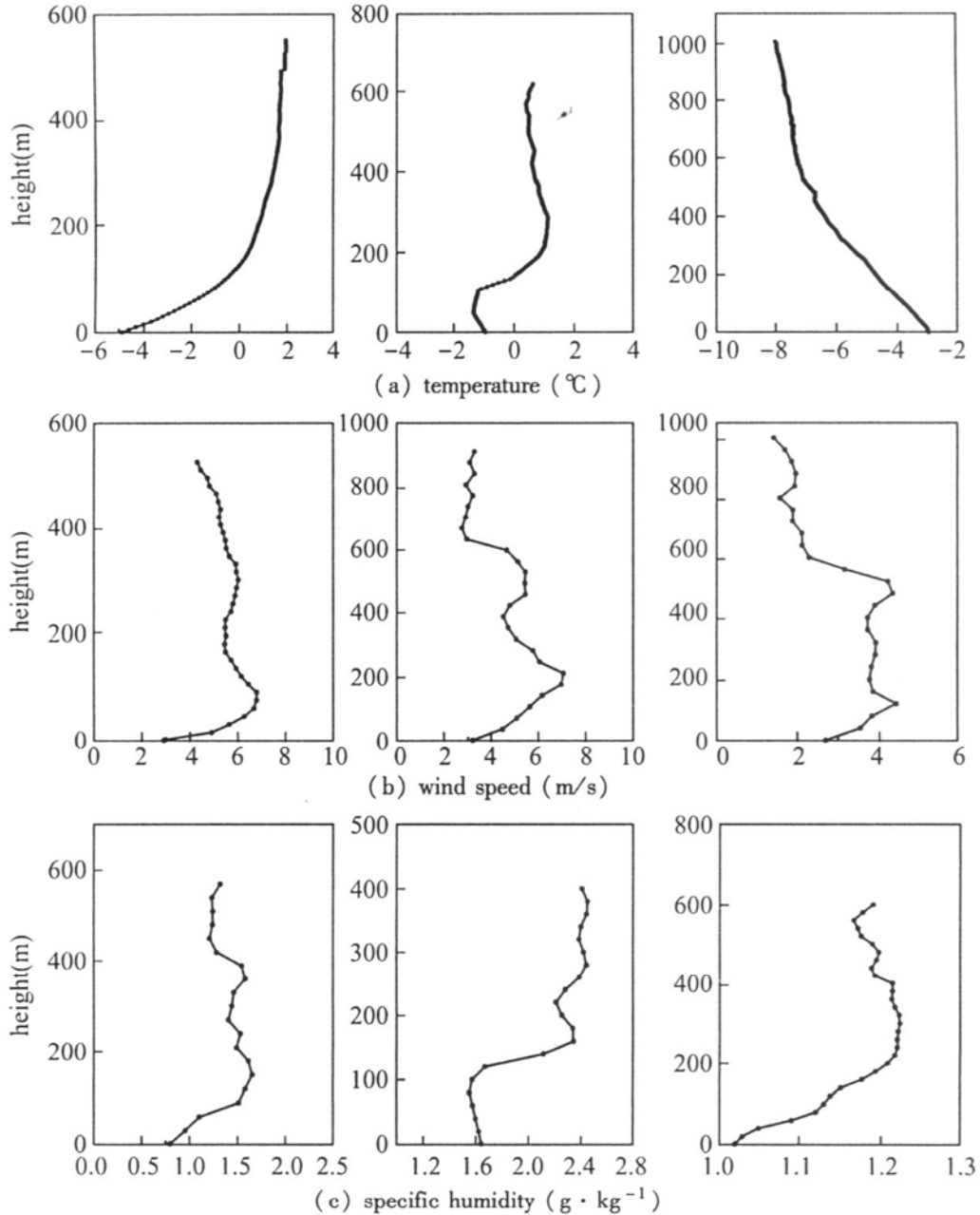


Fig 5 Average structure of temperature (a), wind speed (b) and humidity (c) profiles sounded in the ice camp

with  $4 \text{ m/s}$  wind speed and  $1.0 \text{ g/kg}$  specific humidity to be rather big at 0 to 100 m level. Above the level it is mixed layer where the wind speed and specific humidity change very little with the height.

Synoptic systems, especially windy weather, had great impacts on distribution of sea ice surrounding the station. Multi-layered profiles were often caused by interactions among ocean/sea ice/air (Fig 5b) at the frequency of 48%. Temperature dropped as a function of altitude between 0 to 50 m level, quickly rose between 100 to 200 m level to form an inversion layer, followed by its slow drop to generate a mixed layer at  $> 300 \text{ m}$  height. This multi-layered structure was true for wind velocity and specific humidity, given in their profiles. It follows that temperature difference arising between large-size floe ice and open water leads to the fact that oceanic warm and wet air flows across the station from above the near-surface layer, resulting in the multi-layered structure as shown in Figure 5b, which

was also mentioned by Qu *et al.* (2002)<sup>[4]</sup> who regarded it relate to cloudy and foggy weather in the summer of the Arctic Ocean. The unstable boundary layer refers to the rate of temperature drop with height closing its lapse rate when its inversion disappeared. It is seen from Fig 5c that the lapse rate is on the order of  $0.7^{\circ}\text{C}/100\text{m}$  below 500 m level and less than that given above. Wind speed and specific humidity change with height are close to the cases of above mentioned two structures and a humidity inversion and a gale layer just are above surface. The frequency for this vertical structure was 29%.

### 3.3 Strong Wind Shear Process

With conventional data, it is difficult to discern the genesis and development of wind shear that often occurs in the PBL of the study region. During the observation wind gale of higher than  $8\text{ m/s}$  (Fig 2) occurred in many cases accompanied by temperature inversion and wind shear. In the case the tethered balloon and sensor were lost twice caused by strong wind shear of  $> 14\text{ m/s}$ . The process was associated with the exchange of heat and momentum in the PBL. As an example shown in Figure 6, find a most intense wind shear happened on September 2. It was southerly winds at a speed of  $6\text{--}7\text{ m/s}$  near-surface layer, while the wind turned suddenly into easterlies at a speed of  $17\text{--}19\text{ m/s}$  at 100 m level, resulting in the shear vigor of the order of  $10\text{ m/s}$  for the 100 m range. Meanwhile, abrupt change happened to temperature (humidity), increasing from  $-6$  to  $2^{\circ}\text{C}$  ( $1.4$  to  $1.9\text{ g/kg}$ ), leading to a temperature (humidity) inversion intensity of  $8^{\circ}\text{C}$  ( $0.5\text{ g/kg}$ ) within the range. It is easy to see that upper-level stronger warm and moist air from the southeast interacted vigorously with near-surface-layer cold air in their exchange with the result of the formation of strong wind shear, temperature and humidity inversions. Satellite data has shown such happening may lead to the break of pack sea-ice at high latitudes (figure omitted). Figure 7 gives the synoptic situation at 500 and 1000 hPa on August 31 and September 1. It is indicated that the formation process of intensive shear is related with obviously weather background.

On August 31, a polar vortex was centered to the northwest of the station on the 500-hPa chart and a high ridge in the west of the station was moving to the north on 1000 hPa chart so that the station was under no effect of the weather systems. The next day the vortex moved to the center of the Arctic Ocean and the surface high pressure was cut-off into smaller closed systems. In this case, the station is affected by air current from north side of the closed high and south southwest winds prevailed in the near-surface layer whereas in the upper level, influenced by the flow from east side of the vortex with easterlies. The dramatic interactions of air currents between higher and lower levels caused the vigorous wind shear in the PBLs.

## 4 Results and discussion

Based on analysis of PBL vertical structure in the Arctic region ( $\sim 78^{\circ}\text{N}$ ,  $144\text{--}148^{\circ}\text{W}$ ) from more than 50 atmospheric profiles and relevant data sounded at the ice station the following results could be discussed.



The depth of temperature and humidity inversion as well as the height of wind speed shear layer over the floe-ice area show significant diurnal variation. The height of daytime convective boundary layer is higher than that of the nighttime stable boundary layer.

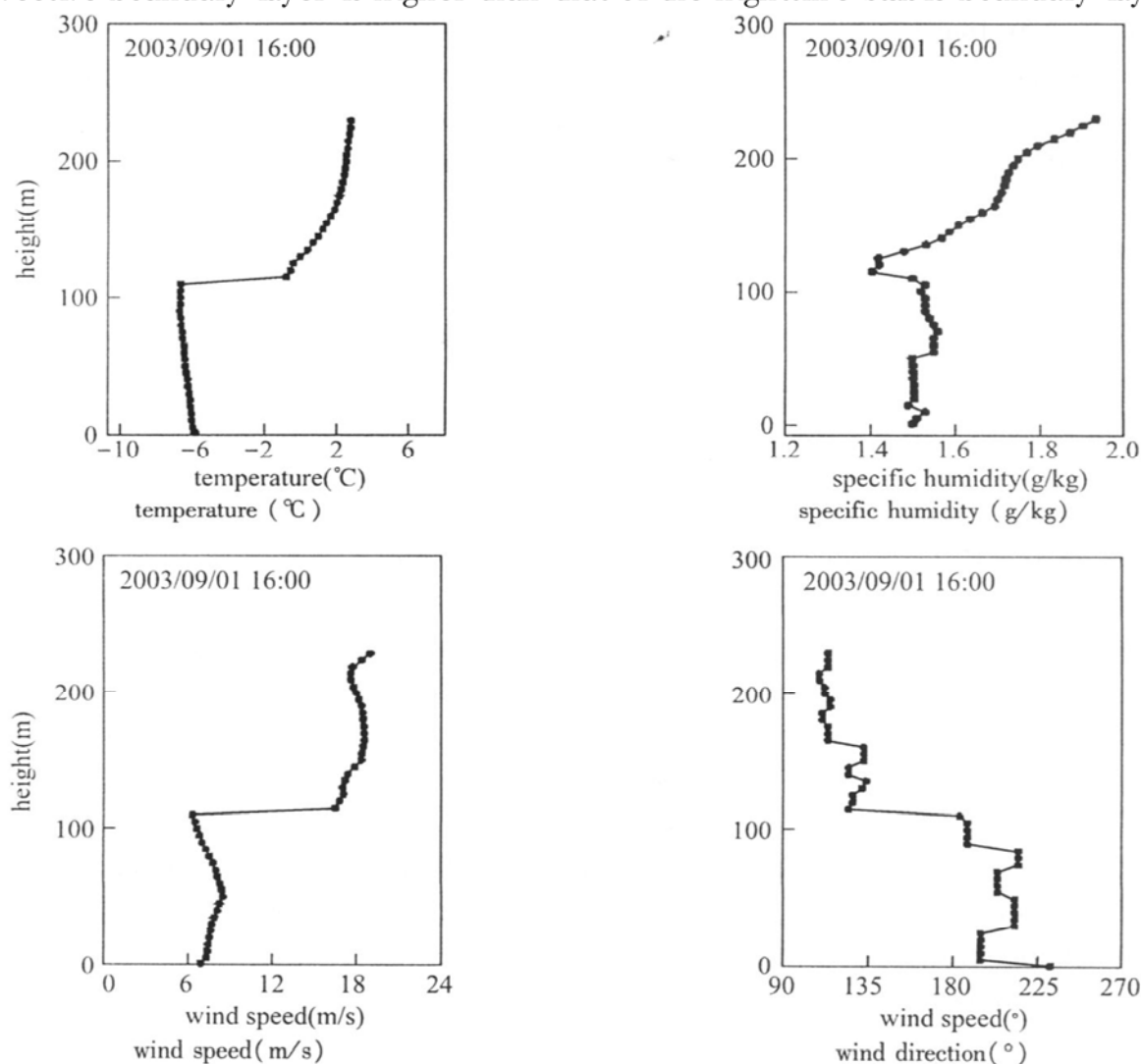
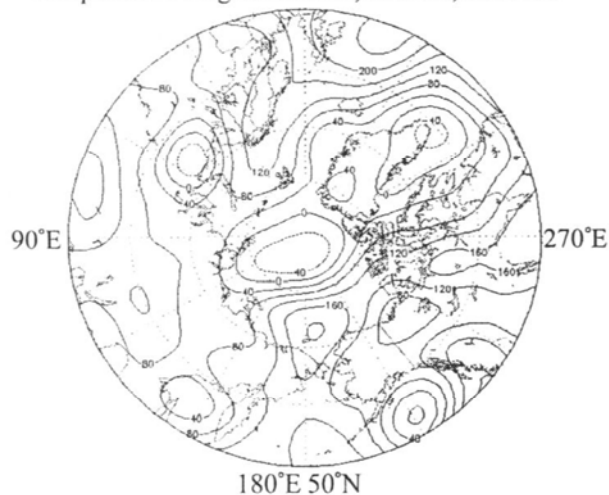


Fig 6 Profiles of temperature, specific humidity, wind speed and wind direction sounded in ice camp in September 1, 2003

Geopotential height in Arctic, 1000mb, 20030901



Geopotential height in Arctic, 1000mb, 20030901

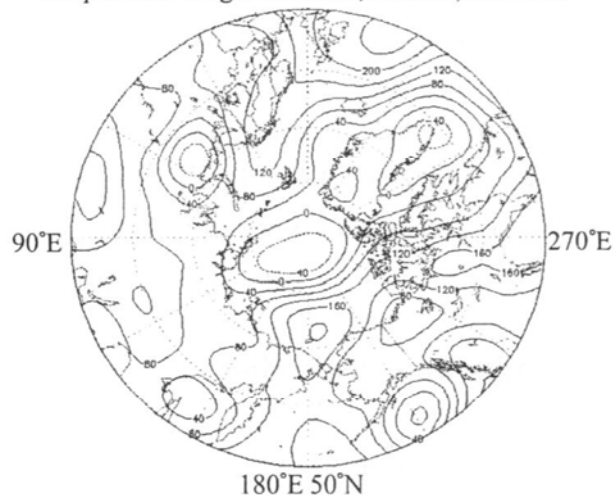


Fig. 7 Geopotential height of 1000 hPa and 500 hPa in Arctic region on 1 Sep, 2003 (data from NCEP).

The PBL features of vertical structures are of stable, unstable and multi-layered structure appeared at the frequency of  $\sim 20\%$ ,  $\sim 30\%$  and  $\sim 50\%$ , respectively in the Arctic region which differs from previous conclusions. For example, in atmospheric or climate models wherein the polar ABL is often assumed to be stable structured. Our observation, in contrast, showed higher frequency of unsteady and multi-layer structures during ice melting, indicating the necessity of improving the model ABL parameterization scheme on the basis of observational experiments on a seasonal basis. Vigorous interaction between stronger upper-level warm, wet air and cold air in the near surface layer is responsible for intense wind shear, temperature and humidity inversions, leading to the intensity of  $10 \text{ m/s}/100 \text{ m}$ ,  $8^\circ\text{C}/100 \text{ m}$  and  $0.5 \text{ g/kg}/100 \text{ m}$ , respectively. Such process would trigger intensifying interactions between ocean and sea ice and air leading of breaking of pack ice, producing open water area, speeding up the ice melting and increasing the Arctic clouds rising surface temperature in the high-latitude region.

As the Arctic Ocean is situated in geographic position and the harsh climate soundings, especially those regarding ABL structure and turbulence is scarcity. As a result, little has been reported about the study on the PBL features, particularly their genesis/development mechanisms and effects upon fast change in the Arctic climate, which needs accumulating more data for further study.

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