

THE FEATURES OF SEA-ICE COVER, SNOW DISTRIBUTION AND ITS DENSIFICATION IN THE CENTRAL ARCTIC OCEAN

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ABSTRACT: Based on the observation of sea-ice cover and measurement of snow depths and stratigraphy during China's First North Pole Scientific Expedition, three types of surface topography of sea ice and correspondingly three categories of snow distribution in the central Arctic are classified. It is considered that the classification will help to determine the sites for snow depth measurement, stratigraphy observation and snowpits sampling. The snow cover is slowly accumulated during the long Arctic winter, approximately from September to early May next year, while its ablation shows abrupt from south to north. By the end of August, the snow cover is almost totally removed. The spatial distribution of snow depth is characterized by a northwardly decreasing trend, which is proposed to result from the remote vapour sources, i. e., the major vapour over the Arctic regions is transported from mid-latitudes. The stratigraphy of the snowpits are characterized by the extensively existed depth hoar at the deeper part of the pits, which is probably a signal of the beginning of the long Arctic winter. The present of infiltration-congelation ice adhering to sea ice surface at the end of the ablation season indicates that the annual accumulation is approximately equals to the annual ablation near north pole.

KEY WORDS: Arctic Ocean, sea-ice cover, snowpack, snow stratigraphy

I. INTRODUCTION

The Arctic Ocean, with an area of approximately $9.5 \times 10^6 \text{ km}^2$, is predominantly sea-ice covered throughout the year in its central area, while the south edge of marginal ice zone(MIZ) varies seasonally. The maximum of ice cover extent occurs between February and March, while the minimum is between August and September. Placing the ice edge to 8% ice concentration (percent areal coverages of sea ice) isopleths, variation of extent of sea-ice cover of the Arctic Ocean is between $9 \times 10^6 - 16 \times 10^6 \text{ km}^2$, by the observation of a satellite-borne scanning multi-spectral microwave radiometer during the interval 1978 – 1987(Gloersen *et al.*, 1991).

Forced by the prevailing wind and ocean currents, the packed ice undergoes a continuous

drift(Fig. 1). The major export of sea ice out of the Arctic Ocean, with the maximum speed of 10 cm/s (Piacsek *et al.* , 1991), is transported through the currents from east Siberia coast to Fram Strait, which is so-called Trans-Polar Drift Stream. In Barents Sea, however, the ice moves in anticlockwise direction under the force of North Atlantic Warm Currents, but the drift does not comprises a enclosed cycle. Part of ice brought by south-flowing North Cape Current converges with the ice brought by Trans-Polar Drift Stream, and eventually melt away in north Atlantic Ocean. The sea ice and currents drifts clockwise in the area north of Bering Strait, which is called Beaufort Gyre.

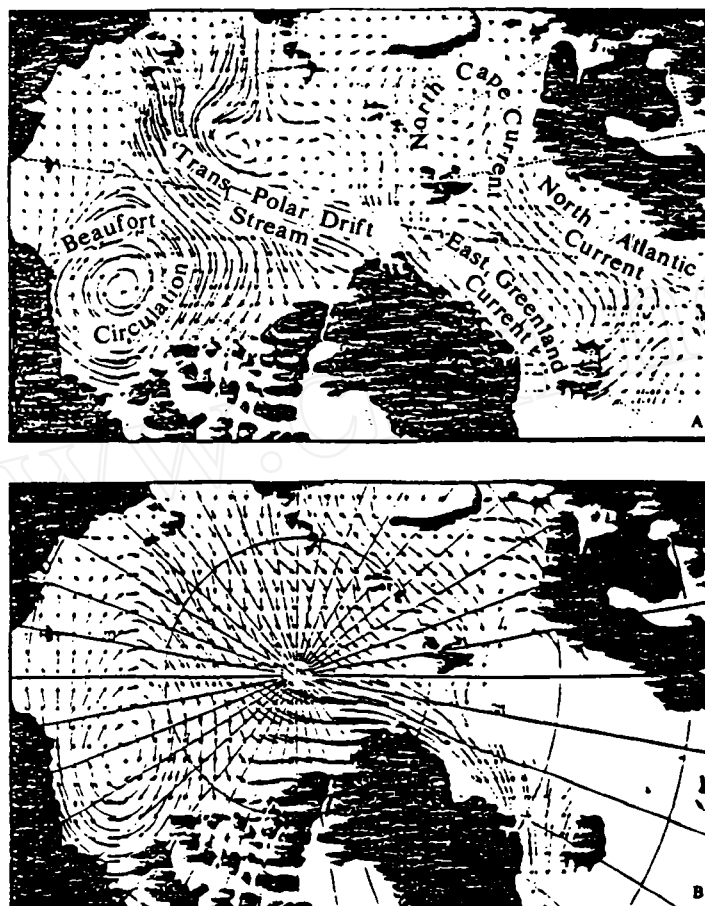


Fig. 1 Distribution of mean geostrophic ocean currents (A) and mean annual ice drift (B) at the surface of Arctic Ocean (After Piacsek *et al.* , 1991)

During China's First North Pole Scientific Expedition (from April 24 to May 6, 1995), the team traversed with dogsleds from 88° N to north pole, approximately along 75° W (Fig. 2). The surface features of sea ice (e. g. , ice concentration, surface roughness, microrelief of snow cover) was investigated, and snowpits stratigraphy was observed along the route. We considered that the snow distribution depends largely on the topography of underlying sea ice.

Thus, the sites for snow depths measurement, stratigraphy observation and sampling should be determined in consideration with features of surface topography.

II. THE FEATURES OF SEA ICE

To large scale of the Arctic Ocean, the feature of multi year floes of interior regions is much different from that of MIZ. Also, the distribution of sea ice versus open water, and the

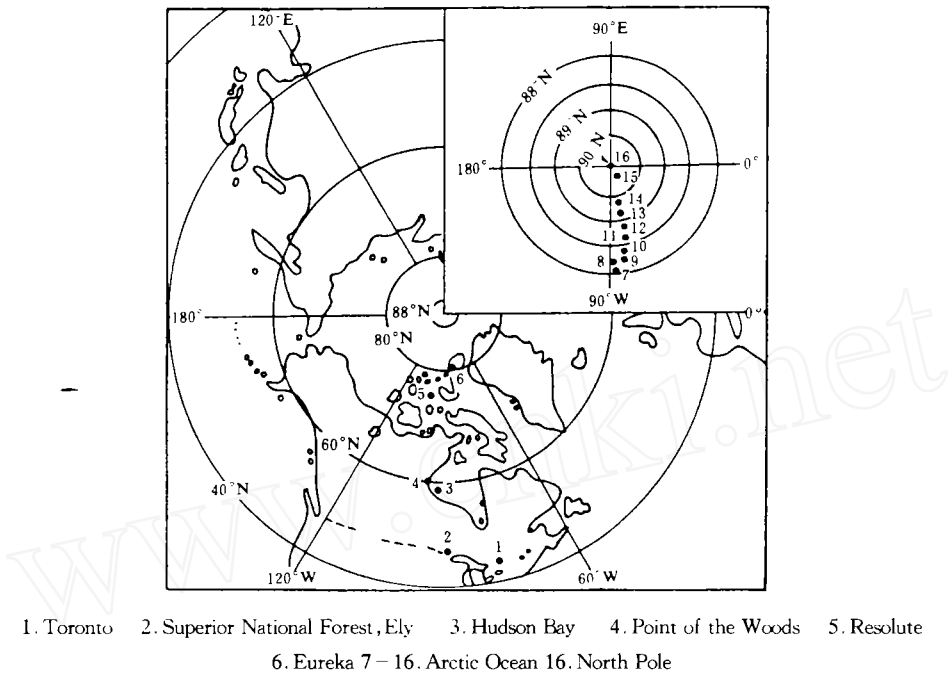


Fig.2 Study sites during China's First North Pole Scientific Expedition

various drift forms of snow surface on both smooth and rough ice show its regional characteristics.

1. Variation of Ice Concentration

Unlike the situation in the MIL, ice concentration around north pole is much higher due to a perennial low temperature. Along the route of traverse, we did not encounter much wide strip of open water north of 88° N, except a shear zone roughly around 89° N. According to Piacsek *et al.*, (1991) and Parkinson (1991), ice concentration in the central Arctic a remains up to 98 % during Arctic winter, except a gradual decreasing from early June until the end of the August, in which season the minimum value is about 70 % . Instead of the gradual decrease of concentration, there is a sharp increase to the winter value during September, after which point the concentration remain relatively constant(over 90 %) during long Arctic winter. On the other

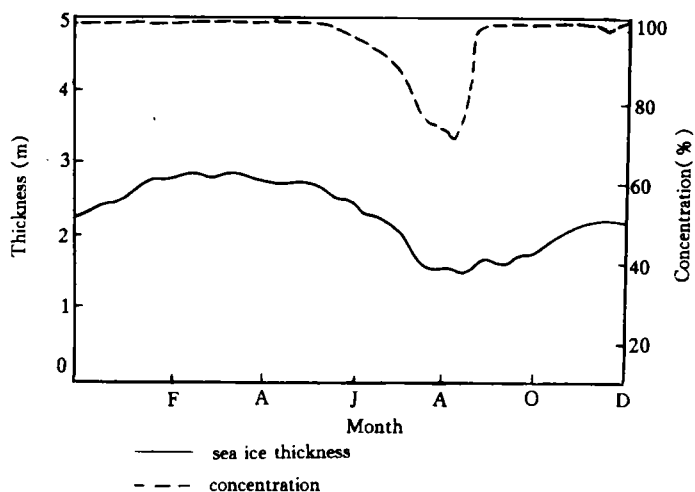


Fig. 3 Seasonal evolution of the ice thickness and ice concentration in the central Arctic(after Piacsek *et al.* ,1991)

hand, the behavior of the ice thickness is much less abrupt in contrast with that of concentration, the average maximum reaches approximately 3 m by the end of March.

The interannual variability of ice coverage in the central Arctic Ocean concentrates in summertime, with the highest variability in September, the second highest in August. Then the variability shows a sharp drop with the progress of ice frozen from September to October. In the central Arctic Ocean, it should be noted that much of the summertime variability results from different patterns of ice distribution rather than from changes in areal extent. For instance, ice extent of the Arctic Ocean in September 1973 and September 1974 differed by only 2%, although in 1973 there was a wide strip of open water northeastward of Alaska and Canada, which did not exist in 1974(Parkinson *et al.* , 1987, 1989). Nevertheless, in 1974 there was much more open water north of Svalbard and north of eastern Siberia than in 1973. Since the observation of a satellite-borne scanning multispectral microwave radiometer during the interval 1978 – 1987 did not show a consistent(or even near-consistent) trend toward either increasing or decreasing ice coverage, the demonstrated short-term variability can not easily be attributed to global climatic change(Parkinson, 1991).

2. Topographic Classification of Sea Ice

The sea ice is not always smoothly extending because it undergoes deformation under the force of wind and ocean current. On the other hand, the shape of deformed ice will become smoother by weathering. One of the results of ice deformation is leads or polynya. Leads are linear extended cracks in the ice, with the length which is estimated to be mostly within 100 m along the route of the expedition. Polynya, with wide-ranged size variation, are any non-linear shaped areas of open water. In most cases, some refrozen types of ice such as new ice, ninas

(0.01 to 0.1 m thick, formed in areas away from wave action, which is characterized by flexible sheets) or young ice (0.1 – 0.3 m thick, median types between ninas and first-year ice) are formed within leads and polynya. However, the estimated open water areas within the route of our traverse was less than 1%, which coincides well with the observation by Nimbus – 7 SMMR (Gloerson *et al.*, 1988).

Except for leads and polynya generated via fracturing, hummocks and ice ridges are formed through processes of hummocking and ridging. Chunks of ice pile up along ridged ice zone, and frequently form enclosed circles. Hummocks and ice ridges tend to get aged due to long-term wind erosion and thermal processes.

Based on the observation of spatial features of hummocks and ice ridges distribution along the traverse route in the central Arctic Ocean, basically three types of topography of sea ice, in scales of hundreds to thousands meters, could be classified, i.e., smooth ice enclosed by hummocks and ridges, extremely rough ice area with no obvious smooth ice, smooth ice area with few hummocks or ridges. The classification is unique not only because there seems no additional types of distribution and is rational for describing the topography of the region, but also help to simplify the determination of the sites for snow depths measurement, stratigraphy study as well as snowpits sampling when the focus of study concentrates to snow cover over ice, which will be discussed here later.

3. Snow Distribution

Besides sea ice, snow cover lying on sea ice is scientifically essential in understanding the ocean-ice-atmosphere processes. The depth of snow varies remarkably with regions and seasons. The spatial and temporal variation of monthly-averaged snow depth in the north polar region is shown in Fig. 4, which is based on the data set of global snow depth provided by data center for glaciology (WDC – D). The data set provides latitudinal values of snow depth every 4 latitudinal degrees, and has one value every 5 longitudinal degrees, that is, in $4^{\circ} \times 5^{\circ}$ grid nets. Therefor, the average snow depth of a parallel is the arithmetic mean of 72 values. It can be seen from Fig. 4 that the main accumulation season is from September to next April. After that, the snow ablation proceeding northwardly from May to August, until which point the snow cover is totally removed. One obvious characteristics of snow cover in the north polar region is its abrupt removal in contrast with its relatively long accumulation season. The spatial variation of snow depth, which is only south to north considered here, is shown as Fig. 4(B). It's clear that the snowfall accumulates parallelly during the main accumulation season. The snow depth variation displays a northward decreasing trend except that of the region between $86^{\circ} - 90^{\circ}$ N. The reason probably lies in the vapour sources for precipitation. In fact, the local vapour for snowfall is rare because the most parts of the ocean are sea-ice-covered during the season of snow accumulation. Thus, air masses over high Arctic regions probably come from mid-latitudes. The northwardly decreasing trend of snow depth shown in Fig. 4(B) is the re-

sult of the lose of water from air mass during long-distance transportation. However, the April profile in Fig. 4(B) drops below the profiles of February and March in south of 70°N, which indicating that in April the ablation proceeds 70°N.

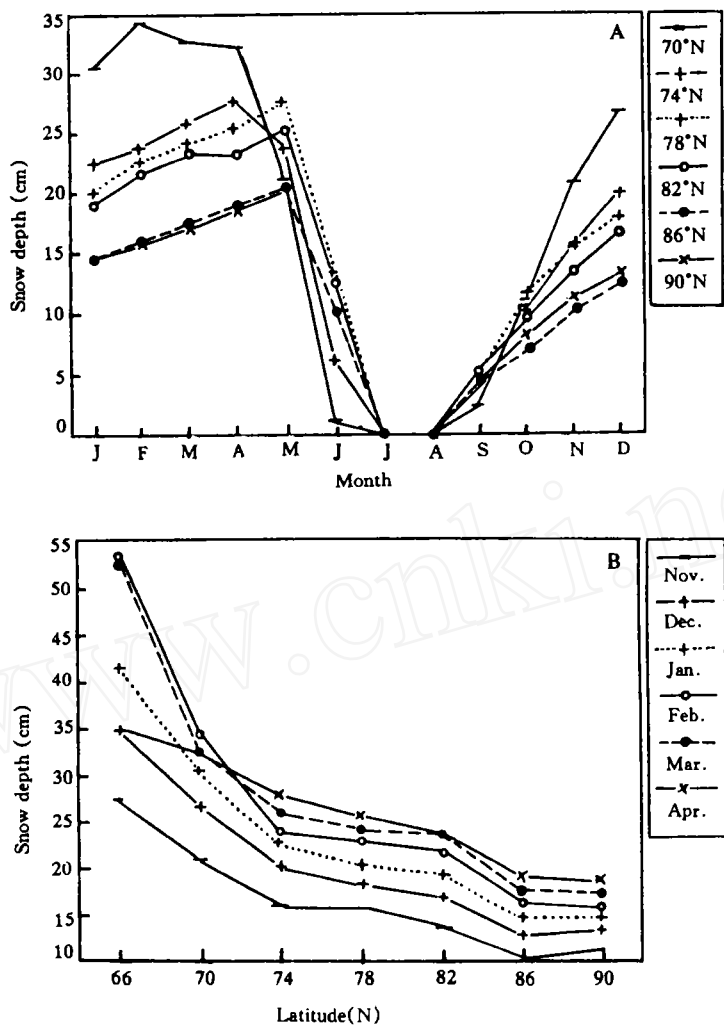


Fig.4 Snow depth variations in seasonal(A) and in northwardly direction(B)

The snow surface on both smooth and rough ice was comprised of various microreliefs: sastrugi, barchan, and long longitudinal dunes(approximately up to 20% of study area). But due to the irregular drift of floes and the disturbance of hummocks and ridges to wind direction, there is no prevailing azimuth(prolonged orientation) of these forms discovered along the traverse route.

Based on the above classification of ice topography along the study route, correspondingly three categories of snow distribution can be classified. (1)The snow cover enclosed by hummocks and ice ridges distributes regularly(Fig. 5); the central area is characterized by lower

depths, higher intensities due to wind packing, while rough areas along the border is characterized by higher depths and lower intensities. Averagely to say, the bands of the concentric circles passing across midpoint of radius may be the most suitable positions for measurements and sampling. (2) In the areas with extremely rough ice, snow distributes irregularly and not suitable for study. (3) In the smooth areas with little deformed ice, the snow cover is free from the turbulence generated by the wind over the rough ice far away, thus the choosing for measurement and sampling has more freedom because the snow distributes relatively uniform.

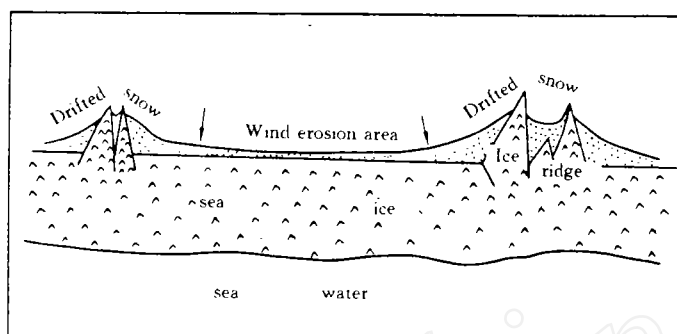


Fig. 5 A scheme of cross-section of snow cover quasi-circled by hummocks(ridges), the arrows point to the ideal positions for snow measurements and sampling

The snowpack on the aged ice in the central Arctic Ocean with size greater than 20 km may best stand for winter accumulation of snowfall(Hanson, 1980). The snow depths measured during April to May of 1995 expedition were between 10 – 60 cm. However, the areal percentages of the three categories of the snow distribution were hard to estimate and is expecting the survey by remote sensing.

There are three morphological factors that may affect variations of snow depth. (1) Ice thickness(or ice age). Depth vary considerably on a local scale in relation to ice type, especially the degree of hummocking, and the age of ice. For instance, measurements at the central Arctic in spring 1954 on multiyear ice of average relief up to 1 m, with individual hummocks rising to 3m, show 10 – 20 cm snow on level areas, 14 – 55 cm in hollows, up to 100 cm near hummocks, but 8 – 11 cm on the level ice of refrozen leads with ice 1.3 m thick(Barry, 1983). A major statistical analysis shows that in the central Arctic in March – May 1974 – 1978 the mean snow depth was 5 cm on level ice 30 – 160 cm thick, 8 cm on level ice 160 – 200 cm thick, 20 – 25 cm in sastrugi, and 75 – 90 cm on ridged areas(Buzuev *et al.*, 1979). (2) The degree of hummocking. Despite a shorter period of accumulation, the mean snow depth is about 50% greater in the border of rough ice surrounding the relatively flat areas. Buzuev *et al.* sited an approximate relationship between mean snow depth h and ridge height H :

$$h = 0.11 H^{1.3}$$

which is well coincides with the measurements in the central Arctic Ocean. (3) Size of floes. It

is found that for individual floes or ridge-surrounded ice, the snow depth partly depends on their sizes. The small floes display a significant trend of decreasing mean snow depth with decreasing size of the floes. This might be expected because larger floes would have more area removed from the disturbance generated by the wind over the bordering rough ice. Hanson's observation(1980) indicates that a minimum mean depth of snow cover is hypothesized to occur on a small floe in the size range 1000 – 3000 m² where the surrounding ridges and piles of ice are 1.5 to 3.5 m high. The mean snow depth would be greater both on larger floes and on smaller floes.

III. ACCUMULATION, MELTING AND STRATIGRAPHY OF SNOW COVER

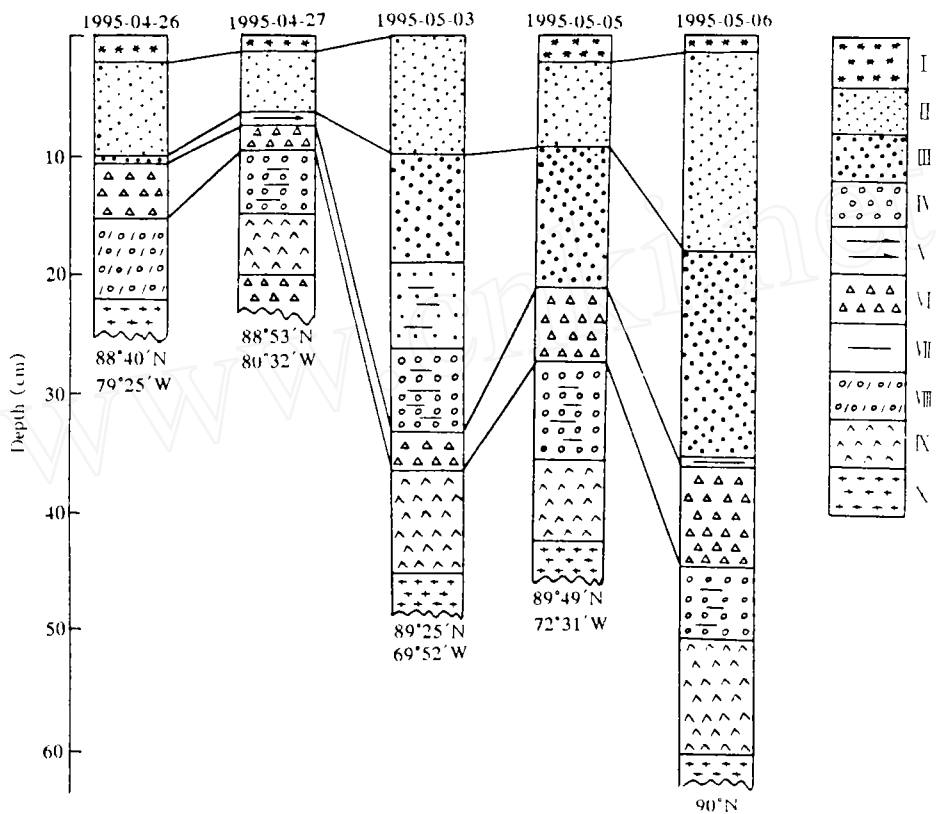
1. Accumulation and Melting Processes

In the Arctic Ocean, the ice mass balance(includes snow cover)involves: new ice growth in leads, polynya and in Marginal Ice Zone, thickness enhancement and snow deposition; large-scale export by currents , top and bottom ablation , and the thickness changes through ice deformation(e. g. , divergence and convergence). If singling the snow cover out, however, the income includes all categories of precipitation, which is mainly snowfall, sleet, frost, diamond dust and water brought via condensation, etc. , while the output of snow includes melting during warm season and during the drift to south regions, snow lose by ice deformation, as well as surface snow blown to open water areas by wind, etc.

Observation in the 1960s in the central Arctic indicated that there was (on an average) a rapid autumn accumulation to about 20 cm(Loshchilov, 1964), followed by a rather slower increase to 30 cm in early February, and then a further increase to 40 cm in early May. Our study at four sites on flat ice from 89° – 90° N, which are 55 cm, 45 cm, 42 cm and 60 cm respectively, shows no remarkable different from the measurement during the same season of the 1960s. The melting of snow cover occurs between May to August(Fig. 4), which starts from south edge. The first melt puddling starts about early June averagely at 75°N, and a month later at 85° N(Yanes, 1966; Marshunova *et al.* , 1978). Generally to say, the snow cover is totally removed until August(Li, 1996). Although the ablation of snow cover is abrupt compared with accumulation, the melting of snow slows down when it is accompanied with new snowfall. According to Hanson's study(1980) in the Beaufort Sea, the snow cover removal took about 22 days(21 June – 13 July), which in the absence of new snowfalls might be reduced to 14 to 15 days. Although the snow cover is almost completely melted at north pole in August, the present of infiltration-congelation ice adhering to sea ice surface at the end of the ablation season indicate that the annual accumulation is approximately equals to the annual ablation near north pole(Shumskii, 1955).

2. Snow Stratigraphy

The stratigraphy observation of snowpit proceeded roughly every 1/5 latitudinal degree a-long 88° - 90°N traverse route, and stratigraphy profiles of total 10 snowpits were observed. As has mentioned above, the snow cover on sea ice is not uniform, the determination of study sites followed the regulation of II - 3 (Fig. 5). For everyday's study sites was near night camp, hence the measurement and sampling had to be canceled when the night camp set up at rough areas. Among 13 days' traverse, 3 days' study was canceled and completed 10 sites in all. Six typical stratigraphy profiles of snowpits are shown in Fig. 6.



- 1. new snow 2. fine firm 3. medium firm 4. coarse firm 5. wind glaze 6. depth hoar
- 7. ice layer 8. very hard coarse firm 9. infiltration - congelation ice 10. sea ice

Fig. 6 The contrast of typical stratigraphy profiles of snowpits along the route of the expedition

The basic features of the snow densification deduced by stratigraphy observation in the study area can be concluded as follows: (1)The final form of snow densification in the central Arctic is firm other than dynamic metamorphic ice because the snow cover preserves as long as one Arctic winter and the snow temperature is extremely low. (2)Depth hoar, which is formed

by sublimation, is ubiquitous in the snow cover, the underlying sea ice may play an important role. The depth hoar is usually an indicator of autumn layer, when the surface is cooling rapidly and the underlying layers are still relatively warm. Evaporation takes place in the lower layers, the vapour rises and condenses to form depth hoar crystals in the cold upper layers. Conditions seem to be especially favorable when the snow is lying on the top of much denser material such as ice. Depth hoar was well developed in the 10 snowpits excavated along 88° – 90°N traverse route, with the thickest layer 9cm and thinnest 1.7 cm. (3) There is a layer of infiltration-congelation ice adhere to the sea ice surface. The layer is proposed to be formed either in the south area before drift to the central Arctic Ocean, or in situ at the end of the ablation season, since the snow layer keeps cold during the accumulation season. Therefore, the formation of infiltration-congelation ice is the result of the combination under certain regions and seasons. (4) The representative stratigraphy profile shows as “new snow – fine firm – medium firm – depth hoar – coarse firm – infiltration-congelation ice”.

Ice layers (or sometimes radiation ice-glazes), with the thickness between 5 – 10 cm, is commonly recognized in the wall of snowpits. In Antarctic Ice Sheet, this sized ice layer usually forms in the surface layer of near coast regions and is scarce in interior regions (Qin, 1995).

Snow temperature largely depends on near surface air temperature, with a difference approximately within 2°C. The former is a little higher than the latter when it is cloudy with south wind, while a little lower when it is clean with north wind.

SUMMARY

(1) The area of open water in the central Arctic Ocean, with ice concentration up to 98% in most seasons, is estimated to be within 1% along the traverse route of the expedition.

(2) The evolution of the topographic features of sea ice is the result of ice deformation and weathering processes. Leads, polynya, hummocks and ice ridges are formed via fracturing, hummocking and ridging of sea ice. The rough appearance of multiyear ice would become smooth by weathering.

(3) Three categories of topographic pattern of sea ice could be classified: flat ice enclosed by hummocks and ridges, large-scale level ice, and extremely rough area. The feasibility for snow measurements and sampling should be determined on the basis of the snow distribution on the three patterns of ice.

(4) The seasonal variation of snow cover is characterized by slow accumulation during long Arctic winter, and abrupt ablation in summer. Remote air mass sources may be responsible for northward decreasing trend of snow depth.

(5) There is no obvious areas with annual accumulation of snow larger than annual ablation, while near North Pole they keep an approximate equilibrium. The snow cover would melt away when drift to the margin of the ocean, so the snow cover is not permanent and always in motion with ice drift.

(6) Depth hoar is ubiquitous in snow cover, the underlying sea ice may play an important role in depth hoar formation. From surface to bottom of a snowpit, the representative stratigraphy profile shows as: new snow – fine firn – medium firn – depth hoar – coarse firn – infiltration-congelation ice. The formation of infiltration-congelation ice is the result of the combination under certain regions and seasons.

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REFERENCES

- Barry R. G., 1983. Arctic ocean ice and climate: perspectives on a century of polar research. *Annals of the Association of American Geographers*, 73(4): 485 – 501.
- Buzuev A. Y., Romanov I. P., Fedykov V. E., 1979. Variability of snow distribution on Arctic ocean ice. *Soviet Meteorology and Hydrology* 9: 975 – 964.
- Gloersen P., Campell W. J., 1991. Recent variations in Arctic and Antarctic sea-ice covers. *Nature*, 352(4): 33 – 35.
- Gloersen P., Campell W. J., 1988. Variation in the Arctic, Antarctic, and global sea ice covers during 1978 – 1987 as observed with the Nimbus SMMR. *Journal of Geophysical Research*, 93(C9): 10666 – 10674.
- Hanson A. M., 1980. The snow cover of sea ice during the Arctic Ice Dynamics Experiment, 1975 – 1976. *Arctic and Alpine Research*, 12(2): 215 – 226.
- Li Peiji, 1996. The Arctic sea ice and climate change. *Journal of Glaciology and Geocryology*, 18(1): 72 – 80. (in Chinese)
- Loshchilov V. S., 1964. Snezhnyipokrov na l'dah tsentral'noi Arktiki. *Problemy Arktiki i Antarktiki*, 17: 36 – 45.
- Marshunova M. S., Chernigovskii N. T., 1978. Radiation regime of the foreign Arctic (Gidrometeorologicheskoe Izdatel'stvo, Leningral, 1971). National Science Foundation, Technical Translation, 72 – 51034.
- Piacsek S., Allard R., Wam – Varnas A., 1991. Studies of the Arctic ice cover and upper ocean with a coupled ice-ocean model. *Journal of Geophysical Research*, 96(C3): 4631 – 4650.
- Parkinson C. L., 1991. Interannual variability of the spatial distribution of sea ice in the North Polar region. *Journal of Geophysical Research*, 96(C3): 4791 – 4801.
- Parkinson C. L., Comiso J. C., Zwally H. J. et al., 1987. *Arctic Sea Ice, 1973 – 1976: Satellite Passive-Microwave Observations*. NASA Spec. Publ. SP – 489, 296pp.
- Parkinson C. L., Cavalieri D. J., 1989. Arctic sea ice 1973 – 1987 seasonal, regional and interannual variability. *Journal of Geophysical Research*, 94: 14499 – 14523.
- Qin Dahe, 1995. *A Study of Present Climatic and Environmental Record in the Surface Snow of the Antarctic Ice Sheet*. Beijing: Science Press, 202pp. (in Chinese)
- Shumskii P. A., 1955. K nucheniiu l'dov severnogo ledovitogo okeana (A study of ice on the Arctic Ocean). *Vestnik Akad Nauk SSSR*, 25(2): 33 – 38.
- Yanes A. V., 1966. Melting of snow and ice in the central Arctic. In: Ostenso (eds.) *Problems of the Arctic and Antarctic*, (11): 1 – 13.