A NUMERICAL STUDY FOR MECHANISM OF THE EFFECT OF NORTHERN SUMMER ARCTIC ICE COVER ON THE GLOBAL SHORT–RANGE CLIMATE CHANGE

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ABSTRACT

In terms of nine–layer global spectral model involving fuller parameterization of physical process, with a rhomboidal truncation at wavenumber 15, experiments are conducted by virtue of two numerical schemes, one with long–range mean coverage of Arctic ice, and the other with supercooled water at the same temperature as the ice, followed by an analysis of the difference field simulated by the two schemes. Results show that (1) the impact of Arctic ice on the northern short–range climate is realized through the change in polar ice coverage to cause local temperature change in the polar region to set up gradient difference in temperature from north to south, thus affecting the atmospheric circulations and, on the other hand, two trains of two–dimensional Rossby waves excited by the atmospheric heat source anomaly have impacts on the Northern Hemisphere (NH) extratropical region, one of which is similar to the JP teleconnection pattern first presented by Nitta (1987); (2) The significant impact of Arctic ice anomaly on the southern short–range climate change is accomplished with the aid of the anomaly of the equatorial heat source that excites a two–dimensional Rossby wavetrain propagating along a great circle route into the Southern Hemisphere (SH) extratropics, and the cross–equatorial propagation of the NH wavetrain also has effects on the SH atmosphere. Simulation indicates that with the 15–day integration the Arctic ice exerts an influence mainly on the NH and when the model atmosphere is getting stabilized, the effect is dominantly on the SH short–range climate change.

Key words: polar ice, wavetrain, short–term climatic change, influence mechanism

I. INTRODUCTION

In recent years, mor attention has been paid to the anomaly of equatorial SST and air–sea interaction. Recent studies indicate that tropical oceans, especially the ENSO phenomenon, exhibit the strongest signal as a generator for the interannual variation of the atmosphere. Generally, the northern winter circulation anomaly is attributable to the ENSO event. However, the analysis of the observations shows that a strongly anomalous pattern in the NH atmosphere can occur in non–El Nino and anti–El Nino years (Fu, 1987), which more or less reveals the fact that the anomaly of atmospheric circulation is not a simple process. Apart from oceans, the climatic process is affected by such factors as ice–snow cover, sea ice, soil moisture and vegetation, particularly the polar ice–cap. The change in the thermal regime between the polar region and equator will certainly cause variation in the atmospheric circulation. In addition, the interaction between ice–snow cover and atmosphere is a positive feedback process (Herman et al., 1978). For this reason, the cold–source effect of polar ice might serve as an important factor for the anomaly of the atmospheric circulation. In recent years, some studies on these aspects have been reported at home and abroad (Walsh, 1978; Fu, 1981; Fang, 1986a; b; c). Previous studies argue that the ice–snow cover influences the atmosphere mainly in two ways: (1) It greatly reduces heat and water–vapor exchanges between the atmosphere and oceans or ground. (2) The ice–snow cover alters the radiation balance due to its relatively bigger albedo compared to the ocean or surface. Fu (1980) showed that the albedo of ice–snow surface is usually four times bigger than that of bare ground, and thus it reflects most of shortwave radiation from the sun. Newson (1973), Warshaw and Rapp (1973) used GCM (general circulation model) to study the effect of polar ice, indicating that when the effect of Arctic ice is removed, there occurs a very significant change statistically, i.e., general weakening of zonal flow and considerable warming at high latitudes. All these show that the polar cold–source effect is first displayed as a local response of the atmosphere, and then it modifies the lower–latitude air through the circulation evolution. However, at present, there are few studies done of the mechanism responsible for such effects and their dynamics, and to our knowledge, no published evidence is available hitherto concerning the mechanism and impact of summer Arctic ice on the global climate investigated by numerical modelling. This paper is an attempt to study, through some experiments, the impact of Arctic ice on the global short–range climate in summer, including Asian monsoon, and to approach the dynamical mechanism for the impact.

II. A BRIEF DESCRIPTION OF MODEL AND EXPERIMENTAL SCHEMES

The model employed in this work is the global atmospheric circulation spectral one developed by Bourke (1977) and McAvaney et al.(1978). Its dynamical framework consists of primitive equations governing atmospheric motion including the vorticity equation, horizontal divergence equation, the continuity equation that gives surface pressure after integration, the thermodynamical and moisture equations, together with static equation and the diagnostic equation of the $\dot{\sigma}$–velocity. The model with σ coordinate in the vertical direction contains nine layers from surface to the top of the atmosphere, and the equations are expanded by spherical harmonic spectrum horizontally, with a rhomboidal truncation at wavenumber 15. The semi–implicit scheme is employed for time integration with the run of 30 minutes.

The physical processes include long–wave and short–wave radiations, large–scale condensation and cumulus convection, the vertical diffusion of momentum, heat and water vapor as well as the impact of thermal feature of the underlying surface (seas, polar ice and snow cover) and topography configuration on the model atmosphere.

For the details of the model, the reader is referred to McAvaney and Bourke (1978).

Two experimental schemes are designed for the impact of Arctic ice on the global short–range climate in northern summer. Experiment 1 (Exp. 1) is a control experiment, in which integration is performed from the atmosphere at rest and the simulation on day 492 is taken as the initial field; subsequently the integration is done for another 40 days, and the average of the last 30 day results is used as the mean for July. The SST, CO_2, O_3, the snow–cap and the polar ice area adopted in the model are all the climatology of July, and the value of the solar altitude angle is taken from mid–July. Experiment 2(Exp. 2) is an experiment, as specified earlier, with supercooled sea water of the same temperature in place of Arctic ice–cap with the integral procedure and the others as indicated in Scheme 1. We examine the effect of the polar ice on the global climate by means of difference (Exp. 2 minus 1).

III. IMPACT OF ARCTIC ICE COVER ON THE GLOBAL SHORT–RANGE CLIMATIC OSCILLATION

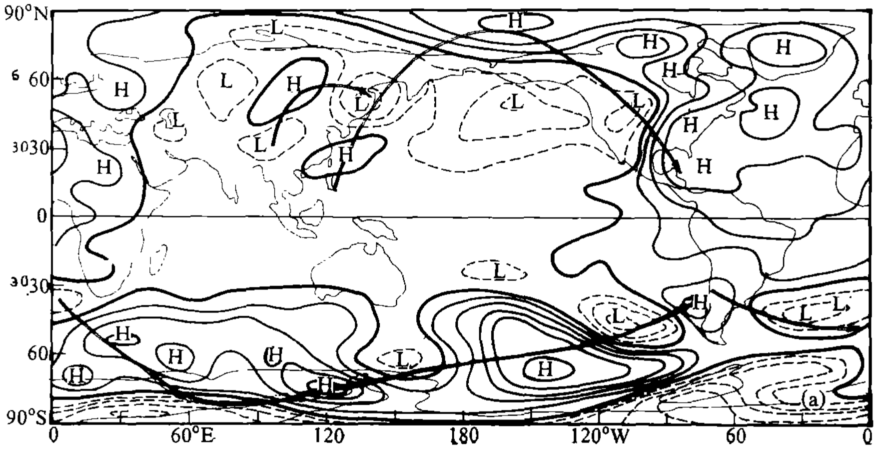

Fig 1a. The monthly mean difference field of 1000 hPa geopotential height in northern summer(Exp. 2 minus 1).

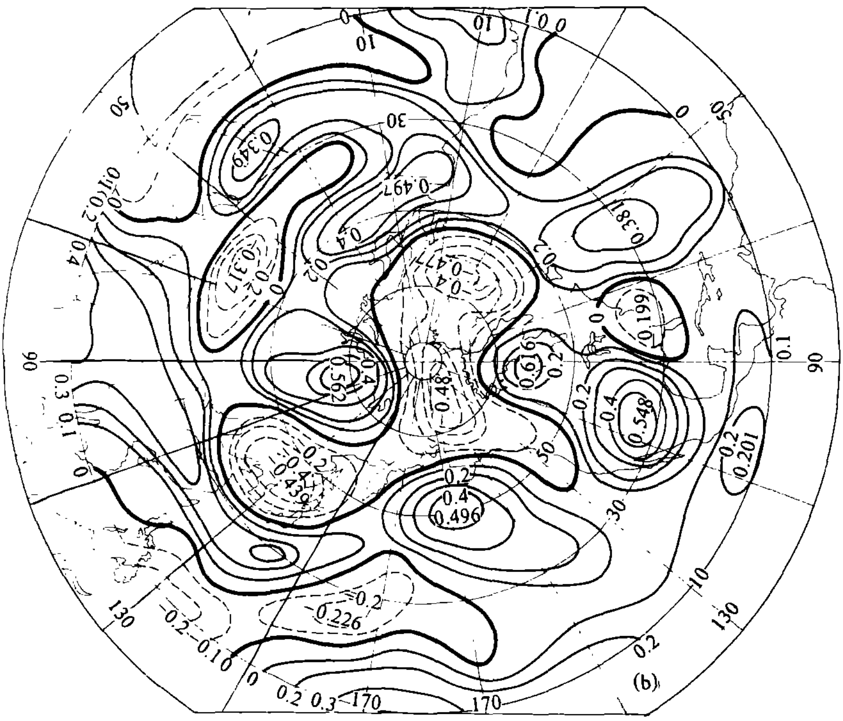

Fig. 1b. The correlation map between Arctic ice coverage and 500 hPa geopotential height in norhtern summer.

Fig. 1 gives a difference field of summertime monthly mean geopotential height. One can see from Fig. 1a that in the NH lower troposphere a wavetrain originating in North Pacific coast emanates from the equtorial western Pacific (EWP), moving along the eastern coast of the Eurasian continent and propagating toward the north as far as around the Bering Strait, then turns to the southeast and travels across North America into the Mexican Gulf. The wavetrain has six alternate positive and negative centers with the 1st, 3rd and 5th being negative. The first is located over Indonesia, the second over the South China Sea and SE China, the third over northeastern China and the Sea of Japan, the fourth over the Bering Strait, the fifth in the mid–latitude eastern Pacific and weastern North America, and the sixth in the Mexican Gulf, a pattern quite resembling the teleconnection proposed by Nitta (1987), that occurs during the convection anomaly in the western Pacific in northern summer. The above result is in concord with the teleconnection pattern in the one–point correlation map of the summer Arctic ice coverage and 500 hPa geopotential height obtained by actual observations (Fang, 1989; Fig.1b). Besides, it is worth noting that there exists a wavetrain over the Asian continent, which consists of three centers: the first, a negative, is situated over the Qinghai–Xizang Plateau; the second, a positive, on the poleward side of the Plateau; and the third, a negative, in northeastern China, (the last coincides with the 3rd (negative) center of the previous wavetrain) and then the wave continues its motion into the equatorial eastern–central Pacific. This wavetrain is excited by the anomaly of the Qinghai–Xizang Plateau heating field due to intensification of South Asian monoon in Exp.1. Meanwhile in the SH lower troposphere there also exists a pronounced disturbance wavetrain. It emanates from the equatorial South American continent, with alternate positive and negative centers. The wavetrain moves along a great circle route and turns equatorward as far as around 70°S, and then gets back to its origin, that is, it has travelled around the globe. Thus it can be seen that through the adjustment of atmospheric circulations themselves the anomaly of Arctic ice effect can be felt beyond the equator as far as the SH extratropics.

In the upper troposphere there are also three wavetrains similar in pattern to those just mentioned (figure omitted). Both in the NH and the SH extratropics, the difference (Exp.2 minus 1)centers have the same negative or positive sign for the top and bottom layers, indicating an equivalent barotropic structure in contrast to the situation at the low–latitudes, especially in the Indian Ocean and the equatorial Pacific, suggesting that low–latitude disturbances are of a baroclinic structure.

Figs. 2a and 2b present the 850 and 300 hPa difference flow fields (Exp. 2 minus 1), respectively. The negative (positive) difference center in the difference field of geopotential height is relative to a cyclonic (acticyclonic) difference circulation in the difference flow field. Fig. 2a shows that there exists an anticyclonic (and cyclonic) difference circulation in the South China Sea and southeastern China (and in Northeast China and around the Sea of Japan), and an anticyclonic difference circulation about the Bering Strait and a cyclonic (and anticyclonic) one in Canadian coast (and the U.S. eastern coast). All of the centers correspond exactly to the positive and negative centers of the first wavetrain discussed in the difference field of geopotential height. For the other two wavetrains, corresponding difference–circulation systems can also be found in the difference flow fields. It is worth noting that when this wavetrain moves along the east coast of North America to the south, a pronounced cross–equatorial propagation occurs in Latin America and the equatorial eastern Pacific. And the wavetrain keeps its motion further to the east, thus affecting the circulation in the SH.

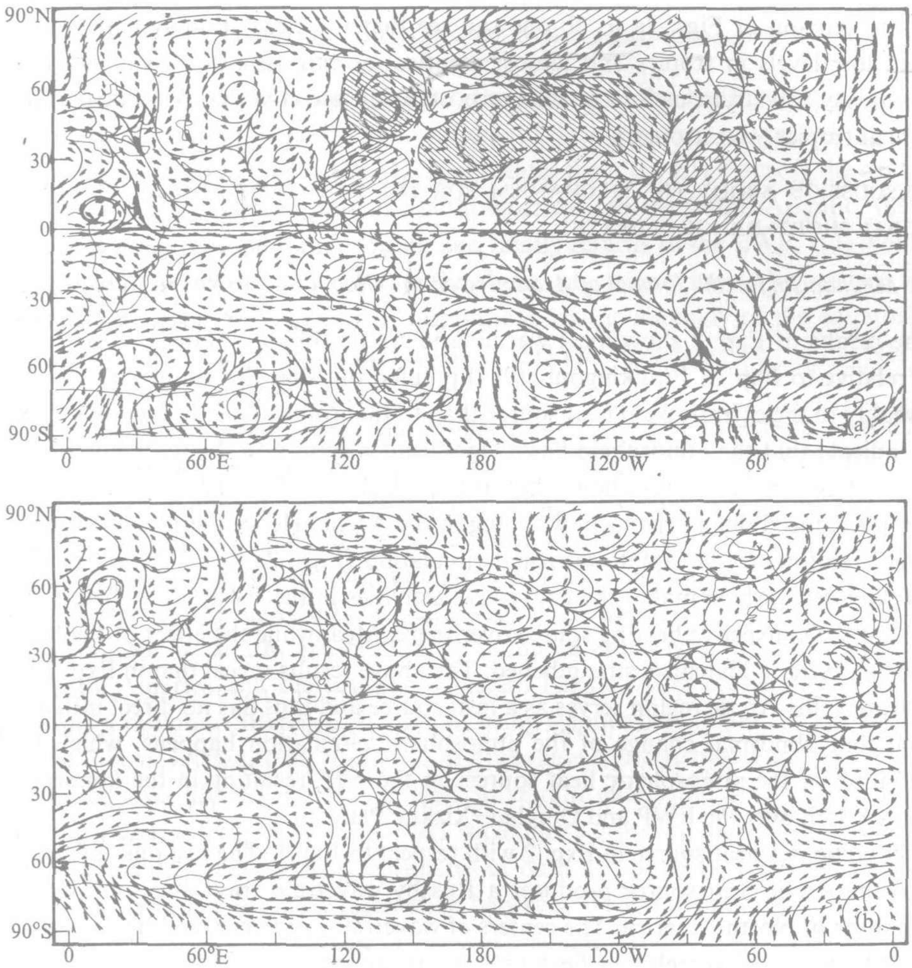

Fig. 2. The difference flow fields (Exp. 2 minus 1). (a) 850 hPa; (b) 300 hPa.

From Figs. 2a and 2b we can also see a significant change of the zonal circulation in the upp er and particularly the lower tropospheres near the equator. In the lower troposphere, equtorial easterlies get strengthened all the way from Indonesia to the South American coasts. There exists a very strong difference flow in a band of Indonesia — the equatorial Indian Ocean — the equatorial Africa — the equatorial Atlantic — the South American coasts and a convergent zone is located in the EWP, while in the upper troposphere the opposite situation is observed in the difference flow field. Such anti–phase allocation at the two levels makes the Walker and the anti–Walker cells intensified, forming a reinforced convergence(divergence) center in the lower (upper) troposphere over the EWP, so that the atmospheric heat source formerly supplied by the convective latent heat gets reinforced. Over the north part of South America, there exists a very strong divergent difference flow, leading to intensified equatorial easterlies in this area. The difference airflow stretches northward from Mexico, forming a long narrow channel at 90°W in the NH, through which the difference flow reaches the NH mid–latitudes. At the moment, it is not clear why the long narrow channel can be formed and what its dynamical significance is.

In comparison of Figs. 2a to 2b one can see that the circulation systems are opposite at high and low levels in tropics and almost identical at extratropics, which indicates that the low–frequency wavetrain under the influence of Arctic ice cover is of baroclinic (barotropic) structure at tropics (extratropics).

VI. A DISCUSSION ABOUT THE MECHANISM FOR THE IMPACT OF ARCTIC ICE COVER ON THE GLOBAL SHORT–RANGE CLIMATE

1. *The Mechanism for the Impact of Arctic Ice on the Global Short–Range Climate*

The results of Exp. 2 show local warming in Arctic (figure omitted), which means a heat source relative to Exp. 1. Frankingoul (1985) pointed out that the atmosphere responds much more weakly to the extratropical heat source than to the tropical one. In contrast, our numerical results indicate that the atmosphere has a significant response to the anomaly of the polar ice coverage. The numerical study shows that in Exp. 2, the south–north temperature gradients in the NH are reduced due to the local warming in the Arctic. Hence meridional transportation is decreased, reinforcing the equatorial zonal circulation (Figs. 2a and 2b), and the Walker and anti–Walker cells, which makes the convective activities in the EWP intensified and causes the anomaly of the convective heating source over there. Meanwhile the effect of the heat source of the Qinghai–Xizang Plateau is strengthened. The above results reveal that in Exp. 2 (with supercooled water), the Arctic region serves as a heat source and thus has no direct influence of polar ice, such that abnormal change of the atmospheric circulation happens, which leads to the redistribution of the atmospheric heat sources in the NH, resulting in the abnormality of the heat source both over the EWP and Qinghai–Xizang Plateau.

The Arctic is a heat source in Exp. 2 with respect to Exp.1. The response of the NH atmosphere to the Arctic heat source produces a Rossby wavetrain travelling southward along the west coastline of North America. The centers of wavetrain correspond with those of action reaching credibility in the correlation field between polar ice coverage and 500 hPa geopotential height (Fig. 1b) calculated on the basis of observational data by Fang (1986). Another wavetrain produced by the forcing of the EWP heat source anomaly and moving along the western Pacific coastline following an great circle route constitutes a pattern analogous to the teleconnection pattern proposed by Nitta (1987), which occurs during the convection anomaly over the EWP in northern summer and whose first center of action is located over Indonesia(see Fig.2a); the second over the South China Sea and southeastern China; the third over northern Japan and northeastern Asia; the fourth over the Bering Strait; the fifth over the mid–latitude eastern Pacific and western part of North America and the last over the Mexican Gulf. It should be noted that the Rossby wavetrain just discussed has its centers of action in the Western Hemisphere coinciding with those of the wavetrain forced by the polar heat source. All these centers can be found on the teleconnection chart (Fig. 1b) drawn by Fang (1986) for the polar ice anomaly, although the correlation coefficients of centers in the western Pacific coast fall short of the credibility level. The anomaly of the heat source over the Qinghai–Xizang Plateau produces another wavetrain, with the centers located separately over the plateau, its north side and the northeastern part of China and the last of the centers coincides with the third one of the previous wavetrain and from there the wavetrain keeps its motion into the equatorial eastern and central Pacific (see Fig. 2b).

2. *The Mechanism for Impact of Arctic Ice on the SH Short–Range Climate*

(1) The response of the SH atmosphere to the forcing of the EWP convection anomaly. From Figs. 1a and 2a and 2b it can be seen that due to the convection anomaly in the EWP, a southeastward wavetrain develops in the SH. It emanates from the EWP across the central part of the South Pacific and southern part of South America into the South Atlantic, then turns northeastward, moving into the Indian Ocean and finally returns to the EWP. It is worth mentioning that when the model is run for 15 days the above wavetrain is most obvious (see Fig. 3a), revealing that the anomaly of Arctic ice is responsible for the anomaly of the equatorial heat source, so that it leads to anomalous response of the SH atmosphere as well as the NH atmosphere.

(2) The impact of the cross–equatorial propagation of the NH wavetrains on the Antarctic atmosphere. Figs. 2a and 2b depict clearly that developed owing to the EWP convection anomaly is a wavetrain similar to the northern summer teleconnection pattern proposed by Nitta (1987). Setting out from the EWP, it propagates northward, turns to the southeast near the Bering Strait, progresses to the south along the west coastline of North America, where it overlaps the south–propagating Rossby wavetrain forced by the polar heat source and thus gets reinforced to continue its southward motion. Pronounced cross–equatorial propagation happens in the Latin America and the equatorial eastern Pacific. After crossing the equator, the wavetrain forms a cyclonic difference circulation being symmetrical about the last disturbance member of the NH wavetrain, then continues to propagate southeastward and merges into the wavetrain located over the EWP. The merged wavetrain enters the South Atlantic, Indian Ocean and finally goes into the EWP. This NH wavetrain's cross–equatorial propagation demonstrates an interaction between the atmospheres of both hemispheres. It can be seen that the anomaly of Arctic ice cover can cause interaction between NH and SH atmospheres, which is reflected mainly in two aspects: the change of the cross–equatorial flow and the cross–equatorial progagation of the wavetrain. Interestingly, as the model is run in a longer time, the low–frequency wavetrain is getting stabilized and in this case the latter will be dominant in affecting SH climate.

Figs. 3a, 3b and 3c are difference (Exp. 2 minus 1) charts of the mean geopotential height integrated for the third, fourth and eighth pentad, respectively.

The above results show that without polar ice available, a heat source is developed in the Arctic and another occurs in the EWP. Figs. 2a and 2b depict an intensified convective heat source formed west of the date–line; and in Fig. 3a we can also see clearly that this amplified convective heat source excites a wavetrain in the NH and SH, which propagates southeastward, then returns to the equatorial central western Pacific, which acts as a feedback to the heat source.

It can be clearly seen in Fig.3b for the run on day 20 that there is a more and more pronounced cross–equatorial propagation of the NH wavetrain in the equatorial eastern Pacific. After crossing the equator from the NH and travelling southeastward, the wavetrain passes

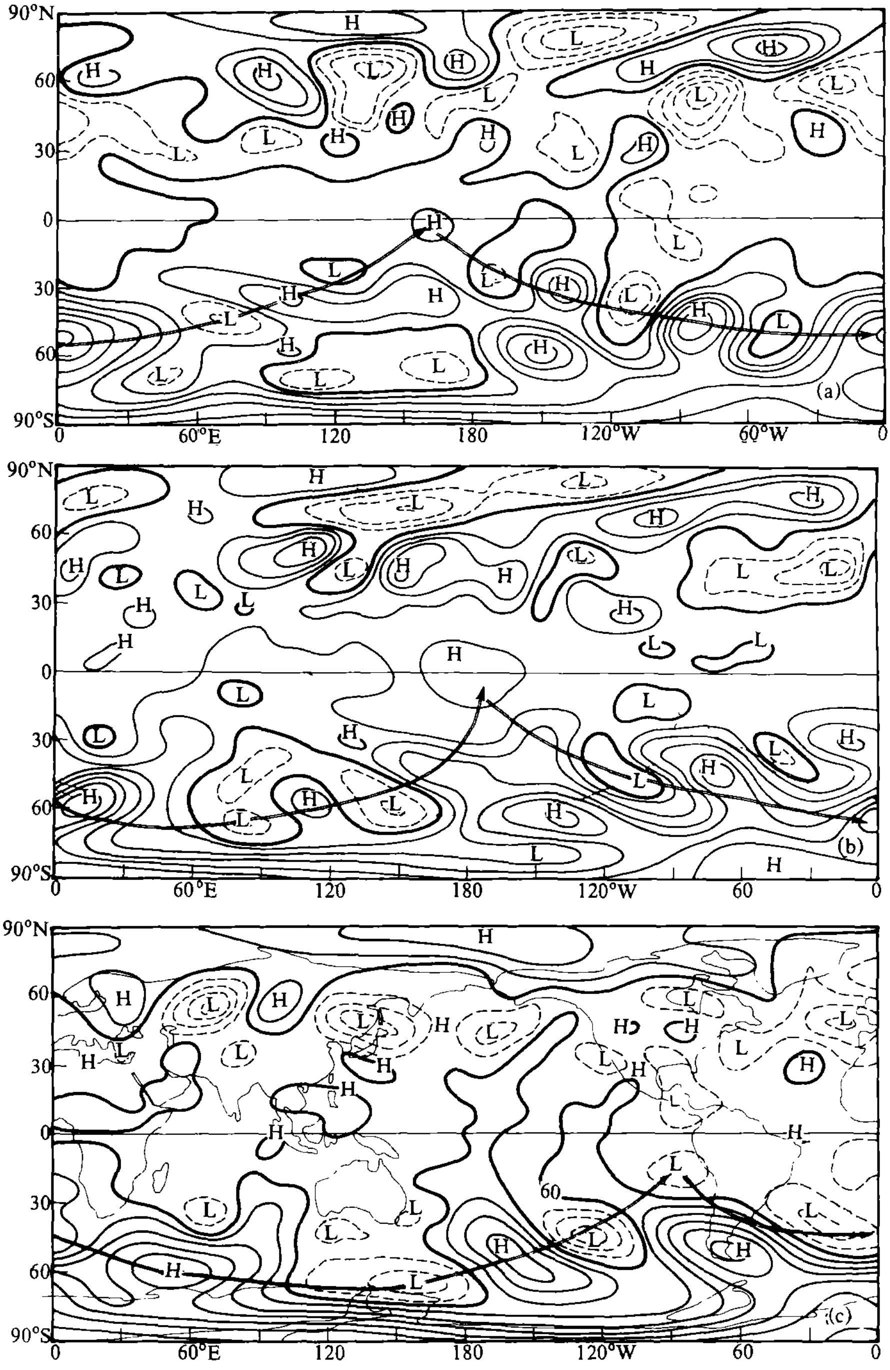

Fig. 3. Differences between the pentad means of the 300 hPa geopotential height (Exp.2 minus Exp.1) for the third pentad mean (a), the fourth pentad mean (b) and the eighth pentad mean (c).

through the southern part of the Atlantic, Indian Ocean and the South Pacific, then changes its direction to the northeast and returns as a feedback to the equatorial eastern Pacific. In the continued integration, this wavetrain remains relatively stable, acting as a main low–frequency feature that influences the climate of the SH (see Fig. 3c).

In summary, Arctic ice exerts its impact on the atmosphere mainly through the anomaly of polar ice coverage that results in the direct forcing of the polar heat source / sink on the atmosphere, and the redistribution of the heat source that produces a new equatorial heat source, and then the response of the atmospheres in both hemispheres to the newly–formed heat source excites a Rossby wavetrain to affect the atmospheric circulation. The other way to modify the SH is through the cross–equatorial propagation of the NH wavetrain.

V. SUMMARY

Based on the analysis of results of the above experiments we come to the following conclusions:

(1) Under the influence of Arctic ice, three heat sources can be formed in the NH, which are located in the Arctic region, Qinghai–Xizang Plateau, and the EWP, and thereby three different low–frequency wavetrains are excited, which overlap and affect each other to form a flow pattern that is in concord with the teleconnection pattern observed. This clearly shows that the anomaly of the polar ice cover causes the atmospheric circulation anomaly, leading to the redistribution of the atmospheric heat source, which, in turn, excites two–dimensional Rossby wavetrain to re–affect the whole NH.

(2) The anomaly of Arctic ice has its impact on the SH short–range climate either through the change of the equatorial atmospheric heat source, exciting a two–dimensional Rossby wavetrain that propagates along the great circle route into the SH extratropics, or through the cross–equatorial propagation of the NH wavetrain. The simulation results show that with a 15–day integration the former case is dominant, but when the model atmosphere approaches a stable state the latter is more important.

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