RESPONSE OF THE ATMOSPHERIC GENERAL CIRCULATION TO WINTER SNOW COVER ANOMALY

CHEN Haishan (陈海山) and SUN Zhaobo (孙照渤)

Key Laboratory of Meteorological Disaster and Environmental Variation (KLME),
Nanjing Institute of Meteorology. Nanjing 210044

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ABSTRACT

In this paper, the response of the atmospheric general circulation to winter anomalous snow cover was investigated through observations studies and model simulation.

Results from the observations show that: (1) the anomalous winter snow cover in the extratropics of Eurasian Continent bears an intimate relation to the contemporary atmospheric general circulation. The positive anomaly of winter snow cover is usually accompanied by positive atmospheric EUP teleconnection pattern and stronger East Asian winter monsoon; or vice versa. (2) The linkage between them suggests that the abnormal winter snow cover has an important impact on winter atmospheric general circulation. The anomalous snow cover pattern can lead to the anomaly of winter atmospheric EUP teleconnection pattern and thus influence East Asian Winter monsoon.

With NCAR CCM2 including BATS land surface scheme, three groups of experiments were performed to examine the atmospheric response to the anomalous snow cover pattern and explore the relevant mechanism. Simulated results agree well with the observations, which testify the significant response of the atmosphere to snow cover anomaly. It is found that the radiative cooling induced by anomalous snow cover plays an important role in above processes. and the feedback of long-wave radiation can not be neglected.

Key words: anomalous snow cover pattern. atmospheric EUP teleconnection pattern. East Asian winter monsoon (EAWM)

I. INTRODUCTION

Snow cover is a crucial component of the climate system. The anomaly of the snow cover has the potential to change the surface thermal and hydrological balances and thus induce complex feedback mechanisms leading to regional and global climate fluctuations. The climatic effects of snow cover include (1) snow albedo effect. The high reflectivity of snow can increase the surface albedo as much as 60%, which can induce the radiative cooling of the land surface and modify the surface heating and energy exchanges at the land-atmosphere interface (Hahn and Shukla 1976); (2) snow-melt hydrological effects. The snowmelt related to abnormal snow cover can induce the abnormality of the surface hydrology and change the water supply to the atmosphere (Yeh et al. 1983; Yamazaki 1989; Yasunari et al. 1991; Meehl 1994); (3) atmospheric tele-response to the snow cover anomaly. The local impact of snow cover, through the modification of the

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Since Blanford's (1884) initial work, much attention has been given to this field and great progress has been made. As a main part of the snow cover in the Northern Hemisphere. Eurasian snow cover plays significant impacts on the climate change. Hahn and Shukla. (1976). Dey et al. (1982). Dickson (1984) investigated the relation between snow cover and Indian monsoon. and pointed out its noticeable impacts on Indian summer monsoon and rainfall. In recent 20 years. Chinese researchers have made lots of explorations on the effects of the Tibetan snow cover on East Asian summer monsoon and Chinese precipitation (Chen and Yan 1979: Guo and Wang 1986: Zhang et al. 1991: Lu et al. 1994: Chen et al. 1996. Wu et al. 1996). Many recent studies have been focused on the mechanism of the snow cover influencing the global climate change and Asian monsoon system (Barnett et al. 1988: Yasunari 1991: Meehl 1994: Vernekar. 1995: Douville et al. 1996: 1998: Walland and Simmonds 1997). and all those studies have testified the importance of snow cover in climate system. especially in the Asian monsoon system.

In fact. most of those researches have emphasized the effects of winter snow cover on the climate in the following summer. As to the impacts of winter snow cover on contemporary atmospheric circulation. only a few works concerned it. Lamb (1955). Namias (1985). Walsh et al. (1985). Leathers and Robinson (1993) emphasized the cooling effect of winter snow on winter air temperature and its feedback on the contemporary atmosphere. but studies in relation to the contemporary interactions between Eurasian winter snow cover anomaly and atmospheric general circulation are hardly documented.

East Asian winter monsoon (EAWM) is a good candidate of the winter atmospheric general circulation of East Asia. The abnormal EAWM impacts not only the winter temperature but also the summer weather and climate in China (Wu 1993: Sun and Sun 1996). More recently. Li (1998) has pointed out that the EAWM plays substantial effects in the global climate change by its triggering of El Nino event. Just for these reasons. it is necessary to explore the abnormal EAWM activities. Acting as an indirect abnormal heating source. can Eurasian winter anomalous snow cover lead to the anomalies of the atmospheric circulation and EAWM? If so. which kind of characteristic will appear in the atmospheric response to the snow cover anomaly?

In this paper. these problems were investigated by using statistical analysis firstly. then NCAR CCM2 coupled with BATS land surface scheme was used to examine the observations and explore the related physics.

II. OBSERVATIONAL STUDIES

1. Possible Linkage between Winter Snow Cover Anomaly and Atmospheric General Circulation

To reflect winter snow cover anomaly in the mid-high latitudes of the Eurasian Continent (10—135°E: 42.5—90°N), the grid number covered by snow in DJF was defined as winter snow cover area index (WSC) (see Fig. 1a). By referring Fig. 1b it is apparent
that the WSC bears positive correlation to the snow depth in the western Europe, the Tibetan Plateau and East Asia, but weak negative correlation in western Asia and the Siberia, which implies that winter snow is deeper than normal in the former and shallower in the latter region when the WSC has a high value. It is worth noting that the snow depth has an evident spatial pattern.

The correlation between WSC, winter sea-level pressure (SLP), and 500 hPa height are calculated separately to explore the possible relationship between the atmosphere and WSC. WSC bears a positive correlation with SLP over Eurasian Continent but a negative over the broad areas over the Pacific east to the Asian Continent (Fig. 2a). The positive anomaly of Eurasian winter snow cover may induce the SLP anomalies over the Eurasian Continent and the broad areas east to Japan, which is favorable to the occurrence of a strong winter monsoon. On the contrary, the negative anomaly of snow cover usually leads to the anomalous SLP associated with a weak winter monsoon. Figure 2b suggests the significant correlation between the winter 500 hPa height and WSC, and an EUP-like correlation pattern appears over western Europe (−), the Siberia (+), and East Asia (−).

For research purposes East Asia winter monsoon index (WMI) was calculated as

\[
WMI_e = \frac{1}{30/\Delta \phi + 1} \left[ \sum_{\phi = 30^\circ} \text{SLP}^* (\phi, 110^\circ E) - \text{SLP}^* (\phi, 160^\circ E) \right],
\]

where SLP* is a standardized variable and WMI is acquired by normalizing WMIe. The

![Fig. 1. (a) Interannual variations of WSC; and (b) contemporary correlation between snow depth and WSC with contours 0.1. The shaded areas show areas higher than the significance level of 0.05.](image)


Fig. 2. Correlation map of WSC between winter SLP (a) and 500 hPa geopotential height (b), with contour interval 0.1. The shaded areas show areas higher than the significance level of 0.05. Strong (weak) winter monsoon is characterized by a positive (negative) WMI (Shi et al. 1996).

In addition, after Wallace’s work (1981) the index of winter EUP was defined as

\[ EUP(i) = \frac{1}{4}Z'(55^\circ N, 20^\circ E) + \frac{1}{2}Z'(55^\circ N, 75^\circ E) - \frac{1}{4}Z'(40^\circ N, 145^\circ E), \]

where \( Z' \) is the standardized winter 500 hPa height. So EUP can be used to reflect the abnormal features of the atmospheric circulation. When EUP is positive, the distribution of winter 500 hPa height embodies stronger Siberian ridge and deeper East Asian trough.

The interannual variations of WSC, WMI and EUP are plotted in Fig. 3. The three have the same tendency on the whole with peaks and valleys in good correspondence. When the winter Eurasian snow cover area is larger than normal, EUP is positive and winter monsoon is strong. In most years before 1986, winter snow cover is above normal with a positive EUP and high monsoon indices; but in the period after 1987, winter snow cover area becomes smaller, and the index of EUP becomes negative and winter monsoon is weak.

Fig. 3. Interannual variations of WSC, EUP and WMI.
Fig. 4. Composite analysis results: (a) winter 500 hPa height departure (heavy minus light snow years), with contour spacing 10 gpm, the shaded areas showing areas higher than the significance level of 0.05; (b) thickness between 500 and 1000 hPa (heavy minus light snow years) with contour spacing 20 gpm; and (c) winter snow depth (snow water equivalent in cm) difference fields between positive and negative atmospheric EUP years. The shaded areas show negative areas.

The preliminary analysis suggests that WSC, EUP and WMI are correlated to some extent, in such a way that the positive (negative) anomaly of winter snow cover is usually accompanied with positive (negative) atmospheric EUP teleconnection pattern and strong (weak) EAWM.

2. Response of the Atmospheric General Circulation to Snow Cover Anomaly

Although the linkage between winter snow cover anomaly and contemporary atmosphere has been disclosed, the physical process is not clear yet.

For further study needs, years 1979, 1980, 1981 and 1984 are selected as the heavy
snow years (WSC > 0.5) and 1988, 1989 and 1992 the light snow years (WSC < 0.5). The characteristics of different meteorological fields for heavy and light snow cover years are analyzed to investigate the linkage disclosed in previous section.

Results from composite analysis show that the 500 hPa height becomes higher over the Siberia, but lower over West Europe and the East of China to Japan in heavy snow cover years; in light snow years, contrary is the case (figure not given). Figure 4a shows its difference (heavy minus light snow years), which has almost the same pattern as the previous correlation map and apparently shows large negative anomalies over West Europe and East Asia, but a large positive anomaly over the Siberia. The atmospheric anomalies over those three regions are above the significance level of 0.05. The \((-\)\(+\)\(-\)\) pattern is very similar to the typical atmospheric EUP pattern.

The atmosphere exhibits completely different features in the abnormal snow cover years, but the whole anomaly of Eurasian snow cover can not give any explanation to these phenomena in the traditional view of the local cooling effect. In fact, Iwasaki (1991), Groisman (1993) disclosed the spatial patterns of snow cover with evident spatial variation in their recent research. In the previous discussion, the anomalous spatial pattern of snow cover was disclosed as well.

So years 1980, 1983 and 1985 are selected as the high EUP index years and 1988, 1989, 1991 and 1992 the low EUP index years. Winter snow depth composite fields are investigated. In positive EUP years, the positive departure is located at the West Europe and the mid-latitude of East Asia; and the negative departure distributes at the Western Asia and the mid-higher latitude of Eurasian Continent east to 50°E. On the contrary, the distribution of snow depth in negative EUP years is out of the phase (figure not given). Figure 4b gives the snow depth difference in positive minus negative EUP years, which embodies the significant difference of snow depth between low and positive EUP years and the\((+\)\(-\)(+)\) pattern of snow anomaly from West Europe, Siberia to East Asia.

In fact, the intrinsic linkage between snow and atmosphere can be concluded by contrasting the spatial patterns of them. From the West Europe, Siberia, to East Asia, the\((+\)\(-\)(+)\) pattern of anomalous snow depth is well associated with the\((-\)(+)\(-\)\) anomalous distributions of 500 hPa height in which a positive snow depth anomaly corresponds a negative geopotential height anomaly.

As we know, the anomalous snow cover influences the atmosphere by changing the surface heating. From this view, the existing relationship between them might be recognized from the thermal features of the atmosphere.

The 500 hPa minus 1000 hPa height difference \((H_{500-1000} \text{ hPa})\) for light and heavy winter snow years are investigated (see Fig. 4c), the mean air temperature between 500 hPa and 1000 hPa \((AT_{1000-500} \text{ hPa})\), and air temperature at various levels are calculated (figure not given). Comparison is carried out among the spatial patterns of the snow cover, 500 hPa height, \(H_{500-1000} \text{ hPa}\) and \(AT_{1000-500} \text{ hPa}\). The corresponding relationships; deeper (shallow) snow — negative (positive) \(H_{500-1000} \text{ hPa}\) — negative (positive) \(AT_{1000-500} \text{ hPa}\) — 500 hPa height negative (positive) departure was found. The air temperatures at various heights drop (arise) consistently.

Above analysis shows that the relationship between the anomalous snow cover and
atmospheric general circulation implies the facts that the anomaly of winter snow cover has an important impact on winter 500 hPa height and thus winter atmospheric general circulation, especially on the atmospheric EUP teleconnection. In those years with a positive (negative) anomalous snow cover, West Europe and the extensive regions from east of China to Japan are covered by 500 hPa negative (positive) departure due to the cooling (warming) effects of surplus (deficit) snow, but the Siberia a positive (negative) departure due to the warming (cooling) of deficit (surplus) snow there. In such a way that the ridge over Siberia becomes much stronger (weaker) and the trough over East Asia much deeper (shallower), which increase (decrease) the meridionality of atmospheric circulation over East Asia and thus intensify (weaken) the activity of cold air flow, resulting in the occurrence of stronger (weaker) than normal winter monsoon.

3. Coupling Mode between Winter Anomalous Snow Cover Pattern and Winter Atmosphere

However, whether the snow cover pattern disclosed above could represent the main characteristics of the snow cover anomaly? Is it accidental due to the selection of the special years? This question will be discussed below.

In order to investigate the intrinsic spatial pattern of snow cover and its coupling relationship to winter atmospheric general circulation, analysis was carried out by SVD analysis. As an efficient statistical method, SVD, has been widely used to disclose the coupled relationship of the spatial patterns between two meteorological fields (Sun et al. 1991; Bretherton et al. 1992; Wallace et al. 1992). For brevity only the results are given, the principle and application of SVD can be found in the documents referred above.

The first couple singular vectors of winter snow depth and 500 hPa geopotential derived form SVD are given in Fig. 5, which represent the typical spatial patterns of winter snow cover anomaly and 500 hPa height respectively. The left singular vector reflects the typical spatial pattern of snow anomaly (Fig. 5a) and the right the 500 hPa height (Fig. 5b). It is evident that the typical spatial pattern of snow depth is almost identical to the snow pattern disclosed in previous analysis, and the coupled relationship testified the strong linkage between the anomalous snow pattern and atmospheric EUP patterns again.

III. MODEL SIMULATION

1. Model Description

The atmospheric model used in this paper is the National Centers for Atmospheric Research Community Climate Model version 2 (NCAR CCM2), which has 18 vertical levels with the top at 2.9 hPa and configures with a T42 resolution. The model includes comprehensive physics, which has been described in detail by Hack et al. (1993). The standard model uses prescribed sea surface temperature (SST), surface albedo and wetness.

The version of NCAR CCM2 used in our studies is coupled to the Biosphere-Atmosphere Transfer Scheme (BATS), which is a comprehensive land surface scheme developed by Dickinson et al. (1986; 1993) to use in GCMs. The description of snow parameterization in BATS and its applications in the snow simulation can refer to the recent work of Yang et al. (1997).
Fig. 5. The first couple of singular vectors from SVD analysis of winter snow depth and 500 hPa geopotential height. (the ratio of covariance to total covariance is 65.5\%): (a1) homogeneous correlation for winter snow depth (WSD); (a2) heterogeneous correlation for winter snow depth (WSD); (b1) same as (a1) but for 500 hPa height; (b2) same as (a2) but for 500 hPa height (all with contour interval 0.2, the shaded areas showing areas higher than the significance level of 0.05.)
2. Experiment Design

For research need, three groups of experiments, each includes five runs, are designed based on the observations. The model was first integrated for 10 years started on 1st September of year 0 with a standard initial value of CCM2 and forced by climatological monthly mean SST before our experiments. The simulation results of the 1st, 2nd, 3rd, 4th, 5th December of model year 10 is used to provide different initial value field respectively for our experiments to eliminate the effects of initial value on the simulated results.

(1) Control runs (CTLs)

Experiment CTLs called control run are to check the capability of the model to simulate the climatology and used to compare with the snow anomaly experiments. The integration was made for three months starting from the five initial values respectively, and the mean results derived from these five runs are discussed.

(2) Anomaly forced runs (EXPAs)

Another two sets of experiments called anomalous snow forced runs (EXPAs) are the same as CTLs except the forced anomaly of the initial snow depth.

EXPAs uses the snow anomaly as described in Fig. 6, which is configured based on the observational results, to reflect the snow anomaly pattern with abnormally deep snow depth in the West Europe and the Tibetan Plateau but abnormally shallow snow depth in the extratropical Eurasian Continent and West Asia. The snow force is only added at the beginning of the runs and 3-month integration is performed.

EXPAs is designed to reflect the effects of the opposite snow pattern. EXPAs is the same as EXPAs but with the contrary snow depth anomaly distribution to Fig. 6.

3. Results of Numerical Experiments

Based on those three sets of numerical experiments, the winter atmospheric response

![Fig. 6. Distribution of anomalous snow water equivalence (SWE) used in EXPAs with contours 10 mm.](image-url)
to snow cover anomaly is investigated by comparing the results from the CTLs and the two EXPAs. For brevity, only the differences of some variables derived by EXPA1 minus EXPA2 are presented in the next section. The atmospheric response to anomalous snow pattern is disclosed with contrast to the observations firstly. Then, the changes of some surface variables related to snow cover anomaly and surface fluxes are used to explore the possible physical mechanism.

(1) 500 hPa potential height and 500–1000 hPa thickness

The difference of 500 hPa height was presented in Fig. 7. The anomaly of the 500 hPa height shows that a positive center appears over the North Atlantic Ocean and the northeast of the North America with a negative value center south to it. Positive values are also found in the Siberia, and the negative values locate in West Europe and the east of China to Japan. An EUP-like wave train can be seen over Eurasian Continent (see Fig. 7), and the thickness field has the similar patterns by comparing with the 500 hPa height anomalies (figure not given). Both the height anomalies and the abnormal thickness can be explained by the abnormal surface heating induced by the snow anomaly discussed in the previous section. The 500 hPa height and the thickness increase in the warming regions but reduce in the cooling areas, which is consistent with the results disclosed by Walsh et al. (1985). Meanwhile features of the atmospheric response to snow anomaly are in good agreement with the observational. The atmospheric anomalies induced by abnormal snow cover pattern can cause the variation of the East Asian winter monsoon (EAWM) system, which will be examined in the next section.

(2) 850 hPa wind

Figure 8 illustrates the difference (EXPA1 - EXPA2) of the 850 hPa wind. The anomaly field of the 850 hPa wind is characterized as three closed circulation systems, i.e. the anticyclonic circulation anomaly over the Siberia and the cyclonic circulation in West Europe and extensive area around Japan, related to the abnormal atmospheric circulation previously discussed. The anomaly of the wind suggests the facts that the upper anticyclonic ridge east to the Ural Mountains intensifies and the cold trough over East Asia deepens, in such a way that a strong than normal EAWM occurs.

The simulated results suggest that the anomalous snow cover pattern discussed can induce the anomaly of the contemporary atmospheric circulation with a positive EUP pattern and strong winter monsoon through the cooling and the warming produced by the surplus and deficit snow respectively. In the case of the opposite snow pattern, negative EUP pattern is triggered and thus weak winter monsoon happens. The results are in good agreement with the observations.

(3) Changes of surface variables and fluxes

In order to explain atmospheric circulation anomalies related to anomalous snow cover pattern discussed, it is necessary to examine the changes of surface fluxes and surface variables relevant to the surface thermal conditions.

Albedo effect represents the main impact of winter snow cover. Albedo increases over
Fig. 7. The differences (EXPA1 minus EXPA2) in DJF 500 hPa potential height with contours 10 gpm.

Fig. 8. The difference (EXPA1 minus EXPA2) in DJF 850 hPa wind.

West Europe and the east of the Tibetan Plateau, but decreases over the extensive regions at the high-mid latitude of the Eurasian Continent, West and East Asia, which is consistent with the abnormal snow distribution (figure not given). The net solar radiation exhibits the same feature as the albedo (figure not given). It has been clearly reduced in the regions with deeper snow but increased in areas covered by abnormally shallow snow due to the direct effect of abnormal albedo induced by the anomalous snow distribution, in such a way to cause the changes of surface thermal conditions.

Figure 9a illustrates the distribution of the surface temperature anomalies over the
Fig. 9. The difference (EXP A1 minus EXP A2) of surface variables and fluxes in DJF. (a) $T_s$ with contours interval 0.5 K; (b) absorbed radiation by the surface ($R_{SRF}$); (c) upward long-wave radiation ($R_{ULW}$); and (d) energy flux from the surface to the atmosphere ($R_{ULW} + Q_{SH} + Q_{LH}$), all with contour's interval 2 W m$^{-2}$. 
Eurasian Continent. A significant warming appears in the Asian Continent north of 35°N and an evident cooling in West Europe and the adjoining regions of the Plateau, which suggests that the surface cooling is mainly driven by the snow mass anomaly. But it is worth noting that the abnormal distribution of the surface temperature can not be explained by the variation of the net solar radiation soundly though the net solar radiation plays a predominant role in the surface energy balance, that is, the anomalies of the surface thermal conditions are not only the direct response to the net solar radiation but also dependent on other components of the energy system.

Therefore it is necessary to discuss the surface energy balance before investigating the changes of surface thermal condition and surface heating to the atmosphere induced by the anomalous snow cover. The net surface heat flux \( F_{\text{NET}} \) at the snow surface is given by

\[
F_{\text{NET}}(T_s) = R_{\text{DSW}} - R_{\text{UPSW}} + R_{\text{DLW}} - R_{\text{UPLW}} - Q_{\text{SH}} - Q_{\text{LH}} - Q_o - Q_{\text{SM}} + Q_F, \tag{1}
\]

where

- \( R_{\text{DSW}} \)= incidental solar radiation,
- \( R_{\text{UPSW}} \)= reflected solar radiation,
- \( R_{\text{DLW}} \)= downward atmospheric long-wave radiation,
- \( R_{\text{UPLW}} \)= upward (emitted) long-wave radiation,
- \( Q_{\text{SH}} \)= sensible heat flux,
- \( Q_{\text{LH}} \)= latent heat flux,
- \( Q_o \)= ground heat flux,
- \( Q_{\text{SM}} \)= energy flux available for snowmelt,
- \( Q_F \)= heat flux from rain, and
- \( T_s \)= surface temperature.

With \( Q_o \), \( Q_{\text{SM}} \) and \( Q_F \) assumed to be negligible compared to other terms, then

\[
F_{\text{NET}}(T_s) = R_{\text{DSW}} - R_{\text{UPSW}} + R_{\text{DLW}} - R_{\text{UPLW}} - Q_{\text{SH}} - Q_{\text{LH}}. \tag{2}
\]

By combining the first three terms on the right-hand of Eq. (2) into one and expressing it as \( R_{\text{SRF}} \) to represent the net radiation flux received by the surface, which consists of the downward solar radiation, reflected solar radiation and the emitted long-wave radiation at the surface and noting that the \( R_{\text{UPLW}} \) is dependent on \( T_s \), then Eq. (2) can take the form:

\[
F_{\text{NET}}(T_s) = R_{\text{SRF}} - R_{\text{UPLW}}(T_s) - Q_{\text{SH}} - Q_{\text{LH}} \Rightarrow F_{\text{NET}}(T_s) = R_{\text{SRF}} - \varepsilon_0 T_s^4 - Q_{\text{SH}} - Q_{\text{LH}} \Rightarrow F_{\text{NET}}(T_s) + \varepsilon_0 T_s^4 \approx R_{\text{SRF}} - Q_{\text{SH}} - Q_{\text{LH}}. \tag{3}
\]

Due to the predominant role of radiation fluxes, the approximation of Eq. (3) can be expressed as

\[
F_{\text{NET}}(T_s) + \varepsilon_0 T_s^4 \approx R_{\text{SRF}}. \tag{4}
\]

According to Eqs. (3) and (4), it is obvious that the surface temperature is affected by \( Q_{\text{SH}} \) and \( Q_{\text{LH}} \), particularly has a strong dependence on \( R_{\text{SRF}} \), the radiation flux received by the snow surface. The anomaly distribution of \( R_{\text{SRF}} \) is presented in Fig. 9b. By comparison, it is easy to find that a more reasonable explanation for the anomaly of surface temperature can be acquired by considering \( R_{\text{DLW}} \), implying that the atmospheric long-wave radiation plays a very important role in the variation of the surface thermal condition related to snow anomaly. In addition, the sensible heat and latent heat fluxes have some influence on the surface temperature despite of their relative order of magnitude compared with radiation fluxes.

Then, how do the changes of thermal condition related to the snow anomaly impact the surface heating to the atmosphere. As we know, the energy flux from the surface to the atmosphere can be written as \( R_{\text{UPSW}} + R_{\text{UPLW}} + Q_{\text{SH}} + Q_{\text{LH}} \), because the absorption of
$R_{UPSW}$ by the atmosphere is relatively small, so it can be expressed as $R_{UPLW} + Q_{SH} + Q_{LH}$ approximately.

Figures 9c and 9d present the surface long-wave heating $R_{UPLW}$ and the surface heat flux $R_{UPLW} + Q_{SH} + Q_{LH}$ to the atmosphere respectively. Since the surface heating to the atmosphere can be reflected by the air temperature. The distribution of surface air temperature ($T_a$) (figure not given) is in good agreement with the $R_{UPLW}$, but some differences with the energy flux $R_{UPLW} + Q_{SH} + Q_{LH}$. It can be concluded that the snow cover anomaly can lead to the abnormal heating indeed, and the long-wave radiation emitted from the land surface takes up an absolutely predominant position in the surface heating. In addition, the atmospheric response of anomalous surface heating has a positive feedback on the surface heating and surface temperature through downward long-wave radiation of the atmosphere $R_{DLW}$ because of the changed $T_a$. The surface cooling is reinforced by a decrease in the atmospheric downward long-wave radiation.

In summary, the radiation fluxes play a predominant role during the anomalous snow cover affecting the atmosphere. The proposed snow cooling effect was testified. In brief, the related physics may be illustrated as follows:

\[ R_{DLW} \leftarrow \text{atmospheric temperature} \leftarrow \text{positive feedback} \]

snow depth $\uparrow$ $\longrightarrow$ albedo $\longrightarrow$ net solar $\downarrow$ $\longrightarrow$ surface temperature $\downarrow$ $\longrightarrow$ $R_{UPLW} \uparrow$

(where $\uparrow$ denotes increase and $\downarrow$ decrease).

Just through the physical processes suggested above, when abnormally deep snow cover exists in West Europe and the adjoining area of the Tibetan Plateau, but shallower in West Asia and the extratropical Eurasian Continent, the anomalous snow cover pattern can induce the anomalies of the contemporary atmospheric circulation with a positive EUP pattern and strong winter monsoon through the cooling/warming produced by the surplus/deficit snow cover respectively, which provided a reasonable explanation to both observations and simulations.

IV. CONCLUSIONS

Based on the foregoing discussion, the major conclusions of the study may be summarized as:

1. The anomaly of winter snow cover in the extratropics of Eurasian Continent bears an intimate relation to the atmospheric EUP teleconnection pattern and EAWM. The anomalous 500-hPa height fields induced by larger than normal snow cover area is favorable to the occurrence of the positive atmospheric EUP teleconnection pattern and thus stronger than normal winter monsoon; and the case for smaller snow cover area is contrary.

2. The anomaly of snow cover can result in a series of variations such as surface albedo, net solar radiation absorbed by the surface, surface temperature or surface thermal conditions, surface heating and atmospheric heating to surface etc. In the case of abnormally deep snow, due to the high reflectivity and decreased solar radiation absorbed,
the land surface temperature drops, and thus induces the decrease of surface long-wave heating to the atmosphere and the atmospheric cooling. Meanwhile the cooled atmosphere can give rise to the further cooling of the land surface because of the decreased atmospheric long-wave heating. The positive feedback mechanism is formed. The reversal is true for the abnormally shallow snow.

(3) The relationship between the anomalous winter snow cover and winter atmospheric general circulation suggested the facts that the anomaly of snow cover can produce feedback on atmospheric general circulation and thus lead to its anomalies. The spatial pattern of snow depth, forming \((+)(-)(+)\) pattern from West Europe, the Siberia, to East Asia, appears under the condition of larger snow cover. Impacted by the snow cover pattern, the air temperature drops and the 500 hPa geopotential height reduces due to the cooling effects over the regions with a deeper snow depth, and vice versa. As a result, the positive EUP pattern at 500 hPa is induced and produces a strong EWAM. When the spatial pattern takes the opposite distribution, contrary is the case.

Certainly, it is deserved to point out that only the atmospheric contemporary response to winter anomalous snow cover was investigated in this paper. The atmosphere interacts with the snow cover strongly, and the impact of the atmosphere on the snow cover is one of the problems to await further exploration.

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