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Influence of Eurasian snow cover in spring on the Indian Ocean Dipole

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ABSTRACT: The Indian Ocean Dipole (IOD) shows a significant negative correlation with the extent of Eurasian snow cover in spring. The anomalies in the land–sea temperature contrast, which are induced by the anomalies of Eurasian snow cover in spring, reverse the patterns of convection activity anomalies over the western and eastern tropical Indian Ocean in summer. Moreover, for heavier and lighter than normal Eurasian snow cover in spring, anomalies in the vertical zonal circulation over the tropical Indian Ocean (Walker circulation) and in the vertical meridional circulation between the Indian Ocean and the Eurasian continent (Hadley circulation) occur in summer. The Walker and Hadley circulation anomalies probably play an important role in the occurrence and duration of IOD events. Eurasian snow cover in spring is presumably one of the factors that trigger IOD events. These results provide a basis for further investigation of the mechanisms linking snow cover, the Indian monsoon, atmospheric circulation, and sea surface temperature.

KEY WORDS: Eurasian snow cover · Indian Ocean Dipole · Ocean–atmosphere coupling · Atmospheric circulation anomalies

1. INTRODUCTION

Snow cover is an important component of the terrestrial surface and plays a role in the formation of climate. The effects of snow cover on climate have been studied by Parthasarathy & Yang (1995), Li & Yanai (1996), Clark et al. (1999), Bamzai & Marx (2000), and Chen & Wu (2000). Higher albedo, lower thermal conductivity and absorption of much latent heat energy when the snow melts result in cooling of the continental climate and produce a significant impact on atmospheric circulation, during and after the period of snow cover (Zhang et al. 2003). The albedo effect is dominant in spring at low latitudes, especially on the Tibetan Plateau, whereas the effect of snow melting is important at mid-latitudes (Yasunari et al. 1991). Although maximum snow cover occurs in winter, the degenerative feedback of snow cover on the radiation balance is greatest in spring, and cooling effects can retard the shift from one season to the next (Groisman et al. 1994a).

Snow cover in Eurasia occurs mainly in the areas of the former Soviet Union and in China. Deep snow cover occurs in northern Eurasia (40 to 120°E, 50 to 70°N) and on the Tibetan Plateau (Fig. 1). The annual cycle of Eurasian snow cover extent is characterized by a gradual accumulation of continental snow from October to March and a rapid ablation of the snow during spring and summer. Snow is absent from most of the Eurasian region in June to September. The maximum variation of Eurasian snow cover occurs in spring (March and April). The impacts of Eurasian snow cover on climate have been investigated by Hahn & Shukla (1976), Barnett et al. (1988, 1989), Vernekar et al. (1995), Kripalani & Kulkarni (1999), and Cohen & Entekhabi (2001).

By analyzing sea surface temperature anomaly (SSTA) in the Indian Ocean, a dipole oscillation (Indian

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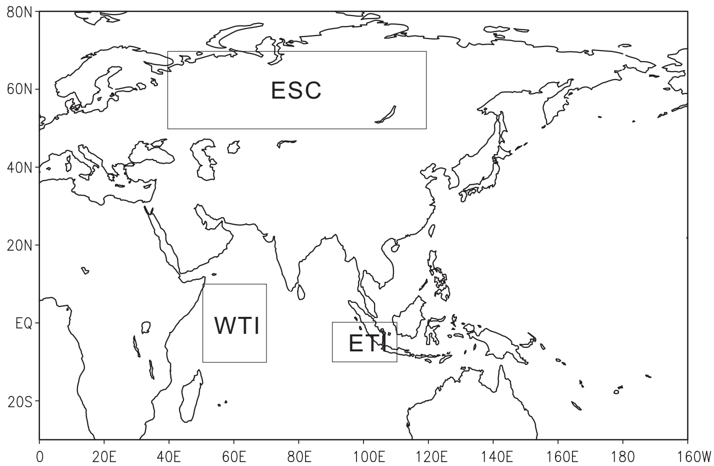

Fig. 1. Eurasian snow cover region (ESC; 40 to 120° E, 50 to 70° N) and Indian Ocean region. WTI: western tropical Indian Ocean (50 to 70° E, 10° S to 10° N); ETI: eastern tropical Indian Ocean (90 to 110° E, 10° S to equator). The Indian Ocean Dipole (IOD) index is defined as the difference in sea surface temperature anomalies (SSTA) between WTI and ETI

Ocean Dipole, IOD) was first found by Saji et al. (1999). They defined an index of the IOD as the difference in SSTA between the western tropical Indian Ocean (WTI; 50 to 70° E, 10° S to 10° N) and the eastern tropical Indian Ocean (ETI; 90 to 110° E, 10° S to the equator). The IOD has 2 patterns: a positive phase (higher SST in the WTI) and a negative phase (higher SST in the ETI). A positive IOD phase leads to drought over the Indonesian region, and to heavy rain and flooding in East Africa, whereas a negative IOD leads to rain and flooding in Indonesia, and to drought in East Africa (Ashok et al. 2001). The IOD is one of the major ocean–atmosphere coupling phenomena in the tropical Indian Ocean; it was originally thought to be unrelated to ENSO (Saji et al. 1999, Webster et al. 1999). Li & Mu (2001) found that the South Asia High and the Subtropical High in the western Pacific Ocean can be influenced significantly by IOD events. The IOD also has a significant influence on the Indian monsoon and Australian winter rainfall (Ashok et al. 2001, 2003).

Correlations between ENSO and snow cover have been reported by Li (1989), Barnett et al. (1989), and Yang (1993). Based on the model experiments, Barnett et al. (1989) demonstrated that Eurasian snow cover can trigger ENSO events. The present study is the first analysis of the links between Eurasian snow cover and the IOD.

Table 1. Correlation coefficients between the monthly mean index of the Indian Ocean Dipole (IOD) and the extent of Eurasian snow cover in spring. Significance levels: *p = 0.1; **p = 0.05

IOD index	Eurasian snow cover		
	March	April	Spring mean
January	–0.115	–0.145	–0.139
February	–0.082	–0.128	–0.112
March	–0.057	–0.118	–0.094
April	–0.079	–0.168	–0.133
May	–0.142	–0.267*	–0.219
June	–0.199	–0.323**	–0.281*
July	–0.268*	–0.377**	–0.348**
August	–0.299*	–0.379**	–0.366**
September	–0.319**	–0.395**	–0.386**
October	–0.324**	–0.385**	–0.384**
November	–0.304**	–0.393**	–0.376**
December	–0.277*	–0.388**	–0.359**

2. DATA

Monthly mean IOD index data were provided by N. H. Saji (pers. comm.) for March 1958 to October 1999; Eurasian snow cover extent data in spring (March and April) are available from the USA National Snow and Ice Data Center (NSIDC), reconstructed by Brown (2000) utilizing the reconstructed daily snow depth and NOAA satellite data. In addition, the NCEP/NCAR reanalysis data, monthly mean outgoing longwave radiation (OLR) and wind fields, as well as monthly long-term mean zonal heat flux with $2.5 \times 2.5°$ resolution, were obtained from the NOAA-CIRES Climate Diagnostics Center (available at www.cdc.noaa.gov).

3. RESULTS

The Eurasian snow cover extent in spring (March, April, and the average of March and April) correlates negatively with the monthly mean IOD index from June to December; the correlation is more significant during September to November (Table 1, Fig. 2), corresponding to the stronger intensity of IOD events in autumn (Li et al. 2002).

In summer, the Tibetan Plateau is a heat source for Eurasia. In years with strong Eurasian snow cover, the intensity of the Tibetan Plateau heat source weakens because of the greater quantity of shortwave radiation reflected in spring (due to the higher albedo), the absorption of much heat in summer (due to the melting of the snow), and the decrease in latent heat release (due to the decrease in summer monsoon rainfall). Inversely, the intensity of the Tibetan Plateau heat source strengthens when Eurasian snow cover is light. Therefore, the land–sea temperature contrast between Eurasia and Indian Ocean is significantly influenced in the summer by Eurasian snow cover anomalies (Barnett et al. 1989). This may affect heat transmission and

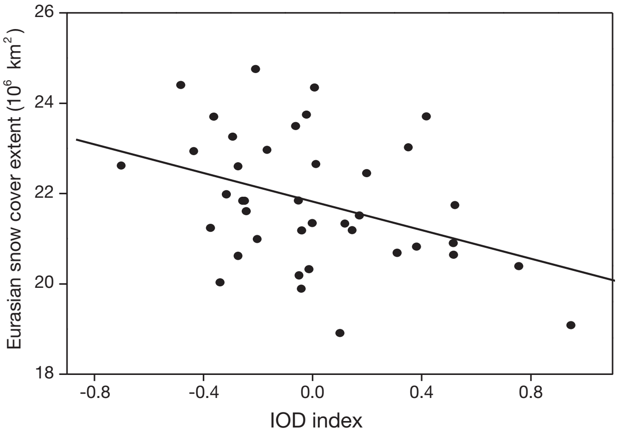

Fig. 2. Scatterplot between the Indian Ocean Dipole (IOD) index (mean from September to November) and Eurasian snow cover extent (mean of March and April). R = –0.386 (significant at p = 0.01)

atmospheric circulation between the Indian Ocean and Eurasia, and between the western and eastern Indian Ocean (Groisman et al. 1994b). Therefore, we analyzed the anomalies of heat transmission and atmosphere circulation patterns in summer (July) to investigate the influence of Eurasian snow cover in spring on IOD events.

In order to define years with heavier and lighter snow cover, the average extent of snow cover in March and April was standardized by subtracting the mean and dividing by the standard deviation (SD). A year with a value >1.0 SD was defined as a year with heavy snow cover. Inversely, a value <–1 SD was defined as light snow cover. Based on this division, there were 7 yr with heavy snow cover (1964, 1969, 1979, 1980, 1981, 1985, 1987) and 6 yr with light snow cover (1962, 1989, 1990, 1992, 1993, 1997). Composite analyses of OLR and wind fields over the Indian Ocean, in years with heavy and light Eurasian snow cover, were used to study the impacts of snow cover in spring on IOD events.

OLR data were lacking before June 1974, which leaves 5 yr of heavy, and 5 yr of light snow cover for analysis. Fig. 3 shows the difference in Indian Ocean OLR in July between years with heavy and light Eurasian snow cover. The distribution pattern suggests that in years with heavy snow cover, convection activity is stronger over the ETI and weaker over the WTI, and vice versa in years with light snow cover. Convection activity is correlated to the temperature in the low troposphere; therefore, when Eurasian snow cover is strong, SST is higher in the ETI and lower in the WTI, which corresponds to the negative phase of an IOD event. The inverse applies in years with light snow cover.

Fig. 4 shows the difference in tropospheric wind vectors in July between years with heavy and lighter snow cover. In the lower troposphere (Fig. 4a), a westerly anomaly occurs over the central tropical Indian Ocean,

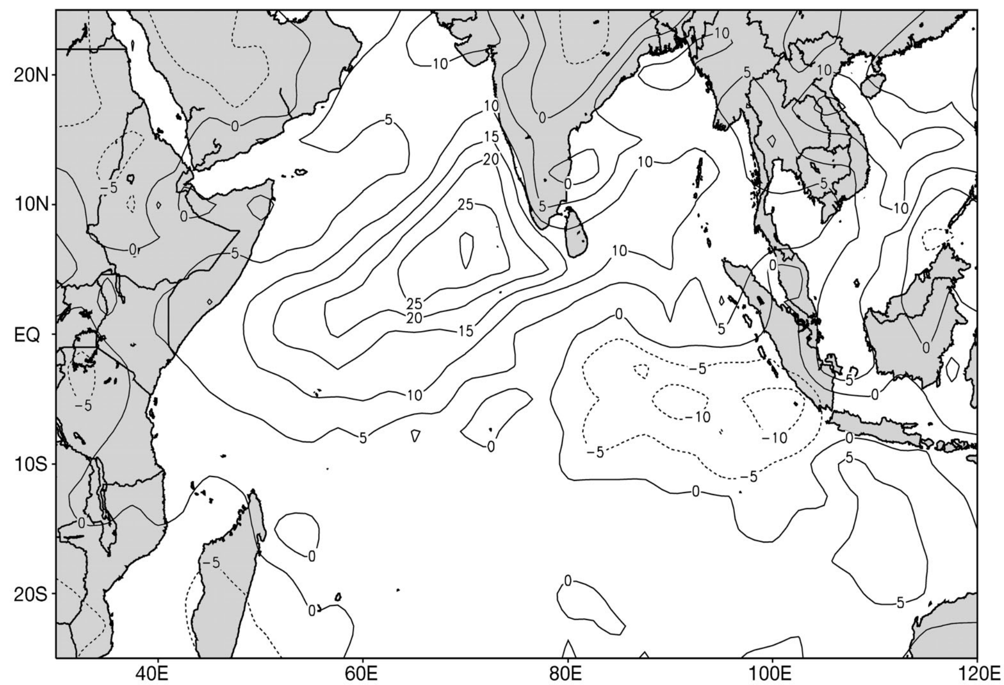

Fig. 3. Difference of outgoing longwave radiation (OLR) in July between years with heavy and light Eurasian snow cover (heavy – light)

a northerly anomaly over the Bay of Bengal, and a northwesterly anomaly occurs west of Sumatra. There is a reverse circulation pattern in upper of troposphere (Fig. 4b), indicating that the vertical meridional circulation in summer (Hadley circulation) between the Indian Ocean and Eurasia weakens and the vertical zonal circulation (Walker circulation) between the WTI and ETI also weakens in years with heavy Eurasian snow cover, and vice versa in years with light snow cover. The vertical zonal circulation anomalies over the tropical Indian Ocean and the meridional circulation anomalies between the Indian Ocean and Eurasia lead to and maintain inverse SST distributions between the WTI and ETI.

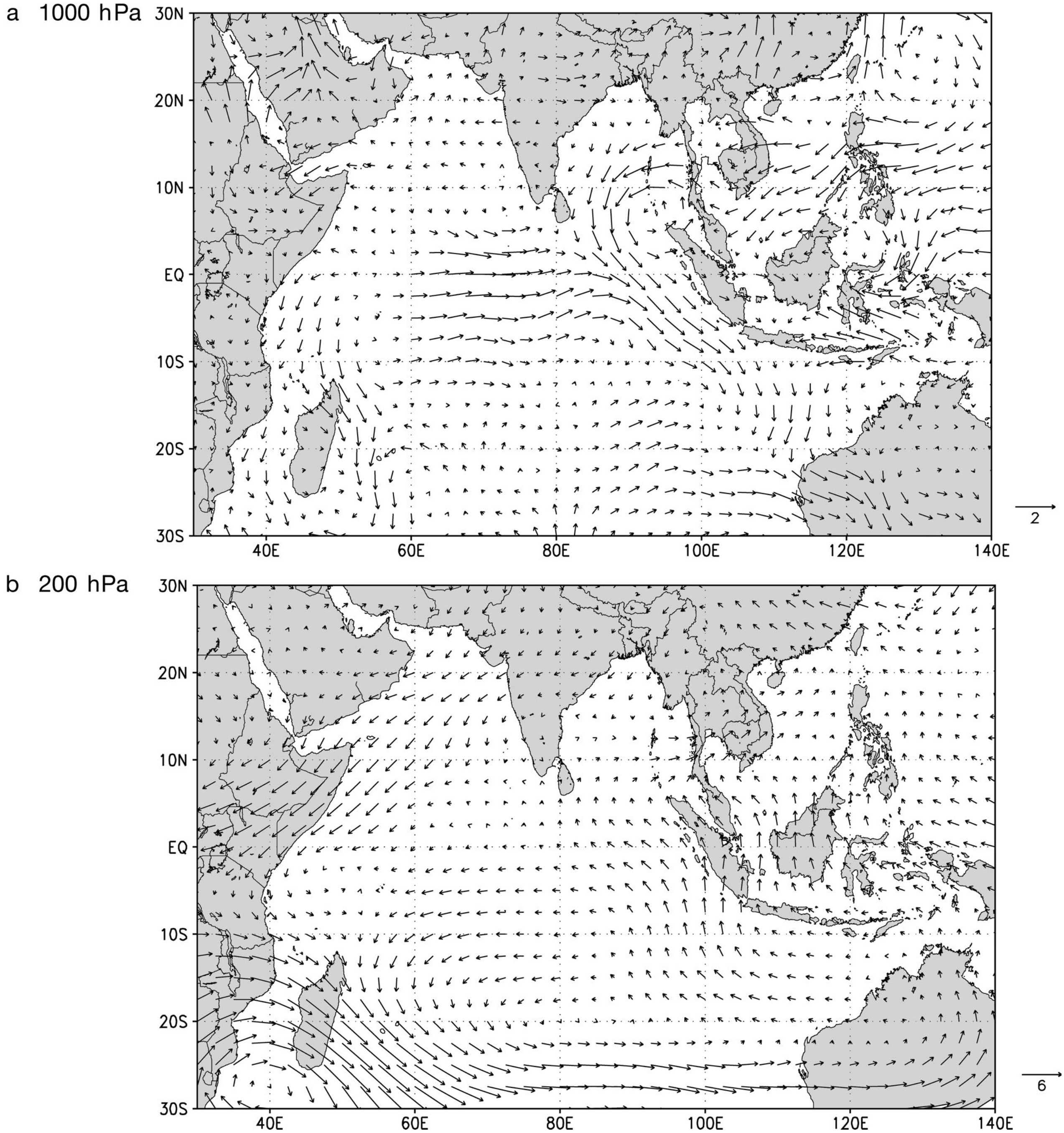

Fig. 4. Difference of wind vectors (arrows) in July in the (a) lower troposphere and (b) upper troposphere between years with heavy and light Eurasian snow cover (heavy – light). Wind vector speed is measured in m s^{-1}

4. DISCUSSION

IOD varies with a periodicity of 4 to 5 yr (Li & Mu 2001), which is consistent with fluctuations of Eurasian snow cover (Yang 1997). Furthermore, the IOD index was weaker in the 1980s and stronger in the 1990s (Yin et al. 2001), probably responding to higher Eurasian snow cover extent in the 1980s and lower cover in the 1990s (Gao et al. 2003).

Monthly long-term mean zonal heat flux variations in July over the Indian Ocean along the equator show that heat is transmitted westwards in the lower troposphere (Fig. 5a) and eastwards in the upper troposphere (Fig. 5b); this is consistent with the zonal wind circulation (Fig. 4) caused by anomalies of Eurasian snow cover in spring. Therefore, zonal heat transmission over the tropical Indian Ocean is also probably affected by anomalies of Eurasian snow cover, leading to heat redistribution between the WTI and ETI. Snow cover extent could indicate large-scale changes in temperature advection, and the cold, dense air generated above a snow surface may be propagated to far away regions by atmospheric teleconnections (Cohen 1994). Thus, Eurasian snow cover in spring and IOD events may be linked by the zonal heat transmission between the WTI and ETI. Moreover, snow melting, soil moisture and evaporation processes in summer influence soil hydrology and modify the meridional gradient of temperature between the land and the overlying atmosphere, and this also leads to anomalous meridional heat transmission between Eurasia and the Indian Ocean. The possible influence of Eurasian snow cover on IOD events is illustrated in Fig. 6. However, the IOD index is closely linked to the seasonal cycle (Saji et al. 1999), which may not be caused by the Eurasian snow cover. Eurasian snow cover in spring may be a triggering factor for IOD

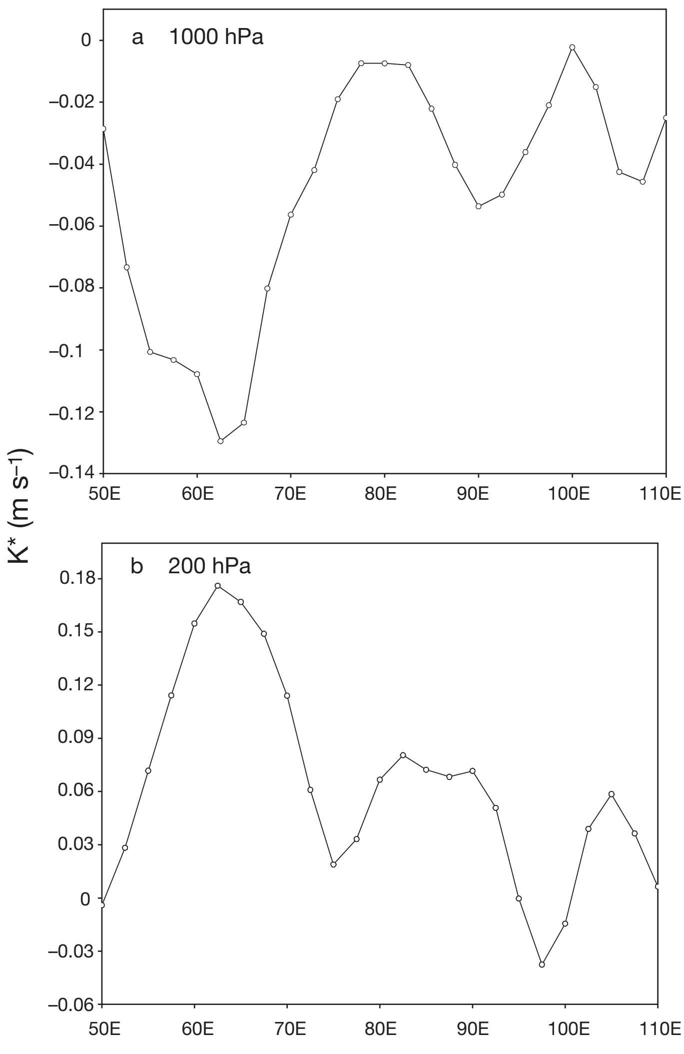

Fig. 5. Monthly long-term mean of zonal heat flux variations in July in the (a) lower troposphere (1000 hPa) and (b) upper troposphere (200 hPa) along the equator over the Indian Ocean

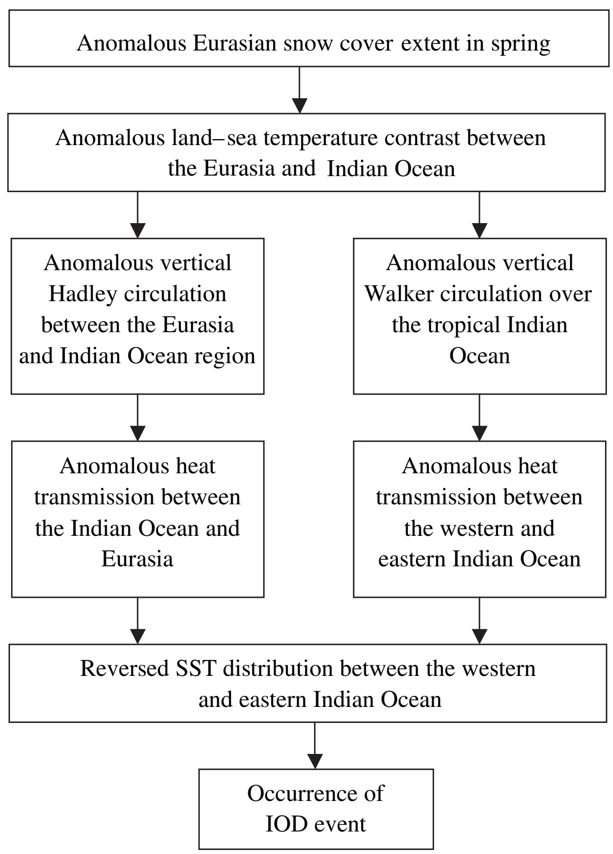

Fig. 6. Possible influence of Eurasian snow cover in spring on the Indian Ocean Dipole (IOD) events. SST: sea surface temperature

events, and may serve to predict the occurrence and intensity of IOD events.

Temperatures in the Northern Hemisphere have increased by 0.4°C between the 1960s and the 1980s, and by about 1.0°C from 1990 to 2000 (IPCC 2001). Chapman & Walsh (1993) and Serreze et al. (2000) found that the strongest warming has occurred during winter and spring. Eurasian snow cover in spring must thus decline. Annual snow cover has been declining since the 1980s (Groisman et al. 1994a), and low cover anomalies have been observed after 1988 (Leathers & Robinson 1993). Therefore, the change in Eurasian snow cover in spring under the global warming probably influences IOD events significantly. According to the negative relationship between the Eurasian snow cover extent and IOD index, the intensity of positive IOD events can be expected to strengthen, and for negative IOD events it will weaken. Therefore, further investigation of the variations in Eurasian snow cover and IOD events and their influences on climate under the global warming are warranted.

5. CONCLUSIONS

The anomalies of Eurasian snow cover in spring probably influence the vertical zonal circulation (Walker circulation) over the tropical Indian Ocean and the vertical meridional circulation (Hadley circulation) between the Indian Ocean and Eurasia. The anomalies of the Walker and Hadley circulations may affect the zonal heat transmission and heat redistribution between the WTI and ETI. Eurasian snow cover in spring is negatively correlated with IOD events, and Eurasian snow cover can probably trigger IOD events.

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