Some Advances in Studies of the Climatic Impacts of the Southern Hemisphere Annular Mode

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ABSTRACT

The Southern Hemisphere (SH) annular mode (SAM) is the dominant mode of atmospheric circulation in the SH extratropics. The SAM regulates climate in many regions due to its large spatial scale. Exploration of the climatic impacts of the SAM is a new research field that has developed rapidly in recent years. This paper reviews studies of the climatic impact of the SAM on the SH and the Northern Hemisphere (NH), emphasizing linkages between the SAM and climate in China. Studies relating the SAM to climate change are also discussed. A general survey of these studies shows that signals of the SAM in the SH climate have been systematically investigated. On interannual scales, the SAM can influence the position of storm tracks and the vertical circulation, and modulate the dynamic and thermodynamic driving effects of the surface wind on the underlying surface, thus influencing the SH air-sea-ice coupled system. These influences generally show zonally symmetrical characteristics, but with local features. On climate change scales, the impacts of the SAM on SH climate change show a similar spatial distribution to those on interannual scales. There are also meaningful results on the relationship between the SAM and the NH climate. The SAM is known to affect the East Asian, West African, and North American summer monsoons, as well as the winter monsoon in China. Air-sea interaction plays an important role in these connections in terms of the storage of the SAM signal and its propagation from the SH to the NH. However, compared with the considerable knowledge of the impact of the SAM on the SH climate, the response of the NH climate to the SAM deserves further study, including both a deep understanding of the propagation mechanism of the SAM signal from the SH to the NH and the establishment of a seasonal prediction model based on the SAM.

Key words: Southern Hemisphere annular mode (SAM), monsoon, climatic impact, climate change, interaction between the Northern and Southern Hemispheres

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1. Introduction

About 70% of the total land surface on the earth is in the Northern Hemisphere (NH), while the oceans occupy more than 60% of the Southern Hemisphere (SH). This land-sea distribution determines the distribution of population, with more than 90% living in the NH. Therefore, observations of and research on NH climate systems started earlier than for the SH and have made more progress. However, the global climate system is an entity and the climate state in the SH can regulate the NH climate via its influence on the exchange of energy, momentum, mass, and water vapor between the two hemispheres. In recent decades, the depletion of Antarctic ozone and the sensitivity of polar climate to global climate change have prompted the investigation of SH climate systems. For example, one key project of the World Climate Research

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Programme (WCRP), the Climate and Cryosphere (CliC), has encouraged the development of the Southern Ocean Observing System (SOOS), while another, the Stratospheric Processes and their Role in Climate (SPARC) project, emphasizes the development of chemistry-climate models related to polar ozone. In China, scientific expeditions to the Southern Ocean and the Antarctic have taken place for many years. Observational data for SH climate systems have gradually accumulated alongside the rapid development of satellite observation, the establishment of ground observation stations in the Antarctic, and the deployment of Argo buoys in the Southern Ocean. This increase in observational data provides a foundation for exploring the variability of SH climate systems.

Atmospheric teleconnections are important phenomena. Earlier studies on atmospheric teleconnection include researches about the Southern Oscillation. The primary teleconnection patterns in the NH include the North Atlantic Oscillation (NAO; Walker and Bliss, 1932), the North Pacific Oscillation (NPO; Rogers, 1981), the Eurasian teleconnection (EU; Wallace and Gutzler, 1981), the Pacific-North American teleconnection (PNA; Wallace and Gutzler, 1981), the Arctic Oscillation (AO; Thompson and Wallace, 1998), and the NH annular mode (NAM; Thompson and Wallace, 2000). These low-frequency teleconnection patterns make a large contribution to circulation variability and play an important role in regulating regional and hemispheric climate, and thus occupy an important position in climate research. As more NH teleconnection patterns have been revealed, research into the SH annular mode (SAM) has rapidly developed.

The SAM, also known as the Antarctic Oscillation (AAO), is the dominant mode of atmospheric circulation in the SH extratropics (Gong and Wang, 1998, 1999; Thompson et al., 2000). The generation and persistence of the SAM are associated with wave-flow interaction, which is an important internal process in the atmosphere (Limpasuvan and Hartmann, 1999; Lorenz and Hartmann, 2001; Zhang et al., 2012). Temporal variability of the SAM is clearly evident on many scales: decadal, interannual, seasonal, monthly, sub-monthly, and daily (Fan et al., 2003; Wang and Fan, 2005; Li and Li, 2010, 2012; Zhang et al., 2010; Yuan and Yonekura, 2011). Spatially, the SAM is quasi-barotropic, and its signal is evident in both the troposphere and the stratosphere. The variability of the SAM reflects the out-of-phase relationship between atmospheric masses in the SH middle and high latitudes, and is accompanied by a meridional shift of the SH jet system. When the SAM is in a positive phase, geopotential height in the SH high and middle latitudes is lower and higher, respectively, and the jet shifts towards the Antarctic. When the SAM is in a negative phase, the situation reverses, and the jet shifts towards the equator. Li and Wang (2003) proposed the concept of an atmospheric annular belt of activity, provided a clear explanation of the structure of the SAM, and defined an SAM index that is widely used in climate research (Ding et al., 2005; Feng et al., 2010; Li and Li, 2012; Sun and Li, 2012).

Figure 1 shows a schematic diagram of the climatological atmospheric circulation in the SH in austral summer (December–February) and the corresponding circulation anomalies during a positive SAM phase. The positive phase of the SAM corresponds to a poleward shift of the SH jets, and a strengthened polar jet but a weakened subtropical jet (Fig. 1b). In addition, the Ferrel cell during the positive phase of the SAM is stronger than in the climatology, indicating the importance of the Ferrel cell (Li and Wang, 2003; Li, 2005a, b) to the SAM behavior. As shown in Fig. 1, the SAM covers a wide latitudinal band around the earth. This large-scale spatial structure means that the SAM has a broad climatic impact. There is abundant evidence in the literature showing that the signals of the SAM are not confined to the Antarctic, the SH middle latitudes and the subtropics, but extend to many regions in the NH. Since the end of the 20th century, there has been a significant positive trend in the SAM activity in step with global warming (Thompson et al., 2000; Marshall, 2003). This trend has induced climate responses in many regions, further highlighting the urgency of investigating the influence of the SAM.

Variability of the SAM and its climatic influences

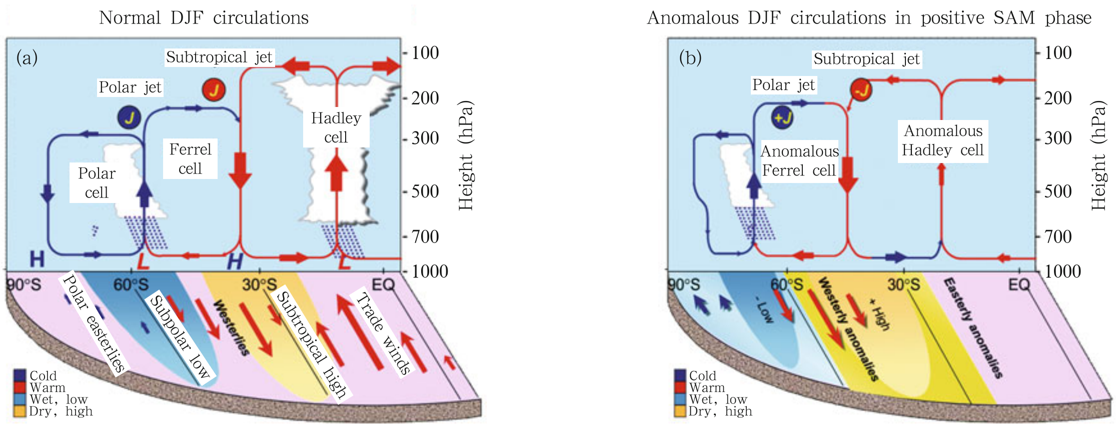

Fig. 1. Schematic diagram of (a) the climatology of atmospheric circulation in the Southern Hemisphere in austral summer (December–February) and (b) the corresponding circulation anomalies during a positive SAM phase.

are new research directions that have rapidly developed both in China and overseas in recent years. Exploring the climatic influences of the SAM is useful in understanding the interactions between the NH and the SH, and between different latitudes. On the interannual timescale, investigation of the influence of the SAM may provide new predictors and ideas for seasonal prediction. On the climate-change timescale, it can provide new clues for the attribution of climate change and new information on downscaling projections of long-term changes in climate variables. Therefore, exploring the climatic influence of the SAM is not only of scientific significance, but also of practical value. In recent years, Chinese and foreign researchers have made significant progress in understanding the climatic influence of the SAM. This paper lists the main achievements and provides a concise review of the new knowledge obtained in recent decades. In this paper, the AAO is referred to as the SAM and the seasons are defined for the NH unless otherwise specified. The remainder of this paper is organized as follows. We briefly review the impact of the SAM on the SH climate systems in Section 2, and its influence on the NH is introduced in Section 3. The modulating effect of the SAM on climate over China is reviewed in detail in Section 4. In Section 5, we document recent progress on the topic of climate change related to the SAM. Finally, conclusions are given in Section 6.

2. Influence of the SAM on SH climate

The SAM is the dominant mode of SH extratropical circulation, and its influence on SH climate systems has been investigated in many studies. We review these studies from three aspects: the atmosphere, the ocean, and the sea ice.

2.1 Atmosphere

Thompson et al. (2000) explored the signal of the SAM in the SH extratropical circulation on monthly scales. Using surface air temperature data from the Climate Research Unit (CRU), they pointed out that when the SAM is in positive phase, mainland Antarctica is cooler due to adiabatic cooling caused by anomalous upward motion in the near-surface layer, whereas the Antarctic Peninsula is warmer because of strengthening warm advection from the ocean, which is related to the intensification of circumpolar westerlies. Kwok and Comiso (2002) and Schneider et al. (2004) reached similar conclusions using satellite infrared surface temperature and passive microwave brightness temperature, and noted that the SAM makes the largest contribution to surface air temperature variations over the Antarctic. Based on the observations from Antarctic ground stations, Marshall (2007) explored the seasonal differences in the relationship between the SAM and Antarctic surface air temperature, by examining the different responses of air temperature over the Antarctic mainland and peninsula to the SAM. The author proposed a new mechanism for explaining this response pattern: when the SAM is in positive phase, the cooling of mainland Antarctica is related to a decrease in oceanic meridional heat transport, and the warming of the Antarctic Peninsula is associated with a decrease in cold air outbreaks from the pole. In addition, Lu et al. (2007) verified the negative correlation between the SAM and surface air temperature in mainland Antarctica using model (HadAM3) simulations.

The influence of the SAM can extend northward to the SH subtropics. Bals-Elsholz et al. (2001) showed that when the SAM is in its positive phase, the austral winter (July–September) jet system in the SH tends to split into a subtropical jet and a polar front jet. The positive phase of the SAM also corresponds to more precipitation over 50°–70°S, but less over 40°–50°S according to Lu et al. (2007), based on model (HadAM3) simulations, leading to a dipole-like precipitation anomaly pattern in the SH extratropics. This model simulation verified the conclusions of Gillett et al. (2006), which were derived from station observations, and agreed with other simulations using different general circulation models (Watterson, 2000; Cai and Watterson, 2002; Karoly, 2003; Gupta and England, 2006; Lu et al., 2007). The dipole-like influence of the SAM on the SH extratropical precipitation is linked to responses of storm tracks, vertical motion, and cloudiness to the SAM.

Many researchers have investigated the influence of the SAM on SH precipitation on regional scale. Their results have shown that precipitation in the southern Andes (González and Vera, 2010), South Africa (Fauchereau et al., 2003; Reason and Rouault, 2005), New Zealand (Renwick, 2002), and Northwest Australia (Feng et al., 2013) responds strongly to variations of the SAM. In addition, the SAM is positively correlated with typhoon frequency over the southern Indian Ocean during the typhoon season (December–March), according to Mao et al. (2013). These authors suggested that when the SAM is in its positive phase, the number of tropical cyclones passing over the northwestern coast of Australia (10°–30°S, 100°–120°E) increases by 50%–100% compared with the climatology, primarily due to more frequent generation of tropical cyclones. The increased frequency of tropical cyclones is associated with strengthened water vapor convergence and anomalous ascending motion, caused by a cyclonic anomaly over the western coast of Australia during the positive SAM phase.

Moreover, the precipitation over southwestern West Australia (SWWA) has shown a significant decreasing trend (Hennessy et al., 1999), and many researchers have investigated the linkage between this drying trend and the SAM. For example, some studies proposed that the SAM can regulate the interannual variability and long-term trend of SWWA precipitation by modulating the frequency of heavy precipitation (Ansell et al., 2000; Cai and Watterson, 2002; Cai et al., 2005; Li et al., 2005; Cai and Cowan, 2006) or the position of the SH midlatitude westerlies (Gupta and England, 2006; Meneghini et al., 2007). Hendon et al. (2007) further noted that this influence of the SAM on precipitation over SWWA is most marked in austral summer (December–February). Is austral winter (June–August) precipitation over SWWA also significantly linked to the SAM? Feng et al. (2010) found that the negative correlation between the SAM and austral winter (June–August) precipitation over SWWA is caused mainly by one extreme year (1964). After removing the data of 1964, the correlation between the SAM and austral winter precipitation over SWWA is quite weak. This analysis by Feng et al. (2010) illustrates the importance of objective statistical analysis for obtaining reliable conclusions when investigating possible connections between variables.

2.2 Ocean

The earth's surface in the SH extratropics has unique characteristics. This region includes the Southern Ocean, which is a critical channel for transmitting climate signals to the Pacific, the Atlantic, and the Indian Ocean, and plays a key role in modulating variability and changes in climate. Therefore, it is important to explore air-sea coupling processes related to the SAM in the SH extratropics.

The primary surface circulation system in the Southern Ocean is the Antarctic Circumpolar Current (ACC), which is characterized by sloping isopycnals and a deep wind-driven current. Lefebvre et al. (2004) used a coupled climate model (ORCA2-LIM) driven by the NCEP/NCAR reanalysis data to show that an enhanced SAM corresponds to an increased surface velocity in the ACC. Gnanadesikan and Hallberg (2000) analyzed the response of the ACC to wind stress using a coarse-resolution ocean model from the perspective of heat and dynamic balance. Their results showed that the strengthening of wind stress over the Southern Ocean can enhance the transport of the ACC, and therefore the SAM can modulate ocean transport in the Drake Passage on the interannual scale (Meredith and Hughes, 2004; Meredith et al., 2004). Zhang and Meng (2011) found that changes in local wind stress caused by the SAM result in modulation of the ACC transport and tilt of the isopycnal surfaces, which leads to changes in the baroclinic energy conversion rate from the background ocean to mesoscale eddies, and thus contributes to the interannual variability of mesoscale eddies. The maximum (minimum) zonal wind stress leads the eddy kinetic energy maximum (minimum) by approximately 3 yr.

The influence of the SAM on the SH oceans is not only manifested in its modulation of oceanic circulation, but also in its regulation of sea surface temperature (SST). When the SAM is in positive phase, the SH circumpolar westerlies shift towards the Antarctic, which forces the changes in ocean dynamics through changes in sea surface wind. The northward Ekman transport is enhanced, leading to a stronger upwelling around the Antarctic and an anomalous downwelling around 45°S. Meanwhile, the changes in sea surface wind associated with the positive phase of the SAM can also thermally force the ocean, with changes in air-sea heat flux (Mo, 2000; Watterson, 2000, 2001; Cai and Watterson, 2002; Hall and Visbeck, 2002; Nan and Li, 2003; Lefebvre et al., 2004; Gupta and England, 2006; Nan et al., 2009; Wu et al., 2009; Zheng and Li, 2012). Therefore, the positive phase of the SAM results in warmer SST in the SH midlatitudes, but cooler SST at high latitudes, leading to a dipole-like SST anomaly pattern. In view of the large heat capacity of the ocean, this SST anomaly pattern usually persists for about one season (Wu et al., 2009; Zheng and Li, 2012). The influence of the SAM on the SH extratropical SST and the persistence of this SST anomaly pattern is an important "bridge" in the modulation of the NH climate by the SAM, as described below.

Furthermore, the association between the SAM and the mixed layer depth is receiving increased attention. The mixed layer depth is regulated by sea surface wind stress, and in turn influences heat exchange between the atmosphere and the ocean, thus determining the ocean's capacity to store heat. Unlike the zonally symmetric response of the SH extratropical SST to the SAM, the mixed layer depth shows a zonally asymmetric response to the SAM according to Sallee et al. (2010). The anomalies in meridional wind and ocean heat transport caused by the SAM are the primary drivers of the zonally asymmetric response of the mixed layer depth.

2.3 Sea ice

The influence of the SAM on SH sea ice is relatively complex, showing some zonal asymmetry (Kwok and Comiso, 2002; Lefebvre et al., 2004). When the SAM is in positive phase, sea ice in the Weddell Sea decreases while that in the Ross Sea increases. This non-zonal response of sea ice to the SAM arises because the westerlies around the Antarctic Peninsula blow toward the southeast, while those around the Ross Sea blow toward the northeast, so that more warmer (colder) air is transported to the Weddell (Ross) Sea (Lefebvre et al., 2004). Lefebvre and Goosse (2005) used model (ORCA2-LIM) simulations to show that this dynamic process is the main reason for the thinning of sea ice over the Weddell Sea, whereas the reduction in the area of sea ice over the Weddell Sea is more closely related to anomalies in thermal processes caused by the SAM.

In general, the non-zonal response of the SH sea ice to the SAM is associated with both dynamic and thermodynamic processes. Gupta and England (2006) investigated the response of the air-sea ice coupled system to the SAM using the NCAR climate model, and showed that the atmospheric and oceanic dynamic and thermodynamic forcings caused by the SAM can explain the variability of the Antarctic sea ice quite well, and that the anomalies in sea ice could persist for several months because of the positive feedback of sea ice albedo.

It is worth noting that the atmosphere and ocean form a coupled system. The SAM can influence SST and sea ice, and these climate sub-systems also feedback to the SAM (Watterson, 2000, 2001; Marshall and Connolley, 2006; Raphael et al., 2011). As these feedbacks are not the key points in this paper, they are not considered in further detail.

3. Influence of the SAM on NH climate

The global atmospheric circulation is a single entity; changes in meridional overturning circulation and other circulation variables in the SH may also influence the NH circulation. In this section, we review the influence of the SAM on climate in the NH except for China, which will be covered in the next section.

The influence of the SAM on the NH atmospheric circulation is evident on both sub-seasonal and interannual scales. On interseasonal scales, Song et al. (2009) pointed out that in boreal winter (December–February), the positive (negative) phase of the SAM corresponds to lower (higher) geopotential height and anomalous westerlies (easterlies) over the mid to high latitudes (45°–65°N) in the Atlantic, but higher (lower) geopotential height and anomalous easterlies (westerlies) over the midlatitudes (25°–40°N), leading to a dipole pattern similar to the NAO (Song and Li, 2009). They suggested the following mechanism to explain this process: the boreal winter SAM can lead to zonal wind anomalies in the eastern tropical Pacific via wave-flow interactions (Thompson and Lorenz, 2004; Song et al., 2009), and these zonal wind anomalies can trigger a PNA-like Rossby wave propagating toward the North Atlantic, which leads to eddy momentum anomalies that further evolve into an NAO-like pattern (Song et al., 2009).

On interannual scales, the SAM is closely linked to climate in East and South Asia. For example, Ho et al. (2005) found that the positive SAM phase in summer (July–September) corresponds to an anomalous anticyclonic circulation over the western North Pacific, which influences the tracks of tropical cyclones, leading to more tropical cyclones over the East China Sea but fewer over the South China Sea. Wang and Fan (2006) reported a significant negative correlation between the summer (June–September) SAM and typhoon frequency in the western North Pacific. This negative correlation arises because the positive phase of the boreal summer SAM usually results in enhanced vertical shear of zonal wind and cooler SST through a meridional teleconnection pattern, and these conditions do not favor the genesis and development of typhoons.

In Africa, the SAM can modulate the behavior of the West African monsoon and precipitation over the Sahel. Sun et al. (2010) found that when the boreal spring (March–April) SAM is in positive phase, the tropical SST in the South Atlantic is warmer, thus changing the gradient of wet static energy between Guinea and the tropical Atlantic. This changed gradient of wet static energy is important to the northward onset of the West African monsoon, and leads to heavier precipitation over the Sahel in the early summer. The positive feedback between the precipitation and soil humidity favors the maintenance of these precipitation anomalies throughout the boreal summer (June–September).

In North America, the positive phase of boreal spring (April–May) SAM usually corresponds to a weaker North American summer monsoon and decreased precipitation. Sun (2010) proposed a mechanism for the above linkage: the positive phase of boreal spring SAM generally corresponds to warmer SST over the tropical Atlantic in spring and the following summer (July–September), which influences the Bermuda high and the North American monsoon and precipitation.

In addition to its effect on the atmosphere, the SAM could also regulate ocean circulation and corresponding oceanic variables in the NH. For example, Gong et al. (2009) found that the austral winter (August) SAM is positively related to the content of strontium (Sr) in coral reefs in the South China Sea, which can be considered as an indicator for SST. Marini et al. (2011) conducted a 500-yr numerical simulation and explored the driving effect of the SAM on the Atlantic meridional overturning circulation (AMOC). Their results showed that the AMOC is related to the SAM on several timescales. On the decadal scale, an enhanced AMOC lags the positive phase of the SAM by 8 yr. The mechanism for this linkage involves the positive phase of the SAM leading easterly anomalies over North Atlantic (50°–70°N) by 1 yr through the persistence of SST. The easterly anomalies increase salinity in the upper 500 m of the ocean near Greenland and Iceland, which leads to deepening of the ocean mixed layer in this region 4 yr later, causing the enhancement of ocean deep convection in North Atlantic, and thus strengthening the AMOC. On longer multidecadal scales, the SAM also modulates the strength of the AMOC through the northward propagation from the SH extratropics of the salinity anomalies caused by the SAM (Marini et al., 2011).

4. Influence of the SAM on climate in China

4.1 Impact of the SAM on the East Asian summer monsoon (EASM) and precipitation in China

The SAM has significant impacts on the EASM system and related climatic features. Firstly, we consider the influence of the boreal spring SAM on boreal summer circulation in China. The positive boreal spring (April–May) SAM is generally associated with a weakened EASM and increased summer (June–August) rainfall in the mid–lower reaches of the Yangtze River valley (MLYRV) (Gao et al., 2003; Nan and Li, 2003, 2005a, b; Bao et al., 2006; Fan, 2006; Fan and Wang, 2006; Wu et al., 2006a; Nan et al., 2009; Li et al., 2011a, b). The studies cited above were in general agreement in identifying circulation anomalies over East Asia as the reason for this association. When the spring SAM is in positive phase, the EASM weakens, the western North Pacific subtropical high strengthens and shifts westward, and ascending motion strengthens in the MLYRV, which leads to more precipitation.

However, there are still two key questions to be resolved about this linkage between the boreal spring SAM and East Asian summer circulation. One is how the boreal spring SAM signals persist in summer, and the other is how the anomalous signals propagate from the SH to the NH. The studies cited above provided different explanations from various perspectives. In response to the first question, Wu et al. (2006a) reported that when the spring (April–May) SAM is in positive phase, SST is warmer offshore of China, with a decrease in the land-sea thermal contrast, thus leading to a weaker EASM. As for the second question, the mechanism by which the anomalous signal propagates from the SH to the NH, Gao et al. (2003) pointed out that the SAM in May is positively correlated with a strong Mascarene high in the lower troposphere in July, which corresponds to an anomalous western North Pacific subtropical high.

Nan and Li (2005a, b) gave a comprehensive answer to the above two questions. They suggested that the spring SAM can regulate the EASM and rainfall in the MLYRV by the "ocean-atmosphere coupled bridge" process in the Indian Ocean. In detail, when the spring (April–May) SAM is in positive phase, SST is warmer in the mid and high latitudes of the southern Indian Ocean, and this SST anomaly moves northward until it reaches the northern Indian Ocean. In summer (June–August), the SST anomalies over the northern Indian Ocean modulate the atmospheric circulation through air-sea interactions, resulting in a weakened EASM and a strengthened western North Pacific subtropical high.

Wu et al. (2006b, c) also explored the relationship between the SAM and the "drought-flood coexistence," or the "drought-flood abrupt alternation" in the MLYRV. Gao et al. (2012) pointed out that the precursory signal for the Asian summer monsoon onset could be traced back to the SAM in the preceding boreal winter (December–February). Sun et al. (2013) indicated that the influence of the boreal spring SAM on summer rainfall in China shows decadal variations.

With regard to the influence of the boreal summer

SAM on contemporary summer monsoon circulation and rainfall over China, Xue and Wang (2004) showed that a positive summer (June–August) SAM is commonly associated with a strengthened Mascarene high in the lower troposphere, which leads to the Pacific-Japan (PJ) wave train from East Asia to the west coast of North America along the North Pacific Ocean, resulting in a stronger Meiyu (Baiu) from the Yangtze River valley in China to Japan (Xue, 2005). Wang and Fan (2005), using historical rainfall data, found a significant negative correlation between the boreal summer SAM and summer (June–August) rainfall in the central region of North China, associated with the anomalous convection in the equatorial western Pacific and the zonal wave train from western Europe to North China. Figure 2 summarizes the conclusions of research on the effect of the SAM on the summer monsoon system and climate in all NH regions.

4.2 Influence of the SAM on the East Asian winter monsoon and air temperature in China

Wu et al. (2009) reported that the positive boreal autumn (September–November) SAM is commonly followed by a weaker winter monsoon in China. When the boreal autumn SAM is in positive phase, SST is warmer over 30°–45°S. Such SST anomalies persist into the boreal winter and weaken the Hadley cell, which gives a weaker winter (December–February) monsoon and warmer air temperatures in China. The boreal autumn SAM leads the variability of air temperature over China by one season, indicating that the SAM provides a meaningful predictor signal for winter climate in China. The effect of the SAM on winter climate is shown in Fig. 3. Qian (2014) analyzed the relationship between the boreal autumn SAM and winter (December–February) rainfall over South China, and reported a significant negative correlation between these two variables on interannual scales. The positive (negative) autumn SAM is usually associated with a significantly stronger (weaker) NH subtropical westerly jet, and abnormal northerly (southerly) wind over most of China, leading to decreased (increased) rainfall over South China.

4.3 Influence of the SAM on spring climate in China

Fan and Wang (2004) found that the preceding boreal winter (December–February) and spring

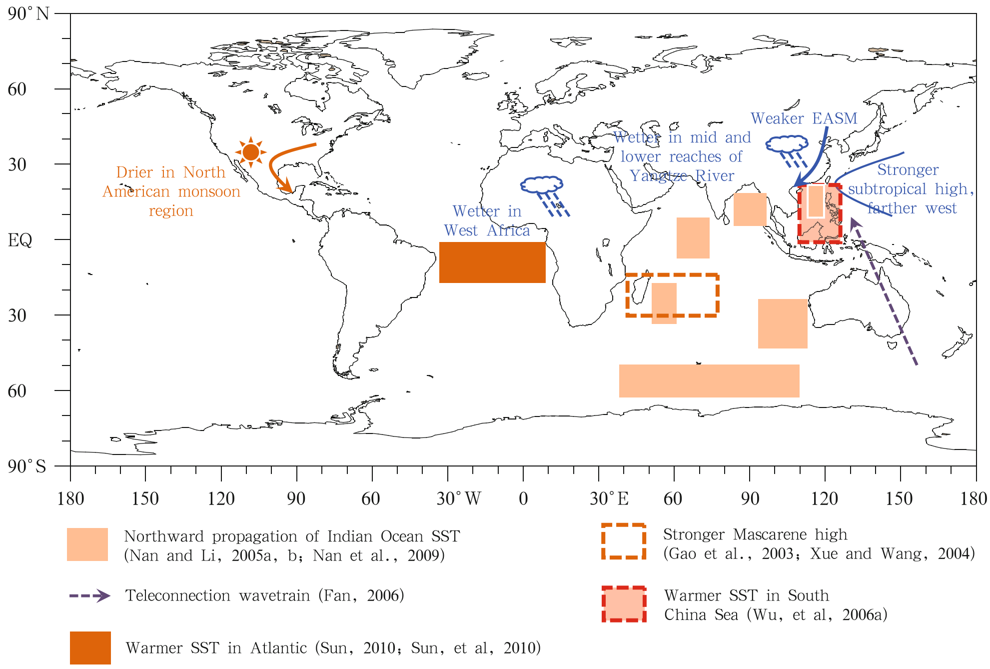

Fig. 2. Influences of the boreal spring and summer SAM on boreal summer Northern Hemisphere climate, together with the corresponding mechanisms (anomalies are shown for the positive SAM phase).

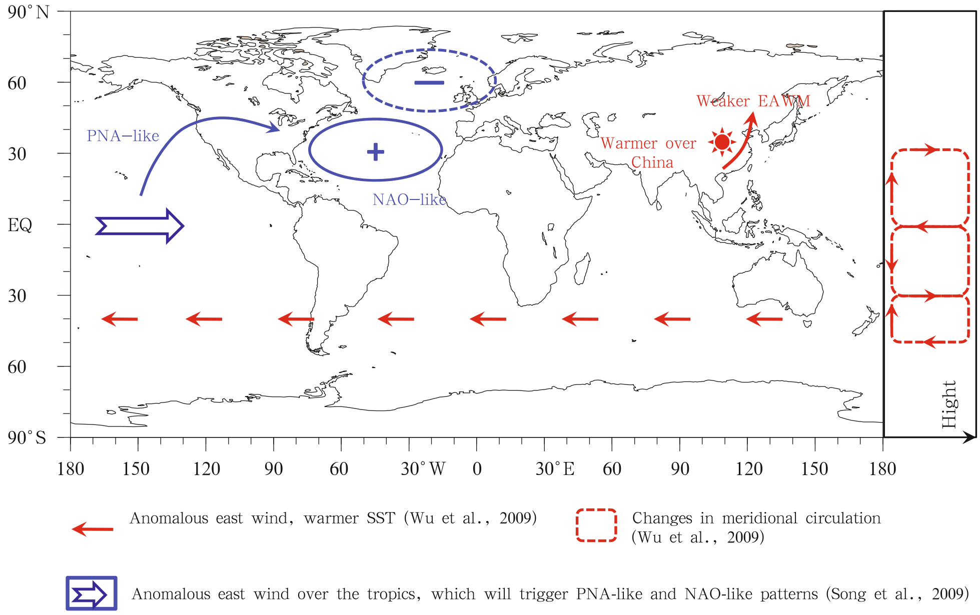

Fig. 3. Influences of the boreal autumn and winter SAM on boreal winter Northern Hemisphere climate, together with the corresponding mechanisms (anomalies are shown for the positive SAM phase).

(March–May) SAM had a significant negative correlation with the frequency of dust weather over North China. Two possible mechanisms account for the above correlation: a meridional teleconnection from the SH high latitudes to the NH high latitudes, and a regional teleconnection over the Pacific Ocean. Fan and Wang (2007) verified these teleconnection patterns using an atmospheric general circulation model (IAP9L-AGCM). Yue and Wang (2008) investigated the relationship between spring North Asian cyclone activity and the SAM, revealing a significant positive correlation between the preceding boreal winter (December–February) SAM and spring (March–May) North Asian cyclones. When the preceding boreal winter SAM was in positive phase, springtime atmospheric convection in the tropical western Pacific intensified and the local Hadley circulation strengthened. As a result, the jet strengthened at high levels, favoring North Asian cyclone activity.

However, what is the mechanism for SAM persistence? Does the preceding boreal winter SAM have an effect on spring precipitation? Recent studies have shown that the preceding boreal winter (December–February) SAM can regulate spring (March–May) precipitation over South China, and there is a significant negative correlation between them (e.g., Zheng and Li, 2012). The "ocean-atmosphere coupled bridge" plays an important role in this cross-seasonal process. When the preceding boreal winter SAM is in positive phase, westerlies strengthen in the SH high latitudes and weaken in the SH midlatitudes. Sea surface evaporation and latent heat release respond to this change in surface wind speed, producing warm and cool SST anomalies in the SH mid and high latitudes, respectively. The large heat capacity of the ocean allows the SST anomaly pattern to persist into the following spring, leading to a series of atmospheric responses. For example, there is abnormal sinking and reduced humidity over South China, and both of these conditions lead to less rainfall there. The preceding boreal winter SAM leads rainfall over South China by one season, indicating that the SAM can be used as a predictor for South China spring precipitation. Quantitative comparison of the rainfall derived from the prediction model based on the SAM with the observed rainfall shows that the model has predictive skills and has some ability to predict continuous drought over South China (Li et al., 2013).

5. The SAM and global climate change

Toward the end of the 20th century, the SAM intensity showed a significant linear positive trend in step with the background global warming. This positive trend is mainly attributed to the depletion of Antarctic ozone (Thompson and Solomon, 2002; Gillett and Thompson, 2003; Gillett et al., 2003, 2005; Karoly, 2003; Marshall et al., 2004; Shindell and Schmidt, 2004; Thompson et al., 2011; Zheng et al., 2013). Greenhouse gases are also external forcings for the linear trend in the SAM (Shindell and Schmidt, 2004). A recent study showed similar strengthening trends in the SAM over the past 500 years, and the increasing trend occurring toward the end of the 20th century is enhanced when superimposed over the natural variability (Zhang et al., 2013). Tropical SST warming also contributes to the positive trend of the SAM toward the end of the 20th century (Grassi et al., 2005).

The remarkable changes in the SAM associated with Antarctic ozone depletion have led to changes in many climate variables in the SH polar region, including surface air temperature, precipitation, and sea ice. Both data diagnosis and numerical simulation have shown that the SAM is the main driver of the SH climate change during the past half century. The changes in the SH climate variables in response to the SAM on long-term scales are similar to those on interannual timescales. The significant warming over the Antarctic Peninsula (Turner et al., 2005), the enhancement of ACC transport (Gupta and England, 2006), and the changes in the mixed layer depth (Sallee et al., 2010) are associated with the changes in the SAM. In fact, climate change caused by Antarctic ozone through its modulation of the SAM can extend northward even to the SH subtropics and the tropics. For example, in concert with the strengthening of the SAM, the SH storm track shifts toward the Antarctic, and precipitation shifts from the midlatitudes toward high latitudes (more precipitation around 60° and 20°S, but less around 45°S)(Son et al., 2009; Kang et al., 2011; Polvani et al., 2011).

However, less attention has been paid to the possible influences of Antarctic ozone depletion on NH long-term climate change via its modulation of the SAM. Using a numerical simulation, Chen et al. (1998) verified that the NH climate responds to Antarctic ozone, but they did not provide a detailed mechanism for this response. Investigation of how the long-term changes in the SAM caused by Antarctic ozone can regulate climate in the NH will provide new clues for climate change attribution analysis.

The possible recovery of Antarctic ozone in the future (Hu and Tung, 2003; Hu et al., 2009, 2011) will favor a decreasing trend in the SAM, opposite to the predicted positive trend related to the increase in greenhouse gases. Therefore, the evolution of the SAM in the future under various scenarios is a focus of climate change research. Projecting the future trend in the SAM is helpful not only for understanding possible changes in atmospheric circulation over the SH mid to high latitudes, but also for climate downscaling projections for regions that are influenced by the SAM. The Coupled Model Intercomparison Project (CMIP) provides a possible way to evaluate changes in the SAM. Most CMIP3 models captured the observed rising trend in the SAM in austral summer (December–February) toward the end of the 20th century (Cai and Cowan, 2007; Fogt et al., 2009; Zhu and Wang, 2010), but the models containing time-varying ozone produced more significant trends. Simpkins and Karpechko (2012) and Zheng et al. (2013) estimated future SAM trends under different scenarios using CMIP3 and CMIP5 models, respectively. Their results showed that, even allowing for the recovery of Antarctic ozone, the SAM will maintain a rising trend in the future due to increased greenhouse gases.

The effect of a different background climate on the influence of the SAM on the SH and the NH climate is an important question worth thorough investigation.

6. Conclusions

In recent years, the variability of the SAM and its influence on climate have become new areas of climate research, and meaningful progress has been made both in China and overseas. This paper has reviewed the relevant achievements reported in the recent literature and gives a concise description of the influence of the SAM on climate over the SH, China, and other NH regions. The main conclusions are as follows.

A systematic understanding of the influence of the SAM on the SH climate has been established. The SAM has a significant influence on the air-sea ice coupled system in the SH. In general, the positive phase of the SAM corresponds to changes in the SH vertical circulation: anomalous ascent at high latitudes leads to anomalous adiabatic cooling and more precipitation; anomalous descent in the midlatitudes leads to less cloudiness and less precipitation. Because of the quasi-barotropic structure of the SAM, the dynamic and thermodynamic forcing caused by SAM-related sea surface wind results in responses of the SH extratropical SST and sea ice to the SAM. In view of the zonally symmetric structure of the SAM, its influence on the SH extratropical precipitation and SST exhibits a large-scale zonal symmetry. However, the responses of the SH circulation and other climate variables to the SAM also have regional features that are zonally asymmetric, especially for sea ice and mixed layer depth. This zonal asymmetry is mainly associated with the meridional wind anomalies caused by the SAM.

Research on the influence of the SAM on the NH climate, especially the climate in China, has also achieved meaningful results. The boreal spring SAM influences the summer monsoon system in East Asia, West Africa, and North America, and modulates tropical cyclone activity over the western North Pacific. The boreal autumn SAM can influence the winter monsoon and winter air temperature in China, while the preceding boreal winter SAM can influence spring precipitation in South China and dust frequency over North China. Air-sea coupled processes play an important role in the influence of the SAM on the NH climate. Air-sea interaction is important to the storage of the SAM signal from one season to the next, in the propagation of the signal from the SH to the NH, and in the release of the signal and its influence on atmospheric circulation. Given that the SAM signal leads climate anomalies by one season, it can be used in seasonal prediction.

Although some progress has been made in understanding the influence of the SAM on the NH climate, there are many scientific questions deserving thorough investigation. For example, much of the present literature focuses on the influence of the SAM on summer monsoon and summer climate, but less attention has been paid to the SAM's influence on climate in other seasons. Spring and autumn are transitional periods between winter and summer. Warm and cold air flows are frequently closely linked in spring and autumn, and climate in these two seasons is critical for agriculture. The literature concerning the influence of the SAM on the NH climate mainly explores the influence of the SAM on regional-scale climate. In view of the zonally symmetric structure of the SAM and its regulation of the meridional overturning circulation, it is likely to play a role in modulating large-scale climate in the NH, a topic that remains poorly explored. In addition, research focusing on the influence of the SAM on regional climate has mainly targeted on climate in the monsoon region and the SAM, while possible linkages between the SAM and climate in other regions are unclear. Aside from the SAM, the El Niño–Southern Oscillation (ENSO), the NAO, and the NAM are also important modes that can regulate the NH climate. Some studies have found a negative correlation between the SAM and the ENSO (Zhou and Yu, 2004; Gong et al., 2010, 2013; Ding et al., 2011, 2012), and the positive phase of the SAM commonly corresponds to a La Niña event. The question of how to distinguish both the influence of the SAM and its synergistic effects from other modes is worth further research.

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