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Climate Change in the Subtropical Jetstream during 1950–2009

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ABSTRACT

A study of six decades (1950–2009) of reanalysis data reveals that the subtropical jetstream (STJ) of the Southern (Northern) Hemisphere between longitudes 0°E and 180°E has weakened (strengthened) during both the boreal winter (January, February) and summer (July, August) seasons. The temperature of the upper troposphere of the midlatitudes has a warming trend in the Southern Hemisphere and a cooling trend in the Northern Hemisphere. Correspondingly, the north–south temperature gradient in the upper troposphere has a decreasing trend in the Southern Hemisphere and an increasing trend in the Northern Hemisphere, which affects the strength of the STJ through the thermal wind relation. We devised a method of isotach analysis in intervals of 0.1 m s^{-1} in vertical sections of hemispheric mean winds to study the climate change in the STJ core wind speed, and also core height and latitude. We found that the upper tropospheric cooling of the Asian mid-latitudes has a role in the strengthening of the STJ over Asia, while throughout the rest of the globe the upper troposphere has a warming trend that weakens the STJ. Available studies show that the mid-latitude cooling of the upper troposphere over Asia is caused by anthropogenic aerosols (particularly sulphate aerosols) and the warming over the rest of the global mid-latitude upper troposphere is due to increased greenhouse gases in the atmosphere.

Key words: subtropical jetstream, upper troposphere, greenhouse gases, aerosols

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1. Introduction

The subtropical jet stream (STJ) is a narrow band of fast moving westerly wind often observed around the 200 hPa level on either side of the equator (Krishnamurti, 1961; Peixoto and Oort, 1992; Bluestein, 1993; Archer and Caldeira, 2008).The intensities of these zonal winds and temperature fields are related through the thermal wind relation, and hence the strength and latitudinal position of the STJ undergo large seasonal variability. In each hemisphere, the STJ is more intense during the winter season and closer to the equator as compared to the summer season (Schulman, 1973; Peixoto and Oort, 1992; Dima and Wallace, 2003; Galvin, 2007).

The tropical Hadley circulation transfers heat and momentum from low to high latitudes, which has important influence on the STJ (Webster, 2004). Through this circulation, westerly angular momentum is transferred poleward to the subtropics (Mitas and Clement, 2005), which contributes to the strong westerly winds associated with the STJ. The latitudinal position of the STJ denotes the poleward edge of the Hadley circulation. Recent studies have shown that the Hadley circulation has widened poleward (Hu and Fu, 2007; Lu et al., 2007; Liu et al., 2012), thereby shifting the position of the STJ (Fu et al., 2006; Seidel et al., 2008; Hudson, 2012). Between 1979 and 2010, the poleward movement of the STJ was 3.7° latitude in the Northern Hemisphere (NH) and 6.5° latitude in the Southern Hemisphere (SH) (Hudson, 2012). For reasons not yet understood, such shifts in the core of the STJ and the northward extent of the Hadley cell due to climate change leads to a change in precipitation patterns causing broad societal impacts. Recently, Sun (2014) found that the weakening of the East Asian upper level jetstream and the extreme high temperatures over the Jianghuai–Jiangnan region of China are closely related.

Abish et al. (2013) studied the climate change and decadal variation of the strength of the tropical easterly jetstream (TEJ) of the June to September season, and found that the weakening of the TEJ from 1950 to 2009 was caused mainly by a cooling trend in the temperature of the Tibetan Plateau region of the upper troposphere. Increased concentrations of anthropogenic sulphate aerosols had a possible role in this cooling. On the contrary, increase of greenhouse gases

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(GHG) are projected to increase tropospheric temperature by 0.3 K (10 yr)$^{-1}$ or 0.2 K (10 yr)$^{-1}$ when including the forcing due to sulphate aerosols (Mitchell et al., 1995).

The present study aims to understand the climate change (1950–2009) in the strength of the STJ during two seasons [January–February (JF) and July–August (JA)] in the NH and SH. Using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data for the period 1950–2009, we analyze the STJ of the monsoon hemisphere (MH, 0°–180°E) and non-monsoon hemisphere (NMH, 180°–360°E). Section 2 describes the data used and section 3 presents the results of the study. Conclusions are given in section 4.

2. Data

The upper tropospheric monthly mean temperature and wind data from the NCEP/NCAR reanalysis dataset at 2.5° × 2.5° are used in this study. NCEP reanalysis data have 28 vertical levels extending from the surface to ∼ 40 km (Kalnay et al., 1996). The network of radiosonde stations in the SH, being covered mostly by ocean, is much less comprehensive than in the NH (Durre et al., 2006). Over Asia, good data coverage in India and China began in around 1950 with the introduction of a wide network of upper-air rawindsonde stations. In the SH, there were considerable pilot balloon data inputs from South America and Australia, among other regions (Kistler et al., 2001). Even though reanalysis datasets are said to be affected by the inhomogeneities of observation systems (Santer et al., 1999; Bengtsson et al., 2004; Bromwich and Fogt, 2004; Simmons et al., 2004; Thorne et al., 2005), the NCEP/NCAR tropospheric wind and temperature data are considered to be free from such changes (Kalnay et al., 1996; Kistler et al., 2001). We compared the results obtained using NCEP data with a similar analysis using ERA-40 reanalysis data for the years 1960–99. ERA-

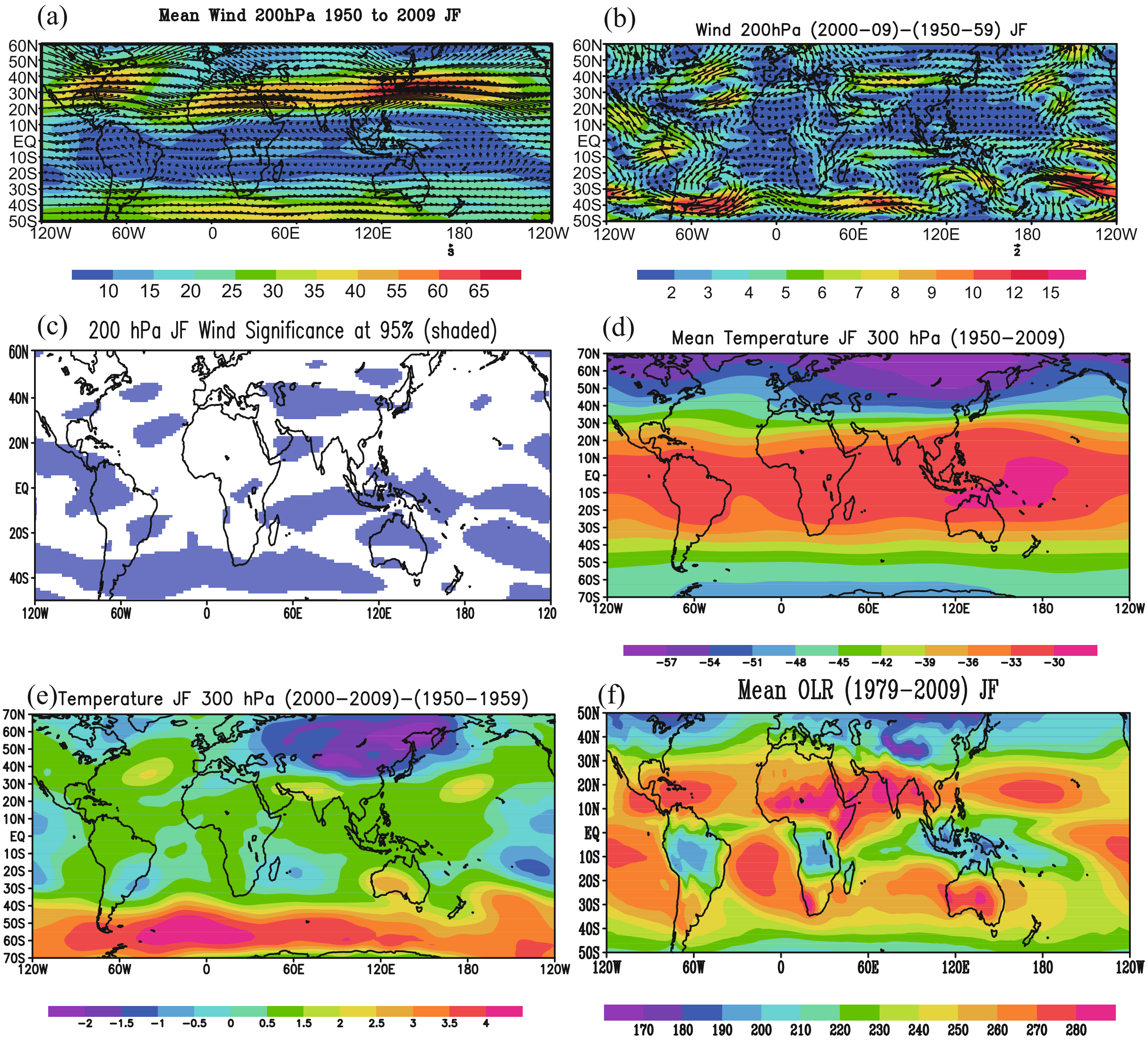

Fig. 1. (a) Mean wind in m s^{-1} at 200 hPa. (b) Change in zonal wind in m s^{-1} during boreal winter (JF). Vectors denote the direction and the coloring indicates the magnitude. Panel (c) shows the regions of statistical significance at the 95% confidence level. (d) Mean temperature in °C at 300 hPa. (e) Horizontal section of the temperature change at 300 hPa (°C). (f) Monthly mean OLR (W m^{-2}) showing deep convection south of the equator.

40 data are based on increased data coverage over the SH, particularly over Australasia and around the Antarctic coast from the early 1960s (Uppala et al., 2005). The comparison showed that, in both reanalysis datasets, the warming of the SH in the midlatitudes and the cooling over the Asian continent are nearly the same, spatially and in magnitude (Abish et al., 2013). However, since NCEP data provide six decades of continuous data, this dataset was selected in preference to ERA-40 for the present study.

To study areas of deep convection in the Inter Tropical Convergence Zone (ITCZ), outgoing longwave radiation (OLR) datasets (Liebmann and Smith, 1996) obtained from the National Oceanic and Atmospheric Administration (NOAA) at 2.5° × 2.5° grid resolution are used. However, these data are only available for the period 1979–2009.

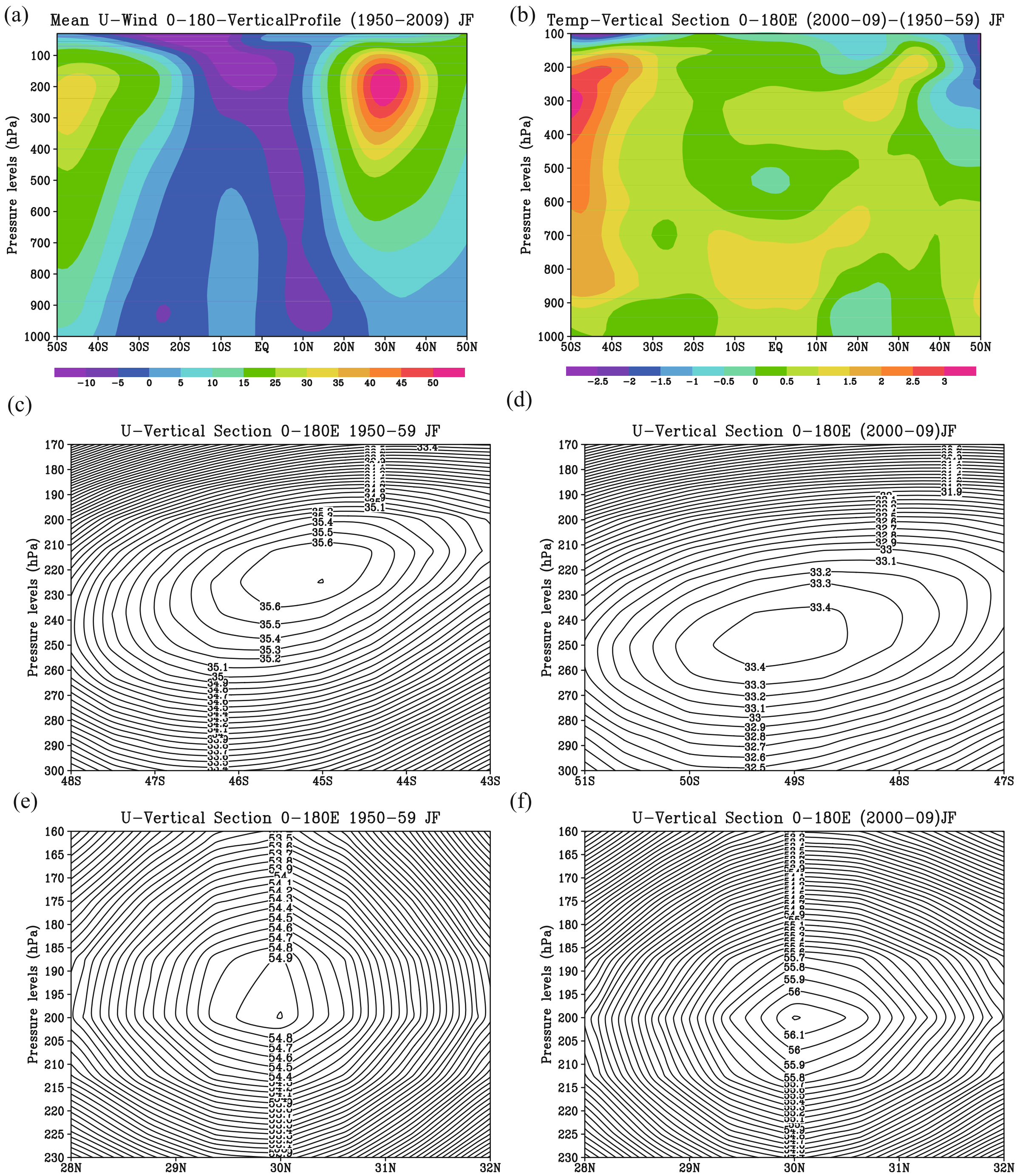

Fig. 2. (a) Vertical section of the climatology in u-wind (m s^{-1}). (b) Temperature change during the JF season. (c, d) Isotachs of u-wind over the SH at 0.1 m s^{-1} resolution for 1950–59 and 2000–09, respectively. Panels (e, f) are the same as (c, d) but for the NH.

3. Results and discussion

3.1. *Climate change in STJ in the MH*

3.1.1. *Boreal winter season (JF)*

Figure 1a presents the mean zonal wind at 200 hPa for the period 1950–2009 during the boreal winter season (JF) in the MH. It can be seen that the STJ is stronger over the winter hemisphere (NH) and its intensity is maximum over Japan, while it is weaker over the summer hemisphere (SH). Note that the STJ over the NH exhibits a three-wave pattern (Krishnamurti, 1961), while such a three-wave pattern is not seen over the SH. The change in STJ winds between 2000–09 and 1950–59 is illustrated in Fig. 1b. It shows a strengthening of the STJ winds by 6–8 m s^{-1} over Asia, while the STJ has weakened over rest of the regions of the NH and throughout the globe over the SH. Statistical analysis using the *t*-test shows that these changes in STJ winds are statistically significant at the 95% confidence (shaded grid cells in Fig. 1c).

Temperature analysis indicates that the upper troposphere is colder over the mid-latitude region (see Fig. 1d), which results in a large north–south temperature gradient over the subtropical upper troposphere that generates the STJ. These temperature gradients at 300 hPa are larger south of the high-speed centers of the STJ in the NH. From (1950–59) to (2000–09) the upper troposphere has shown a large-amplitude cooling over the Asian continent, centered over China (Fig. 1e), which is related to the strengthening of the STJ in the NH (0°–180°E), as apparent in Fig. 1b.

Figure 1e shows three areas of warming between 20°N and 30°N and three areas of cooling between 20°S and 30°S at the 300 hPa level. The climate change in the STJ is strong poleward of these areas (Fig. 1b), particularly over the SH. These warming and cooling areas are near the locations of the subtropical anticyclones at 300 hPa. The reasons for the temperature changes are not known and therefore require further study. Over the SH, temperature at 300 hPa (Fig. 1e) has

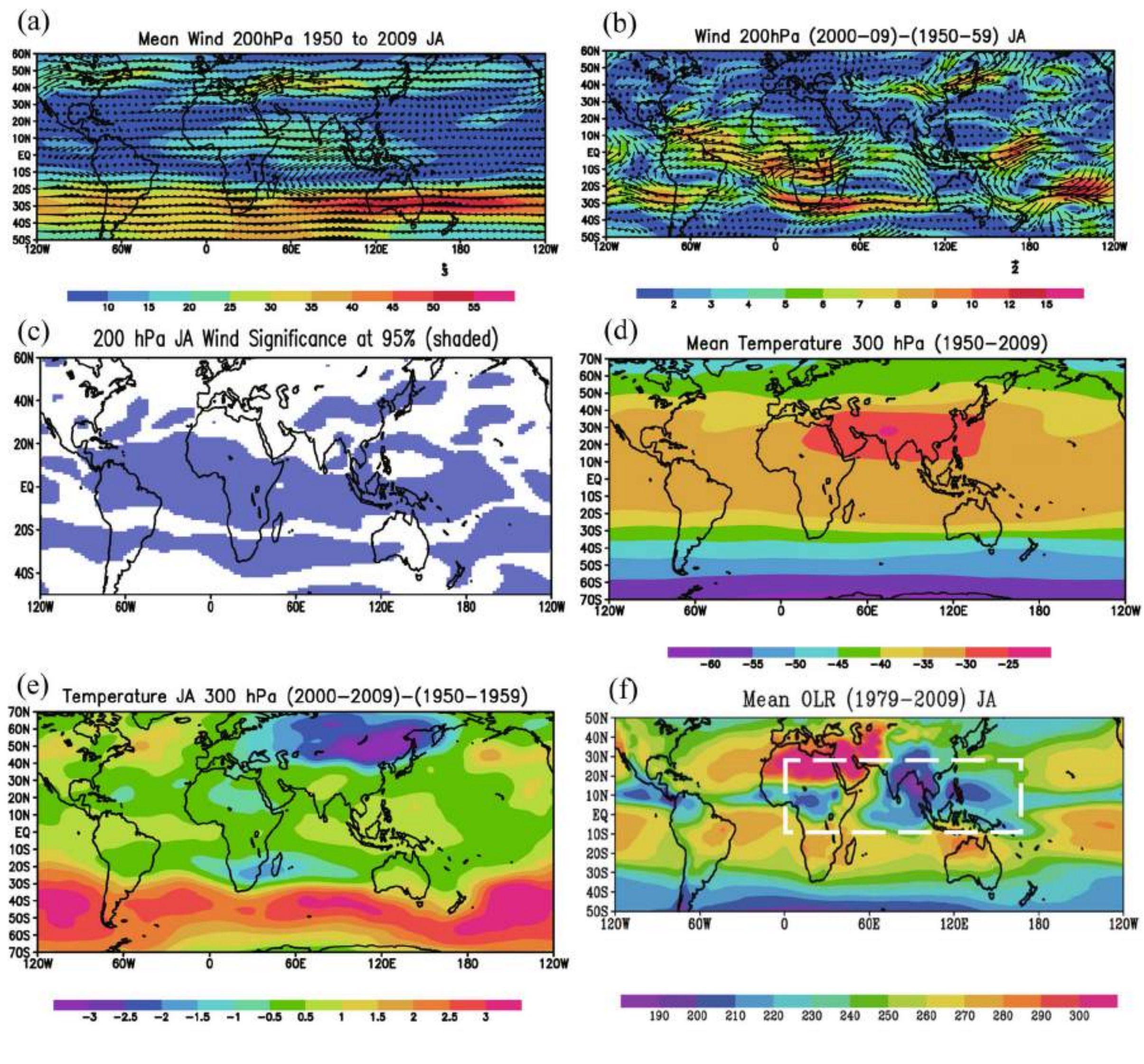

Fig. 3. The same as Fig.1,but (a–e) for the JA season and (f) indicating deep convection associated with the summer monsoon and adjoining regions.

shown a warming trend of about 4°C (2000–09 minus 1950–59) in the latitudinal belt from 40°S to 70°S. The equatorial upper troposphere has warmed during the same period, but only by about 1°C. As a combined effect, the upper tropospheric temperature gradient shows a decreasing trend, resulting in the weakening of the STJ in the SH. There are three regions of intense deep convection in the ITCZ [over the equatorial regions around the maritime continent, Africa and South America, as shown by the mean OLR (JF) of 1979–2009 in Fig. 1f], which are linked to the three velocity maxima in the STJ of the NH (Krishnamurti, 1961).

Regarding the large area of negative temperature trend at 300 hPa over Asia (centered over China), Ming et al. (2011) found that the large number of industries in this region emits excessive quantities of mineral aerosols such as sulphates, which scatter incoming solar radiation and cause the cooling. Based on observational data, Kaiser and Qian (2002) showed that, since 1980, the dimming effect of rapidly increasing anthropogenic aerosols could have contributed to the cooling trend over eastern China. Duan (2007) reported a strong cooling trend of 0.62°C (per decade) in the upper troposphere and lower stratosphere over China based on the records of 109 radiosonde stations during the period 1980–2004. These studies indicate that anthropogenic sulphate aerosols play a dominant role in the cooling trend over China.

Figure 2a depicts the vertical section of the zonal wind (u) as a mean for the longitudinal band from 0° to 180°E, and Fig.2b shows the change in the mean air temperature of (2000–09 minus 1950–59) for JF. The mid-latitude cold anomaly of the NH and the warm anomaly of the SH extend vertically between 500 hPa and 100 hPa, with a maximum anomaly near the 200 hPa level. Figures 2c–f show the vertical section of u around the core of the STJ for JF, averaged for the MH, in the decades 1950–59 and 2000–09.The isotachs marked are at intervals of 0.1 m s^{-1}. Following this method, the location of the core of the STJ in a latitude–height vertical section can be determined precisely. For studying the climate change of the STJ, the main problem is that the STJ core has differences in its wind speed, latitudinal position, and also height (hPa level), and so analysis of temporal changes in wind at one isobaric level will not help. To study the STJ variability, Strong and Davis (2008) used the surface of maximum wind analyses, whereas Archer and Caldeira (2008) computed a mass weighted average wind speed between 400 and 100 hPa. Using isotach analysis, we find that, in the JF season in the SH, there has been change in the latitude of the STJ core through 4°, from 45°S during 1950–59 to 49°S during 2000–09,with a weakening of the STJ.

3.1.2. *Boreal summer season (JA)*

Figure 3a gives the mean zonal wind at 200 hPa for the period 1950–2009, which shows a stronger STJ over the SH compared to the NH during the JA season. The TEJ, studied by Abish et al. (2013), is seen prominently in Fig. 3a. In Fig. 3b, the climate change in 200 hPa wind from 1950–59 to 2000–09 is similar to that for the JF season. The STJ intensi-

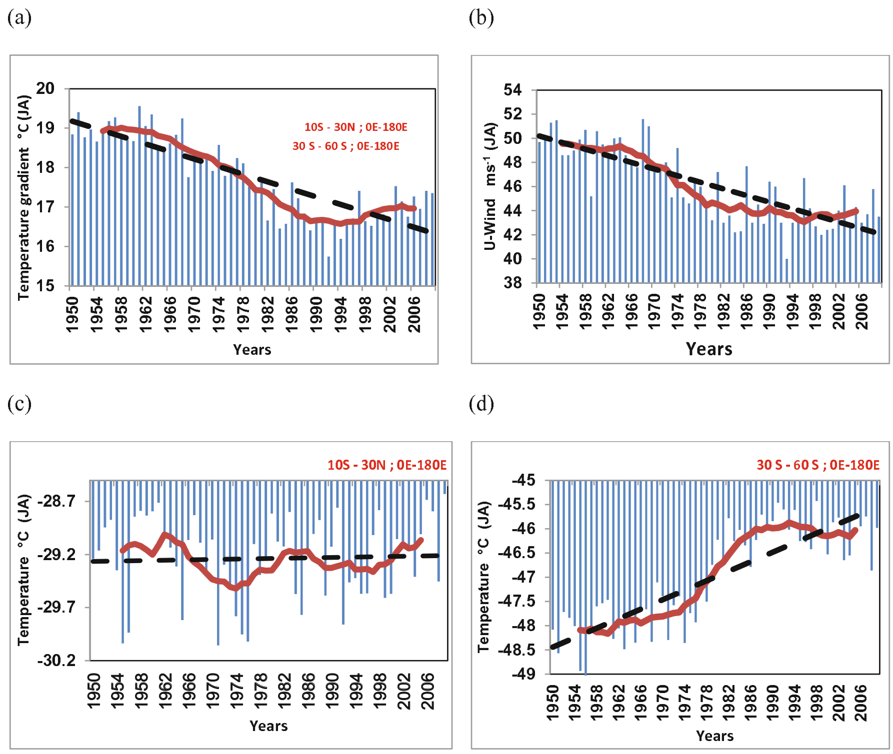

Fig. 4. (a) Temperature gradient at 300 hPa during JA over the SH. (b) Corresponding wind speed in m s^{-1} during the same season. (c, d) 11-yr moving average of temperature in °C over the tropics and mid-latitudes, respectively, during JA.

fies over the NH over Asia, and these regions show statistical significance at the 95% confidence level (see Fig. 3c). The mean temperature during the season (Fig. 3d) shows that the tropical Asian region is warmer compared to the surrounding regions. In Fig. 3e, the temperature change at 300 hPa between 1950–59 and 2000–09 shows that, as in the JF season, there is upper-tropospheric cooling of the mid-latitude region centered over China in the NH, and warming in the mid-latitudes of the SH. Correspondingly, the STJ shows a strengthening trend in the NH and a weakening trend in the SH (Fig. 3b). The box marked in Fig. 3f between 0° and 180°E, and 10°S and 30°N, contains the area of low OLR or the area of convective heating of the troposphere. This is taken as the broad region of upward motion in the Hadley circulation of the JA season that warms the upper troposphere there.

The temperature gradient at 300 hPa between the equatorial (10°S–30°N, 0°–180°E) and mid-latitude (30°–60°S,

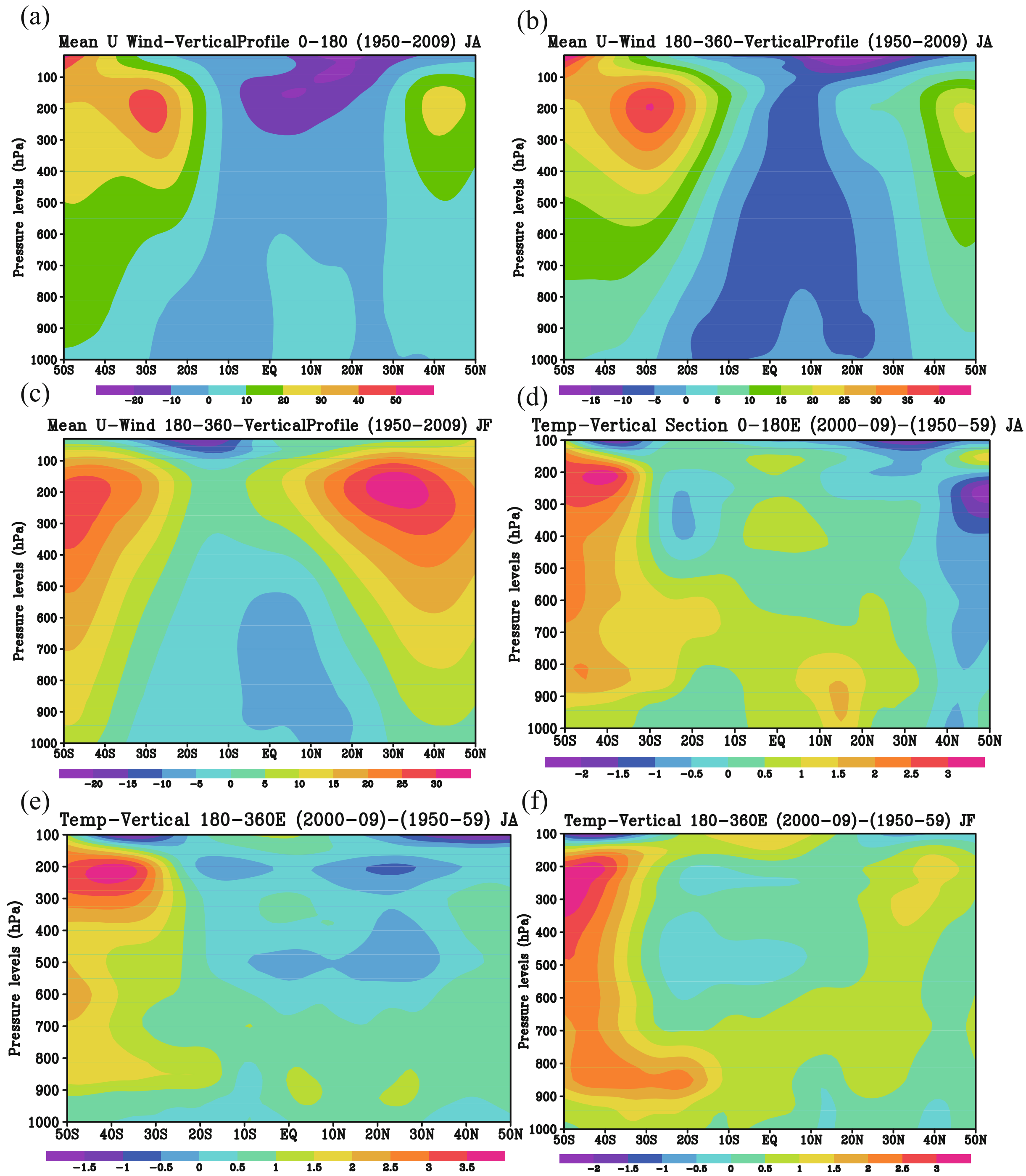

Fig. 5. (a–c) Vertical sections of the climatology in *u*-wind (m s^{-1}). (d–f) Temperature change in °C during the JA and JF seasons.

0°–180°E) boxes for each JA season is given in Fig. 4a. Figure 4b gives the mean *u*-wind of the STJ core of the SH (0°–180°E) for each year of the period 1950–2009, drawing isotachs in a vertical section at intervals of 0.1 m s^{-1}, as described earlier. The linear trend in the STJ wind speed and the 11-yr moving average are also marked. The main weakening of the STJ was during the third and fourth decades of 1950–2009. Across the five decades, the weakening was from 50.9 m s^{-1} in 1950–59 to 43.3 m s^{-1}in 2000–09. The corresponding standard deviations of the STJ wind for these two decades are 2.7 and 1.3 m s^{-1}, respectively. Using the *t*-test, the difference between the mean STJ core winds of these two decades is statistically significant at the $>$ 99% confidence level, implying a significant climate change in the STJ.

The mean temperature at 300 hPa of the equatorial (10°S–30°N, 0°–180°E) and mid-latitude (30°–60°S, 0°–180°E) boxes for each JA season, as well as their linear trend and 11-yr moving average, are given in Figs. 4c and d. The equatorial box shows only a weak warming trend, while the mid-latitude box shows strong warming trend. The linear correlation coefficient between the temperature gradient of each JA season and the corresponding STJ core wind speed for the period 1950–2009 is 0.83, and that between their 11-yr moving averages is 0.97, which are both high and statistically significant. This reveals that the climate change in the STJ core wind is controlled mainly by the climate change in the upper-tropospheric temperature gradient. Computations similar to that performed by Abish et al. (2013) for the Tropical Easterly Jetstream showed that the thermal wind change in the 500–200 hPa layer is the main factor in the climate change of the STJ core wind speed.

3.2. *Climate change in the STJ of NMH*

Vertical sections of the mean zonal wind during 1950–2009 are given in Figs. 5a, b, and c, showing the intensity of the STJ in the SH. Figures 5d, e, and f gives the difference in temperature for the decades (2000–09 minus 1950–59), which show the subtropical cooling between 20°S and 30°S, the mid-latitude cooling of the NH, and the mid-latitude warming of the SH. The equatorial upper troposphere (10°S–30°N) shows only a weak warming. The mid-latitude upper-troposphere warming of the SH is as prominent as

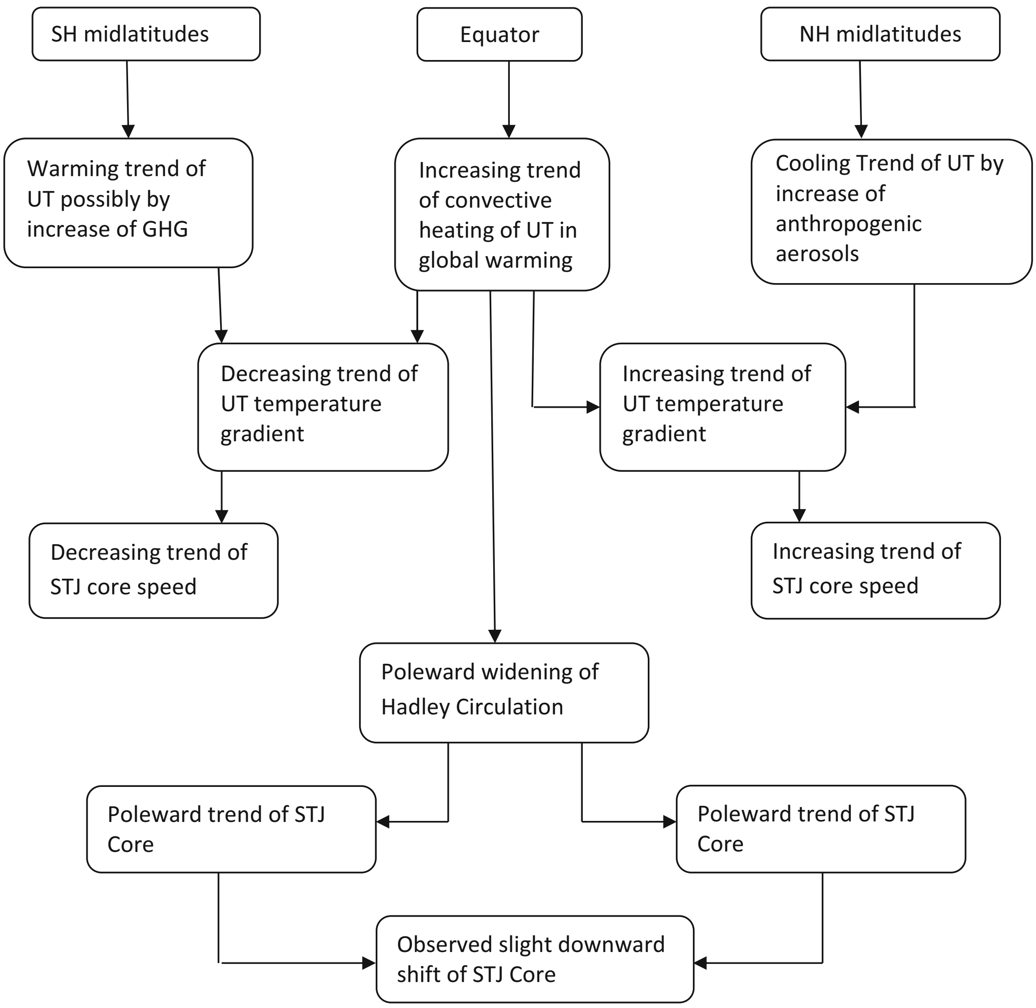

Fig. 6. Schematic diagram showing the mechanism of climate change in the STJ.

Table 1. Wind strength (m s^{-1}), latitude and height (hPa) of the STJ core in the JA and JF seasons of the MH and NMH during 1950–59 and 2000–09.

Year, season, hemisphere	Sector 0°–180° Strength	Sector 0°–180° Latitude	Sector 0°–180° Height	Sector 180°–360° Strength	Sector 180°–360° Latitude	Sector 180°–360° Height
1950–59, JA, NH	22.2	42	195	21.3	48	220
2000–09, JA, NH	25.2	42	200	21.9	48	215
1950–59, JF, NH	55	30	200	32.8	27	190
2000–09, JF, NH	56.2	30	200	32.4	33	200
1950–59, JA, SH	50.9	30	200	44.1	28	195
2000–09, JA, SH	43.3	29.5	200	38.3	30	205
1950–59, JF, SH	35.7	45	220	29.5	44	220
2000–09, JF, SH	33.4	49	250	29.5	50	250

that for the MH discussed in section 3.1. In the NH, the mid-latitude upper troposphere of the JF season has shown a warming trend between 30°N and 50°N. In the JA season, this latitudinal zone shows only a weak warming. Studies indicate that the warming over these oceanic regions is due to increase in GHGs and are less affected by cooling due to sulphate aerosols. The subtropical zones of 20°–30°N and 20°–30°S have shown cooling in both the JF and JA seasons. Thus, while the north–south temperature gradients in the mid-latitude upper troposphere show a strong decreasing trend in the SH, there has been very little change in the corresponding areas of the NH.

4. Conclusions

A prominent feature highlighted in this study is the large warming trend of the upper troposphere in the midlatitudes of the SH, at all longitudes (0°–360°), in both the JF and JA seasons. Over this vast ocean-covered area, research suggests that the cause of the observed warming trend is the increase in GHGs. Another prominent feature is the mid-latitude upper-tropospheric cooling trend in the NH between 0° and 180°E. This cooling trend is due to the increased emission of anthropogenic sulphate aerosols, which offset the warming trend due to GHGs. We designed an isotach analysis method to study the climate change in the core of the STJ. The differences (climate change) in wind strength, latitude and height of the STJ core winds during the JF and JA seasons during 1950–2000 are given in Table 1, and the causative mechanisms are described schematically in Fig. 6. According to Hadley cell theory, one of the effects of global warming and its increasing convective heating of the equatorial upper troposphere (UT) is the upward and poleward expansion of the Hadley circulation. The schematic (Fig. 6) is for the monsoon half of the globe (continental region) between 0° and 180°E. For the non-monsoon half, which is mainly ocean-covered, the mid-latitude UT shows a warming trend in the SH; whereas, in the NH, it shows only a mild warming trend.

The main findings of this study are:

(1) STJ has weakened over the SH and strengthened over the NH in the monsoon hemisphere. The changes in the NMH are much smaller in magnitude, apart from the STJ weakening in the JA season in the SH.

(2) There has been a large poleward shift of the STJ in the JF season in the MH, and in the JF and JA seasons in the NMH.

(3) In general, there has been very little change in the height of the STJ core, except in the JF season of both the MH and NMH, where the STJ core has moved downwards from 220 hPa to 250 hPa.

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