GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L22212, doi:10.1029/2004GL021270, 2004

Tropospheric cooling and summer monsoon weakening trend over East Asia

Rucong Yu,[1] Bin Wang,[2,3,4] and Tianjun Zhou[1]

Received 16 August 2004; revised 12 October 2004; accepted 25 October 2004; published 27 November 2004.

[1] A distinctive strong tropospheric cooling trend is found in East Asia during July and August. The cooling trend is most prominent at the upper troposphere around 300 hPa. Accompanying this summer cooling the upper-level westerly jet stream over East Asia shifts southward and the East Asian summer monsoon weakens, which results in the tendency toward increased droughts in northern China and flood in Yangtze River Valley. The observational evidences raise the possibility that the East Asian summer tropospheric cooling links to the stratosphere temperature changes and the interaction between the troposphere and stratosphere. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1630 Global Change: Impact phenomena; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Yu, R., B. Wang, and T. Zhou (2004), Tropospheric cooling and summer monsoon weakening trend over East Asia, *Geophys. Res. Lett.*, *31*, L22212, doi:10.1029/2004GL021270.

1. Introduction

[2] In the past half century, a moderate surface-cooling trend is observed downstream of the Tibetan Plateau, especially during summer, which contrasts the common warming trends elsewhere [*Folland et al.*, 2001; *Houghton et al.*, 2001; *Hu et al.*, 2003]. During the same period, summer precipitation has increased in the middle-lower valley of Yangtze River whereas decreased in northern China [*Xu*, 2001; *Hu et al.*, 2003]. This noticeable precipitation trend is called "southern flood and northern drought" in China. It has been suggested that the summer surface-cooling trend in the southeast China is linked to the increase in coal burning [*Xu*, 2001]. The precipitation trend has been attributed to the effect of increase in human-made black carbon [*Menon et al.*, 2002]. These temperature and precipitation trends have been examined and explained in isolation, whether these trends are related has not been addressed and causes of these trends are not well understood.

[3] By examining the changes of surface temperature and precipitation in China month by month, the most significant persistent "southern flood and northern drought" and "surface-cooling" occurs in July and August. Therefore, the current study is focused on July–August (JA) analysis. We present evidence to reveal a distinct tropospheric cooling trend (TCT) over mid-latitude East Asia in JA and show how the TCT is responsible for the distinctive surface climate changes in China.

2. The Tropospheric Cooling Trend in East Asia

[4] By examining both of reanalysis data from the European Centre for Medium-range Weather Forecasts (ECMWF) (http://www.ecmwf.int/research/era/Project/Plan/Project_plan_TOC.html) and the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data (NCEP/NCAR) [*Kalnay et al.*, 1996], it is found that a distinctive persistent cooling had occurred in the upper troposphere of East Asia in JA in the recent four decades as shown in Figure 1. Figure 1 is derived from ECMWF data. The result from NCEP/NCAR data is almost the same (not shown). Figure 1a shows the long-term change (1980–2001 mean minus 1958–1979 mean) of the JA mean temperature averaged in the upper troposphere between 200 hPa and 500 hPa. The region of significant cooling covers a large area between 30°N and 45°N and from 90°E to 130°E. This region is located to the northeast of the Tibetan Plateau. The East Asia cooling is unique and in a sharp contrast to the common warming elsewhere in the low-middle latitude of Northern Hemisphere (Figures 1a and 1b). Figure 1c shows the time series of JA mean 200–300 hPa departure temperatures averaged in the core region of cooling over the midlatitude East Asia (90°E–130°E, 30°N–45°N). The departure is from zonal mean between 10°N to 60°N. Evidently, the interdecadal temperature change depicted in Figures 1a and 1b reflects primarily a relative downward trend from 1958 to 2001, although a decadal variation is superposed on this trend. Recent analysis based on radiosonde station data confirms that July temperature at 300 hPa displays a linear cooling trend from 1964 to 1988 [*Alduchov and Chernykh*, 2004].

3. Weakening of the East Asian Summer Monsoon

[5] Accompanying the TCT, large-scale circulation and rainfall have experienced significant changes in East Asia. The upper troposphere westerly jet stream is one of the most important circulation systems in East Asia. Its variability reflects major climate variations in this region. During summer, the jet axis is normally located around 40°N and right beneath the tropopause at 200 hPa. The major rain-

---

[1] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.

[2] Department of Meteorology, University of Hawaii, Honolulu, Hawaii, USA.

[3] Also at International Pacific Research Center, University of Hawaii, Honolulu, Hawaii, USA.

[4] Formerly at State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.

0094-8276/04/2004GL021270$05.00

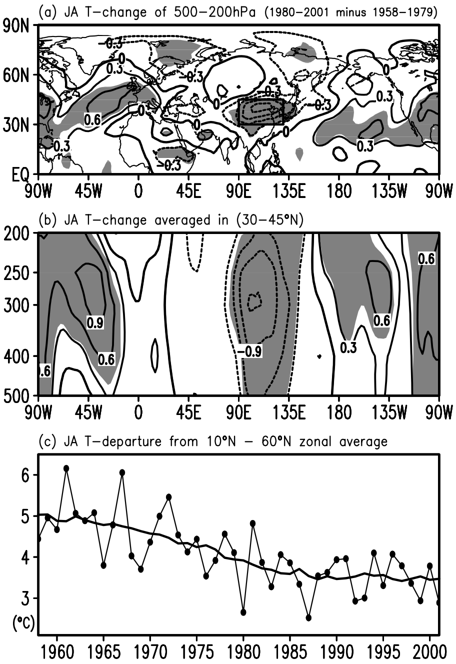

Figure 1. (a) 22-yr mean JA temperature change (1980–2001 mean minus 1958–1979 mean) averaged between 200 hPa and 500 hPa (contour interval 0.3°C). (b) Longitude-height cross section of 22-yr mean JA temperature change averaged between 30°N and 45°N (contour interval 0.3°C). (c) Departure of JA mean (thin) and 10-yr running mean (thick) 200–300 hPa air temperature averaged in the core region (90°E–130°E, 30°N–45°N) that is outlined by the rectangular box in (a). The departure is from zonal belt mean between (10°N–60°N). The shaded areas in (a) and (b) are statistically significant at 95% confidence level according to student T-test. The air temperature data come from ECMWF reanalysis.

producing system is the subtropical front that is also known as Meiyu (China) or Baiu (Japan) front in summer as it is located along the Yangtze River Valley extending to south Japan.

[6] Figure 2a shows that 300 hPa air temperature has cooled by one degree more over North China and Mongolia. As a result, the pressure at the uppermost troposphere decreases as shown in the meridional cross section Figure 3a. This pressure drop increases poleward pressure gradient force to the south of cooling region, which in turn enhances the 200 hPa subtropical jet through geostrophic balance between the Coriolis force and pressure gradient force. Hence, the maximum increase in westerlies is found around 30°N and the largest decrease of westerly occurs along 45°N (Figure 2a). As such, the 200 hPa jet over East Asia displaces southward. Figures 2a and 3a indicate that the shift of the jet stream is dynamically consistent with the TCT in East Asia.

[7] The tropospheric cooling-induced mass change also enhances the lower-tropospheric (below 500 hPa) pressure, resulting in an anomalous anticyclone beneath the upper tropospheric cooling (Figure 3a). To the east of the anticyclonic center, anomalous northerly winds have increased, which signifies a weakening of the East Asian summer monsoon (Figures 2a and 2b).

[8] As seen from Figure 2a, cyclonic vorticity trend is significant over East China to south of Japan where climatological west Pacific subtropical high is located. The decrease in the southerly monsoon index corresponds to a weakening of the subtropical high. The weakening and southward retreat of the subtropical high was previously noticed [*Nitta and Hu*, 1996]. Figure 2b shows the high correlation between the lower-tropospheric meridional wind averaged in (100°E–120°E, 30°N–40°N, 850–500 hPa), which can be defined as East Asian Monsoon (EAM) index, and the upper-tropospheric air temperature averaged in (100°E–130°E, 35°N–45°N, 500–200 hPa). The correlation coefficient is 0.69. The result here suggests that weakening and southward retreat trend of the subtropical high is in part a result of the TCT over the continental East Asia.

[9] As a result of the weakening of East Asian summer monsoon and the retreat of west Pacific subtropical high, the East Asian subtropical front and associated major rain band have experienced a southward displacement, causing excessive precipitation in the Yangtze River valley and deficient monsoon rain over the North China. Figure 2c indicates that this southerly monsoon index is negatively

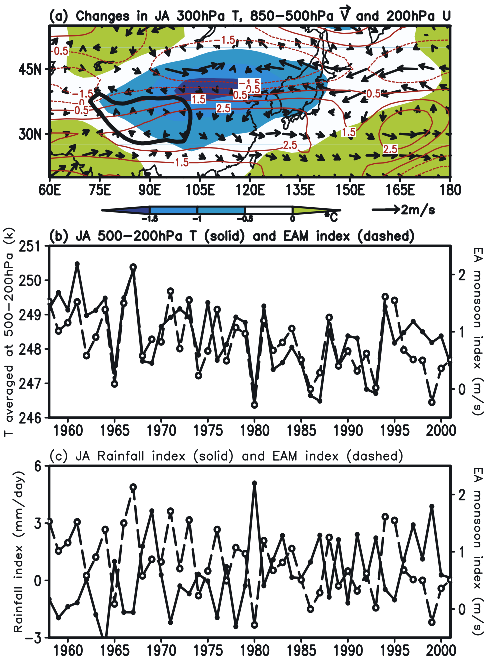

Figure 2. (a) Changes (1980–2001 minus 1958–1979) in JA upper tropospheric (300 hPa) air temperature (color shading), 200 hPa westerly (contours), and lower tropospheric (850–500 hPa) layer-averaged winds (arrows). The heavy solid line is 3000 m contour outlining the Tibetan Plateau. (b) the upper tropospheric (500–200 hPa) air temperature averaged over (100°E to 130°E, 35°N to 45°N) (solid line with filled circle) and the lower tropospheric (850–500 hPa) southerlies averaged over (100°E to 120°E, 30°N to 40°N) (dashed line with open circle). (c) the solid line shows July–August mean rainfall rate difference between the Yangtze River valley (107°E–120°E, 27°N–32°N) and the North China (108°E–120°E, 34°N–40°N), and the dashed line is same as that in (b). The circulation data come from ECMWF reanalysis and the rainfall data come from Chinese surface station rain-gauge observations.

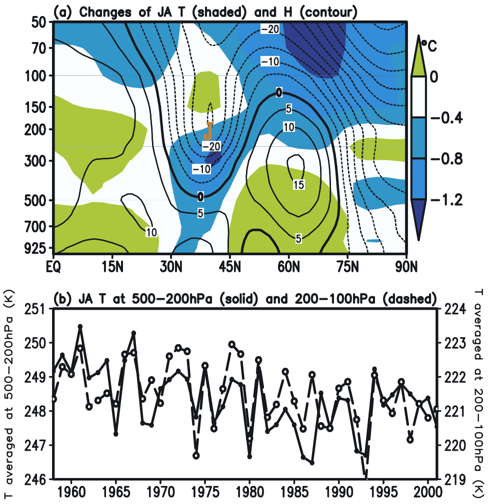

Figure 3. (a) Latitude-height cross section averaged over the longitudes between 90°E and 130°E for JA. The ordinate is in log-pressure (hPa) scale. The color shading shows the 22-yr mean temperature changes (1980–2001 minus 1958–1979). The black contours show the corresponding changes in geopotential height (contour interval 5 gpm). The capital letter 'J' represents the center of the subtropical jet stream. (b) the solid line is same as that in Figure 2b and dashed line shows the lower stratospheric (200–100 hPa) air temperature averaged over (110°E to 150°E, 50°N to 60°N). All of used data come from ECMWF reanalysis.

correlated with the variation of the JA rainfall rate difference between the Yangtze River valley (107°E–120°E, 27°N–32°N) and the North China (108°E–120°E, 34°N–40°N) on both the interannual and decadal scales. The correlation coefficient reaches 0.74 for 1958–2001. The moderate surface-cooling trend downstream of the Tibetan Plateau could result from the wetting trend [*Hu et al.*, 2003] and could be indicated from Figure 3a. Therefore, we suggest that the TCT is responsible for a large-scale circulation change, which in turn weakens the East Asian summer monsoon, causing the observed "southern flood and northern draught" and "surface cooling" trend in China.

4. Discussion

[10] We have shown that the precipitation trend in China is a result of the East Asia TCT. However, the cause of the TCT remains elusive. The present analysis raises the possibility that the East Asia TCT is linked to the stratosphere. It has been recently recognized that the stratosphere is a player in determining the memory of the climate system [*Baldwin et al.*, 2003].

[11] To unravel the linkage of the TCT to stratosphere, we present, in Figure 3a, vertical-latitudinal dependence of the JA mean cooling trend averaged between 90°E and 130°E. The cooling expands all of troposphere, from tropopause to surface, with maximum centered at 300 hPa. Figure 3a indicates that the potential vorticity (PV) has increased in the tropopause layer and the mid-latitude tropopause could move downward, which is manifested by the decreased geopotential height (a cyclonic vorticity change) and increased static stability (warming in the lower stratosphere and cooling in the upper troposphere). It has been suggested that in the tropopause falling region of middle latitude exists downward flow from the stratosphere to the troposphere [*Holton et al.*, 1995; *Stohl et al.*, 2003]. In the upper troposphere, weak changes to the winds could be amplified by interactions with "synoptic" scale waves, which are strongest in the upper troposphere but extend several kilometers into the stratosphere [*Baldwin et al.*, 2003].

[12] The East Asia is located east to the Tibetan Plateau. During summer, the plateau is an elevated heat source [*Yeh et al.*, 1957; *Yeh*, 1981; *Yeh and Chang*, 1974; *Luo and Yanai*, 1984; *Yanai et al.*, 1992]. Deep convection is more vertically developed and is characterized by rapid injection of surface air near and through tropopause. Ozone depletion has been found over the eastern Plateau [*Zhou et al.*, 1995]. Upward propagating gravity waves generated by these deep convections are shifted northward by the prevailing stratosphere winds [*Jiang et al.*, 2004]. The enhanced troposphere-stratosphere interaction is favored in the downstream and to the north of the Tibetan Plateau. Figure 3b compares the JA mean upper tropospheric air temperature as in Figure 2b and the lower stratospheric air temperature averaged in (110°E–150°E, 50°N–60°N, 200–100 hPa), which confirms the relationship between the upper tropospheric cooling in East Asia and the air temperature change in stratosphere, with correlation coefficient 0.65.

[13] It is noteworthy that the evidence presented in this paper is consistent with the idea that the root cause is the global cooling trend in the stratosphere. Depletion of ozone is the major radiative factor while increases in water vapor could be a significant contributor in accounting for the lower stratospheric cooling trend [*Ramaswamy et al.*, 2001; *Hartmann et al.*, 2000]. This unique large-scale cooling trend over East Asia can be used as a more rigorous test for the current climate models that are used to predict future climate changes. The current observations are not sufficient to test this hypothesis but could be checked with improved satellite observations and with sufficiently realistic models in the future.

[14] Previous studies have speculated that increasing coal burning could play a major role [*Xu*, 2001; *Menon et al.*, 2002]. This argument, while plausible in explaining the summer cooling in the central-eastern China, does not seem to explain why the strongest cooling trend occurring in the upper troposphere. Of course, it should be further investigated to identify the role of human activity and to understand the relationship between the changes among the tropical ocean thermal condition, stratosphere temperature and the climate in East Asia.

[15] **Acknowledgments.** Rucong Yu and Tianjun Zhou are jointly supported by the "Innovation Program of CAS" under Grant ZKCX2—SW—210 and the National Natural Science Foundation of China under Grant No. 40233031 and 40221503. Bin Wang is supported by Climate Dynamics of NSF under award number ATM03-29531.

References

Alduchov, O. A., and I. V. Chernykh (2004), About inhomogeneities of warming and cooling in troposphere, *CLIVAR Exch. 28*, *8*(4), 1–3. (Available at http://www.clivar.org/publications/exchanges/ex28/pdf/s28_aldushov.pdf)

Baldwin, M. P., D. W. J. Thompson, E. F. Shuckburgh, W. A. Norton, and N. P. Gillett (2003), Weather from the stratosphere, *Science*, *301*, 317–319.

Folland, C. K., et al. (2001), Global temperature change and its uncertainties since 1861, *Geophys. Res. Lett.*, *28*, 2621–2624.

Hartmann, D. L., J. M. Wallace, V. Limpasuvan, D. W. J. Thompson, and J. R. Holton (2000), Can ozone depletion and greenhouse warming interact to produce rapid climate change?, *Proc. Nat. Acad. Sci.*, *97*, 1412–1417.

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister (1995), Stratosphere troposphere exchange, *Rev. Geophys.*, *33*, 403–439.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 881 pp., Cambridge Univ. Press, New York.

Hu, Z., S. Yang, and R. Wu (2003), Long-term climate variations in China and global warming signals, *J. Geophys. Res.*, *108*(D19), 4614, doi:10.1029/2003JD003651.

Jiang, J. H., B. Wang, K. Goya, K. Hocke, S. D. Eckermann, J. Ma, D. L. Wu, and W. G. Read (2004), Geographical distribution and interseasonal variability of tropical deep convection: UARS MLS observations and analyses, *J. Geophys. Res.*, *109*, D03111, doi:10.1029/2003JD003756.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–472.

Luo, H., and M. Yanai (1984), The large-scale circulation and heat sources over the Tibetan Plateau and surrounding areas during the early summer of 1979. Part II: Heat and moisture budgets, *Mon. Weather Rev.*, *112*, 966–989.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo (2002), Climate effects of black carbon aerosols in China and India, *Science*, *297*, 2250–2253.

Nitta, T., and Z.-Z. Hu (1996), Summer climate variability in China and its association with 500 hPa height and tropical convection, *J. Meteorol. Soc. Jpn.*, *74*, 425–445.

Ramaswamy, V., et al. (2001), Stratospheric temperature trends: Observations and model simulations, *Rev. Geophys.*, *39*, 71–122.

Stohl, A., H. Wernli, P. James, M. Bourqui, C. Forster, M. A. Liniger, P. Seibert, and M. Sprenger (2003), A new perspective of stratosphere troposphere exchange, *Bull. Am. Meteorol. Soc.*, *84*, 1565–1573.

Xu, Q. (2001), Abrupt change of the mid-summer climate in central east China by the influence of atmospheric pollution, *Atmos. Environ.*, *35*, 5029–5040.

Yanai, M., C. Li, and Z. Song (1992), Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon, *J. Meteorol. Soc. Jpn.*, *70*, 319–351.

Yeh, T.-C. (or Ye, D.) (1981), Some characteristics of the summer circulation over the Qinghai-Xizang (Tibet) Plateau and its neighborhood, *Bull. Am. Meteorol. Soc.*, *62*, 14–19.

Yeh, T.-C., and C.-C. Chang (1974), A preliminary experimental simulation on the heating effect of the Tibetan Plateau on the general circulation over eastern Asia in summer, *Sci. Sin., Chin. Ed.*, *17*, 397–420.

Yeh, T.-C., S.-W. Lo, and P.-C. Chu (1957), The wind structure and heat balance in the lower troposphere over Tibetan Plateau and its surroundings (in Chinese), *Acta Meteorol. Sin.*, *28*, 108–121.

Zhou, X. J., C. Luo, W. L. Li, and J. E. Shi (1995), Ozone changes over China and low center over Tibetan Plateau, *Chin. Sci. Bull.*, *4*, 1396–1398.

R. Yu and T. Zhou, LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. (yrc@lasg.iap.ac.cn; zhoutj@lasg.iap.ac.cn)

B. Wang, Department of Meteorology, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, USA. (wangbin@hawaii.edu)