Article ID: 1006-8775(2015) S1-0057-09

NUMERICAL SIMULATION OF ATMOSPHERIC POLLUTANTS DURING THE ONSET STAGE OF SOUTH CHINA SEA SUMMER MONSOON IN 2011

YANG Zhao-li (杨兆礼), ZHENG Bin (郑　彬), WU Dui (吴　兑), HUANG Hui-jun (黄辉军)

(Guangzhou Institute of Tropical and Marine Meteorology/Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction, CMA, Guangzhou 510080 China)

Abstract: Using the 2006 Global Emissions Data and 2011 NCEP Final Analysis data as the initial and boundary condition, we simulated the three-dimensional distribution of atmospheric chemical pollutants (such as sea salt, PM_{10}, CO_x, SO_2, NO_x, O_3, etc) during the onset stage of South China Sea (SCS) summer monsoon from 25 April to 25 May in 2011 over the monsoon area of 70°–160°E, 0°–40°N. Simulation results shows that, many changes have taken place in the distribution of atmospheric chemical pollutants near 950 hPa and 400 hPa due to the enhancement of the westerlies and southerlies over the SCS as a result of the monsoon outbreak. Especially, the concentration of pollutants over the SCS is much higher than that over other places because of the strong wind convergence near the surface *in situ*. Moreover, the vertical distribution of pollutants is also greatly affected by the westerlies and southerlies in the onset process of SCS summer monsoon. Meanwhile, the concentration over land is much greater than that at sea in pre-monsoon period, while the difference between land and sea in the concentration of most pollutants decreases greatly with the onset of SCS summer monsoon.

Key words: South China Sea summer monsoon; atmospheric pollutant; diffusion characteristics; numerical simulation

CLC number: P435 **Document code:** A

doi: 10.16555/j.1006-8775.2015.S1.006

1 INTRODUCTION

Recently, the atmospheric pollution is becoming serious because of the development of the industrialization process and the anthropogenic activities including the agriculture and the traffic, as well as the emission of various exhaust gas, dust particles and mineral substance resulted from the desertization (Dong et al.[1]; Zhao et al.[2]; Sun et al.[3]; Zeng et al.[4]; Xi et al.[5]; Pu[6]; Liu and Yu[7]). Therefore, the issue of atmospheric pollution has attracted more and more attentions. With the fast progress of computer science many studies have investigated the distribution of atmospheric pollutants to understand their preliminary characteristics by numerical simulation (Meng et al.[8]; Wang et al.[9]; Lu et al.[10]; Zhao and Li[11]; Zhong and Tan[12]; Wu and Du[13]; Ma and Sun[14]; Luo and Li[15]; Luo and Yang[16]). But considering the close association between the transportation and diffusion of atmospheric pollutants and the weather condition (i.e., wind direction and speed) in many scales (Li et al.[17]; Liang et al.[18]; Li et al.[19]), the distribution of atmospheric pollutants is sensitive to the changes in general circulation induced by the synoptic (or climate) systems.

The Asian monsoon is the strongest and most typical monsoon over the world in the perspective of climate (Li and Zhang[20]). And the Asian summer monsoon starts over the South China Sea (SCS) and the adjacent region, then advances to the South Asia and the East Asia gradually (Li and Zhang[21]). Thus the researches on the SCS summer monsoon are of great importance for examining the large-scale transportation and the diffusion of atmospheric pollutants. Much achievement of the SCS summer monsoon has been obtained (Huang et al.[22]; Wang et al.[23]; Liu et al.[24]; Chen et al.[25]; Li and Liang[26]; Fan and Guo[27]; Gao and Zhu[28]; Chen and He[29]; Zhu et al.[30]; Hu et al.[31]; Liu et al.[32]; Wei et al.[33];

Received 2014-04-04; **Revised** 2015-08-04; **Accepted** 2015-09-15

Foundation item: National Natural Science Foundation of China (41175013); National Key Basic Research Development Plan Project (2011CB403403); Special Fund for Meteorological Research in the Public Interest (GYHY201406009); Science and Technology Planning Project for Guangdong Province (2012A061400012); Meteorological Bureau of Guangdong Province Science and Technology Research Project (2013A04); Project from China Meteorological Administration (GYHY201406009)

Biography: YANG Zhao-li, M.S., Senior Engineer, mainly engaged in the application of meteorological research.

Corresponding author: YANG Zhao-li, e-mail: zlyang@grmc.gov.cn

Jiang et al.[34]; Zhu et al.[35]; Ding et al.[36]; Lan et al.[37]; Xu et al.[38]; Tan et al.[39]; Li et al.[40]; Liang et al.[41]; Feng et al.[42]; Gao and Liang[43]; Li and Zhang[44]; Liu et al.[45]; Song et al.[46]; Lv et al.[47]; Krishnam et al.[48]; Tao and Chen[49]; Chan and Chen[50]), and we have a relevant comprehensive understanding on its activities. Zheng et al.[51] found out that the extinction characteristics of aerosol in Guangzhou was decreased following an increment process during the active episode of SCS summer monsoon. Hou and Zhu[52] pointed out that the monthly mean maximum of ozone over different regions in spring ascribed to the propagation of East Asian summer monsoon occurred at different time. Wang et al.[53] proposed that the black carbon over the South Asia could influence both the onset and strength of South Asian summer monsoon and the intensity of East Asian summer monsoon. Furthermore, the relationship between the monsoon rainfall and circulation and the aerosol has been investigated by Lau and Kim[54] and Yoon et al.[55]. However, little research has been conducted on the transportation and diffusion of atmospheric pollutants induced by SCS summer monsoon onset. And such study will be significant for further understanding the interaction between the monsoon activity and transportation of atmospheric pollutants, as well as the related mechanisms. This paper aims to analyze the characteristics of atmospheric pollutants in the onset stage of SCS summer monsoon in 2011 by the numerical simulation.

2 DATA DESCRIPTION

The annual mean Global emissions data (including dust, sea salt, and biomass burning) in 2006 and the 4 times per day NCEP Final Analysis data in 2011 with a horizontal resolution of 1°×1° were treated as the initial and boundary condition of WRF-Chem 3.0 model. The CO_2 concentration is 270 ppm before the industrial revolution in 1850, and it is 387 ppm in 2008. It increases 117 ppm during the 160 years, say that the raising rate is 0.73 ppm per year. Then the variation of climatological emissions is weak enough to ignore within 5 years. And the error induced by using the boundary values of sea salt, PM_{10}, CO_x, SO_2, NO_x and O_3 in 2006 is acceptable when simulating the distribution of atmospheric pollutants in 2011. In addition, the model is outputted every 6 hours, and the chemical scheme is ADM2 chemical mechanism and MADE/SORGAM aerosols, while the GOCART RACM_KPP emissions is used as the diffusion parameter. Here the simulating period is selected from 25 April to 25 May and from 10 September to 20 October in 2011. The former is for the episode before and after the SCS summer monsoon onset, and the latter represents the time before and after the ending of SCS summer monsoon. The simulating region is within 70°–160°E, 0–40°N. Thus we can investigate the 3-dimensional distribution of sea salt, PM_{10}, CO_x, SO_2, NO_x and O_3 in the monsoon region by analyzing the simulating results.

3 DISTRIBUTION OF ATMOSPHERIC POLLUTANTS DURING THE ONSET STAGE OF SCS SUMMER MONSOON FROM APRIL 25 TO MAY 25 IN 2011

3.1 *Near the surface (at 950 hPa)*

The onset time of SCS summer monsoon is 8 May in 2011, presenting that the southerly and westerly are prevailing over the SCS at Pentad 26 when the local convection is strong. During the onset period of SCS summer monsoon, the zonal wind in the lower troposphere is changed from easterly to westerly. The concentration of CO, NO_2, SO_2, O_3, sea salt and PM_{10} is increased to the south of 30°N in the pre-monsoon stage. On 8 May when the SCS summer monsoon builds up, three high value centers of atmospheric pollutants concentration appear in the regions with low value center of TBB where the monsoon convection is flourishing. The centers of atmospheric pollutants concentration could maintain for a moment after the SCS summer monsoon onset (Fig.1). Fig.2 shows that the strong southwesterly flows into the region marked by red rectangle from its southern edge, then they arrive at 15°N. In the meantime, the outflow over this region from the edges is weak. Thus the atmospheric pollutants brought by the strong southwesterly are stacked in the red rectangle area. Whereas the weak southwesterly stays at 5°N before the SCS summer monsoon onset. Therefore, it is speculated that the high concentration of atmospheric pollutants in the red rectangle region is ascribed to the enhancement of westerly and southerly and the northward and eastward movement of jet stream accompanied by the monsoon onset. Moreover, note that the low-layer zonal wind is turned from the easterly in pre-monsoon stage to the westerly after the monsoon onset. Then the strong cyclonic flow is converged in the blue rectangle area. Also the inflow is strong on the southern and eastern edges of this region, but only is the weak outflow on the northern edge. The strong inflow results in the accumulation of atmospheric pollutants over this region. As a result, the high concentration of atmospheric pollutants over the SCS is primarily attributed to the transition of zonal wind from easterly to westerly over the SCS in the lower troposphere before and after the SCS summer monsoon onset. Similarly, the strong southwesterly blows into the blue rectangle area from its southern edge with the strong northerly from its northern edge, bringing the atmospheric pollutants into this region form the high concentration of atmospheric pollutants. Whereas, before the onset of SCS summer monsoon, the northerly to the north of this region could not cross 40°N, and the strong southwesterly is located near 35°N. Hence the belt of high concentration of atmospheric pollutants shifts 3°–5° southward and intensifies with the onset process of SCS summer monsoon.

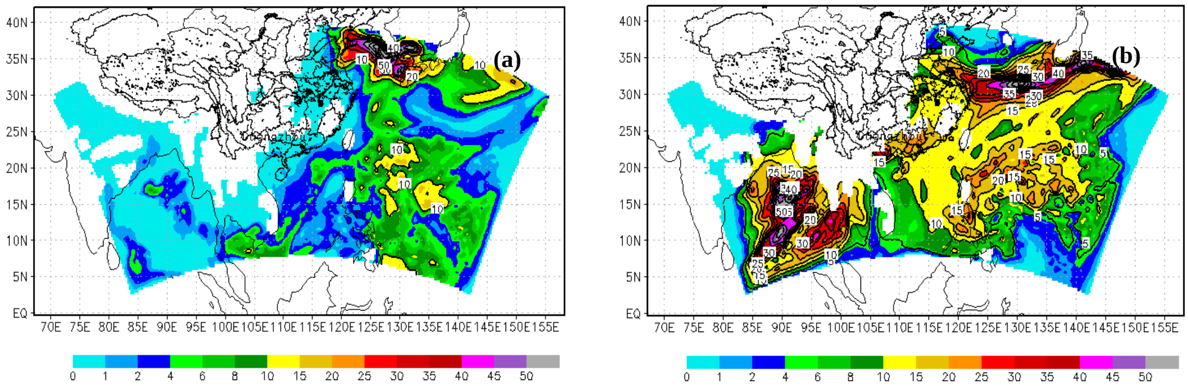

Figure 1. Horizontal distribution of sea salt before the SCS summer monsoon onset (a: 06UTC on 26 April in 2011, b: 00UTC on 8 May in 2011, units: ppmv).

3.2 *In the upper troposphere (at 400 hPa)*

The simulating results point out that the distribution of sea salt, PM_{10}, CO, NO_2, SO_2 and O_3 in the upper troposphere is also affected by the evident changes of circulation before and after the SCS summer monsoon onset. There are 4 areas with high value of PM_{10} before the SCS summer monsoon onset (Fig.3). One is near the Philippines, and the other three high value belts are situated in the area of (110°–130°E, 30°–35°N), to the south of 25°N along 85°–110°E, and over the western Pacific (110°–145°E, 25°–35°N), respectively.

Before the SCS summer monsoon onset, the upper-level jet stream crossing the three high-value belts acts as the steady transportation source of atmospheric pollutants to make the wind converge within the long and narrow belts, where the concentration of atmospheric pollutants is high (Fig.4a). While after the SCS summer monsoon onset, the wind is weak to the south of 25°N, the westerly jet stream settled near 20°N withdraws northward to the north of 25°N (Fig.4b). Hence the two belts of high concentration of atmospheric pollutants between 5°N and 30°N are merged with the high value of atmospheric pollutants concentration near the Philippines to form a large area of high concentration of atmospheric pollutants, which covers the whole region over (90°–150°E, 5°–30°N). Meanwhile the high concentration belt between 30°N to 35°N is maintained and strengthened. On one hand, the strong jet stream to the north of 25°N could bring the atmospheric pollutants to the south of 25°N. On the other hand, the pollutants produced by human activities are stored to the south of 25°N without favorable convective condition. As a result, the concentration of atmospheric pollutants is increasing in this region.

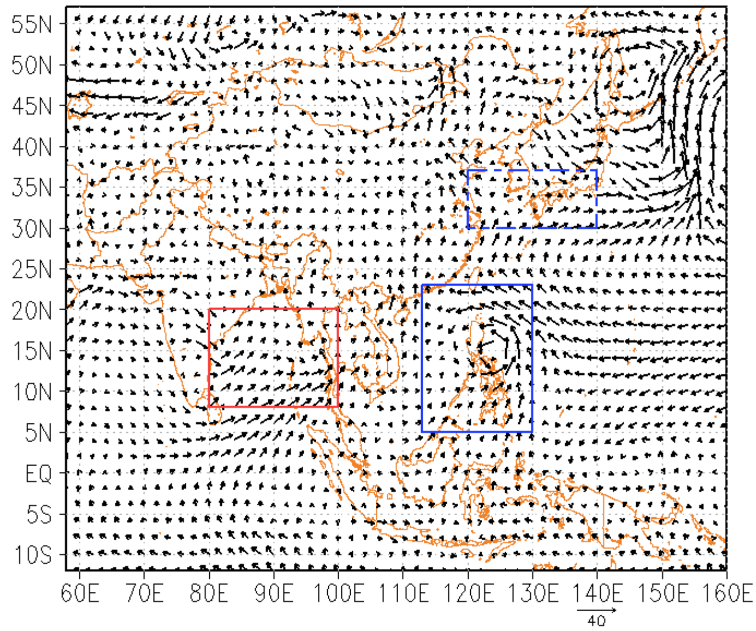

Figure 2. Horizontal distribution of 925-hPa wind field at 00UTC on 8 May in 2011 (m/s).

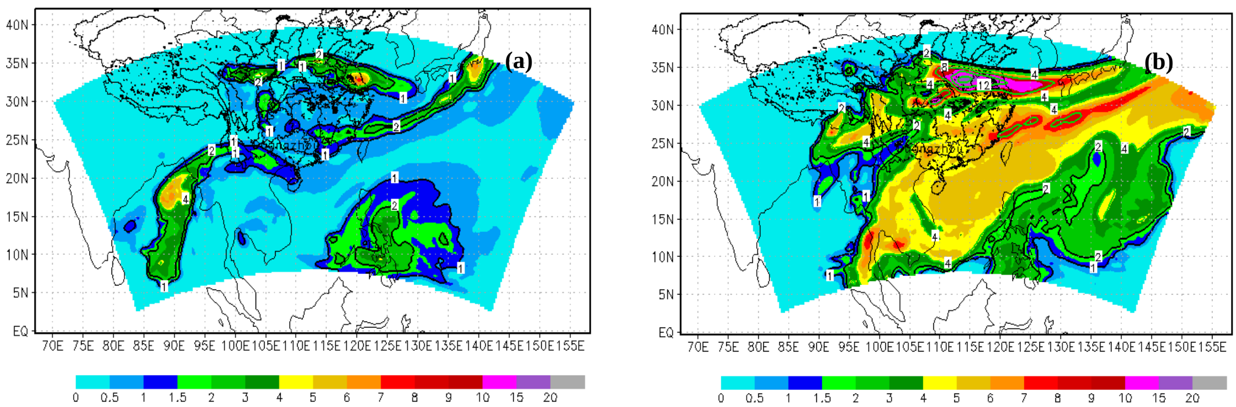

Figure 3. Horizontal distribution of PM_{10} before the SCS summer monsoon onset (a: 12UTC on 1 May in 2011, b: 18UTC 13 on May in 2011, units: ug/m^3).

The distribution of sea salt resembles that of atmospheric pollutants (Fig.5). Specifically, only two high value belts of sea salt exist over the Southwest China–Bay of Bengal between 5°N and 23°N near 85°E and near the Philippines (120°–145°E) before the SCS summer monsoon onset, respectively. Subsequently the low-layer convergence is generated over the SCS after the summer monsoon onset. Then the atmospheric pollutants are uplifted to the upper troposphere by the ascending flow. Finally the two high value belts are combined into a high concentration of sea salt over the SCS (90°–135°E, 5°–35°N).

3.3 *Vertical distribution*

3.3.1 DISTRIBUTION OF VERTICAL CROSS SECTIONS

The vertical cross section of NO_2 along 23.2°N at 12UTC on 10 May in 2011 is shown in Fig.6. A high value region between 400 and 100 hPa is situated over the area from 115°–135°E, and the other two high value centers are located to the west of 125°E from the surface to 750 hPa and to the east of 145°E above 400 hPa, respectively. It is also shown that there are two westerly centers settling to the west of 125°E from surface to 400 hPa and to the east of 145°E above 400 hPa, corresponding to the two centers of NO_2 (Figure omitted). During the SCS summer monsoon onset, the collocation between westerly and NO_2 distribution indicates that the NO_2 is affected by the westerly, which could influence the distribution of SO_2, NO and O_3 over the two regions with high concentration.

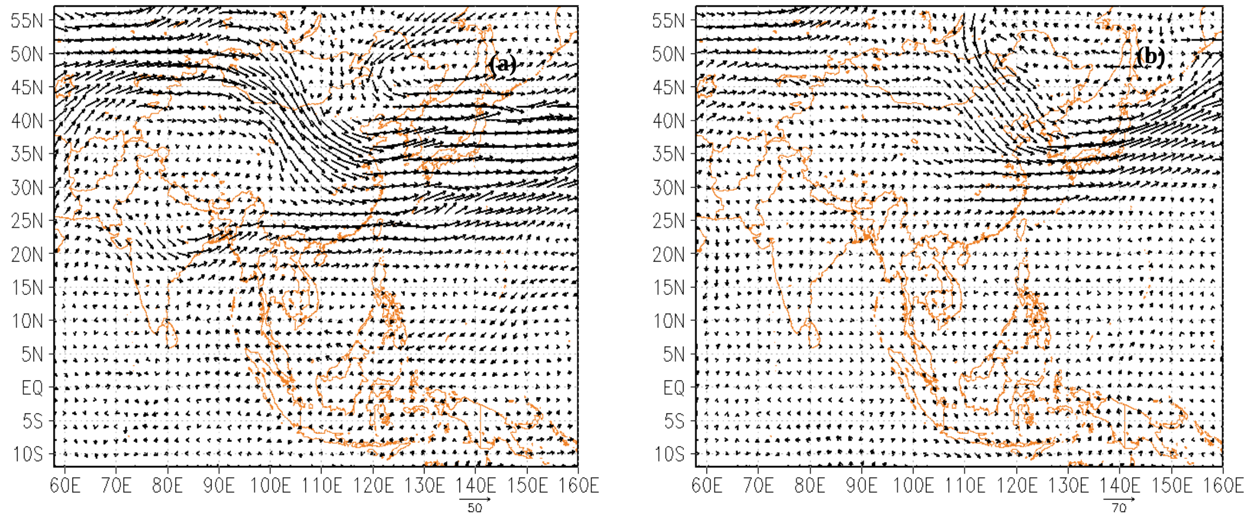

Figure 4. Horizontal distribution of 400-hPa wind field in NCEP reanalysis dataset (a: 12UTC on 1 May in 2011, b: 18UTC on 13 May in 2011, units: m/s).

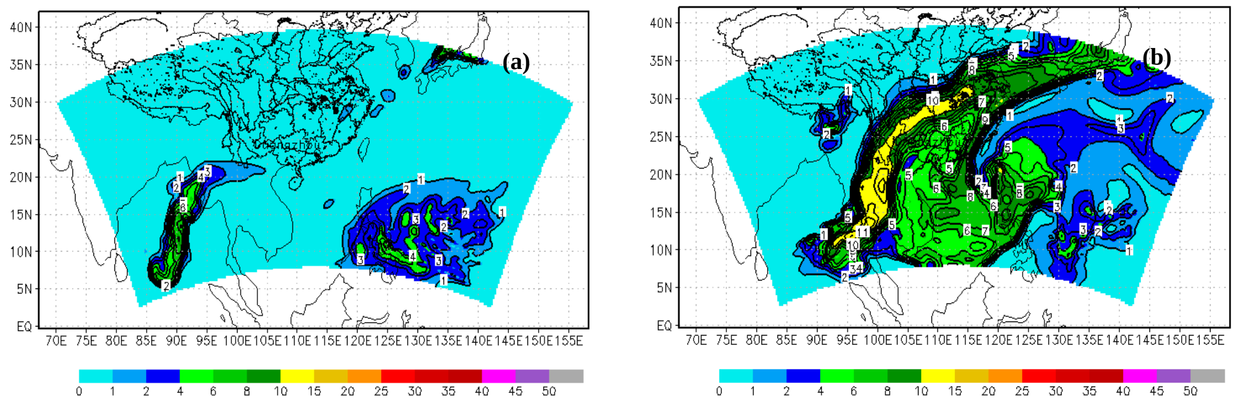

Figure 5. Horizontal distribution of sea salt before the SCS summer monsoon onset (a: 18UTC on 30 April in 2011, b: 18UTC on 10 May in 2011, units: ppmv)

Figure 7 is the vertical distribution of NO_2 along 113.28°E at 12UTC on 10 May in 2011. It is presented that a high concentration center is located between 21°N and 41°N from surface to 600 hPa. It is also seen that this high concentration center is corresponding to a maximum of southerly, implicating the evident effect of southerly on the distribution of NO_2 in this area (Figure omitted). Also in some region the southerly maximum is consistent with the high concentration center of SO_2, O_3 and PM_{10}, respectively.

3.3.2 DIFFERENCE OF VERTICAL STRUCTURE BETWEEN LAND AND SEA BEFORE AND AFTER THE SCS SUMMER MONSOON ONSET

The influence of monsoon on the atmospheric pollutants over the ocean is quite different from that over the land, so that the vertical distribution of pollutants is different over the sea and the land before and after the SCS summer monsoon onset (Fig.8). The vertical distribution of various pollutants is closely associated with the underlying of land and ocean. In the pre-monsoon stage, the human activities lead to the larger concentration of CO, O_3, SO_2 and NO_2 over the land than the counterpart over the ocean from the surface to the upper troposphere, and the concentration is decreased with increasing height. When the SCS summer monsoon onset, the strengthened westerly and southerly facilitates the convection over the land. Thus the atmospheric pollutants concentration is attenuated over the land at this moment. In the meantime, the strong convergence takes place over the ocean to increase the concentration near the sea surface, and then the contrast of concentration between land and ocean is weakened from the surface to the upper troposphere. Specifically, the concentration of SO_2, NO_2 over the land is equal to that over the ocean above 900 hPa, while the CO and O_3 concentration the land is similar to that over the ocean above 500 hPa. However, the land-sea contrast of concentration of PM_{10} and sea salt exhibits little change after the SCS summer monsoon onset, especially above 900 hPa (Fig.9).

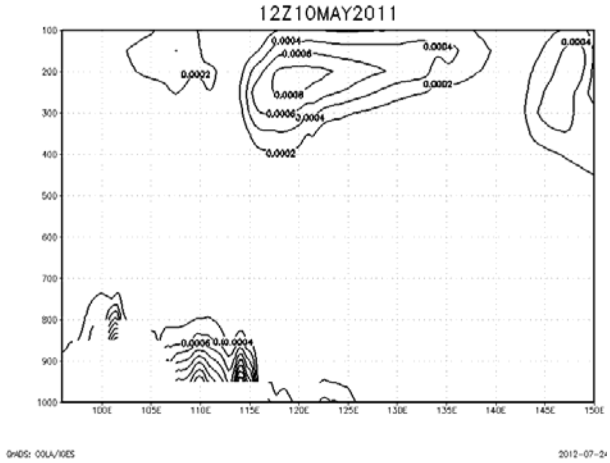

Figure 6. Vertical cross section of NO_2 along 23.2°N at 12UTC on 10 May in 2011 (units: ppmv).

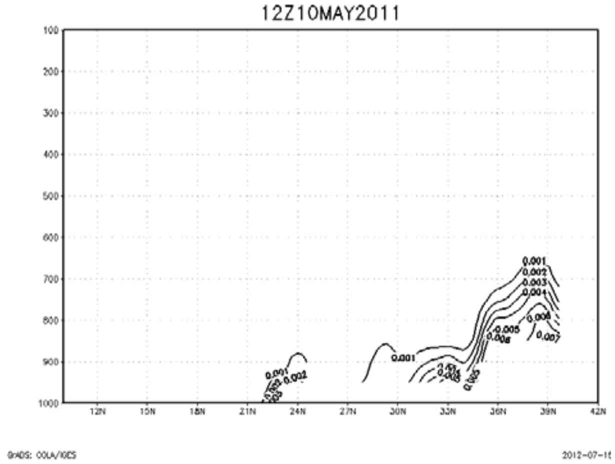

Figure 7. Vertical cross section of NO_2 along 113.28°E at 12UTC on 10 May in 2011 (units: ppmv).

4 CONCLUSIONS

(1) Before and after the SCS summer monsoon onset on 8 May, there are three near-surface high value centers of concentration of atmospheric pollutants at 950 hPa, corresponding to the low value centers of TBB. The westerly and southerly are strengthened with the onset process of SCS summer monsoon, and the low-level zonal wind is turned from easterly to westerly after the summer monsoon onset. Then the local cyclonic circulation leads to a strong convergence over the SCS, accompanied by the 3°–5° southward shifting of the northerly near 40°N and the southwesterly near 35°N. The variation of circulation is the major reason for the changes in near-surface concentration of atmospheric pollutants during the SCS summer monsoon onset in 2011.

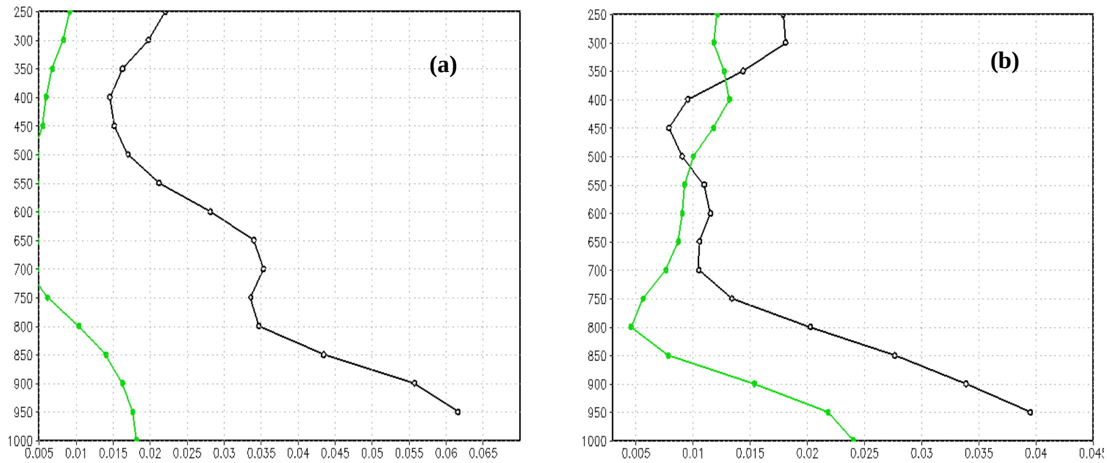

Figure 8. Vertical profile of CO before the SCS summer monsoon onset (a: 0600UTC on 2 May in 2011, b: 0000UTC on 8 May in 2011, units: ppmv. Green and black lines are for the land (113.23°E, 23.16°N) and the ocean (113.23°E, 10°N), respectively.)

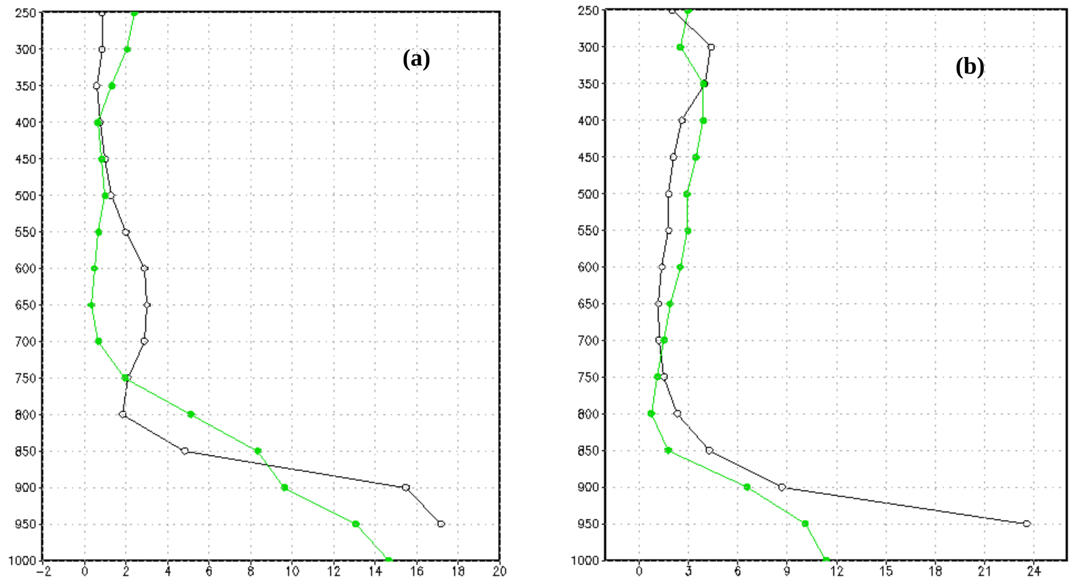

Figure 9. The same as Fig.8, but for the PM_{10} (unit: ug/m^3).

(2) After the SCS summer monsoon onset, the strong jet stream settling to the north of 25°N brings the atmospheric pollutants from a distance to the region to the south of 25°N. Meanwhile, the atmospheric pollutants produced by human activities are stacked over this region without favorable convective condition. Consequently, the concentration of atmospheric pollutants is increased gradually to the south of 25°N, especially over the SCS.

(3) As to the vertical distribution along 23.2°N, the high value of concentration of SO_2, NO, O_3 and NO_2 is located to the west of 125°E between surface and 400 hPa, as well as to the east of 145°E above 400 hPa. The high value centers are collocated by the maximum of westerly, implicating the important influence of westerly on the concentration of atmospheric pollutants during the SCS summer monsoon onset. While the vertical distribution of concentration of SO_2, O_3, PM_{10} and NO_2 along 113.28°E presents that its high value is consistent with the maximum of southerly, thus the effect of southerly is more important for the concentration of atmospheric pollutants over this region with the onset process of SCS summer monsoon.

(4) In the pre-monsoon stage, the concentration of atmospheric pollutants is decreased with increasing height. And the declining range is associated with the category of atmospheric pollutants. In horizontal the concentration of atmospheric pollutants is stronger over the land than that over the ocean because of the human activities. When the SCS summer monsoon builds up, the convection is intensified to attenuate the concentration of atmospheric pollutants over the land. Meanwhile, it is increased over the ocean due to the strong convergence *in situ*. As a result, the land-sea contrast of concentration of most kinds of atmospheric pollutants is weakened evidently after the SCS summer monsoon onset.

REFERENCES:

[1] DONG Xue-ling, LIU Da-meng, YUAN Yang-sen, et al. Distribution characteristics of extractable organic matter in atmospheric PM_{10} in Beijing [J]. Geosci, 2008, 22(2): 325-332 (in Chinese).

[2] ZHAO Guo-jun, BAO Qing-hua, DONG Chen-yang, et al. Research on the distributing characteristic and diversification disciplinarian of air contaminations in Changchun city [J]. J Changchun Univ Sci Technol, 2005, 28(3): 123-126 (in Chinese).

[3] SUN Xun-ying, WEI Yuan-ming, PANG Zhao-yun, et al. Analysis on air pollutant distribution characteristic of Lanzhou city [J]. J Arid Land Res Environ, 2004, 18(6): 15-18 (in Chinese).

[4] ZENG Fan-gang, PENG Lin, LI Jian, et al. The distribution characteristics and origins of organic pollutants in the atmospheric aerosols in Lanzhou city [J]. Rock Miner Anal, 2002, 21(2): 125-128 (in Chinese).

[5] XI Xiao-xia, SONG Qing-hai, HUANG Jian-guo, et al. The regularities of distribution of the air pollutants over the Lanzhou basin in the winter half year [J]. J Lanzhou Univ, 1995, 31(3): 136-140 (in Chinese).

[6] PU Fa-gui. Research on distribution situation of pollutants and air quality in Yuxi city [J]. Yunnan Environ Sci, 2004, 23(1): 174-175 (in Chinese).

[7] LIU Yun-guo, YU Hai-shan. A study of distribution law of air pollutants in Yuancun industrial quarter [J]. J Central South Forestry Univ, 1996, 16(4): 59-66 (in Chinese).

[8] MENG Wei, GAO Qing-xian, ZHANG Zhi-gang, et al. The numerical study of atmospheric pollution in Beijing and its surrounding regions [J]. Res Environ Sci, 2006, 19(5): 11-18 (in Chinese).

[9] WANG Ze-liang, WANG Ri-xin, TAO Jian-hua, et al. Numerical simulation of tidal current and pollutant distribution of Bohai bay[J]. Oceanol Limnol Sinica, 1999, 30(2): 224-230 (in Chinese).

[10] LU Jun, FENG Yuan, GONG Qi, et al. Numerical simulation of air pollution [J]. J Chongqing Univ (Nat Sci Ed), 2005, 28(9): 88-91 (in Chinese).

[11] ZHAO Cai, LI Qi-tai. Numerical simulation of serious air pollution in Guiyang city [J]. J Guizhou Meteorol, 1995, 19(5):10-13 (in Chinese).

[12] ZHONG Zhong, TANG Jian-ping. Simulation study on the onset of South China Sea summer monsoon in 1998 [J]. J PLA Univ Sci Technol (Nat Sci Ed), 2002, 3(6): 80-84 (in Chinese).

[13] WU Liang, DU Dong-sheng. A Numerical study on the onset of South China Sea summer m onsoon in 2006 [J]. J Graduates Sun Yat-Sen Univ (Nat Sci & Med), 2006, 27(4): 93-99 (in Chinese).

[14] MA Shu-jie, SUN Shu-qing. Characteristics of persistent anomaly of the South China Sea summer monsoon and its influence on the global atmospheric circulation Part Ⅱ. Numerical experiment [J]. Clim Environ Res, 2003, 8(3): 356-369 (in Chinese).

[15] LUO Mei-xia, LI Chong-yin. A study of the onset of the summer monsoon over the South China Sea [J]. Clim Environ Res, 2004, 9(3): 494-509 (in Chinese).

[16] LUO Mei-xia, YANG Hui. A numerical forecast experiment on the onset of the summer monsoon over the South China Sea [J]. Clim Environ Res, 2001, 6(1): 43-52 (in Chinese).

[17] LI Yan, WANG You-qiang, LIU Qiang, et al. Effect of weather and climate condition on the spatial distribution of atmospheric pollutants [J]. J Anhui Agri Sci, 2009, 37(4): 1 781-1 782 (in Chinese).

[18] LIANG Han-ming, MIAO Chun-sheng, JIANG Yan-ru, et al. Preliminary study of relation of low-level vertical circulation features to pollutant distribution over China [J]. J Nanjing Inst Meteorol, 1995, 18(3): 427-432 (in Chinese).

[19] LI Lan, WEI Wan-hu, WEI Jing, et al. Air pollution-meteorological condition relationship in Wuhan city [J]. J Hubei Meteorol, 2004(3): 18-22 (in Chinese).

[20] LI Chong-yin, ZHANG Li-ping. Index and features of the summer monsoon over the South China Sea [J]. Progr Nat Sci, 1999, 9(6): 536-541 (in Chinese).

[21] LI Chong-yin, ZHANG Li-pin. Summer monsoon activities in the South China Sea and its impacts [J]. Chin J Atmos Sci, 1999, 23(3): 257-266 (in Chinese).

[22] HUANG Fei, XING Wen, LI Yuan-ni, et al. Seasonal variability of the South China Sea monsoon system before and after the decadal shift in 1990s [J]. Periodic Ocean Univ China, 1999, 9(6): 536-541 (in Chinese).

[23] WANG Wei-guo, ZUO Qun-jie, WANG Hao-yue, et al. The analysis of the water vapor transport difference in Asian monsoon regions in 1997-1999 summers [J]. J Yunnan Univ (Nat Sci), 2009, 31(2): 165-172 (in Chinese).

[24] LIU Yan-ju, DING Yi-hui, SONG Yan-ling, et al. The moisture budget over the South China Sea before and after the summer monsoon onset in 1998 [J]. J Trop Meteorol, 2005, 21(1): 55-62 (in Chinese).

[25] CHEN Yi-de, JIANG Guo-rong, ZHANG Ren, et al. Analysis and comparison of air-sea flux in the northern South China Sea (SCS) during the monsoon onset in 2002 [J] .Chin J Atmos Sci, 2005, 29(5): 761-770 (in Chinese).

[26] LI Chun-hui, LIANG Jian-yin. A review of activities of summer monsoon over South China Sea in 2004 [J]. J Trop Meteorol, 2005, 21(6): 561-569 (in Chinese).

[27] FAN Ling-li, GUO Pin-wen. Comparison of characteristics between South China Sea summer monsoon in 2004 and 2008 [J]. J Trop Meteorol, 2011, 17(1): 73-78.

[28] GAO Hui, ZHU Yan-feng. Abrupt change features of the general circulation during onset period of South China Sea summer monsoon in 2007 [J]. J Nanjing Inst Meteorol, 2009, 32(4): 467-473 (in Chinese).

[29] CHEN Shuang-xi, HE Cai-fu. Relationship between westerly jet and summer monsoon activities in the South China Sea [J]. Meteorol Mon, 2002, 28(5): 11-16 (in Chinese).

[30] ZHU Cong-wen, ZHOU Xiu-ji, ZHAO Ping, et al. Onset of East Asian sub-tropical summer monsoon and rainy season in China [J]. Sci China Earth Sci, 2011, 41(8): 1 172-1 181 (in Chinese).

[31] HU Yin-jia, ZHONG Zhong, NI Tian-jun, et al. The specific characteristics of the phase relationship of air sea system over East Asian monsoon region in summer [J]. Clim Environ Res, 2009, 14(3): 293-300 (in Chinese).

[32] LIU Peng, QIANG Yong-fu, YAN Mi. The relation between the underlying surface thermal anomalies and the onset and intensity of the South China Sea summer monsoon [J]. J Trop Meteorol, 2011, 27(2): 209-218 (in Chinese).

[33] WEI Jin, HE Jin-hai, ZHONG Shan-shan, et al. Characteristics of topographic trough on south side of TP and BB trough and relationship between them and SCSSM onset [J]. Plateau Meteorol, 2008, 27(4): 764-771 (in Chinese).

[34] JIANG Ji-xi, QIN Dan-yu, LIU Chun-xia. A primary study of summer monsoon index over the South China Sea and East Asia based on satellite observation [J]. J Trop Meteorol, 2007, 13(1): 21-24.

[35] ZHU Min, ZUO Rui-ting, ZHANG Ming. Study on relation between wind direction change index and onset of South China Sea monsoon [J]. Sci Meteorol Sinica, 2009, 29(6): 787-792 (in Chinese).

[36] DING Yi-hui, LI Chong-yin, HE Jin-hai, et al. South China Sea monsoon experiment (SCSMEX) and the East-Asian monsoon [J]. Acta Meteorol Sinica, 2004, 62(5): 561-586 (in Chinese).

[37] LAN Guang-dong, WEN Zhi-ping, HE Hai-yan. Characteristics of atmospheric heat source associated with the summer monsoon onset over South China Sea and the possible mechanism responsible for its late or early onset [J]. J Trop Meteorol, 2004, 10(2): 190-200.

[38] XU Hai-ming, HE Jin-hai, ZHOU Bing. Composite analysis of summer monsoon onset process over South China Sea [J]. J Trop Meteorol, 2001, 7(1): 29-40.

[39] TAN Zhi-nian, JIN Long, HE Hui. Characteristics of the cross-equatorial flow in the years with earlier and later onset of South China Sea summer monsoon [J]. J Guangxi Meteorol, 2007, 28(3): 8-11 (in Chinese).

[40] LI Chun-hui, LIANG Jian-yin, ZHENG Bin, et al. The period of South China Sea summer monsoon advanced northward with the related circulation change features [J]. Quart J Appl Meteorol, 2007, 18(2): 202-210 (in Chinese).

[41] LIANG Jian-yin, WU Shang-sen, YOU Ji-ping. The research on variations of onset time of the South China Sea summer monsoon and its intensity [J]. J Trop Meteorol, 1999, 15(2): 97-105 (in Chinese).

[42] FENG Rui-quan, WANG An-yu, WU Chi-sheng, et al. Climatological features of the establishment of South China Sea summer monsoon I—40-year mean [J]. J Trop Meteorol, 2001, 17(4): 345-354 (in Chinese).

[43] GAO Hui, LIANG Jian-yin. Definition of South China Sea summer monsoon's onset date and East Asian summer monsoon's index [J]. J Trop Meteorol, 2005, 21(5): 525-532 (in Chinese).

[44] LI Chong-yin, ZHANG Li-ping. Features and index of the South China Sea summer monsoon [J]. Progr Nat Sci, 1999, 9(6): 536-541 (in Chinese).

[45] LIU Yan-ju, YAN Jun-yue, DING Yi-hui. Anomalies of

the South China Sea summer monsoon and their influence on the atmospheric and oceanic elements over the South China Sea as well as its adjacent regions [J]. Acta Oceanol Sinica, 2008, 30(6): 39-50 (in Chinese).
[46] SONG Ming-kun, LI Yao-dong, HU Liang. An analysis of precipitation during South China Sea monsoon onset period in South China Sea [J]. J Trop Meteorol, 2010, 26(3): 339-348 (in Chinese).
[47] LV Jun-mei, ZHANG Qing-yun, TAO Shi-yan, et al. Characteristics of onset and advancing of Asian summer monsoon [J]. Chin Sci Bull, 2006, 51(3): 332-338 (in Chinese).
[48] KRISHNAM U, ARDANUYP, RAMANATHANY, et al. On the onset vortex of summer monsoon [J]. Mon Wea Rev, 1981, 109(2): 344-363.
[49] TAO S Y, CHEN R X. A review of resent research on the East Asia summer monsoon in China [M]// Monsoon Meteorology, CHANG C P, KRISHNAMURTI T N, eds, Oxford: Oxford Press, 1987: 60-92.
[50] CHANG C P, CHEN T J. Tropical circulation associated with southwest monsoon onset and westerly surge over South China Sea [J]. Mon Wea Rev, 1995, 123: 3 254-3 267.
[51] ZHENG Bin, WU Dui, LI Fei, et al. Variation of aerosol optical characteristics in Guangzhou during South China Sea summer monsoon events [C]// Relationship between atmospheric composition and the changes of weather and climate, the 28th Annual Meeting of Chinese Meteorological Society-S8, 2011-11-01.
[52] HOU Xue-bin, ZHU Bin. The impact of East Asia monsoon’s conversion on the surface ozone spring maximum in the northwest pacific region [C]// Relationship between atmospheric composition and the changes of weather and climate, the 28th Annual Meeting of Chinese Meteorological Society-S8, 2011-11-01.
[53] WANG Zhi-li, ZHANG Hua, GUO Pin-wen. Effects of black carbon aerosol in south Asia on Asian summer monsoon [J]. Plateau Meteorol, 2009, 28(2): 419-424 (in Chinese).
[54] LAU K M, KIM K M. Observational relationships between aerosol and Asian monsoon rainfall, and circulation [J]. Geophys Res Lett, 2006, 33: L21810.
[55] YOON S C, KIM S W, CHOI S J, et al. Regional-scale relationships between aerosol and summer monsoon circulation, and precipitation over Northeast Asia [J]. Asia-Pacific J Atmos Sci, doi:2010.1007/s13143-010-0018-X.

Citation: YANG Zhao-li, ZHENG Bin, WU Dui, et al. Numerical simulation of atmospheric pollutants during the onset stage of South China Sea summer monsoon in 2011 [J]. J Trop Meteorol, 2015, 21(S1): 57-65.