Modeling of the anthropogenic heat flux and its effect on regional meteorology and air quality over the Yangtze River Delta region, China

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Abstract:

Anthropogenic heat (AH) emissions from human activities caused by urbanization can affect the city environment. Based on the energy consumption and the gridded demographic data, the spatial distribution of AH emission over the Yangtze River Delta (YRD) region is estimated. Meanwhile, a new method for the AH parameterization is developed in the WRF/Chem model, which incorporates the gridded AH emission data with the seasonal and the diurnal variations into the simulations. By running this upgraded WRF/Chem for two typical months in 2010, the impacts of AH on the meteorology and air quality over the YRD region are studied. The results show that the AH fluxes over YRD have been growing in recent decades. In 2010, the annual mean values of AH over Shanghai, Jiangsu and Zhejiang are 14.46, 2.61 and 1.63 W/m^2 respectively, with the high values of 113.5 W/m^2 occurring in the urban areas of Shanghai. These AH emissions can significantly change the urban heat island and urban-breeze circulations in the cities of the YRD region. In Shanghai, 2-m air temperature increases by 1.6 ℃ in January and 1.4 ℃ in July, the planetary boundary layer height rises up by 140m in January and 160m in July, and 10-m wind speed is enhanced by 0.7 m/s in January and 0.5 m/s in July, with higher increment at night. The enhanced vertical movement can transport more moisture to higher levels, which causes the decrease of water vapor at the ground level and the increase in the upper PBL, and thereby induces the accumulative precipitation to increase by 15-30% over the megacities in July. The adding AH can impact the spatial and vertical distributions of the simulated pollutants as well. The concentrations of primary air pollutants decrease near surface and increase at the upper levels, due mainly to the increases of PBLH, surface wind speed and upward air vertical movement. But surface O_3 concentrations increase in the urban areas, with maximum changes of 2.5ppb in January and 4 ppb in July. Chemical direct (the rising up of air temperature directly accelerate surface O_3 formation) and indirect (the decrease in NO_x at the ground results in the increase of surface O_3) effects can play a significant role in O_3 changes over this region. The meteorology and air pollution predictions in and around large urban areas are highly sensitive to the anthropogenic heat inputs, suggesting that AH should be considered in the climate and air quality assessments.

Key words: Anthropogenic heat; WRF/Chem; Urban canopy model; Ozone; PM_{10}

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Nearly all energy used for human purposes can eventually turn into anthropogenic heat (AH) within Earth's land-atmosphere system (Flanner, 2009; Chen et al., 2012). According to the distinctive human activities all over the world, this heat flux might vary spatially and temporally. On the global scale, the averaged value of AH flux has been estimated to be only 0.028 W/m^2. But it can reach to 0.39, 0.68 and 0.22 W/m^2 respectively over the continental United States, Western Europe and China (Flanner, 2009). In the densely populated and economically vibrant urban areas, the AH fluxes have been reported to typically range from 20 to 70 W/m^2 (Crutzen, 2004; Sailor and Lu, 2004; Fan and Sailor, 2005; Pigeon et al., 2007; Lee et al., 2009), whereas the fluxes might occasionally exceed the value of 100 W/m^2 as well (Quah and Roth, 2012; Xie et al., 2015). Under some extreme conditions, the magnitude of AH fluxes in cities can be a substantial heat source equivalent to the daily mean solar forcing (Ichinose et al., 1999; Hamilton et al. 2009; Iamarino et al. 2012), with a high value of 1590 W/m^2 reported in the densest part of Tokyo at the peak of air-conditioning demand (Ichinose et al., 1999). Consequently, accurate prediction of AH emissions is always a key issue that can improve our understanding of human impacts on urban climate and environment.

Anthropogenic heat can increase turbulent fluxes in sensible and latent heat, which might result in the atmosphere reserving more energy (Oke, 1988). Thus, the abovementioned heat fluxes exhausted from human activities in cities can exert a significant influence on the dynamics and thermodynamics of urban boundary layer (Ichinose et al., 1999; Block et al., 2004; Fan and Sailor, 2005; Chen et al., 2009; Chen et al., 2012; Bohnenstengel et al., 2014), and thereby change the surface meteorological conditions (Khan and Simpson, 2001; Block et al., 2004; Fan and Sailor, 2005; Ferguson and Woodbury, 2007; Chen et al., 2009; Zhu et al., 2010; Menberg et al., 2013; Wu and Yang, 2013; Feng et al., 2014; Bohnenstengel et al., 2014). Most previous studies of AH have focused on these effects. For instance, some researchers have found that AH strengthens the vertical movement of urban surface air flow, change the urban heat island circulation, and make the urban boundary layer more turbulent and unstable (Ichinose et al., 1999; Block et al., 2004; Fan and Sailor, 2005; Chen et al., 2009; Bohnenstengel et al., 2014). Others showed that AH in cities can result in significant and extensive warming, and tend to cause urban air temperatures to increase by several degrees (Fan and Sailor, 2005; Ferguson and Woodbury, 2007; Chen et al., 2009; Zhu et al., 2010; Menberg et al., 2013; Wu and Yang, 2013; Feng et al., 2014; Bohnenstengel et al., 2014). Moreover, Feng et al. (2014) reported that AH enhances the convergence of water vapor and rainfall amounts over urbanized areas, and changes the regional precipitation patterns to some extent. Urban air quality and local meteorological condition are inextricably linked. Therefore, all the findings above are likely to have important implications for air quality in urban areas as well. However, in the past, few researchers paid attention to this issue, and only a couple of studies have estimated the effects of AH on air pollutants (Ryu et al., 2013; Yu et al., 2014; Yang et al., 2014).

Over the past decades, along with the accelerated urbanization process and rapid economic development, many cities in China have been suffering the successive deterioration of air quality (Xie et al., 2014). Located in the coastal region in East China, the Yangtze River Delta (YRD) region also experienced a rapid urban expansion with the urbanization rate as high as 70% and suffered from air pollutions (Liao et al., 2015). Consequently, several previous studies have tried to figure out the effects of urbanization on the severe atmospheric environmental problems in this region. For example, by using WRF/Chem model, Wang et al. (2009) quantified that the urban sprawl in YRD region has caused surface O_3 to increase by 2.9-4.2% during the daytime and 4.7-8.5% at night. Employing the WRF/CMAQ model, Li et al. (2011) showed that O_3 and haze problem had become an important issue due to the increasing of urban land-use. Liao et al. (2015)

further quantified the increase of O_3 and the decrease of PM_{10} (or NO_x) related to the urban expansion. Kang et al. (2014) discussed the impact of Shanghai urban land surface forcing on downstream city meteorology. Zhu et al. (2015) further studied this impact on O_3 chemistry. However, the above studies only took the expansion of urban land-use into account. We still need to know how the excessive anthropogenic heat from urban expansion impacts on urban climate and air quality. Among previous studies, a couple of researchers have tried to fill the knowledge gap. For instance, He et al. (2007) incorporated AH into a PBL (planetary boundary layer) model for Nanjing 2002 and found a temperature increase (0.5 - 1 °C) at night. Wang et al. (2015) reported that AH can cause notable warming in almost the whole YRD, which is more significant in winter than in summer. These studies only focused on the effects of AH on local meteorological fields. Till now, none studies have evaluated the influence of AH on air quality over the YRD region.

The main purpose of this study is to improve our understanding about the influence mechanism of anthropogenic heat on atmospheric environment, especially in the typical polluted areas of China such as the YRD region. In this paper, we focus on (1) quantifying the spatial and temporal distribution of AH emissions in the YRD region, (2) implementing the gridded AH data into the modified WRF/Chem model with improved AH flux parameterization, and (3) evaluating the impacts of AH fluxes on meteorological condition and air quality over the YRD region. Detailed descriptions about the estimating method for anthropogenic heat flux over the YRD region, the adopted air quality model with configuration, and the observation data for model evolution are given in Sect. 2. Main results, including the spatial and temporal distribution of AH, the performance of WRF/Chem, and the exact impacts of AH on urban climate and air quality are presented in Sect. 3. In the end, a summary is given in Sect. 4.

2. Methodology

2.1 Anthropogenic heat flux modeling

We estimate the AH fluxes during the period from 1990 to 2010 over the area between (117°E, 28°N) and (123°E, 34°N), which covers the YRD region including Shanghai, southern Jiangsu province and northern Zhejiang province (shown in Fig. 1). In order to get the spatial distribution, this study area is also gridded as 144 rows and 144 columns with the grid spacing of

2.5 arcmin (approximately 4 km).

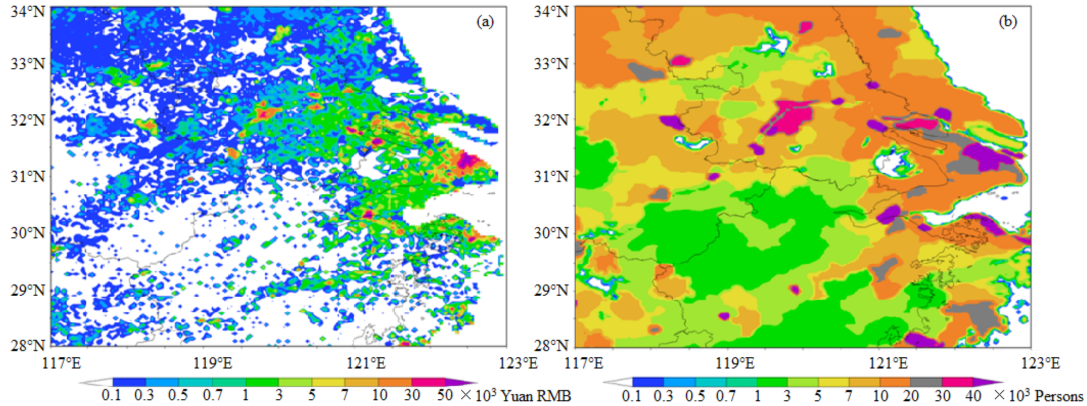


Fig. 1. Spatial distribution of Gross Domestic Product (a) and population (b) in 2010 over the region between (117°E, 28°N) and (123°E, 34°N) with the resolution of 2.5 arcmin. Data are obtained from the website http://sedac.ciesin. columbia.edu/gpw.

The anthropogenic heat flux Q_F (W/m^2) is the rate at which waste energy is discharged by human activities to the surroundings (Iamarino et al., 2012). In urban areas, it usually consists of the heat flux deriving from energy consumption in buildings ($Q_{F,B}$), from the transportation sector ($Q_{F,T}$) and from human metabolism ($Q_{F,M}$) (Grimmond 1992; Sailor and Lu, 2004; Allen et al., 2011; Iamarino et al., 2012; Quah and Roth, 2012). Three general approaches have been recognized to estimate these terms (Sailor, 2011), including the building energy modeling approach for the building sector (Kikegawa et al., 2003), the closure of the energy budget (Offerle et al., 2005), and the use of statistics on energy consumption (Sailor and Lu, 2004; Flanner, 2009; Hamilton et al., 2009; Lee et al., 2009; Allen et al., 2011; Iamarino et al., 2012; Quah and Roth, 2012). The third method, which is also called the top-down energy inventory method, was the most common approach and widely applied in AH flux predictions in China (Chen et al., 2012; Lu et al., 2014; Xie et al., 2015). Based on these previous investigations, Q_F in this study is calculated by the following equation:

$$Q_F = Q_{F,I} + Q_{F,B} + Q_{F,T} + Q_{F,M} \quad (1)$$

where $Q_{F,I}$ represents the heat emitted from the industry sector (W/m^2).

According to the second law of thermodynamics, most energy used for human economy is immediately dissipated as heat, other energy temporarily stored as electrical, mechanical, chemical or gravitational potential energy can finally transform to high entropy thermal energy as well, and only a neglectful portion (<< 1%) might convert to radiation and escape to space (Flanner, 2009). So, it is reasonable to assume that all non-renewable primary energy consumption is dissipated thermally in Earth's atmosphere. From another perspective, in this study, the gridded AH data is finally incorporated into the single layer urban canopy model SLUCM (Kusaka and Kimura, 2004; Chen et al., 2011), in which we do not need to strictly distinguish different sources of AH. In a consequent, $Q_{F,I} + Q_{F,B} + Q_{F,T}$ at each grid can be estimated on the basis of energy consumption from non-renewable sources (coal, petroleum, natural gas, and electricity etc.) by using the following equation:

$$Q_{F,I} + Q_{F,B} + Q_{F,T} = \eta \cdot \varepsilon_s \cdot C_s / (t \cdot A) \qquad (2)$$

where, C_s is the primary energy consumption that has been converted to standard coal (t) at a grid. ε_s is the calorific value of standard coal (the conversion factor from primary energy consumption to heat), which is recommended to be 29271 kJ/kg in many previous studies(Chen et al., 2012; Lu et al., 2014; Xie et al., 2015). η is the efficiency of heat release in different sectors, with the typical value of 60% for electricity or heat-supply sector and 100% for other sectors (Lu et al., 2014). t is the time duration of used statistic data, and is set to be 365 (days in a year) ×24×3600 = 31536000 s in this study. A represents the area of a grid, which is about 4×4 km^2. To quantify the values of C_s, the authoritative statistics of annual standard coal consumption from 1990 to 2010 in provincial level are firstly obtained from China Statistical Yearbooks and the Yearbooks in Shanghai, Jiangsu and Zhejiang. Then, the total provincial energy consumption is apportioned to each grid according to population density and converted to annual-mean gridded energy flux. The population density with the resolution of 2.5 × 2.5 arcmin in 1990, 1995, 2000, 2005 and 2010 can be downloaded from Columbia University's Socioeconomic Data and Applications Center (http://sedac.ciesin.columbia.edu/gpw). That for 2010 is shown in Fig. 1b for example.

With respect to the heat flux generated by the human metabolism ($Q_{F,M}$), the grid value is computed as:

$$Q_{F,M} = P_g \cdot (M_d \cdot 16 + M_n \cdot 8) / 24 \qquad (3)$$

where P_g is the population at a grid. M_d and M_n represent the average human metabolic rate (W/person) during the daytime and nighttime. 16, 8 and 24 are the hours of daytime, nighttime and a whole day, respectively. Following the previous research work (Sailor and Lu, 2004; Chen et al., 2012; Lu et al., 2014; Xie et al., 2015), we assume that the sleeping metabolic rate M_d for a typical man is 75 W, and the average daytime metabolic rate M_n in urban areas is 175 W.

2.2 Air quality model and configuration

The WRF/Chem version 3.5 is applied to investigate the impacts of AH fluxes on climate and air quality over the YRD region. WRF/Chem is a new generation of air quality modeling system developed at National Center for Atmospheric Research (NCAR), in which the meteorological component (WRF) and the air quality component (Chem) are fully coupled using the same coordinates and physical parameterizations. The feedbacks between meteorology and air pollutants are included in the model. It has been proved to be a reliable tool in simulating air quality from city-scale to meso-scale in China (Liu et al., 2013; Yu et al., 2014; Liao et al., 2014; 2015).

As shown in Fig. 2a, three nested domains are used in this study, with the grid spacing of 81, 27 and 9 km, respectively. The outermost domain (Domain 1, D01) covers most of the East Asia and South Asia, the second domain (Domain 2, D02) covers central-east part of China, and the finest domain (Domain 3, D03) centered at Nanjing covers the entire YRD region (Fig. 2b). For all domains, from the ground level to the top pressure of 50hPa, there are 36 vertical sigma layers with about 10 in the PBL. The height of the lowest level is about 25 m.

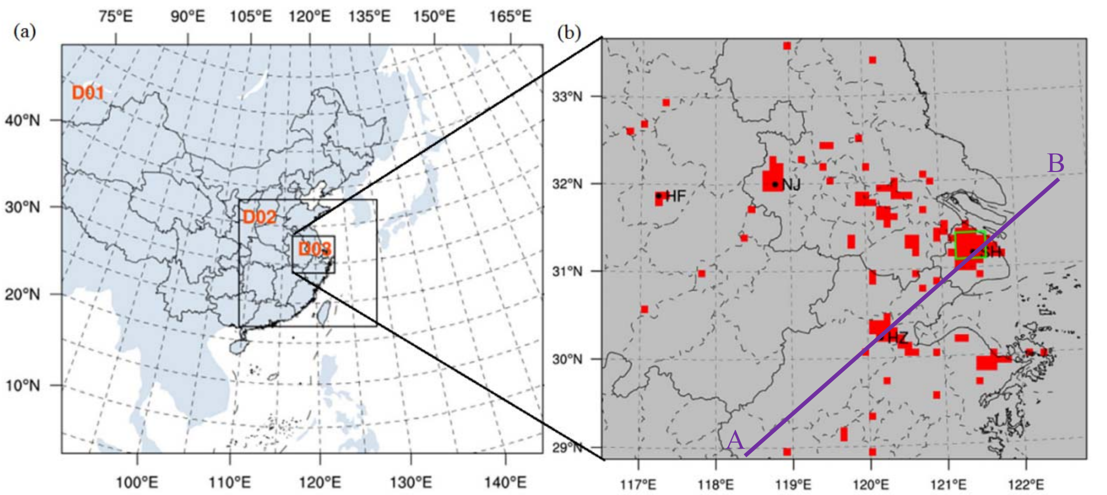


Fig. 2. The three nested modeling domains (a) and MODIS urban land-use category dataset used in D03, with the locations of the four meteorology observation sites (b). SH, HZ, NJ and HF in (b) represent Shanghai, Hangzhou, Nanjing and Hefei, respectively. Line AB denotes the location of the vertical cross section used in Fig. 9 and Fig. 12.

Two simulation cases are conducted. One incorporates the urban canopy model with the gridded AH fluxes that are estimated in Sect. 2.1 (referred to as ADDAH case hereafter). The other only applies the same model but ignores the contribution of AH (referred to as NONAH case hereafter). To exclude the uncertainty conceivably caused by different configurations, all the physical schemes, chemical schemes and emission inventory are the same in both NONAH and ADDAH simulations. Thus, the difference between the modeling results of NONAH and ADDAH can demonstrate the impacts of anthropogenic heat. In the YRD region, January and July can be representative of dry and wet season, respectively (Liao et al., 2015). Consequently, two time periods are chosen for simulations and analysis. One is from 0000 UTC 01 January to 0000 UTC 01 February 2010, and the other is from 0000 UTC 01 July to 0000 UTC 01 August 2010, which also match the time when observation data are available. The monthly averaged difference between ADDAH and NONAH can be calculated by the following algorithm:

$$ADDAH - NONAH = \frac{\sum_{t=1}^{744}(V_{ADDAH,t} - V_{NONAH,t})}{744} \quad (4)$$

where $V_{ADDAH,t}$ and $V_{NONAH,t}$ are the hourly modeling outputs of variable V (meteorological factors or air pollutants) from ADDAH and NONAH, respectively. The monthly averaged differences of variables are calculated grid by grid. To guarantee the differences of one variable are statistically significant, student t test is carried out based on the data set from NONAH and ADDAH for each grid. At one grid, if the difference is non-significant under the 95% confidence level, we can assert that the AH flux cannot significantly change the meteorology or air quality at this grid (Zhuang et al., 2013a; 2013b; Liao et al., 2015).

The detailed options for the physical and chemical parameterization schemes used in this study are shown in Table 1. The major selected physical options include Purdue Lin microphysics scheme, RRTM (Rapid Radiative Transfer Model) long-wave radiation scheme, Goddard short-wave radiation scheme, Kain-Fritsch cumulus parameterization scheme, Noah/LSM (Land Surface Model) scheme and MYJ (Mellor-Yamada-Janjic) PBL scheme. Specially, SLUCM (coupled with Noah/LSM) is adopted for better simulating the urban effect on meteorological conditions and pollutant distribution. The 30-sec MODIS 20 category land datasets (Fig. 2b) are used to replace the default USGS (U.S. Geological Survey) land-use data, because USGS data are too outdated to illustrate the intensive land cover change over the YRD region. The default values for urban canopy parameters in SLUCM, such as building morphometry, urban fraction and roughness length etc., are replaced by the typical values in the YRD region as well, following the work of He et al. (2007) and Liao et al. (2015). The initial meteorological fields and boundary conditions (forced every 6 h) are from NCEP global reanalysis data with 1°× 1° resolution.

With respect to the major chemical options, the CBM-Z gas-phase chemistry scheme and the MOSAIC aerosol scheme are chosen. CBM-Z (Carbon-Bond Mechanism version Z) contains 55 prognostic species and 134 reactions (Zaveri and Peters, 1999). In MOSAIC (Model for Simulating Aerosol Interactions and Chemistry), the aerosol size distribution is divided into eight discrete size bins (Zaveri et al., 2008). Besides, aerosol direct and indirect effects through interaction with atmospheric radiation, photolysis, and microphysics routines are also taken into account in our simulations. The modeling results from the global chemistry transport model MOZART-4 are used to provide the initial chemical state and boundary conditions as described by Liao et al. (2015). The anthropogenic emissions are mainly from the inventory developed for the NASA INTEX-B mission (Zhang et al., 2009), and modified for simulations in the YRD region (Liao et al., 2014; 2105). The ammonia emission and biomass burning emissions, which are not contained in the INTEX-B inventory, are obtained from the inventory developed for TRACE-P (Streets et al., 2003). For Shanghai area, we use the additional 1 km × 1 km source emission compiled by Shanghai Environmental Monitoring Center during EXPO 2010 (Wang et al., 2012). The biogenic emissions are estimated by using MEGAN2.04 (Guenther et al., 2006).

Table 1. The grid settings, physics and chemistry options used in this study for WRF/Chem

Items	Contents
Dimensions (x,y)	(85,75), (76,70), (76,70)
Grid size (km)	81, 27, 9
Time step (s)	360
Microphysics	Purdue Lin microphysics scheme (Lin et al., 1983)
Long-wave radiation	RRTM scheme (Mlawer et al., 1997)
Short-wave radiation	Goddard scheme (Kim and Wang, 2011)
Cumulus parameterization	Kain-Fritsch scheme, only for D01 and D02 (Kain, 2004)
Land surface	Noah land surface model (Chen and Dudhia, 2001)
Planetary boundary layer	Mellor-Yamada-Janjic scheme (Janjic, 1994)

Urban canopy model	SLUCM (Kusaka and Kimura, 2004)
Gas-phase chemistry	CBM-Z (Zaveri and Peters, 1999)
Aerosol module	MOSAIC using 8 sectional aerosol bins (Zaveri et al., 2008)

2.3 Methodology for incorporating gridded AH emission data

Within the Single Layer Urban Canopy Model SLUCM, the AH for each grid is determined by the fixed AH value for the urban land-use category, the fixed temporal diurnal pattern and the urban fraction value on each grid (Chen et al., 2011). AH with its diurnal variation is generally considered by adding them to the sensible heat flux from the urban canopy layer by the following equation:

$$Q_H = F_V \cdot Q_{HV} + F_U \cdot (Q_{HU} + Fix_{AH}) \tag{5}$$

where Q_H is the total sensible heat flux. F_V and F_U are the fractional coverage of natural and urban surfaces, respectively. Q_{HV} is the sensible heat flux from Noah LSM for natural surfaces, and Q_{HU} is that from SLUCM for artificial surfaces. Fix_{AH} represents the fixed AH value for all urban areas (Chen et al., 2011). In ADDAH simulation case of this study, we basically follow the Eq. 4, but incorporate the gridded AH data (Q_F) to replace the fixed AH value (Fix_{AH}) in order to considering the spatial distribution of AH fluxes. The data estimated in Sect. 2.1 with the resolution of about 4km are re-projected to domain 3 (9km) by the latitude and longitude of each grid. To account for temporal variability, the annual-mean AH fluxes in 2010 over the modeling area are further scaled with weighting functions dependent on local time of day (t_d) and time of year (m_y):

$$Q_F(t_d, m_y) = Q_F \cdot w_d(t_d) \cdot w_y(m_y) \tag{6}$$

where the diurnal cycles of w_d are obtained from the work of He et al. (2007) for the YRD region (shown in Fig. 3). According to the findings of Sailor and Lu (2004) and Flanner (2009), the values of w_y for January and July are set to be 1.2 and 0.8, respectively.

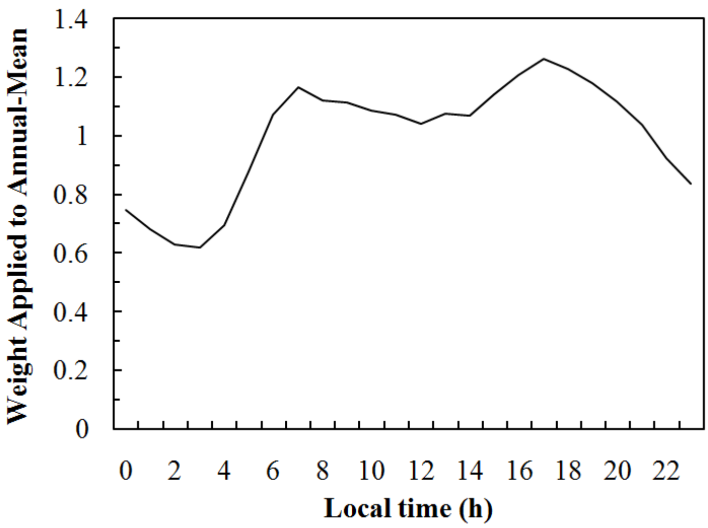


Fig. 3 Diurnal variation of anthropogenic heat flux based on He et al. (2007), applied as weights to the annual-mean flux.

2.4 Evaluation method and relevant observation data

Meteorological and chemical observation records are used to evaluate the model performance in this study. The mean bias (MB), root mean square error (RMSE) and correlation coefficient (CORR) between observation and the ADDAH model results are used to verify model performance. In statistics, they are usually defined as:

$$MB = \frac{1}{N}\sum_{i=1}^{N}(S_i - O_i) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2} \tag{8}$$

$$CORR = \frac{\sum_{i=1}^{N}(S_i - S_m)(O_i - O_m)}{\sqrt{\sum_{i=1}^{N}(S_i - S_m)^2}\sqrt{\sum_{i=1}^{N}(O_i - O_m)^2}} \tag{9}$$

where S_i is the simulation and O_i is the observation. S_m and O_m are average value of simulations and observations, respectively. In general, the model performance is acceptable if the values of MB and RMSE are close to zero and those of CORR are close to 1.

With respect to observed meteorological data, four observation sites are selected, which are NJ (32.00°N, 118.80°E) located in Nanjing, HF (31.87°N, 117.23°E) in Hefei, HZ (30.23°N, 120.16°E) in Hangzhou, and SH (31.40°N, 121.46°E) in Shanghai, respectively (marked in Fig.

2b). Their time series of 2-m temperature, 10-m wind speed and 2-m relative humidity in January and July of 2010 can be obtained from hourly records of atmospheric sounding dataset compiled by University of Wyoming (http://weather.uwyo.edu). In order to evaluate model performance of chemical fields, hourly chemical series of PM_{10} and O_3 during the modeling period are acquired from Caochangmen (CCM) site. CCM is located in the central and highly residential area of Nanjing (32.06°N, 118.74°E), and is running by the Nanjing Environmental Monitoring Center. The assurance/quality control (QA/QC) procedures at CCM strictly follow the national standards.

3. Results and discussions

3.1 Spatial and temporal distribution of anthropogenic heat flux in the YRD region

Using the methodology outlined above in Sect. 2.1, we construct the spatial distribution of anthropogenic heat fluxes over the YRD region from 1990 to 2010 with a 5-year interval. Fig. 4 illustrates the gridded distribution in 1995, 2000, 2005 and 2010 (The magnitude and spatial distribution pattern in 1990 are similar to 1995). Obviously, big cities, such as Shanghai, Nanjing, Hangzhou etc., have the largest values among neighboring areas from the early 1990s till now. Before 2000, except for some megacities, AH fluxes are generally less than 2.5 W/m^2 in most parts of the YRD region. However after 2000, the AH fluxes are more than 5 W/m^2 in many areas, with the high values over 25 W/m^2 centrally appearing along the Yangtze River, around Lake Taihu and beside Hangzhou Bay. The temporal variation of the spatial pattern fits in well with the economic boom in the YRD region over the past decades.

Being the largest city, Shanghai always has the highest anthropogenic heat emissions in the YRD region. As shown in Table 2, the annual mean value over the whole administrative district is 5.47 W/m^2 in 1990 and 14.45 W/m^2 in 2010, with the annual growth of 0.45 W/m^2. In recent years, the AH fluxes in the city center of Shanghai have exceeded 100 W/m^2, which is comparable to those in the most crowded megacities, such as Tokyo (Ichinose et al., 1999), Hong Kong (Flanner, 2009), London (Hamilton et al. 2009; Iamarino et al. 2012) and Singapore (Quah and Roth, 2012). The annual mean values in the downtown area are much higher than the regional ones. With respect to Jiangsu Province and Zhejiang Province, the AH fluxes there also increase from 0.68 and 0.33 W/m^2 in 1990 to 2.61 and 1.63 W/m^2 in 2010. The regional annual mean values in Jiangsu higher than those in Zhejiang can be attributed to the facts that there are more large state-own enterprises (including petrochemical companies and power plants) in Jiangsu. Furthermore, the AH fluxes in the urban areas of Jiangsu and Zhejiang range from 20 to 50 W/m^2 in recent decade. These high values are close to those in Toulouse of France (Pigeon et al., 2007), Seoul of Korea (Lee et al., 2009), and some large US cities (Sailor and Lu, 2004; Fan and Sailor, 2005).

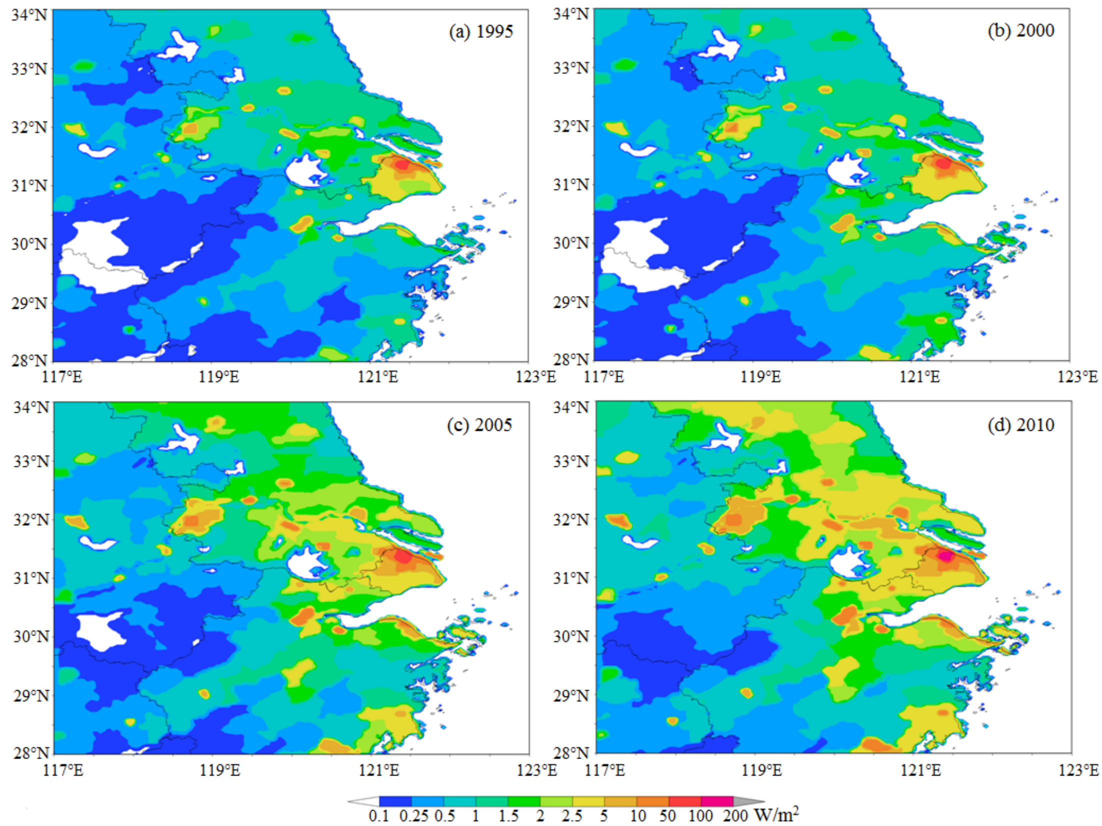


Fig. 4. Estimates of annual-mean anthropogenic heat fluxes resulting from the consumption of non-renewable energy sources (coal, petroleum, natural gas, and electricity) and human metabolism between (117°E, 28°N) and (123°E, 34°N) with the resolution of 2.5 arcmin for 1995 (a), 2000 (b), 2005 (c) and 2010 (d), respectively.

Table 2 The statistics of annual average anthropogenic heat flux in different administrative district over the YRD region (W/m^2)

Province or Municipality		This study					Previous results (year)	References
		1990	1995	2000	2005	2010		
Shanghai	Regional	5.47	7.85	9.2	12.39	14.45	16.54 (2008)	Chen et al., 2012
							16.10 (2010)	Lu et al., 2014
	Downtown	42	60.8	71.6	96.9	113.5	117.7 (2010)	Lu et al., 2014
Jiangsu	Regional	0.68	0.94	0.99	1.83	2.61	2.32 (2008)	Chen et al., 2012
	Downtown	5.1	9.5	12.5	28.6	50.2	40 (Nanjing, 2007)	He et al., 2007

							20-70 (2010)	Lu et al., 2014
Zhejiang	Regional	0.33	0.54	0.73	1.25	1.63	1.60 (2008)	Chen et al., 2012
	Downtown	2.7	7.4	12.1	25.1	39.3	50 (Hangzhou, 2007)	He et al., 2007
							20-70 (2010)	Lu et al., 2014

* Regional represents the average value over the whole area of an administrative district, while Downtown represents the high value in the city center.

In 2010, nearly all areas of the YRD region have the AH fluxes more than 2.5 W/m^2 (shown in Fig. 4d). High fluxes generally occur in and around the cities, such as Shanghai, Nanjing, Hangzhou, Yangzhou, Zhenjiang, Taizhou, Changzhou, Wuxi, Suzhou, Nantong, Huzhou, Jiaxing, Shaoxing, and Ningbo etc., with the typical values of 113.5, 50.2 and 39.3 W/m^2 in the urban areas of Shanghai, Jiangsu and Zhejiang, respectively (shown in Table 2). Comparing Fig. 4d with Fig. 1, we can easily find that the spatial distribution of AH based on the population reflects the economic activities in the YRD region as well, suggesting that our method is effective and the results are reasonable. Moreover, as shown in Table 2, parts of our conclusion can be supported by some other previous studies (He et al., 2007; Chen et al., 2012; Lu et al., 2014; Xie et al., 2015). Therefore, the gridded AH fluxes can be used in meso-scale meteorological and environmental modeling to investigate their impacts on urban climate and air quality.

3.2 Model evaluation for WRF/Chem

Table 3 shows the statistical comparisons between meteorological observations and the model results from both January and July simulations in ADDAH case. Mean values, MB, RMSE and CORR are all quantified for 2-m temperature (T_2), 2-m relative humidity (RH_2) and 10-m wind speed (WS_{10}) at four grids where NJ, HF, HZ and SH are located. As shown in Table 3, the correlation coefficients between observations and simulations (CORR) are over 0.9 in January and about 0.8 in July for T_2, higher than 0.7 for RH_2 at most sites in both months, and close to 0.7 for WS_{10} in January. So WRF/Chem simulates the urban meteorological conditions over the YRD region quite well. With respect to T_2, the modeling results are slightly overvalued at all sites, which might be attributed to the uncertainty caused by urban canopy and surface parameters (Kusaka and Kimura, 2004; Chen et al., 2011; Liao et al., 2015). But the level of overestimation is acceptable, because the MB values of T_2 are only 1.1 - 1.7 ℃ in January and 0.7 - 2.0 ℃ in July with the RMSE of T_2 are 1.6 - 2.2 ℃. The lowest value 0.7 ℃ for MB and the highest value 0.94 for CORR illustrate the best T_2 estimation at SH. For RH_2, compared with the observations, the simulation results are underestimated at all sites. Though worst simulation of RH_2 occurs at HF, the results are reasonable at other three sites. We find that the land-use dataset cannot well describe waters around HF. In view that HF is not in the center area of the YRD region, the deviation at HF cannot introduce crucial uncertainty into our main conclusion. In regard to WS_{10}, the modeling values from the ADDAH case are slightly overestimated at NJ, HF and HZ, whereas underestimated at SH. The MB for WS_{10} is generally less than 0.5 m/s, and the RMSE is less than 1.3 m/s. These over- or under-estimates are attributable to near-surface wind speed being influenced by local underlying surface characteristics more than other meteorological parameters. Further improvement of urban canopy parameters might improve the simulations (Zhang et al., 2010; Liao et al., 2015).

Table 3 The statistics of meteorological conditions from the ADDAH simulation at four sites

Vars[a]	Sites[b]	January					July				
		Mean[c]		MB	RMSE	CORR[d]	Mean[c]		MB	RMSE	CORR[d]
		OBS[e]	SIM[f]				OBS[e]	SIM[f]			
T_2 (℃)	NJ	3.5	5.1	1.6	2.2	0.92	28.2	30.2	2.0	2.0	0.83
	HZ	5.7	7.4	1.7	1.9	0.93	28.7	30.5	1.8	2.2	0.80
	HF	3.6	5.1	1.5	2.2	0.91	28.9	30.6	1.7	2.1	0.76
	SH	5.6	6.7	1.1	1.6	0.94	28.8	29.5	0.7	1.7	0.85
RH_2 (%)	NJ	65	53	-12	14	0.74	76	68	-9	10	0.71
	HZ	67	60	-7	10	0.83	74	70	-4	17	0.71
	HF	71	51	-20	13	0.75	88	69	-19	12	0.62
	SH	70	64	-6	11	0.79	76	72	-4	11	0.77
WS_{10} (m/s)	NJ	2.6	3.1	0.5	1.2	0.61	2.9	3.2	0.3	1.3	0.53
	HZ	2.5	2.6	0.1	1.0	0.69	2.4	2.5	0.1	1.3	0.34
	HF	2.6	2.9	0.3	1.1	0.67	2.3	2.7	0.4	1.2	0.40
	SH	4.1	3.8	-0.3	1.2	0.78	4.1	3.6	-0.5	1.2	0.66

[a] Vars represents the variables, including temperature at 2m (T_2), relative humidity at 2m (RH_2) and wind speed at 10m (WS_{10}).

[b] Sites indicates the observation meteorological sites used in this study, including NJ in Nanjing, HF in Hefei, HZ in Hangzhou and SH in Shanghai.

[c] Mean represents the average value.

[d] CORR indicates the correlation coefficients, with statistically significant at 95% confident level.

[e] OBS represents the observation data.

[f] SIM indicates the simulation results from WRF/Chem.

Fig. 5 presents time series comparisons between the observation data of O_3 and PM_{10} at CCM and their modeling results from the ADDAH simulation case. Obviously, WRF/Chem with gridded AH fluxes can capture diurnal variations and magnitude of these pollutants. For O_3, the correlation coefficient between observations and simulations (CORR) is 0.60 in January and 0.71 in July (statistically significant at 95% confident level). The value of MB is -0.8 ppb in January and 7.0 ppb in July, which can be explained that stronger solar radiation reaches to urban surface in July causing positive biases in T_2, and thereby produces more O_3 within PBL (Zhang et al., 2010; Liao et al., 2015). In regard to PM_{10}, the model prediction underestimates the concentration with MB being -19.9 μg/m^3 in January and -10.8μg/m^3 in July respectively. This underestimate can be partially ascribed to positive biases of T_2, which induce an increase of PBL height and cause PM_{10} diluting within PBL (Liao et al., 2015). Furthermore, uncertainties in emissions may also cause these biases.

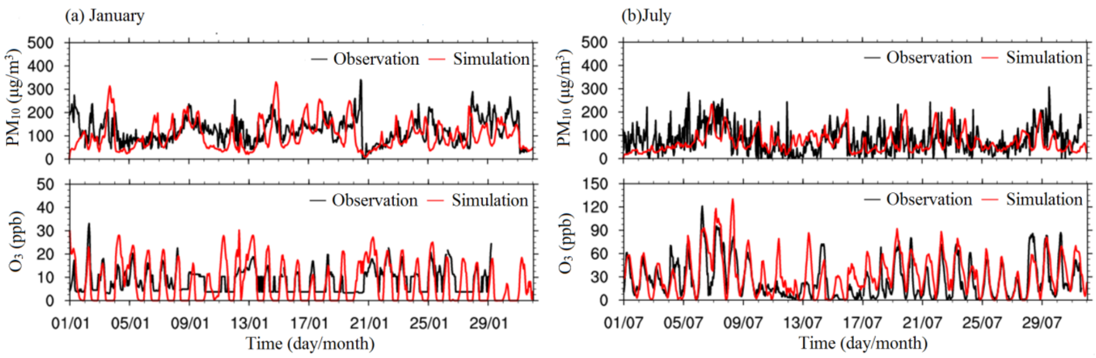


Fig. 5. Hourly variations of PM_{10} (μg/m^3) and O_3 (ppb) from the observation data and the ADDAH simulation results at CCM monitoring site in Nanjing for January (a) and July (b).

Liao et al. (2014) also simulated the same time periods in the YRD region by running WRF/Chem with a fixed AH flux in SLUCM. They found that the default SLUCM scheme tends to underestimate 2-m temperature in January but overestimate it in July, and overestimate the wind speed in both months. In a consequent, their chemical predictions are not so perfect as well, with the CORR of 0.44-0.52 for O_3 and 0.19-0.33 for PM_{10}. Compared with their results, our simulations accounting for the temporal and spatial distribution of AH improve the accuracy of the model results, and well predict the urban climate and air quality.

Generally, the WRF/Chem with gridded AH fluxes has relatively good capability on simulating urban climate and air quality over the YRD region in this study. Though the biases are still found, the difference between the modeling results from NONAH and ADDAH can still quantify the impacts of anthropogenic heat on meteorology and pollution, because all other conditions are the same in both simulations.

3.3 Impacts of AH on meteorological conditions

3.3.1 Horizontal meteorology changes

Fig. 6 presents the monthly-averaged differences of main meteorological factors between ADDAH and NONAH (ADDAH-NONAH) over the modeling domain 3 (D03). Differences that are non-significant under the 95% confidence level using student t-test have been masked out. Obviously, the emissions of anthropogenic heat increase the sensible heat fluxes from the urban canopy layer over the YRD region. As shown in Fig. 6a and b, the spatial patterns of sensible heat changes in both January and July are similar to the spatial distribution of AH fluxes (Fig. 4d). High values of variation (> 10 W/m^2) generally occur around mega-cities with a positive magnitude. For instance, in Shanghai, due to the maximum AH fluxes in the city center, the biggest increase of sensible heat flux for January can be 82 W/m^2, and the value is 75 W/m^2 in July. In other cities, such as Hangzhou, Changzhou and Nantong etc., high values over 20 W/m^2 can be found in both months as well. In order to better understand the different behavior during the daytime and at night, the monthly-averaged diurnal variations of these modeled meteorological factors over the urban area of Shanghai in January and July are also calculated. As illustrated in **Fig. 7, the addition** AH fluxes lead to an obvious increase of sensible heat flux (SHF) from 07:00 to 21:00, with the daily mean increase of 22 W/m^2 for January and 20.5 W/m^2 for July. **The** increases are insignificant at night because the AH fluxes are small during these time. On account that AH and its diurnal variation are only added to the sensible heat item, there are no significant differences between the ADDAH and the NONAH simulation for ground heat flux (GRDFLX) and latent heat flux (LH). It is worth mentioning that many AH emission processes are related to water vapor releasing, and thereby latent heat fluxes might be affected by the human activities that release AH.

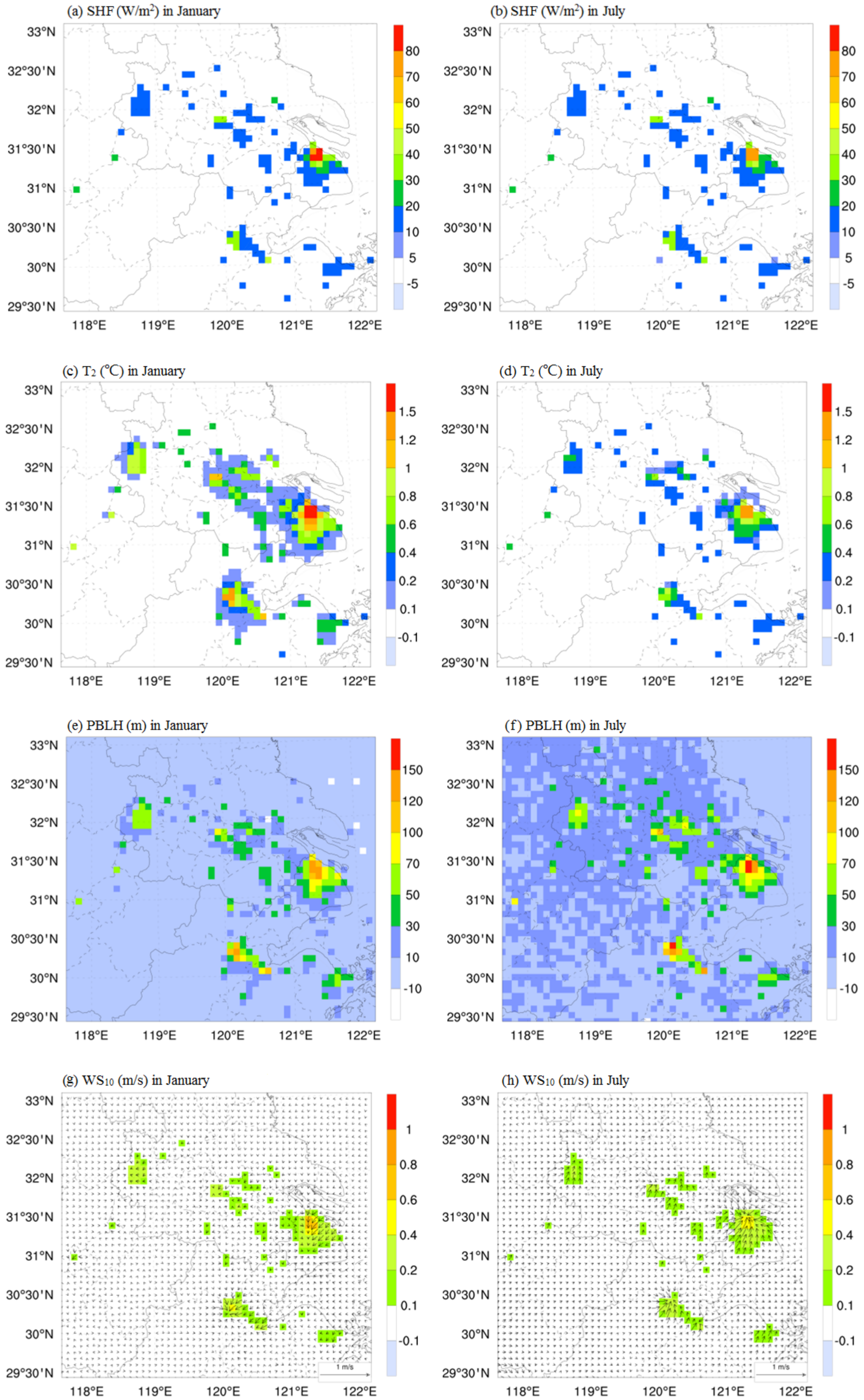

(a) SHF (W/m²) in January
(b) SHF (W/m²) in July
(c) T₂ (℃) in January
(d) T₂ (℃) in July
(e) PBLH (m) in January
(f) PBLH (m) in July
(g) WS₁₀ (m/s) in January
(h) WS₁₀ (m/s) in July
33°N
32°30'N
32°N
31°30'N
31°N
30°30'N
30°N
29°30'N
118°E
119°E
120°E
121°E
122°E
1 m/s

Fig. 6. The spatial distributions of monthly-averaged differences for sensible heat flux (SHF), air temperature at 2 m (T_2), the height of planetary boundary layer (PBLH), and wind speed (WS_{10}) at 10 m between ADDAH and NONAH (ADDAH-NONAH). (a), (c), (e) and (g) show changes in January. (b), (d), (f) and (h) illustrate variations in July. The arrows in (g) and (h) are the differences of wind fields. Differences that are non-significant under the 95% confidence level (student t-test) are masked out.

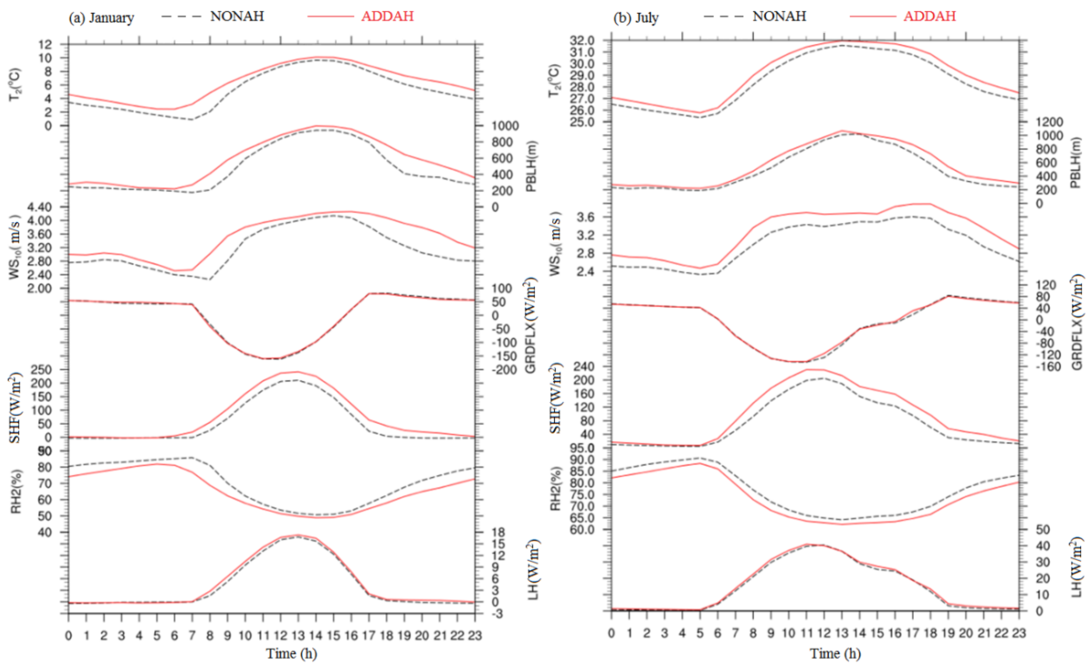


Fig.7. The monthly-averaged diurnal variations of modeled meteorological factors in January (a) and July (b) over the urban area of Shanghai. NONAH and ADDAH represent the simulation cases with and without AH fluxes, respectively. LH means latent heat. SHF indicates sensible heat flux. GRDFLX represents heat flux from ground level. T_2, RH2, WS_{10}, and PBLH indicate 2-m air temperature (℃), 2-m relative humidity (%), 10-m wind speed (m/s) and the height of planetary boundary layer (m), respectively.

By adding more surface sensible heat into the atmosphere, the AH flux changes can influence the 2-m air temperature (T_2) as well. The patterns of the monthly-averaged T_2 changes (Fig. 6c and d) are similar to those of SHF (Fig. 6a and b). For city centers like Shanghai, Hangzhou and Nanjing, adding AH can lead to the increase of T_2 over 1℃ in January and over 0.5℃ in July, generating an enhanced Urban Heat Island. The maximum T_2 changes usually occur in the city center of Shanghai, with the typical value of 1.6 ℃ in January and 1.4 ℃ in July. These findings are comparable to the values estimated in megacities all over the world (Fan and Sailor, 2005;

Ferguson and Woodbury, 2007; Chen et al., 2009; Zhu et al., 2010; Menberg et al., 2013; Wu and Yang, 2013; Bohnenstengel et al., 2014; Feng et al., 2014; Yu et al., 2014). Moreover, the mean increase of T_2 at night in January (1.2℃) is larger than that in the daytime (1.0℃), whereas the increase during the daytime and nighttime is all equal to 0.6℃ in July, suggesting that AH can help to form a weakened diurnal T_2 variation in winter.

The vertical air movement in PBL can be enhanced by the warming up of surface air temperature, which might increase the height of PBL (PBLH). Consequently, the enhanced AH fluxes increase the PBLH by more than 50m in January and more than 70m in July over the YRD urban areas, with the maximum changes (140m for January and 160m for July) occurring in Shanghai (shown in Fig. 6e and f). In summer, the weather is more unstable and the vertical convection is easy to form. So the adding AH induces more increase of PBLH in July. For both months, as shown in Fig. 7, the daytime relative increase of PBLH (10%-15%) is smaller than that at night (23% - 33%), which can be attributed to the facts that the absolute PBLH values are lower and the air temperature increases more during the nighttime.

Fig. 6g and h show the changes in wind components over the YRD region, and demonstrate that AH can enhance the 10-m wind speed (WS_{10}) in the urban areas. The maximum increase is located in Shanghai, with the increment of 0.7 m/s (19%) in January and 0.5 m/s (17%) in July. In other cities like Hangzhou and Nanjing, the added value is only about 0.3 m/s. Over the YRD region, increase of WS_{10} is more obvious in January (Fig. 6g) than in July (Fig. 6h), and is slightly higher at night than in daytime (Fig. 7). As mentioned in previous studies, the above increase of wind speed can be ascribed to the strengthened urban-breeze circulation caused by the enhanced AH fluxes (Chen et al., 2009; Ryu et al., 2013; Yu et al., 2014), which can be further clarificated by the surface stronger convergence wind patterns occurring around the megacities shown in Fig. 6g and h. The simulated divergence at the surface near cities decreases 0.07-0.23 /s in January and 0.08-0.31 /s in July (not shown), also providing further evidence that the convergence is enhanced in these areas.

The strengthened urban-breeze circulation caused by adding AH can also enhance the vertical movement of atmosphere. As shown in Fig. 8a, the simulated vertical velocity above the megacities on 850 hPa layer increases about 2 cm/s in July, suggesting that the convection movements that can transport moisture and pollutants from surface to upper layer are strengthened in the urban areas. Thus, the spatial and vertical distributions of moisture are modified. Fig. 8c and d illustrate the spatial plots for monthly-averaged differences of 2-m relative humidity (RH_2) caused by adding AH (ADDAH-NONAH). The negative centers over the cities (the AH centers) can be seen in both January (-2 to -8%) and July (-2 to -6%), meaning the air near the surface became dryer. More moisture transported into the mid-troposphere (the vertical profile is discussed in Fig. 9g and h in details) might enhance rainfall inside urban areas as well. As shown in Fig. 8b, the increase of rainfall in July can be 72.4, 84.6 and 63.2 mm in Shanghai, Hangzhou and Ningbo, respectively. However, because of the negligible accumulative precipitation in winter, the increment of rainfall over the YRD region in January can be ignored (not shown).

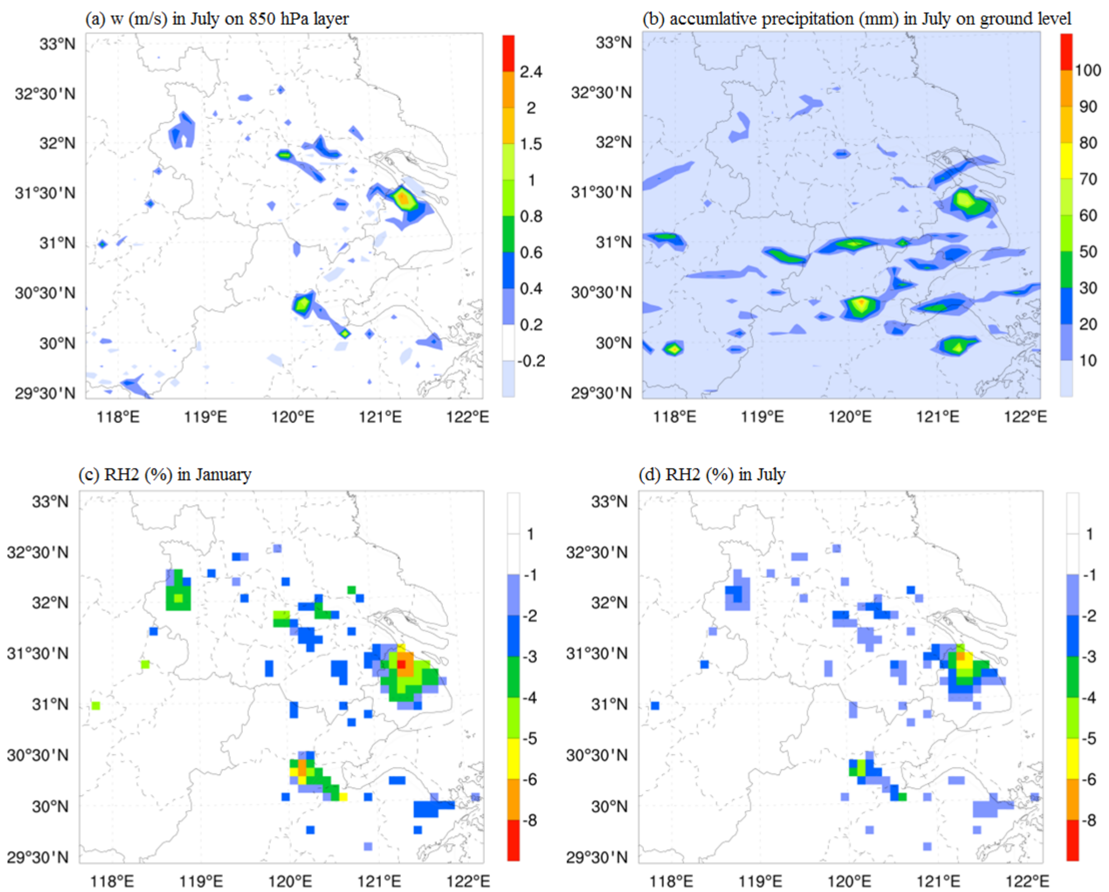
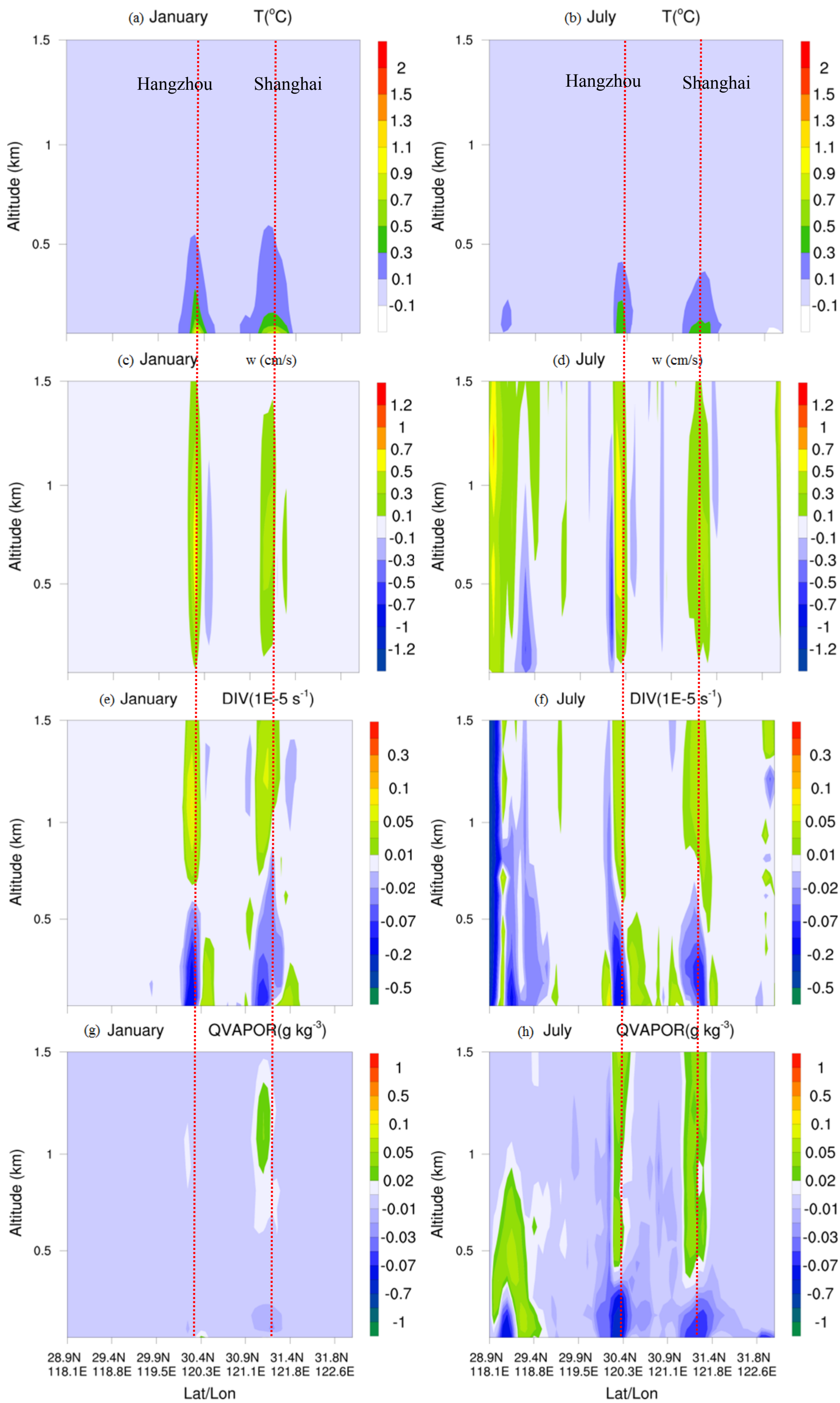


Fig. 8. The spatial distributions of monthly-averaged differences for 2-m relative humidity (RH2), surface accumulative precipitation and vertical wind velocity on 850 hPa layer (w) between ADDAH and NONAH (ADDAH-NONAH). Differences that are non-significant under the 95% confidence level (student t-test) are masked out

3.3.2 Vertical meteorology changes

To better understand how AH change the vertical and spatial distribution of meteorology in the YRD region, we present changes (ADDAH - NONAH) of air temperature (T), vertical wind velocity (w), divergence (DIV) and water vapor mixing ratio (QVAPOR) along a cross-section from (28.9°N, 118.1°E) to (31.8°N, 122.6°E) as shown by the solid line AB in Fig. 2b. The vertical cross sections for T changes (Fig. 9a and b) illustrate that adding AH leads to a significant increase in air temperature near the surface around the cities (Shanghai and Hangzhou) , while the changes are close to 0 in the rural areas and free troposphere. The monthly mean increment of T over Shanghai and Hangzhou at ground level in January (0.7℃) is bigger than that in July (0.4℃), which can be attributed to the facts that the relative increase of heat is higher in January due to background heat fluxes are much lower in winter.

The warming of air temperature near surface in cities, as well as the rising of PBLH in these areas (Fig. 6e and f), can generate an enhanced urban heat island. As shown in Fig. 9c and d, the vertical wind velocities above Shanghai and Hangzhou increase with added values of 0.3 – 0.7 cm/s in both months, whereas w in the rural areas decreases about -0.3m/s in January and -0.5 cm/s in July, suggesting that there are an enhanced upward movement in cities and an enhanced downward movement in countryside. We also analyze the divergence changes along the cross-section including Shanghai and Hangzhou (Fig. 9e and f). It can be seen that adding AH decreases DIV from surface to 750m and increases DIV at higher levels, which means that there is a stronger convergence wind pattern in lower PBL and a more divergent wind pattern in higher PBL. This changing implies that the atmosphere is more unstable, and intends to promote the development of deep convection in troposphere. Consequently, impacted by the strengthened urban-breeze circulation, more moisture is transported from surface to the upper levels (over 1km), with 0.6g/kg decrease of QVAPOR at the ground level and 0.1g/kg increase for the upper PBL in July as presented in Fig. 9g and h. Furthermore, the abovementioned vertical changes of w, DIV and QVAPOR are only restricted to the air column over the AH emission centers (Shanghai and Hangzhou) in January, while the changes distribute widely (the adding AH fluxes can impact wider areas) in July. This seasonal difference can be ascribed to the facts that the atmosphere is more stagnant in winter and more convective in summer.


(a) January T(°C)
(b) July T(°C)
Hangzhou
Shanghai
(c) January w (cm/s)
(d) July w (cm/s)
(e) January DIV(1E-5 s-1)
(f) July DIV(1E-5 s-1)
(g) January QVAPOR(g kg-3)
(h) July QVAPOR(g kg-3)
Altitude (km)
1.5
1
0.5
2
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
1.2
1
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-1
-1.2
0.3
0.1
0.05
0.01
-0.02
-0.07
-0.2
-0.5
1
0.5
0.1
0.05
0.02
-0.01
-0.03
-0.07
-0.7
-1
28.9N 118.1E
29.4N 118.8E
29.9N 119.5E
30.4N 120.3E
30.9N 121.1E
31.4N 121.8E
31.8N 122.6E
Lat/Lon

538

Fig. 9 The vertical distribution of monthly-averaged differences for air temperature (T), vertical wind velocity (w), divergence (DIV), and water vapor mixing ratio (QVAPOR) between ADDAH and NONAH (ADDAH-NONAH) from surface to 1.5km altitude along the line AB (shown in Fig. 2b). (a), (c), (e) and (g) show changes in January. (b), (d), (f) and (h) illustrate variations in July. Differences that are non-significant under the 95% confidence level (student t-test) are masked out.

3.4 Impacts of AH on air pollutants

3.4.1 Changes of surface PM_{10} and O_3

Adding AH changes spatial and vertical meteorology conditions, and thereby undoubtedly affects the transportation and dispersion of air pollutants. Due to PM_{10} is the main pollutant in YRD region (Wang et al., 2012; Xie et al., 2014; Liao et al., 2015), it is chosen as an indicator to show the changes of primary air pollutants in this study. Fig. 10 illustrates the influence of AH on PM_{10} spatial distribution in typical months of winter and summer (differences that are non-significant at 95% confidence level using t-test are masked out). Results show that PM_{10} in the lowest modeling layer is reduced at all times around the cities, especially in Shanghai, Nanjing and Hangzhou. The maximum decrease usually appears in Shanghai, with the monthly mean reduction of 29.3μg/m^3 (24.5%) in January and 26.6 μg/m^3 (18.8%) in July. Compared with the distribution of AH emissions (Fig. 4) and meteorology changes (Fig. 6), the reduction in surface PM_{10} should be mainly related with the increase in PBLH, the rising up of surface wind speed and the enhanced upward movement of air, because these modifications of meteorological conditions caused by adding AH over the urban areas can facilitate PM_{10} transport and dispersion within the urban boundary layer. Furthermore, on account that the precipitation around the cities increases by 15-30%, the wet scavenging can contribute to the reductions of the surface PM_{10} concentrations as well.

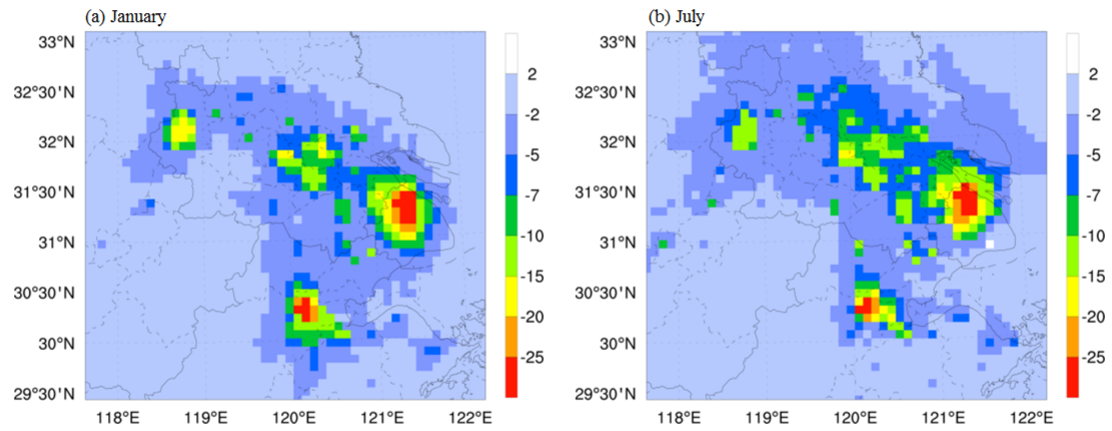


Fig. 10 The spatial distributions of monthly-averaged differences for PM_{10} between ADDAH and NONAH (ADDAH-NONAH). Differences that are non-significant under the 95% confidence level (student t-test) are masked out.

Spatial distribution of O_3 concentration can also be influenced by the changes of meteorological conditions due to adding AH. It should be noted that the increase of wind speed might facilitate O_3 transport, and the rising up of PBLH can lead to O_3 dilution within planetary boundary layer. Thus, the surface O_3 concentrations are seemingly reduced. However, unlike PM_{10}, O_3 is a secondary air pollutant formed by a series of complex chemical reactions involving oxides of nitrogen (NO_x=NO+NO_2) and volatile organic compounds (VOCs), so only considering the factors affecting O_3 transport and dispersion is not sufficient. In fact, O_3 changes are different from those of PM_{10}. As illustrated in Fig. 11a and b, the increases of surface O_3 level can be seen in both January and July over the YRD region, with large increase centers occurring in megacities. In January (Fig. 11a), the maximum O_3 difference appears in Shanghai, with the monthly mean increment of 2.5ppb (18%). In July (Fig. 11b), the highest O_3 change occurs in Hangzhou, with the added value of 4 ppb (15%). In the surrounding areas of these high value centers, increase of O_3 associated with the introduction of AH can be over 0.5 ppb in January and more than 1 ppb in July. This change pattern and the magnitude are consistent with the findings reported in Beijing (Yu et al., 2014) and Seoul (Ryu et al., 2013).

Chemical direct and indirect effects should play a more important role in O_3 changes than other physical influencing factors. On the one hand, the rising up of air temperature (Fig. 6c and d) can directly accelerate O_3 formation by increasing the chemical reaction rates, and thereby straightly increase the O_3 level at surface. On the other hand, O_3 changes are inextricably influenced by the changes of NO_x (indirect chemical effects). Similar to other primary air pollutant (such as PM_{10}), NO_x at ground level are reduced in both January and July due mainly to the increase in PBLH, surface wind speed and upward air movement caused by adding AH (Fig. 11c and d). It was reported that the O_3 formation over the cities in the YRD region is sensitive to VOC (Xie et al., 2014), which means that a decrease in surface NO_x might lead to a slight increase of O_3 during the daytime. At night, when the process of NO_x titration (O_3 + NO → O_2 + NO_2) supersedes the O_3 sensitivity to be the governing factor of O_3 chemistry, less NO_x can only consume less O_3 as well. Consequently, the decrease in NO_x at the ground can result in the increase in O_3. This indirect function might be clearly illustrated in vertical distribution of O_3 changes in Sect. 3.4.2.

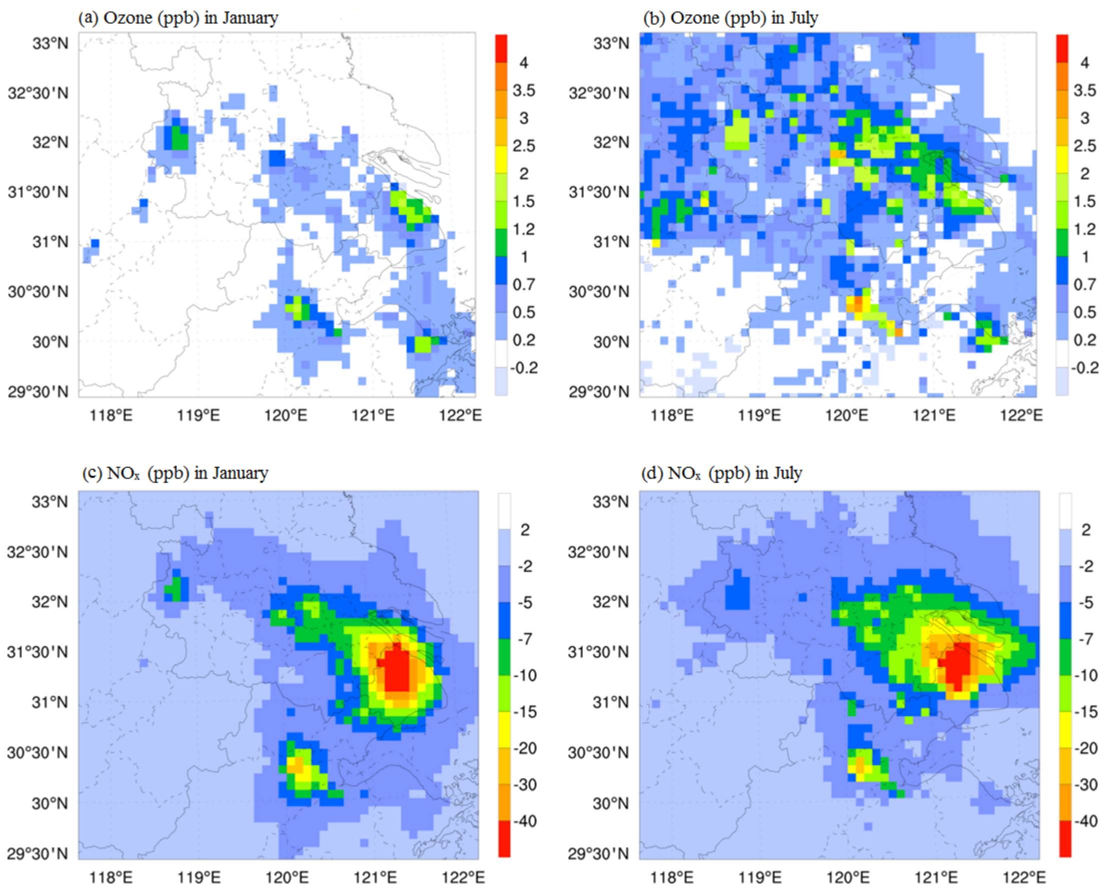


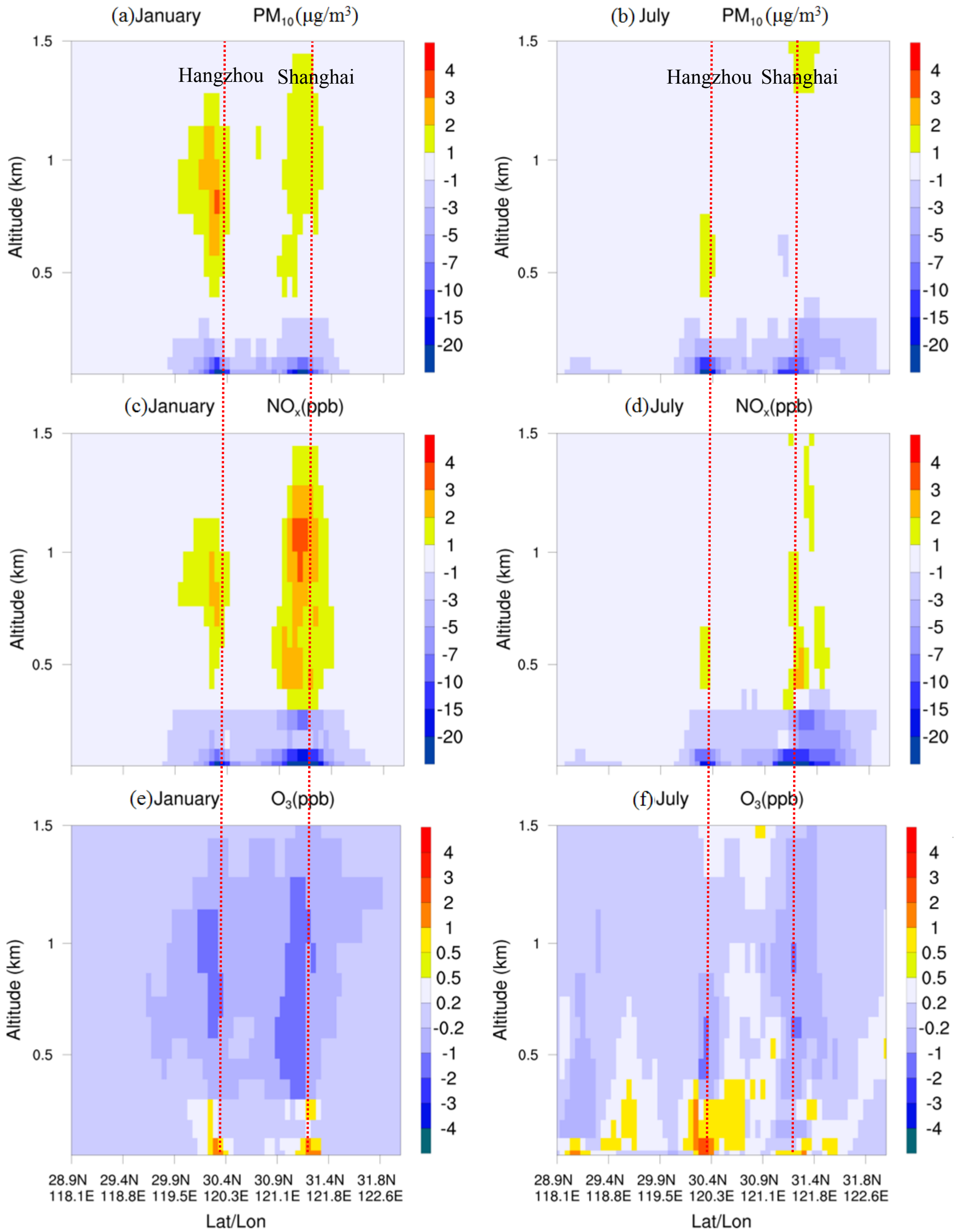
Fig. 11 The spatial distributions of monthly-averaged differences for O_3 and its precursor NO_x between ADDAH and NONAH (ADDAH-NONAH). Differences that are non-significant under the 95% confidence level (student t-test) are masked out.

3.4.2 Vertical changes of PM_{10} and O_3

Fig. 12 shows the vertical plots on the cross-sectional line AB (presented in Fig. 2b) for the changes of chemical species impacted by adding AH (ADDAH-NONAH). Differences that are non-significant at 95% confidence level using t-test have been masked out. For the primary air pollutants such as PM_{10} and NO_x, the AH fluxes can decrease their concentrations near surface. As shown in Fig. 12a and b, in the atmosphere below 300m above Shanghai and Hangzhou, the concentrations of PM_{10} decrease 2.3-16.2μg/m^3 in January and 2.1-15.8μg/m^3 in July, respectively. Surface NO_x concentrations near Shanghai and Hangzhou can be reduced over 15 ppb in both month as well (Fig. 12c and d). Meanwhile, it can be also found that there are increases in PM_{10} and NO_x concentrations at the upper levels over the cities. For instance, the added values of PM_{10} and NO_x can be more than 3μg/m^3 and 3ppb at about 1km above surface in January, respectively. This vertical changing pattern for primary chemical species is quite similar to that for water vapor (Fig. 9g and h), indicating that this is a reflection of the change in vertical transport patterns in the region due to AH (Yu et al., 2014). It should be noted that the maximum vertical changes of air pollutants in Hangzhou usually occur at about 1km above surface, whereas those in Shanghai generally appear at higher levels (> 1km), implying that more surface air pollutants in Shanghai might be transported into higher levels due to higher AH emissions in this biggest city in the YRD region. Furthermore, Fig. 13 shows the vertical profiles of the changes for PM_{10}, NO_x and O_3 caused by adding AH over Shanghai. In winter, the large increases of PM_{10} and NO_x appear at 500m to 1500m above surface. But the maximum increases usually occur at more than 1.5 km above surface in summer. This phenomenon can be attributed to the facts that the atmosphere is more convective in summer than in winter.

On the contrary to the primary air pollutants, O_3 changes show increases near surface and decreases at the upper levels over the urban areas. Fig. 12e and f illustrates that the increases of O_3 concentrations are limited within 400m above the surface over the cities, with the high values of 2.6 ppb in January and 4.2 ppb in July. As mention in Sect. 3.4.1, this may be the result of both the increase in O_3 production caused by higher surface temperature and the decrease in O_3 depletion resulting from less surface NO. With respect to O_3 concentrations from 400m to 1.5km above surface, they generally decrease with the reduction values of more than 1ppb in both January and

July. Comparing Fig. 12e and f with Fig. 12c and d, we believe that the increases of NO_x concentrations at these upper levels can lead to the depletion of O_3, because of the VOC-sensitive O_3 chemistry in the daytime and NO_x titration at night in this region. In some previous studies on the O_3 variations induced by urban land-use, researchers also found that O_3 chemical production is increased at the surface around big cities in summer (Liao et al., 2015; Zhu et al., 2015) and in winter (Liao et al., 2015). However, it was also found that the averaged daytime O_3 in the upper PBL could significantly increase by 20-40ppbv because of strong urban heat island circulation in the summer of Shanghai (Zhu et al., 2015). This result implies that the vertical transport of O_3 caused by urban land-use should be stronger than that caused by AH. Thus, more upward O_3 can compensate the depletion of O_3 at upper levels.



644

645 **Fig. 12 The vertical distribution of monthly-averaged differences for PM_{10}, NO_x and O_3 between ADDAH**
646 **and NONAH (ADDAH-NONAH) from surface to 1.5km altitude along the line AB (shown in Fig. 2b). (a), (c)**
647 **and (e) show changes in January. (b), (d) and (f) illustrate variations in July. Differences that are**
648 **non-significant under the 95% confidence level (student t-test) are masked out.**

649

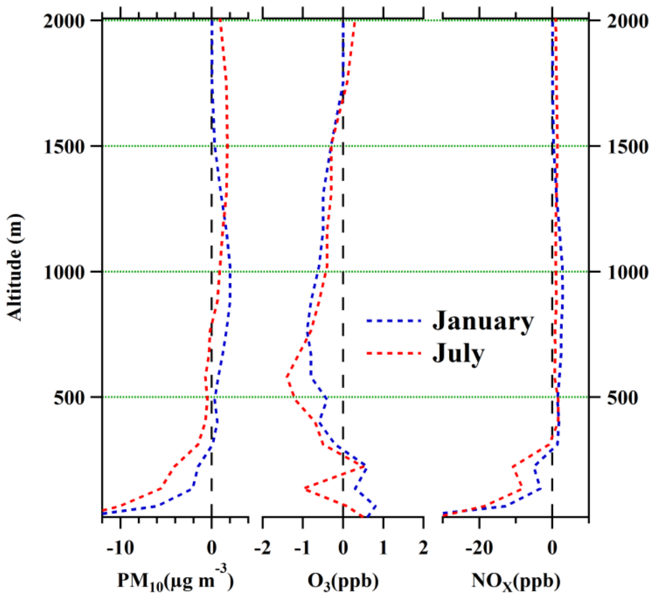


Fig. 13. The vertical profiles of monthly-averaged differences for PM_{10}, NO_x and O_3 between ADDAH and NONAH (ADDAH-NONAH) over Shanghai.

4. Conclusions

Anthropogenic heat (AH) emissions from human activities caused by urbanization can affect the city environment. In this paper, we specially address its impacts on meteorological conditions and air pollution over the cities in the YRD region. Firstly, based on the energy consumption and the gridded population data, we estimate the spatial distribution of AH fluxes by a top-down energy inventory method. Secondly, the gridded AH data with the seasonal and the diurnal variation are added to the sensible heat flux in the modified WRF/Chem. Finally, the WRF/Chem is applied to investigate the impacts of AH. Two simulation cases are conducted. One incorporates the single layer urban canopy model (SLUCM) with the gridded AH fluxes, while the other ignores the contribution of AH.

The results show that the AH flux in YRD region has been increased continually since 1990. During the period between 1990 and 2010, the annual mean values of AH fluxes over Shanghai, Jiangsu and Zhejiang have been increased from 5.47 to 14.45 W/m^2, 0.68 to 2.61 W/m^2, and 0.33 to 1.63 W/m^2, respectively. High AH fluxes generally occur in and around the cities. The typical values of AH in 2010 over the urban areas of Shanghai, Jiangsu and Zhejiang can reach 113.5, 50.2 and 39.3 W/m^2, respectively.

The model results of WRF/Chem fit the observational meteorological conditions and air quality very well. Inclusion of the AH can enhance the urban heat island in the cities over the YRD region. 2-m air temperature can be increased by more than 1℃ in January and over 0.5℃ in July. The PBL heights can be increased with the maximum changes of 140m for January and 160m for July in Shanghai. The strengthened urban-breeze circulation resulted from adding AH can enhance the 10-m wind speed and the vertical air movement as well. Thus, more moisture is transported from surface to the upper levels, with 0.6g/kg decrease at the ground level and 0.1g/kg increase for the upper PBL in July, which might induce the accumulative precipitation to increase by 15-30% in Shanghai, Nanjing and Hangzhou.

Influenced by the modifications of meteorological conditions, the spatial and vertical distribution of air pollutants is modified. With respect to the primary air pollutants (PM_{10} and NO_x), their transport and dispersion in PBL can be facilitated by the increases of PBLH, surface wind speed and upward air movement, which causes the decreases of concentrations near surface and the increases at the upper levels. Usually, PM_{10} can be reduced by 2-16 μg/m^3 within 300m above the surface of the cities, and added over 3μg/m^3 in upper PBL. However, surface O_3 concentrations increase in the urban areas, with maximum changes of 2.5ppb in January and 4 ppb in July. Besides the rising up of air temperature directly accelerating the surface O_3 formation, the decrease in NO_x at the ground can also result in the increase of surface O_3 due to the VOC-sensitive O_3 chemistry in the daytime and NO_x titration at night in this region. Furthermore, O_3 concentrations at higher levels are reduced by about 1ppb due mainly to the increase of NO, and the impacts of AH are not only limited to the urban centers but also extended regionally.

Impact of anthropogenic heat emission on urban climate and air quality is undoubtedly an important and complex scientific issue. Our results show that the meteorology and air pollution predictions in and around large urban areas are highly sensitive to the anthropogenic heat inputs. In a consequent, for further understanding of urban atmospheric environment issues, good information on land use, detailed urban structure of the cities and more studies of the anthropogenic heat release should be better considered.

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