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Supplement of

Effects of urban land expansion on the regional meteorology and air quality of eastern China

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S1 Urban land expansion scenarios

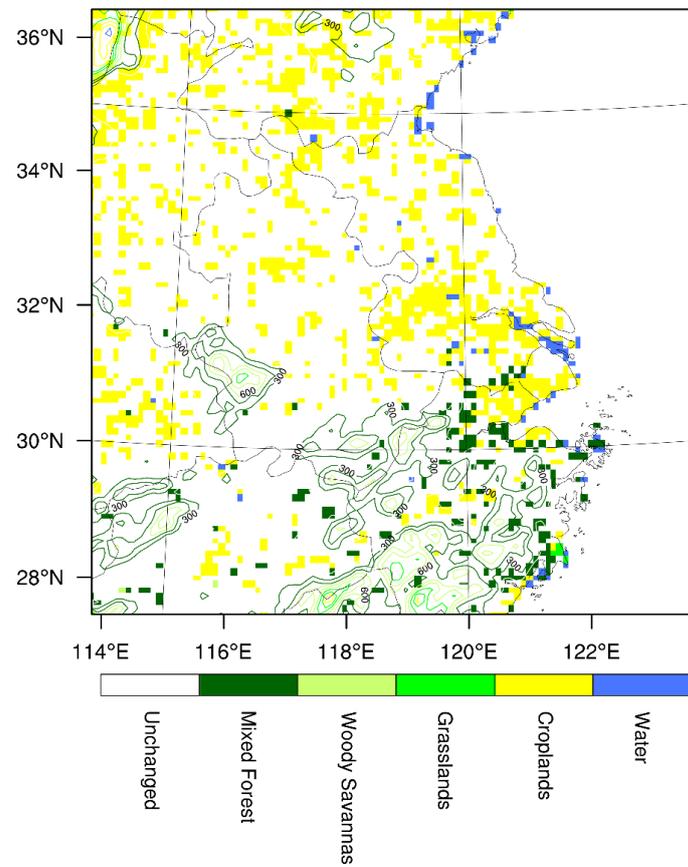


Figure S1: The original main land use categories of newly urbanized grids in GT0 run and contour map for the terrain height (meters) in the domain of interest.

S2 Verification of IPR

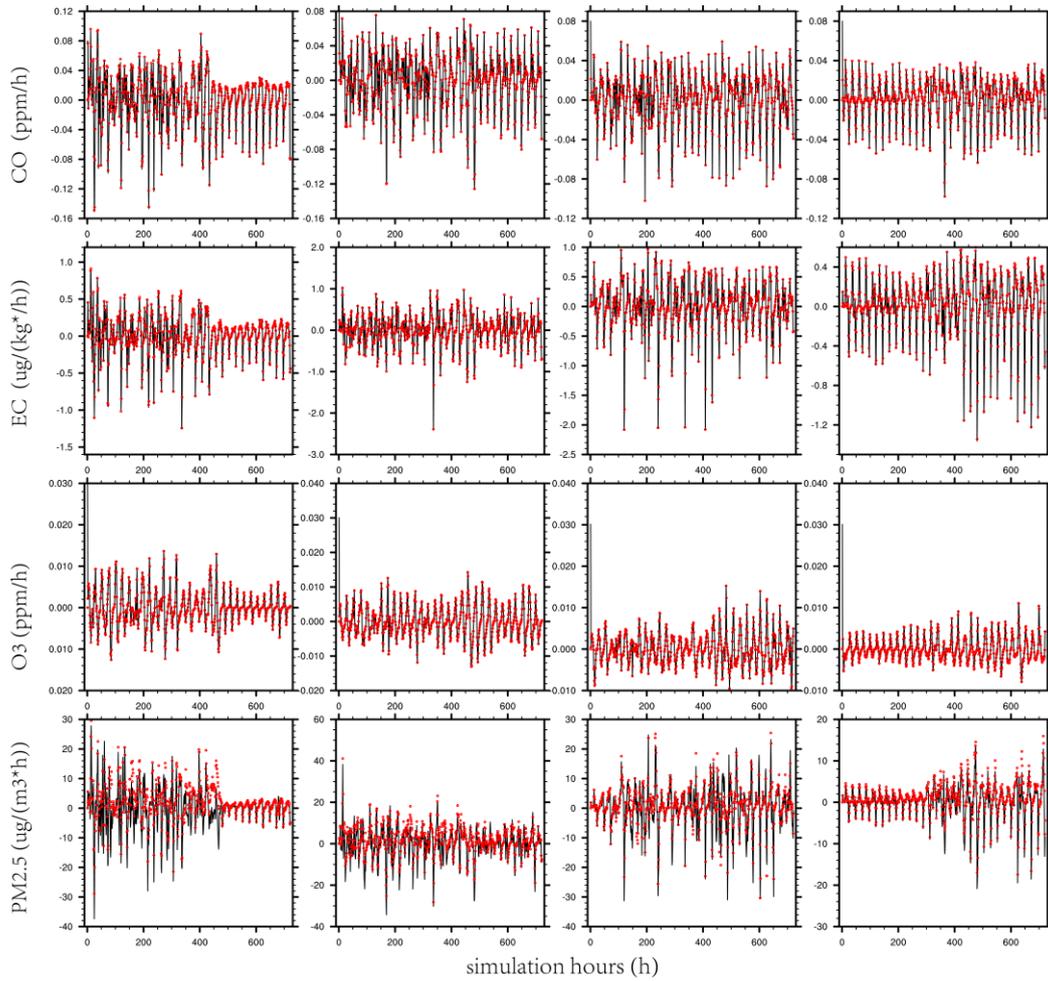


Figure S2: Hourly concentration change (black solid line) and the sum of hourly IPR of ten processes (red dot) averaged over four random 10km×100km subregions during July of 2012.

S3 Sensitivity of meteorological fields to land use changes

Fig. S3 shows the 5-year averaged July mean of 10-meter wind speed (W10), boundary layer height (PBLH), hourly precipitation (PREC), 2-meter temperature (T2) and 2-meter relative humidity (RH2) in BASE run and the three sensitivity tests. It illustrates that the expansion of urban land could significantly modify 5-year July mean values of local W10, PBLH, T2 and RH2 to different extents (one-tailed t-tests with the significance level of 95% were utilized). To begin with, terrestrial W10 (less than 4 m s^{-1}) was typically weaker than the marine W10 by $1\text{-}3 \text{ m s}^{-1}$, probably due to

difference in roughness length of underlying surfaces. The replacement of crop land (mixed forest) by urban land could significantly reduce (increase) W10.

In Fig. S3, higher values of PBLH (600-800 m) and T2 ($\sim 30^{\circ}\text{C}$) as well as lower values of RH2 (60%-70%) were found in urban areas. Terrestrial precipitation mostly ranged from 0.3 mm to 0.9 mm per hour. It can be also found that a relative higher PBLH and lower RH2 zone appeared in northern terrestrial domain. Urban land expansion could significantly increase PBLH (max. 64%; avg. 24%, $\sim 130\text{m}$ in the GT0 run), surface temperature (max. 11%; avg. 6%, $\sim 1.6^{\circ}\text{C}$ in the GT0 run) and reduce RH (max. 70%; avg. 15%, $\sim 11\%$ in the GT0 run). Note that one-tailed t-tests were also performed for each year, and the effect of urban land expansion on W10, PBLH, T2 and RH2 was simulated to be consistent for each year but with slightly different magnitudes. Other relevant mesoscale modeling studies reported similar results, and such phenomena could be explained by the parameterization of urban land's unique physical properties with a higher albedo and roughness length, a greater thermal capacity and conductivity, as well as lower intensities of evaporation and transpiration. It can also be found that, besides the local effects, the forcing of urban land expansion can affect the W10, PBLH, T2 and RH2 of nearby non-urbanized areas, but the BASE magnitude is much weaker. Given a certain large-scale synoptic background, the magnitude of urban land climatic perturbation did not respond linearly to urban land fraction, this will be discussed later.

As for July mean PREC, unlike other meteorological variables, the results of one-tailed t-tests did not show consistency from year to year, the PREC in many newly urbanized grids was significantly enhanced in some years while hindered in other years. When averaging the PREC over 5 years, PREC was only significantly intensified in some newly urbanized areas over the central domain. Previous studies have demonstrated diverse results. Factors potentially leading to more PREC include updraft induced by urban heat island circulation convergence (Wang et al., 2012), increment of condensation nuclei due to emissions of airborne pollutants, and drag of

precipitation system by urban buildings. Conversely, factors hindering PREC include reduction in water vapor ratio (“dry island” effects) (Kaufmann et al., 2007) and the perturbed cloud microphysics processes by smoke with small CCN (Rosenfeld, 2000). Zhang et al. (2010) declared that precipitation tended to decreased about 15% over urban or leeward areas in summer but changed slightly in winter in Yangtze River Delta of China if urban land were replaced by crop land. But as reported in a WRF/UCM simulation, with increasing urban land fraction, the rainfall was increased in Beijing-Tianjin-Hebei metropolitan area while decreased in Pearl River Delta and Yangtze River Delta (Wang et al., 2012), such results are exactly the opposite of the 50-year observation results (Li, 2013), maybe due to that the long-term evolution of regional precipitation is subject to circulation changes of larger spatial and temporal scales. The issues of how urbanization would impact the precipitation remain uncertain. Nonetheless, the modeling results in Sect. 6 show that precipitation played a trivial role in forcing the spatial distribution of airborne pollutants on the time scale of a month.

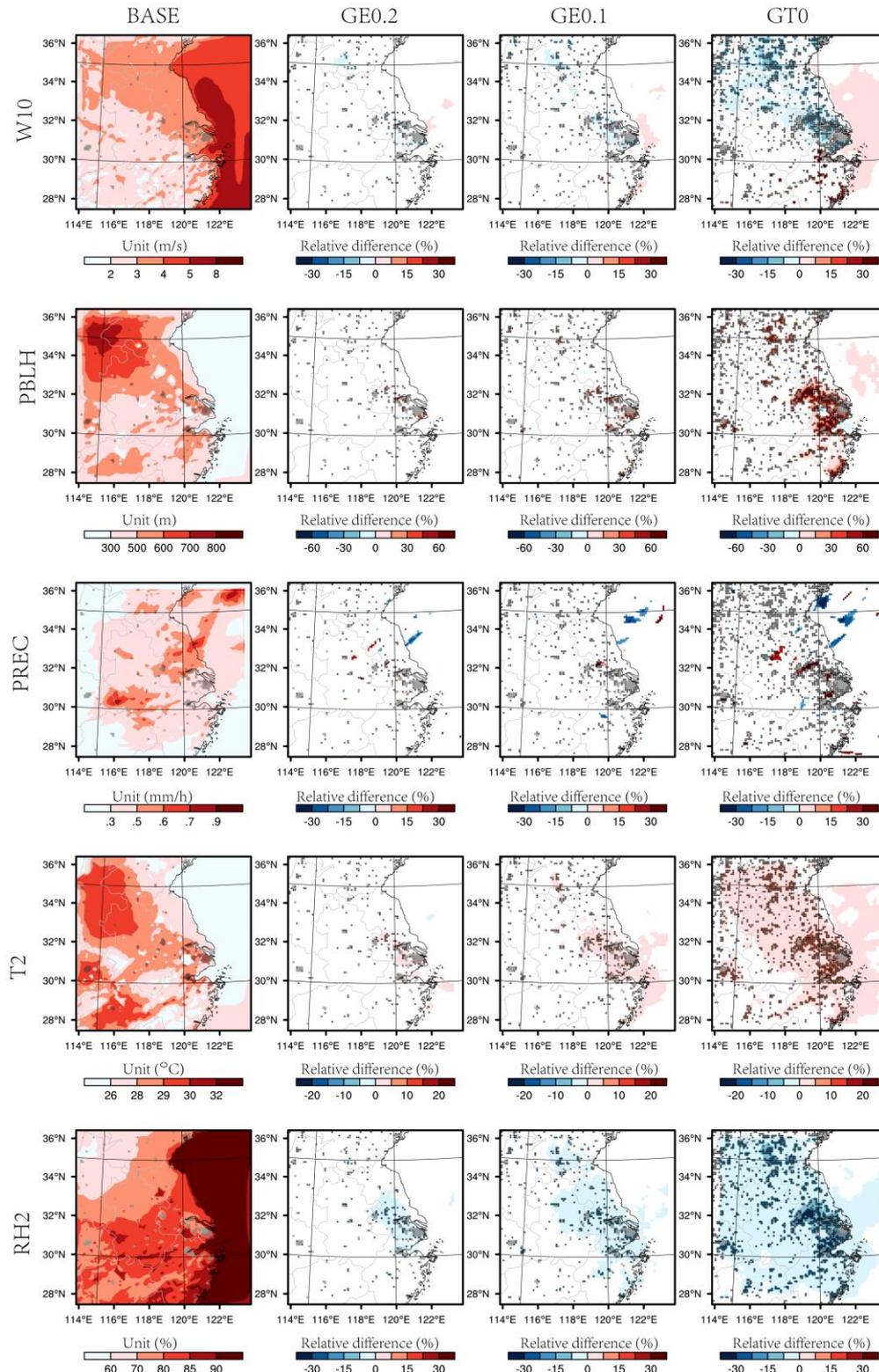


Figure S3: Averaged levels (July from 2008 to 2012) of 10-meter wind speed (W10), boundary layer height (PBLH), hourly precipitation (PREC), 2-meter temperature (T2) as well as 2-meter relative humidity (RH2) of BASE run, and the relative difference (one-tailed t-tests with the significance level of 95% were utilized, only the significant changes were drawn) between each sensitivity run and BASE run. Circle markers indicate the locations of urban areas in the BASE run, while cross markers indicate the locations of newly urbanized areas in 3 urban land expansion

scenarios of GE0.2 run, GE0.1 run and GT0 run.

S4 The synergistic effect of urban land forcing on meteorological factors

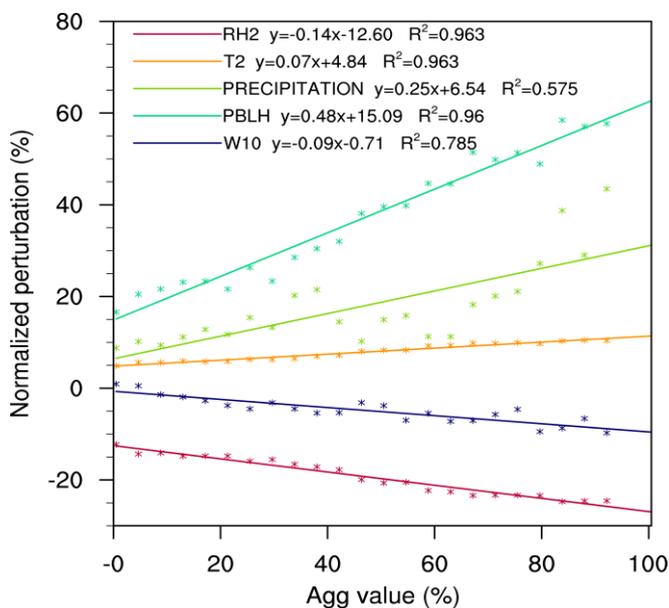


Figure S4: The linear regression of 5-year July mean level perturbations of 2-meter temperature (T2), boundary layer height (PBLH), 2-meter relative humidity (RH2), hourly precipitation (PREC) and 10-meter wind speed (W10) to Agg value.

S5 The impacts of humidity on the formation of PM_{2.5}

The humidity could impact the formation of PM_{2.5} in two ways, as simulated within the framework of aerosol module of MADE (Ackermann et al., 1998) used in this study. Firstly, water molecules act as reactants and solvents in gas phase/particle partitioning, thus impact the formation of both secondary inorganic aerosols, as described by MARS scheme (Saxena et al., 1986) and secondary organic aerosols, as described by SORGAM scheme (Schell et al., 2001). In addition, the cloud chemistry in MADE simulates the formation of aerosols in clouds through a series of aqueous-phase reactions. (Baklanov et al., 2008; Mlawer et al., 1997). Figure S5 shows that, besides primary pollutants, the emerged new urban land also relocate the gaseous and liquid water. Over newly urbanized areas, the mixing ratios of water vapor and cloud water decrease near the surface while increase above about 1.5 km. The production of PM_{2.5} through cloud chemistry increase (decreases) exactly where

the humidity increases (decreases). However, the production of $PM_{2.5}$ through aerosol processes decreases near the surface (reduction in humidity and abundance of gaseous precursors), but increases above about 500 m (please refer to Figure in the manuscript, concentrations of precursors also increase above about 500 m, indicating that humidity is not the limiting factor constraining the aerosol processes).

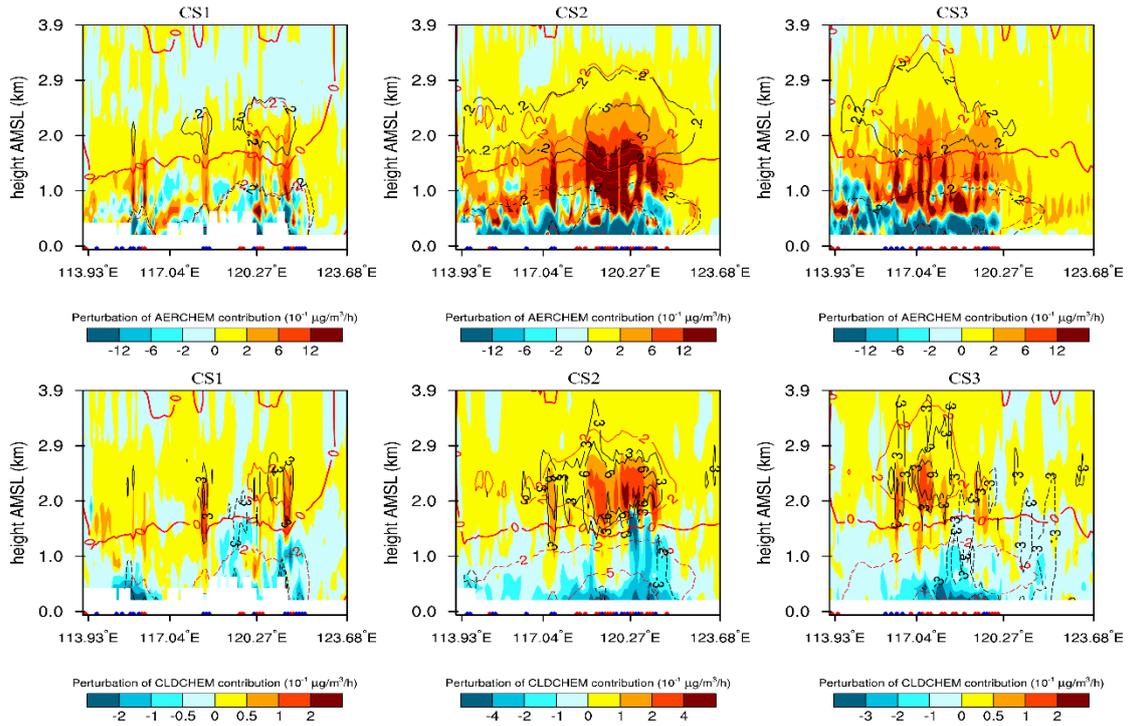


Figure S5. Distribution of 5-year mean July perturbations (GT0 minus BASE) of contributions of aerosol processes (color, $\mu\text{g}/\text{m}^3/\text{h}$), relative humidity (red line, %) and water vapor mixing ratio (black line, g/kg) in top three plots; contributions of cloud chemistry processes (color, $\mu\text{g}/\text{m}^3/\text{h}$), relative humidity (red line, %) and cloud water mixing ratio (black line, mg/kg) in bottom three plots in CS1, CS2, and CS3 (the same cross-sections as in the manuscript). Red and blue dots indicate the longitudes of LOCAL cells in the GT0 run along the cross-section lines and adjacent areas, respectively.

S6 The emission augment scenario

The expansion of urban land is necessarily accompanied with the changes of anthropogenic emissions. To understand this emission effect, we conduct 5 additional simulations with anthropogenic emissions in the LOCAL cells of GT0 run amplified by a factor of 1.0, 1.1, 1.3, 1.6 and 2.0, respectively. As shown in Figure S6, surface O_3 concentrations over land in all emission scenarios are larger than the BASE case

(O₃ over marine decreases. This could be explained by the inhibition of O₃ transport from land to sea. Please refer to the perturbation of southerly/southeasterly wind in Figure 9 of the manuscript). However, CO, EC and PM_{2.5} share a different pattern that the diluting effects of urban land could be offset only if the emission augment is high enough. Figure S7 shows the perturbation of surface concentrations averaged over domain-wide LOCAL and ADJACENT cells. Concentration perturbations increase nearly linearly with increased emissions for CO, EC and PM_{2.5}. Urban land expansion (i.e. GT0) induced CO decrease keeps in both type cells until emission augment factor is larger than 40%. For EC and PM_{2.5}, even more emission increase (>50%) is needed to compensate the dilution effect of urban land expansion. For O₃, urbanization induced surface concentration perturbations do not change linearly with emissions, mainly due to the complexity of nonlinear ozone chemistry. Changes in vertical profiles of O₃, CO, EC and PM_{2.5} concentrations are shown in Figure S8. The main feature is that, as emission increases, all species increase consistently above the near surface layers.

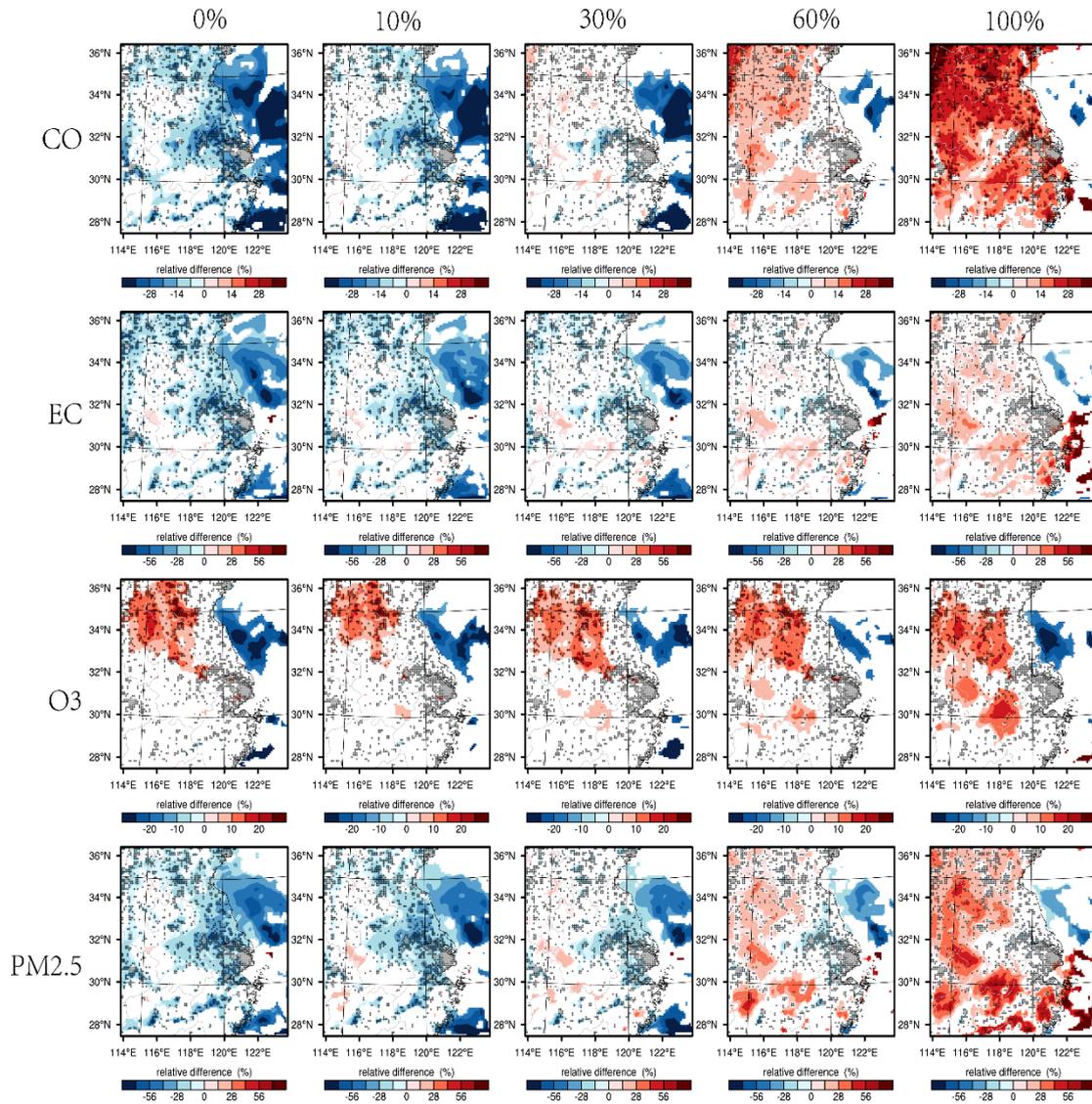


Figure S6. The surface concentration changes (only cells exceeding the 95% significance level are shown) of CO, EC, O₃ and PM_{2.5} in five emission scenarios in which all anthropogenic emissions only in LOCAL cells of GT0 run are increased by 0%, 10%, 30%, 60% and 100%, respectively, compared with BASE run in July of 2010. Grey circles indicate urban areas in the BASE run; black crosses indicate LOCAL cells in GT0.

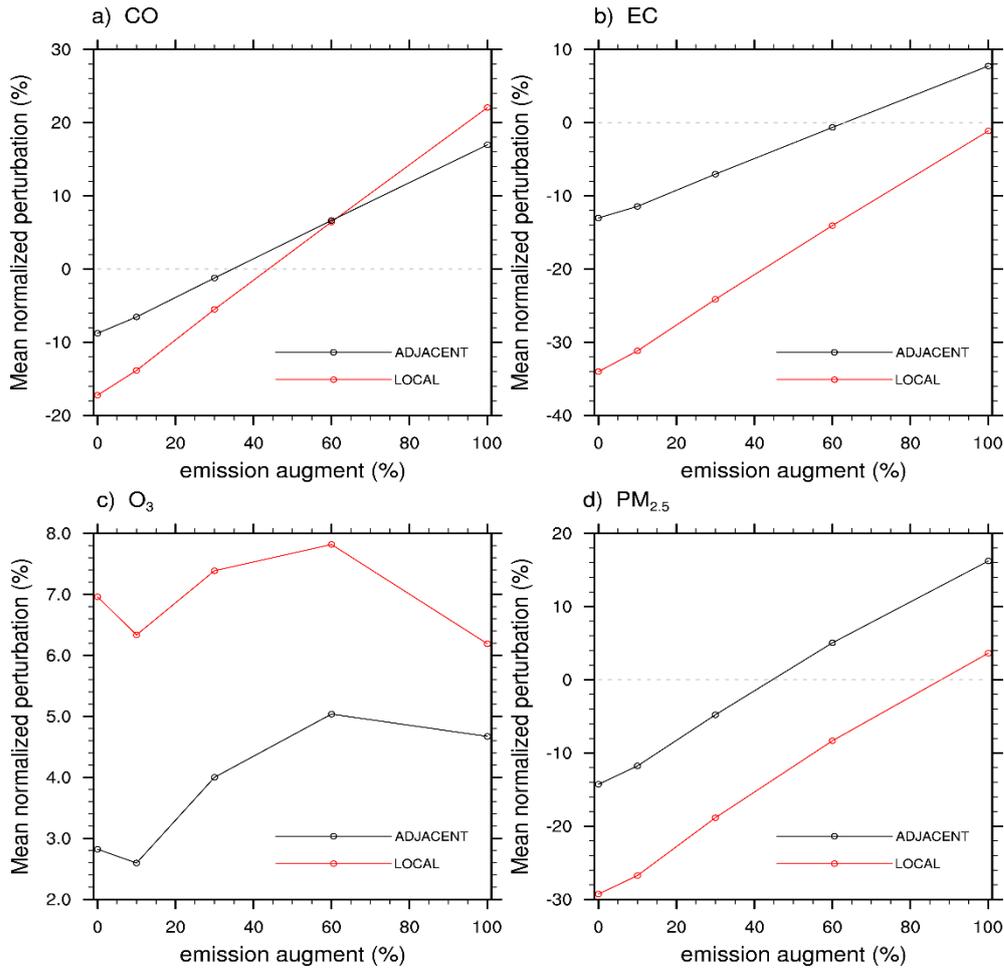


Figure S7. The mean normalized perturbation of surface concentrations of CO, EC, O₃ and PM_{2.5} over domain-wide LOCAL and ADJACENT cells in five emission scenarios in which all anthropogenic emissions only in LOCAL cells of GT0 run are increased by 0%, 10%, 30%, 60% and 100%, respectively, compared with BASE run in July of 2010.

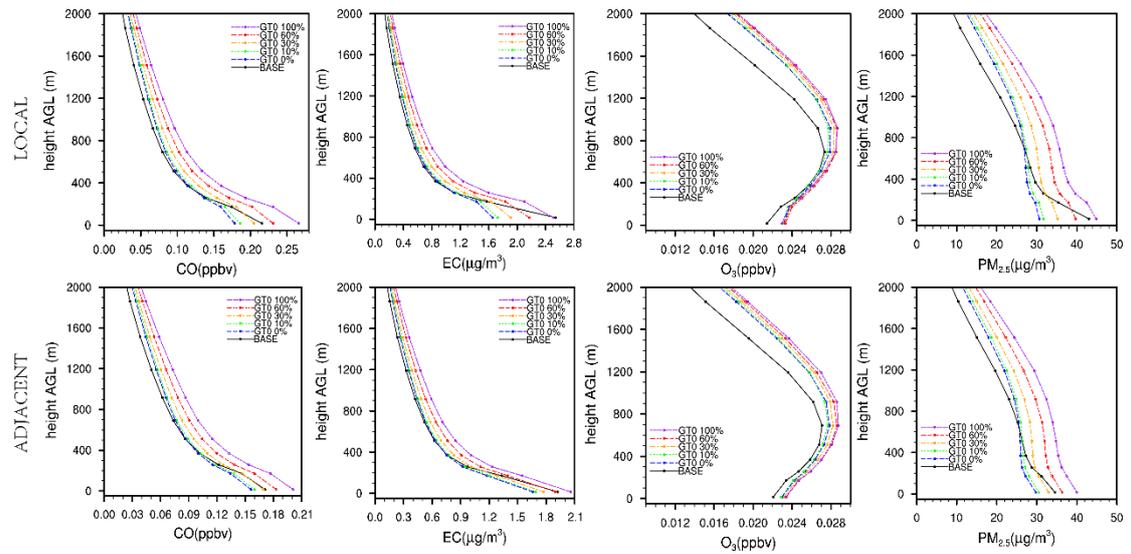


Figure S8. The mean vertical profile of CO, EC, O₃ and PM_{2.5} over domain-wide LOCAL(top four

plots) and ADJACNET(bottom four plots) cells in urbanization scenario of BASE and GT0(all anthropogenic emissions only in LOCAL cells are increased by 0%, 10%, 30%, 60% and 100%, respectively).

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