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Atmospheric Chemistry and Physics Discussions

Current and future prediction of inter-provincial transport of ambient $PM_{2.5}$ in China

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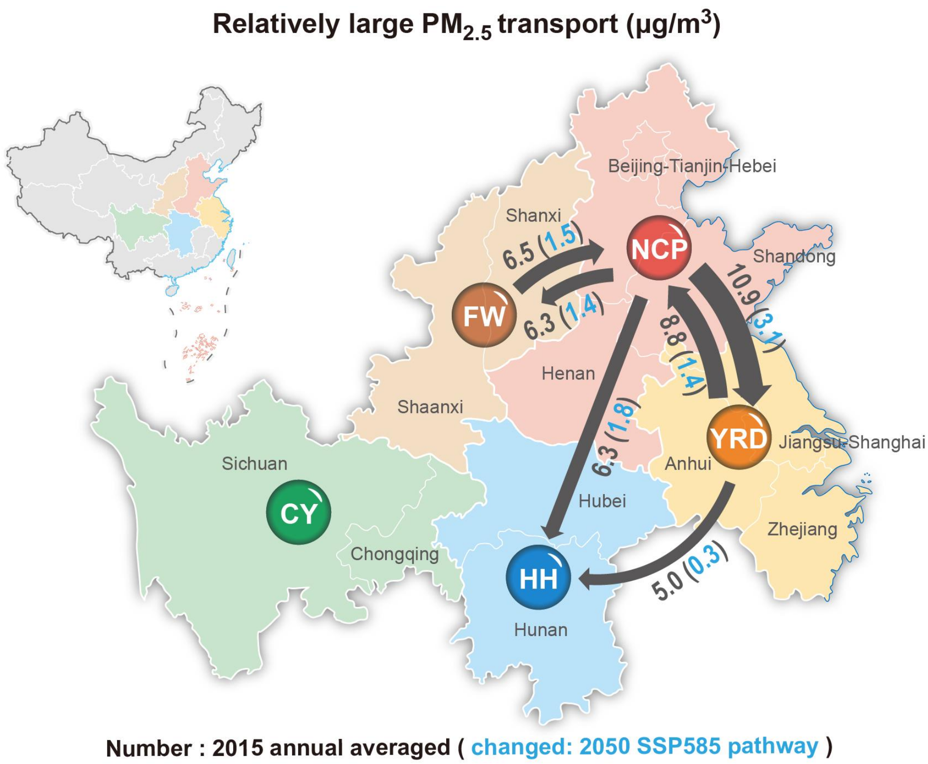
Abstract: Regional transport is as much important as local sources that contributing to $PM_{2.5}$ pollution and causing associated environmental inequality. In the context of future climate change, the effect of the responses of regional transport to the warming meteorology has not been thoroughly investigated. Here we establish cross-province $PM_{2.5}$ source-receptor matrix in China in 2015 and two climate pathways in 2050s (SSP585 and SSP126), using Community Multi-scale Air Quality model embedded with the Integrated Source Apportionment Method. Results suggest that across-regional transport contributes 27 % - 56.8 % of $PM_{2.5}$ in five severely polluted regions, which is even more important compared to inner transport within the target region (13.2 % - 20.9 %), especially in Chuanyu and Fenwei regions where suffers large $PM_{2.5}$ transport (over 50 %) from outside regions. Such results imply that joint-control policy should not only focus on neighboring provinces. Future warming scenario (SSP585) will exacerbate $PM_{2.5}$ pollution (2 - 5 μg/m^3) and also enhance its regional transport (> 3 %) mostly by modulating the across-regional transport rather than inner regional transport. Such enhancement of regional transport of $PM_{2.5}$ can be significantly weaken (approximately by half) under SSP126 pathway, demonstrating the importance of climate change mitigation on weakening the regional transport of $PM_{2.5}$ to maximize the co-benefits in both air quality and climate.

Keywords: air quality, $PM_{2.5}$, CMAQ-ISAM, climate change, inter-provincial transport

Graphical abstract



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Short Summary: Future warming meteorological conditions may enhance the influence of regional transport on $PM_{2.5}$ pollution. Our results prove that climate-friendly policy could lead to considerable co-benefits in mitigating the regional transport of $PM_{2.5}$ in future. Meanwhile, climate change will exert larger impacts on across-regional (long-distance) transport than inner (neighboring provinces) regional transport, highlighting the significance of multi-regional cooperation in the future.

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1. Introduction

China has been suffering from severe $PM_{2.5}$ (fine particulars with a diameter of 2.5 micrometers or less) pollution over the past few years (Zhang et al., 2014; Wang et al., 2014; Wang et al., 2014; Wang et al., 2014). After enforcement of the Air Pollution Prevention and Control Action Plan in 2013 (Chinese State Council, 2013) and the three-year action plan to fight air pollution in 2017 (Ministry Of Ecology And Environment, 2017), air quality improved significantly (Ministry Of Ecology And Environment, 2017), while the $PM_{2.5}$ concentrations are still far above the new World Health Organization (WHO) Air Quality Guidelines (5 μg m^{-3}). One big challenge to further reduce $PM_{2.5}$ is for its large contribution from external sources (Qin et al., 2015) (i.e., regional transport) which can be even more important under strengthened local emission controls as witnessed during the COVID-19 lockdown period (Zhao et al., 2020; Shen et al., 2021). Moreover, the problem of environmental inequality occurs due to air pollution transport, causing the receptor region to suffer additional health damage or economic burden from other regions. Zhang et al (2017) found that about 411,100 premature deaths (12 % of global 3.45 million deaths) were associated with air pollutants emitted from other parts of the world. Dedoussi et al (2020) indicated that in US about 41 to 53 percent of air quality-related premature mortality resulting from one state's emissions occurs outside that state. Jiang et al (2021) reported that people staying in rural areas in China are subjected to 22 % more impacts of regional transport to $PM_{2.5}$-related deaths as compared with urban compatriots.

The relatively long lifetime of $PM_{2.5}$ particles (approximately a week) allows them for long-range transport. Previous studies mainly concentrated on the transport within city clusters, such as Beijing-Tianjin-Hebei (BTH) (Chang et al., 2019; Dong et al., 2020), Yangtze River Delta (YRD) (Li et al., 2015; Li et al., 2016), and Pearl River Delta (PRD) region (Wu et al., 2013; Lu et al., 2019) . However, the long-range transport among those city clusters has not been well studied. In fact, $PM_{2.5}$ pollution is not restricted to surrounding influence, which requires joint controls with multi-regional policy implementation across the whole country (Zhang et al., 2017; Han and Zhang, 2021). Therefore, quantification of both inner regional and long-range transport on $PM_{2.5}$ pollution across China is prerequisite for designing an effective multiple-regional joint control strategy.

Furthermore, climate change could play an important role in air quality and regional transport (Wang et al., 2014; Li et al., 2019; Dong et al., 2020) in the context of global warming, leading to increasing extreme weathers (Wang et al., 2017; Johnson et al., 2018; Ma et al., 2018; Zhang and Wang, 2019; Pinkerton et al., 2019) and weakening global atmospheric circulation (Wang et al., 2017; Johnson et al., 2018; Ma et al., 2018; Zhang and Wang, 2019; Pinkerton et al., 2019). Most previous studies are based on current meteorological conditions (Wang et al., 2017; Johnson et al., 2018; Ma et al., 2018; Zhang and Wang, 2019; Pinkerton et al., 2019), without considering the effects of future climate change. It is still unclear whether the variation of atmospheric circulation driven by climate change could strengthen or weaken regional transport of $PM_{2.5}$, thus modulating the source-receptor relationship. Meanwhile, an ambitious target named carbon peaking and carbon neutrality was put forward by the Chinese government, which aims to achieve short-term and long-term climate goals before 2030 and 2060 (Dedoussi et al., 2020), respectively. Quantifying the change of regional transport of $PM_{2.5}$ under different climate change pathways would be of great interest for a better understanding of the synergy of climate change and air quality, and thus for designing a cooperative control strategy to mitigate both air pollution and climate change.

To fill the gap, this study aims to address two following questions: (1) What is the effect and quantitative variation of across-regional transport of $PM_{2.5}$ among city-clusters across China? 2) How will the regional transport of $PM_{2.5}$ respond to the variation of future climate change? Here we conduct multiple simulations to quantify and compare the inter-provincial regional transport of $PM_{2.5}$ in China under current (2015) and future (2050) meteorological conditions.

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2 Data and methods

2.1 Model configuration and Methods

The model configurations used in this experiment are as follows. Weather Research and Forecasting Model (WRF, version 4.2) is used to simulate three-dimensional meteorology fields. We follow the same model parameterization scheme as previous study (Liu et al., 2021; Liu et al., 2021) , including the Pleim-Xiu land surface physics scheme (Xiu and Pleim, 2001), Asymmetric Convective Mode (Pleim, 2007) planetary boundary layer physics, Morrison double-moment (Morrison et al., 2009) microphysics, Rapid Radiative Transfer Model (Iacono et al., 2008) radiative scheme, and Kain-Fritsch cumulus cloud parameterization (Kain, 2004). A 5-day spin-up simulation is conducted to eliminate the influences of initial condition.

Pollutant concentration distribution is simulated by the latest version of Community Multiscale Air Quality Model (CMAQ, version 5.3.2) configured with the Carbon Bond 6 (CB6) gas-phase chemical mechanism (Sarwar et al., 2008) and AERO6 aerosol module (Sarwar et al., 2008), with improvements in predictions for ozone and other secondary gas-phase species and dry deposition in the latest version (Zheng et al., 2019; EPA, 2020). The Integrated Source Apportionment Method (ISAM) modeling system is used to simulate the distribution, transport, transformation and deposition of aerosols and their precursors. Tagged species in ISAM module are updated by apportioning the change during each chemical and physical process, to track $PM_{2.5}$ and its precursors from different emission regions. The ISAM is calculated simultaneously with the CMAQ model (see the flowchart of ISAM in CMAQ in Fig.1 of Kwok et al (2013)), thus it can well capture the complex interactions among the atmospheric physical and chemical processes during the transport. The source-receptor matrix established with ISAM is able to reflect the contributions from source to receptor (i.e., the number in transport matrix).

We also estimate the impacts of regional transport at regional level (including several receptors) by taking the weighted average of individual impact, as follows. This formula is intended to be used to calculate the contribution of multi-regional transboundary transport.

$$Contribution = \frac{\sum(\text{transport}\%\times\text{Concentration}_{\text{receptor}})}{\sum \text{Concentration}_{\text{receptor}}}, \quad (1)$$

where *transport %* represents the percentage of regional transport to one receptor, implying the impact of one source to a receptor region; $Concentration_{receptor}$ represents the baseline concentration of a receptor. So the result denotes the total amount of regional transport received by all receptors in that region.

2.2 Study area

The modeling domain covers the mainland China with a horizontal spatial grid resolution of 27 km × 27 km (182 × 232 cells) and 14 vertical layers of the meteorological fields which is sufficient to capture the across-region transport at provincial and inter-provincial level (Li et al., 2019) . China is divided into 21 quasi-provinces (as some similar administrative provinces have been combined as one single quasi-province, see Supplemental Material Fig. S1a). To analyze regional transport across and within city-clusters, we further combine 21 quasi-provinces into 5 densely populated and severely polluted regions (Fig. S1b): the North China Plain (denoted as NCP, including Beijing-Tianjin-Hebei region, Shandong and Henan province), the Yangtze River Delta (denoted as YRD, including Jiangsu-Shanghai region, Zhejiang and Anhui province), the Central China (denoted as HH, including Hubei and Hunan province), the Chengyu area (denoted as CY, including Sichuan province and Chongqing region) and the Feiwen Plain (denoted as FW, including Shanxi and Shaanxi province). The Pearl River Delta (PRD) is not included simply due to its relatively lower $PM_{2.5}$ pollution level than other regions (see Fig. 1a).

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2.3 Data

The FNL (Final) operational global analysis and forecast data from National Centers for Environmental Prediction (NCEP) are used for the 2015 simulation (the baseline scenario) in WRF, the baseline year is the same as our previous study (Liu et al., 2021; Liu et al., 2021). The spatio-temporal resolution of data is on 0.25 degree by 0.25 degree grids prepared operationally every six hours. Assimilated data include global surface and upper observational weather data.

The ensemble averages of five Coupled Model Intercomparison Project (CMIP6) multi-model simulations (i.e., BCC-CSM2-MR from China, MRI-ESM2-0 from Japan, IPSL-CM6A-LR and CNRM-CM6-1 from France, and EC-Earth3 from Europe) were used to represent the future meteorological conditions for 2050 in two warming scenarios including SSP126 (low GHG emission pathway) and SSP585 (high GHG emission pathway). We conducted dynamic downscaling to drive the WRF simulations over China domain, following the same configurations and data as our previous study (Liu et al., 2021) . Biogenic emission was simulated with the Model of Emissions of Gases and Aerosols from Nature (MEGAN version 2.10)(Liu et al., 2021) driven by the WRF simulated meteorological conditions.

$$\mathrm{WRF}_{\mathrm{input2050}} = \mathrm{fnl}_{2015} + \Delta\mathrm{CMIP6}_{\mathrm{ssp}} \qquad (2)$$

The monthly anthropogenic emission in this study is the Emission Inventory of Air Benefit and the Cost and Attainment Assessment System (ABaCAS- EI) emission inventory by Tsinghua University for 2015 (Zheng et al., 2019; Xing et al., 2020). We use the same anthropocentric emissions for current and future simulations, so their differences are only considered as the meteorology changes. Four typical months, namely, January, April, July, and October are chosen to represent winter, spring, summer, and autumn, respectively (Li et al., 2019). Here, sensitivity analysis were conducted to fixed on anthropogenic emission, the only change reveal on meteorological conditions (Table 1).

Table 1 Scenarios

Case	Meteorology	Emission	Objective
1	2015	2015	Baseline scenario
2	2050_SSP126	2015	2050 friendly climate scenario, current emission
3	2050_SSP585	2015	2050 uncontrolled climate scenario, current emission

2.4 Model performance

We compared the CMAQ model simulations with ground observations from the China National Environmental Monitoring Center (http://beijingair.sinaapp.com/) (Supplementary materials Fig. S2). The simulated R-squared (R^2) equals 0.41, mean fractional bias (MFB) equals -0.39, mean fractional error (MFE) equals 0.41. Although the simulated $PM_{2.5}$ concentration tends to be relatively lower compared to the station observations, which is probably due to the uncertainties of secondary aerosol formations, the validation results indicate that the WRF-CMAQ model performance is acceptable, as the MFB and MFE are within the recommended standard (MFE⩽ +75 % and MFB⩽ ±60 %) of Boylan and Russell (2006) and Emery et al (2001) and comparable with previous studies (Chang et al., 2019; Liu et al., 2021; Liu et al., 2021; Dong et al., 2020)

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3 Results

3.1 inter-provincial regional transport of $PM_{2.5}$ across China in 2015

In 2015, severe $PM_{2.5}$ pollution (>50 μg/m^3) occurs on five typical regions including NCP, YRD, HH, CY and FW, as seen in Fig. 1a. Strong seasonality was also observed, with the worst severe pollution in winter followed by fall, spring, and summer (Fig. S3).

Figure 1b and 1c represent the amount and contribution of regional transport (defined as the sum of contribution except for local emission produced) to total $PM_{2.5}$ concentration in 2015, respectively. Results suggest that regional transport accounts for approximately 20 % to 40 % in densely populated areas, ranging from 2.63 μg/m^3 (CY) to 5.89 μg/m^3 (NCP). The largest contribution by regional transport occurs in CY region, which accounts for 37 % of the total amount in the region. This is probably attributed to the fact that western Sichuan is on the periphery of the Tibetan Plateau (Fig. 1c), with sparse population, resulting in local clean air and a large contribution of regional transport, followed by FW region (26.24 %), NCP region (20.37 %), HH region (19.58 %), and YRD region (19 %), respectively. It is noted that high regional contribution occurs in inter-provincial boundary lines in NCP, YRD and CY regions (Fig. 1b), which is attributed to the fact that the areas at boundary lines and low topography suffer more influences from the regional transport.

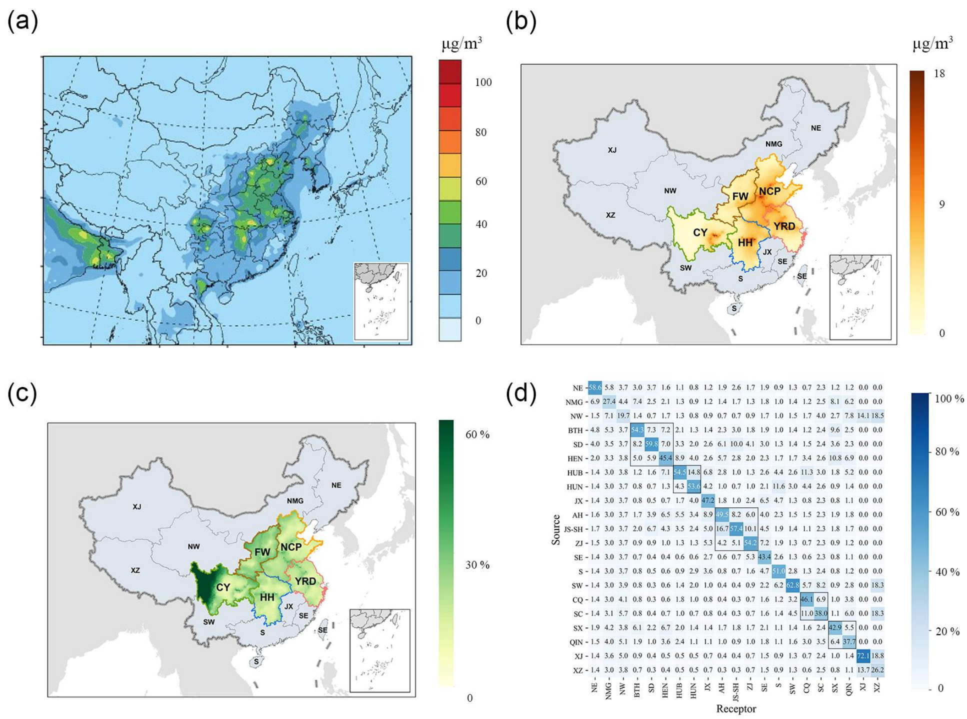

Figure 1. Simulated $PM_{2.5}$ concentration and associated regional transport in 2015 four month averages; (a) spatial distribution of simulated $PM_{2.5}$ concentration (μg/m^3) and impacts of regional transport on $PM_{2.5}$ concentration in (b) absolute value (μg/m^3) and (c) relative ratio (percent)* ; (d) cross-province $PM_{2.5}$ source-receptor matrix (percent) * the ratio of sum of $PM_{2.5}$ concentrations contributed from all ISAM tagged foreign regions to the baseline $PM_{2.5}$ concentration

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The cross-province $PM_{2.5}$ source-receptor matrix represents the percentage of regional transport contribution across all ISAM tagged regions, implying the interactions (pollutant transport) between sources and receptors (Fig. 1d). The values in the diagonal line represent the local contribution (i.e., the receptor is also the source), and each value in the table represents the 4-month averaged contribution (in percentage) of the source region to the receptor region. In general, the largest source of $PM_{2.5}$ is local contribution, particularly in isolated provinces such as Xinjiang (XJ, 72.1 %) and Southwest (SW, 62.8 %) which are far away from polluted regions (also in the upwind of primary precursor sources in eastern China under the prevailing westerly winds) thus suffering less regional transport of $PM_{2.5}$. Nevertheless, pollutants could be transported from FW areas during specific season (Fig. S9). Large local contributions are also found in Shandong province (SD, 59.8 %) and Northeast (NE, 58.6 %), both of which are important bases of China's traditional heavy industries. The smallest local contribution is shown in Inner Mongolia (NMG), Northwest (NW) probably due to limited local emission sources. Moderate local contributions are found in densely-populated areas such as BTH region (54.3 %), and YRD region (Jiangsu-Shanghai (JS-SH, 57.4 %), Zhejiang (ZJ, 54.2 %)), probably due to their stronger interactions due to the regional transport of $PM_{2.5}$. Our results are basically consistent with previous study. Wang et al (2019) used the zero-out method to calculate inter-provincial transport of $PM_{2.5}$ and discovered that heavily polluted areas such as the NCP and YRD suffered half of the local contributions; Xinjiang and Tibet regions showed extreme high (over 80 %) and low local contribution. Chang et al (2018) pointed out that Shandong province contributes the most (6.8 μg/m^3 or 8.4 % on average) to the BTH area, followed by Henan province (HEN, 3.7 μg/m^3 or 4.5 % on average) in 2014, which is consistent with our results as Shandong (SD) is the largest share to BTH region (8.2 %), followed by Inner-Mongolia (NMG, 8.1 %) and Henan province (HEN, 5 %) in 2015.

In densely populated areas, the local contribution exhibits the largest in winter (22.23 - 76.84 %) partly due to the largest anthropogenic emissions associated with extensive heating activities (Fig. S4). Besides, pollutants diffusion is dramatically inhibited in winter, due to the relatively stable atmospheric condition (Sun et al., 2014; Zhang et al., 2014; Ding et al., 2017; Liu et al., 2017) which may also reduce the contribution of regional transport. Chang et al (2019) also demonstrated that a larger range and amount of regional transport occurs in summer in 2014, rather than winter, which is coincident with our seasonal matrix results (Fig. S4). This phenomenon is probably associated with the enhanced east Asian summer monsoon circulation under a warming climate (2019).

3.2 Comparison of $PM_{2.5}$ regional transports among five key regions

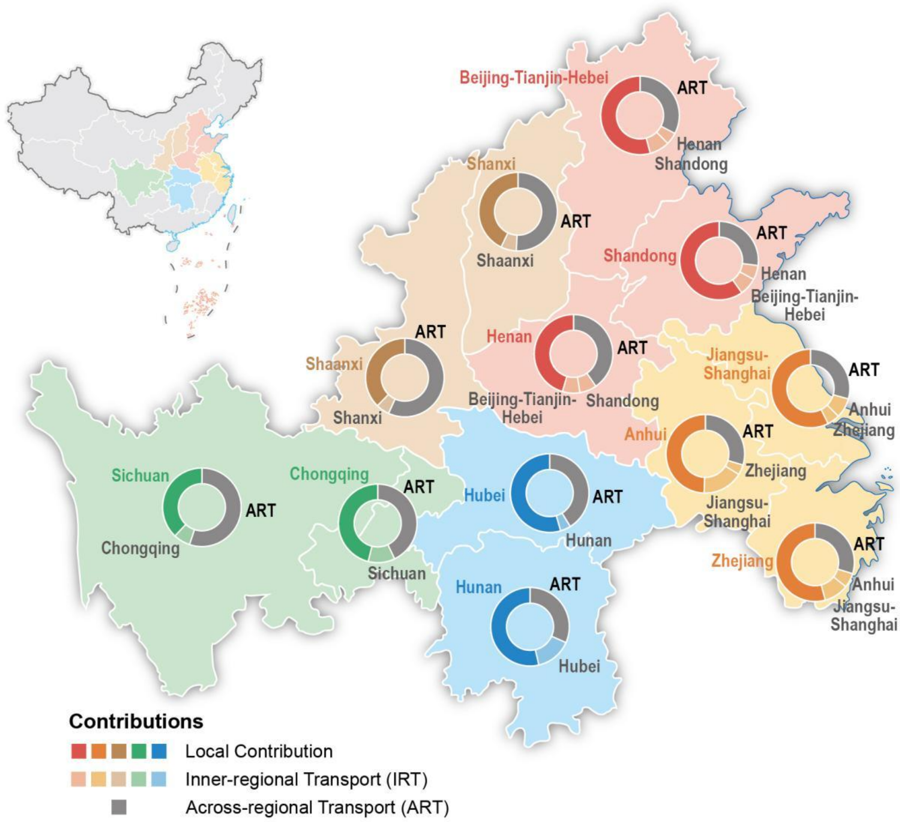

Figure 2. The division of local, inner-regional transport, and across-regional transport contributions to $PM_{2.5}$ concentration in five key regions in 2015. (local means pollution produced by self-emission and marked in darker color; inner-regional transport means the surrounding province within the same region marked in the same color; across-regional transport means other areas in China outside the target region marked in grey color)
* Inner-regional Transport (IRT); Across-regional Transport (ART)

Considering the strong link between the administrative division of national policies, and the similarity of natural conditions such as topography and climate, we further explore the source contribution distinguished among local (province itself), inner-regional transport (from nearby provinces within the same region), and across-regional transport (from other areas in China outside the target region) in five typical regions, as presented in Fig. 2. Firstly, it is reasonable that the contribution from local emission is the largest air pollution source. We noted that Sichuan province is presented relatively low local ratio because it included the western Sichuan plateau, which reveals low emission. Secondly, in general, surrounding areas (inner-region) are supposed to exhibit the largest contributions if their contributions are counted individually. However, at the aggregated level, the inner-region transport may account for less contribution than across-regional transport. As seen from Fig. 2, for example, inner-regional transport contribution accounts for 13.2 %-14.2 % in the NCP and 13.3 %-20.9 % in the YRD region. On the contrary, across-regional transport shows 27 %-56.8 % contributions in these five typical regions, indicating that across-regional transport outside the target region is even more important compared to inner transport within the region. For the YRD region,

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approximately 30 % of the total contributions come from provinces far away from the receptor region. For the HH region, local self-contribution is equal to across-regional contribution. A similar situation occurs in CY and FW regions, which are presents less local self-contribution (37.7 % to 46.1 %) compared to NCP, YRD and HH regions.

In additional to the greatest contribution from local emission, regional transport are also important. Here we further analyze the interactions among key regions, as displayed in Fig. 3 which emphasizes the relationship between polluted sources and receptors. From the point of view of pollution source, on average, the least polluted source of $PM_{2.5}$ is CY (1.2 μg/m^3) (Fig. 3g) while the highest polluted source is NCP (6.41 μg/m^3) (Fig. 3a), followed by YRD (4.23 μg/m^3), HH (2.91 μg/m^3) and FW (3.1 μg/m^3) regions (Fig. 3 left panel). It is obvious that the NCP source has the highest contribution proportion to other receptors ranging from 6.53 % to 19.07 % (Fig. 3a). In particular, the NCP source has the largest impact on the YRD receptor (10.88 μg/m^3 or 13.38 %), followed by NCP to FW receptor (6.28 μg/m^3 or 19.07 %). In contrast, NCP, as a receptor, suffering $PM_{2.5}$ mostly from YRD (8.85 μg/m^3 or 9.52 %) (Fig. 3c and 3d), HH (3.97 μg/m^3 or 4.27 %) (Fig. 3e and 3f) and FW (6.54 μg/m^3 or 7.03 %) (Fig. 3i and 3j) regions, demonstrating that NCP is closely related with the other four regions. The CY region shows the weakest connection with other areas (less than 2 μg/m^3 or 6 %) (Fig. 3g and 3h). From Fig. 3, we found that the strongest across-regional interactions (exerts the largest influences on other regions and also suffers the most influences from others) occur in NCP, followed by YRD, HH, FW, and CY regions. Noted that Li et al (2019) used the CMAQ-ISAM model to quantify typical transport contributions in NCP, YRD, PRD, and CY region in 2017, which illustrates that transport from NCP to YRD approximately accounts for one-third of its local contribution (15 - 25 μg/m^3). The result slightly larger than our results (10.88 μg/m^3), which is primarily because in their study the NCP also included surrounding areas (Shanxi, Inner Mongolia, and Shaanxi) which is larger than we defined. Different model resolutions (they used is based on 64 × 64 km^2 grid resolution while our is 27 × 27 km^2) might also contribute to such discrepancy.

Overall, the cross-regional transport contribution is considerably large, implying that the current joint-regional controls that exclusively focused on the cities within the region should also pay attention to the simultaneous controls on other provinces outsides the region. Joint controls across regions are also recommended to enhance inter-provincial coordinated governance.

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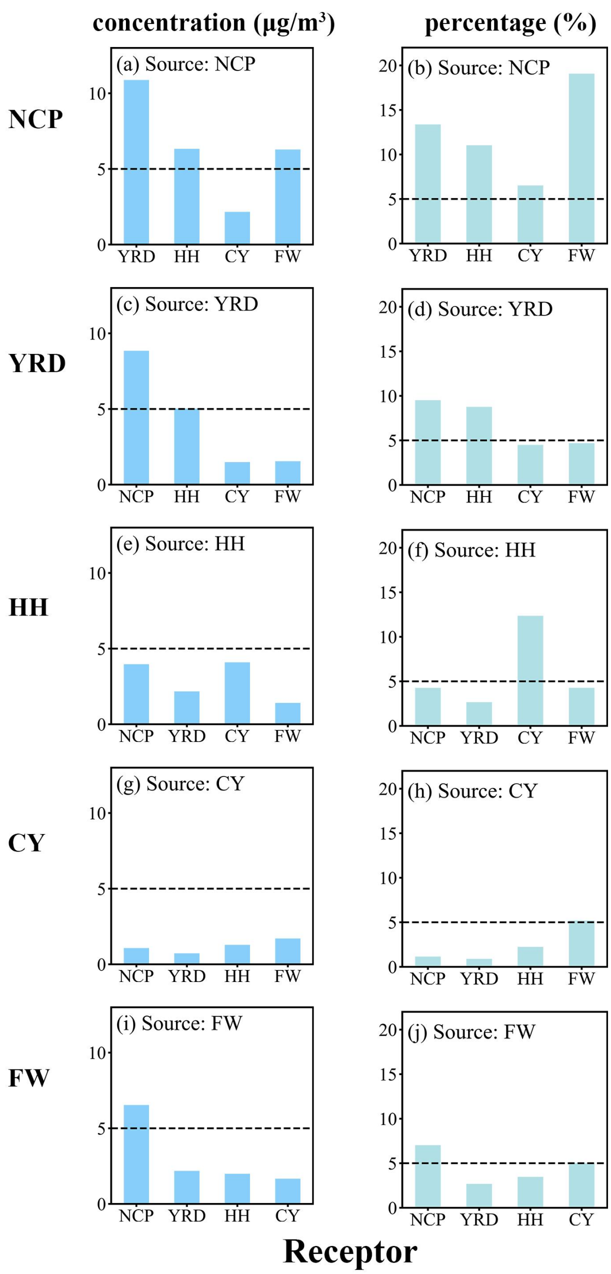

Figure 3. The interactions between five sources and receptors in 2015 baseline.
(Each subplot represents the effect of a single source on the other four receptors; Percentage is calculated according to Formula 1 described in the Method)

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3.3 Prediction of inter-provincial regional transport of $PM_{2.5}$ across China in 2050

To analyze the difference between baseline and future scenarios, we used two SSPs of CMIP6 datasets (SSP585 and SSP126) to predict future regional transport in 2050 (in Fig. 4). Compared with Fig. 1a, the $PM_{2.5}$ concentration is predicted to increase by 3.12 μg/m^3 across China in 2050 under high warming climate pathway (SSP585) (see Fig. 4a, seasonal variation are shown as Fig. S5), particularly in five key regions as NCP (4.82 μg/m^3), YRD (4.59 μg/m^3), HH (5.24 μg/m^3), CY (2.62 μg/m^3) and FW (3.36 μg/m^3) (see Fig. 4a). Such results indicate that the high warming climate scenario will exacerbate $PM_{2.5}$ pollution. In addition, regional transport of $PM_{2.5}$ will be enhanced simultaneously in most regions (> 3 %) (Fig. 4c, e), particularly in central China including Henan (2.43 μg/m^3), Anhui (2.23 μg/m^3) and Hubei (2.07 μg/m^3). The transport matrix also revealed a declined contribution of local emission (by 3 - 7 %, as shown in the diagonal values in Fig. 4g, the seasonal details are shown as Fig. S6), particularly in the BTH region which exerts considerable impacts on other regions by across-regional transport of $PM_{2.5}$. Such results suggest the enlarged influences from regional transport under future high warming climate scenario.

On the other hand, mitigation of global warming will lead to co-benefits in reducing air pollution. As seen in Fig. 4b (seasonal variation is shown as Fig. S7), the $PM_{2.5}$ concentrations are increased much less (0.87 μg/m^3) under SSP126 (Fig. 4b) than SSP585. The $PM_{2.5}$ in five key regions increased within 2 μg/m^3 which are approximately half of that in SSP585. Correspondingly, regional transport of $PM_{2.5}$ will be also weakened significantly under SSP126 from SSP585. The enhancement of regional transport contribution is less than 1 μg/m^3 (Fig. 4d) and 1 % (Fig. 4f) in five target regions. Such reduced regional transport is likely attributed to the weakened atmospheric circulation (Kjellsson, 2015). Meanwhile, the change of transport matrix is also smaller than that in SSP585 (Fig. 4h, the seasonal details are shown as Fig. S8), as the decreases of self-contribution are much smaller than that in SSP585, implying the weaker enhancement of influences from regional transport in SSP126 compared to SSP585. We also noted that western Sichuan (on the periphery of the Tibetan Plateau) presented opposite situation between SSP585 and SSP126 (Fig. 4 e and 4f), resulting exacerbation of environmental inequality during high GHG emissions scenario.

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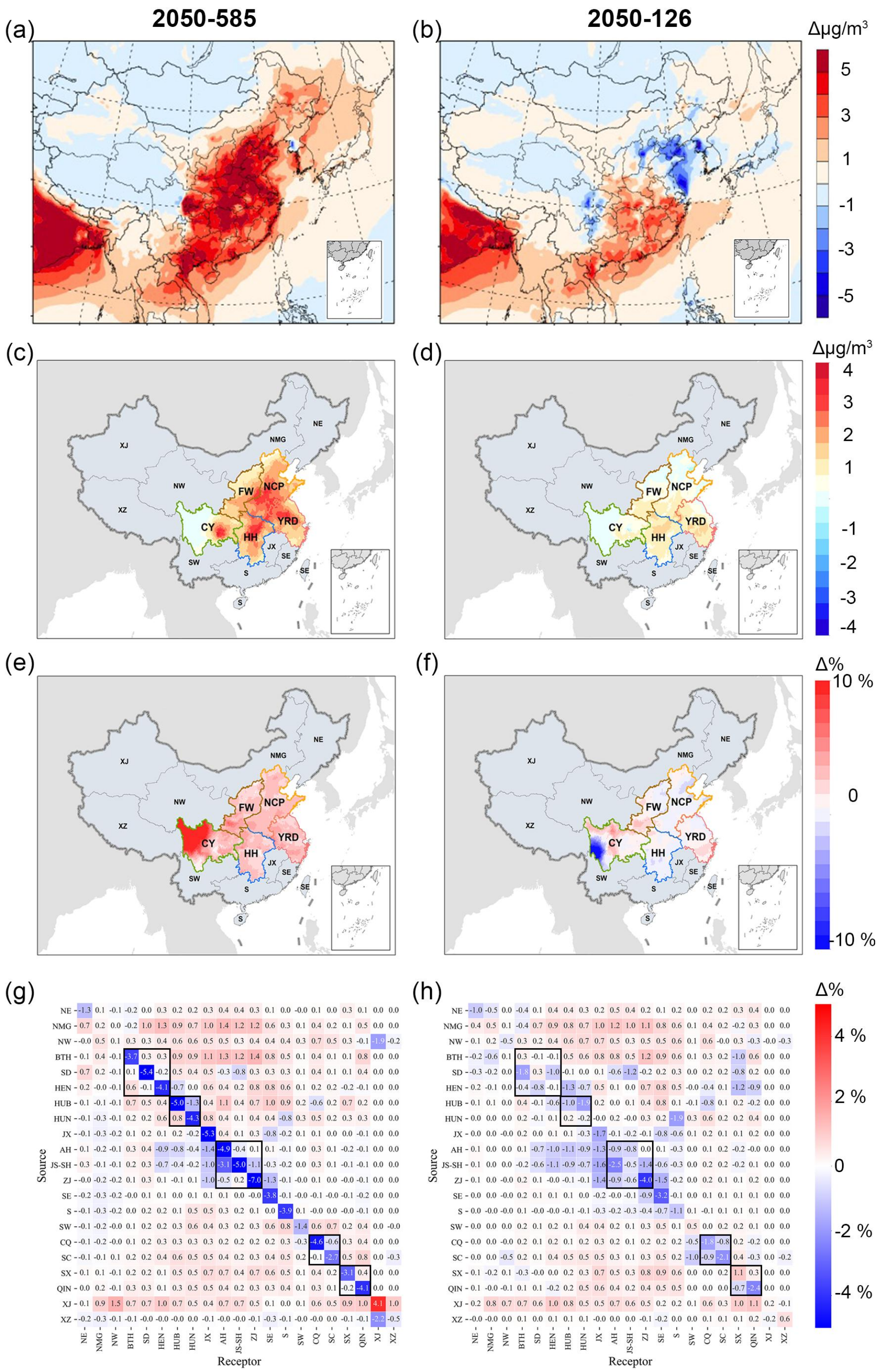

260 **Figure 4.** Similar to Figure 1, the difference distribution map of regional transport between 2050 and 2015, the left panel displays the SSP585 in 2050 and the right is SSP126.

3.4 Future regional transports and interactions of $PM_{2.5}$ in five key regions in 2050

Figure 5 summarizes regional transports and interactions of $PM_{2.5}$ in five key regions in 2050. The contributions of local and regional transport to $PM_{2.5}$ exhibit greater variations under SSP585 than SSP126, with larger reduction of local emissions and more enhancement of across-regional transport contributions. Compared with the 2015 baseline, local self-contributions in five regions decreased significantly under SSP585 (with scale from 2.7 % to 7.1 %), which is much larger than that under SSP126 (-4 % to 1.1 %).

So far inner province transport received wide public concern, however, the average level (grey bar in Fig. 5) of inner regional transport in five typical regions displays only slightly change as 0.37 % (NCP), -1.57 % (YRD), -0.25 % (HH), -0.35 % (CY) and 0.1 % (FW) under SSP585 and -1.37 % (NCP), -2.1 % (YRD), -0.85 % (HH), -0.8 % (CY), -0.25 % (FW) under SSP126. Across-regional transport, on the other hand, reveals a larger change of 4 %, 7.23 %, 4.85 %, 4 % and 3.5 % in NCP, YRD, HH, CY and FW, respectively under SSP585 and 1.17(NCP), 3.87 % (YRD), 1.45 % (HH), 2.8 % (CY), 0.9 % (FW) under SSP126. Thus, the impacts from inner surrounding regions exhibit slightly change (-2.1 % to 0.37 %), but that of across-regional transport is from 0.9 % to 7.23 %, indicating that the climate change impacts on the contribution from across-regional transport are considerably greater than that of inner regional transport. Therefore, across-regional transport is more likely to change under future climate change scenarios in comparison with inner short-distance regional transport, which is associated with the change of atmospheric circulation (Fig. S9-S10) and can be verified from IPCC AR6 (https://interactive-atlas.ipcc.ch/). Moreover, the contribution of across-regional transport decreases significantly under the SSP126 pathway, implying that strict GHG emission policy will most likely weaken across-regional $PM_{2.5}$ transport. For individual regions, the inner transport contribution on $PM_{2.5}$ in BTH increased by 0.7 % under SSP585 but decreased 2.3 % under SSP126 pathway (Fig. 5a and 5b). The YRD region, particularly Anhui province, has significantly weakened inner transport as its contribution decreased by 3.4 % under SSP126 (Fig. 5c and 5d). In HH, the inner transport contribution to Hunan province decreased by 1.3 % in the SSP585 and decreased by 1.9 % in SSP126 (Fig. 5e and 5f). In comparison to the above three polluted regions, a relatively small fraction (less than 1 %) of inner $PM_{2.5}$ transport change occurs in CY and FW regions, implying little influences from future climate on the $PM_{2.5}$ transport within these two regions (Fig. 5g, 5h, 5i, and 5j). Above data are summarized in Fig. 5k and 5l, demonstrating less variation of $PM_{2.5}$ regional transport under SSP126 compared to SSP585. More importantly, the difference between the variations of outer and inner contributions (i.e., ΔOuter minus ΔInner) suggests that outer regions decreases more significantly than that of inner, demonstrating the effective control of across-regional transport of $PM_{2.5}$ under strict GHG policy. Also, the decrease in CY region under SSP126 is not as significant as the other regions, probably due to the long distance and relatively low impact from other regions.

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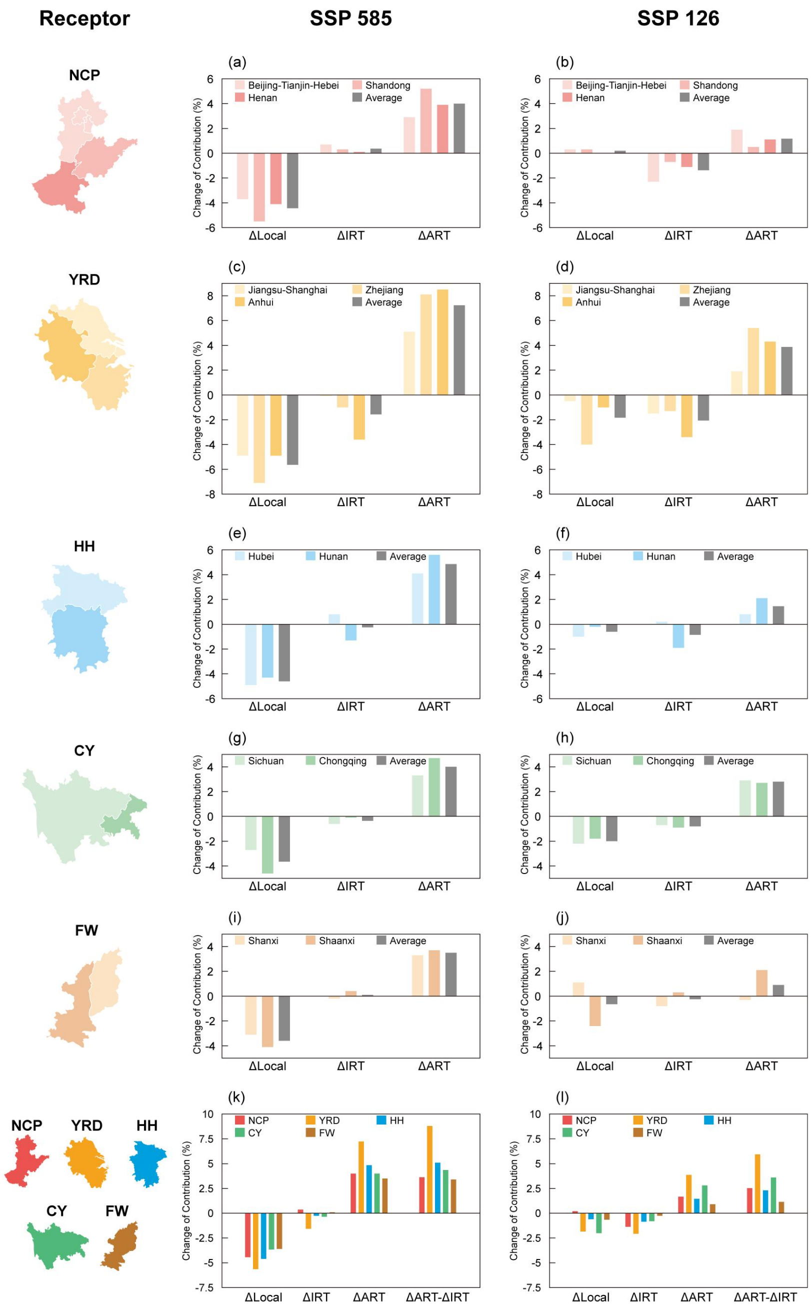

295 **Figure 5.** The contribution difference between 2050 and 2015, including the division of local, inner and across-regional contribution of regional transport. The left panel shows SSP585 (minus 2015 baseline), and the right is SSP126 (minus 2015 baseline). The last row (k) and (l) show the average change of local, inner and across-regional in each region, as well as the percentage of outer to inner changes.
* Inner-regional Transport (IRT); Across-regional Transport (ART)

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We quantify the future change of the interactions among key regions as shown in Fig. 6. Stronger interactions occur under SSP585 compared to SSP126 (the left bar is higher than the right bar in each subplot), as the more variations of regional transport impacts under SSP585. Similar to Fig. 3, on average, the NCP presents the greatest change under SSP585 (Fig. 6a and 6b), while the CY region exhibits the least change (Fig. 6g and 6h). In particular, the impacts of NCP to YRD will increase the most by 3.09 μg/m^3 (or 1.31 %) under SSP 585, followed by NCP to HH receptor (1.83 μg/m^3 or 0.99 %) as shown in Fig. 6a and 6b. On the contrary, as a receptor, NCP suffered $PM_{2.5}$ mostly from YRD (1.44 μg/m^3), HH (1.56 μg/m^3) and FW (1.5 μg/m^3) regions (Fig.6c, 6e, and 6i). However, there was less changes in SSP126, with an increase of 0.73 μg/m^3 (0.12 %) from NCP to YRD receptor and 0.21 μg/m^3 (-0.46 %) from NCP to HH receptor increased (Fig.6a and 6b). Similar to Fig. 3, the CY region shows the weakest connection with other areas, compared with the above three regions, the CY region has a little variation (less than 1 %) in 2050 scenarios. More $PM_{2.5}$ across-regional transport to CY and FW regions in future climate change under both SSP585 and SSP126, implying the increased $PM_{2.5}$ concentrations from other sources to CY and FW regions. Such results highlighted the significance of inter-provincial cooperation, and the climate-friendly SSP126 scenario could effectively reduce the inter-provincial regional transport of $PM_{2.5}$ driven by the global warming.

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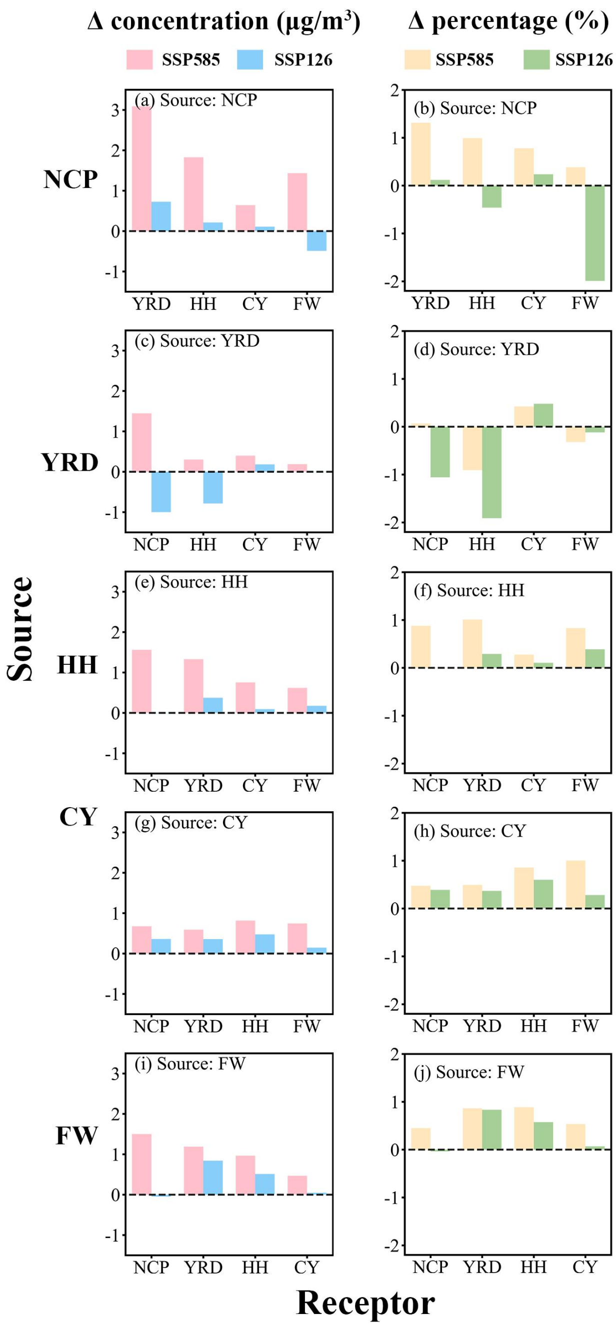

Figure 6. Similar to Figure 3, the relationship between five sources and receptors in 2050 (red and yellow bar show SSP585, blue and green bar show 126 scenarios). Each subplot represents the effect of a single source on the other four receptors.

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4 Conclusion

Regional transport plays an important role in the aerosol pollution over China by accumulating pollutants and exacerbating environmental inequality. Particularly in the context of global warming, quantifying the change of regional transport of $PM_{2.5}$ under different climate change pathways would be of great interest for a better understanding of the synergy of climate change and air quality. Our results demonstrated that the change extent of across-regional transport is greater than inner short-distance transport in the future of 2050. The transport among neighboring regions present slight change (-2.1 % to 0.37 %) in 2050 future climate change scenarios while across-regional transport ranges from 0.9 % to 7.23 %, indicating that the contribution from across-regional change is much greater than the inner neighboring regions. More importantly, if we execute strict GHG emission (SSP126), both outer and inner regional transport contribution will weaken significantly. Apparently, modulation of regional $PM_{2.5}$ transport also reflects the synergy of climate change and air pollution.

Although this study only considers the role of climate change, emission reduction is undoubtedly the most important, and emission reduction can further weaken regional transport. We aim to arouse the attention of air transport due to climate change, rather than deny the contribution of anthropogenic emission controls and the contribution from local emission is still the largest pollution source. China is facing the enormous challenge of continuous improvement in air quality, striving to peak CO_2 emissions before 2030, and achieving carbon neutrality before 2060. Considering GHG and air pollutants originate from the same sources, controls emissions is necessary to fundamentally solve the problem of air pollution and promote sustainable eco-environment. Therefore, we suggest policymakers strengthen province-to-province cooperation and source control in the face of future climate change. Furthermore, the issue of human health caused by air pollution transport is worth studying, and more uncertainty will emerge along with the future climate change. Nevertheless, our results provide a comprehensive perspective of the transport contribution of $PM_{2.5}$ concentration in China. Through this study, regional joint and emission control should not only pay attention to neighboring provinces in the future, but also pay more attention to across-regional transport between major urban clusters. Also, strict GHG emission controls could lead to considerable co-benefits in reducing the regional transport of air pollution in the future.

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Appendices

Data availability

We also acknowledge NCAR for the NCEP GDAS/FNL meteorological data are openly available at

https://rda.ucar.edu/datasets/ds083.3/index.html#!access;

The NCEP surface observational weather data are openly available at

https://rda.ucar.edu/datasets/ds461.0/#!access;

The NCEP upper air observational weather data are openly available at

https://rda.ucar.edu/datasets/ds351.0/#!access

Abbreviations

$PM_{2.5}$, fine particulars with a diameter of 2.5 micrometers or less; BTH, Beijing-Tianjin-Hebei; NCP, the North China Plain; YRD, Yangtze River Delta; HH, Hubei and Hunan provinces; CY, Sichuan and Chongqing area; FW, Fenwei Plain; SSP126, Shared Socioeconomic Pathways 1-2.6; SSP585, Shared Socioeconomic Pathways 5-8.5; CMAQ, Community Multiscale Air Quality Model; ISAM, The Integrated Source Apportionment Method; WRF, Weather Research and Forecasting Model; GHG, Greenhouse gas; CMIP6, Coupled Model Intercomparison Project;

Author Contributions

SW, SL, JX designed the methodology and conducted the WRF-CMAQ, and experiment. YD, SH, SL helped with the data process. YQ helped with Figures. ZD, JD, GS, LD helped with the analysis. SW,SL and JX prepared the paper. All authors contribute to writing to the paper.

Competing interests

The authors declare no conflict of interest.

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