第十一届长三角空气质量管理技术研讨会

全球变暖背景下极端高温与复合型大气污染预测与应对

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2013年8月31日，上海

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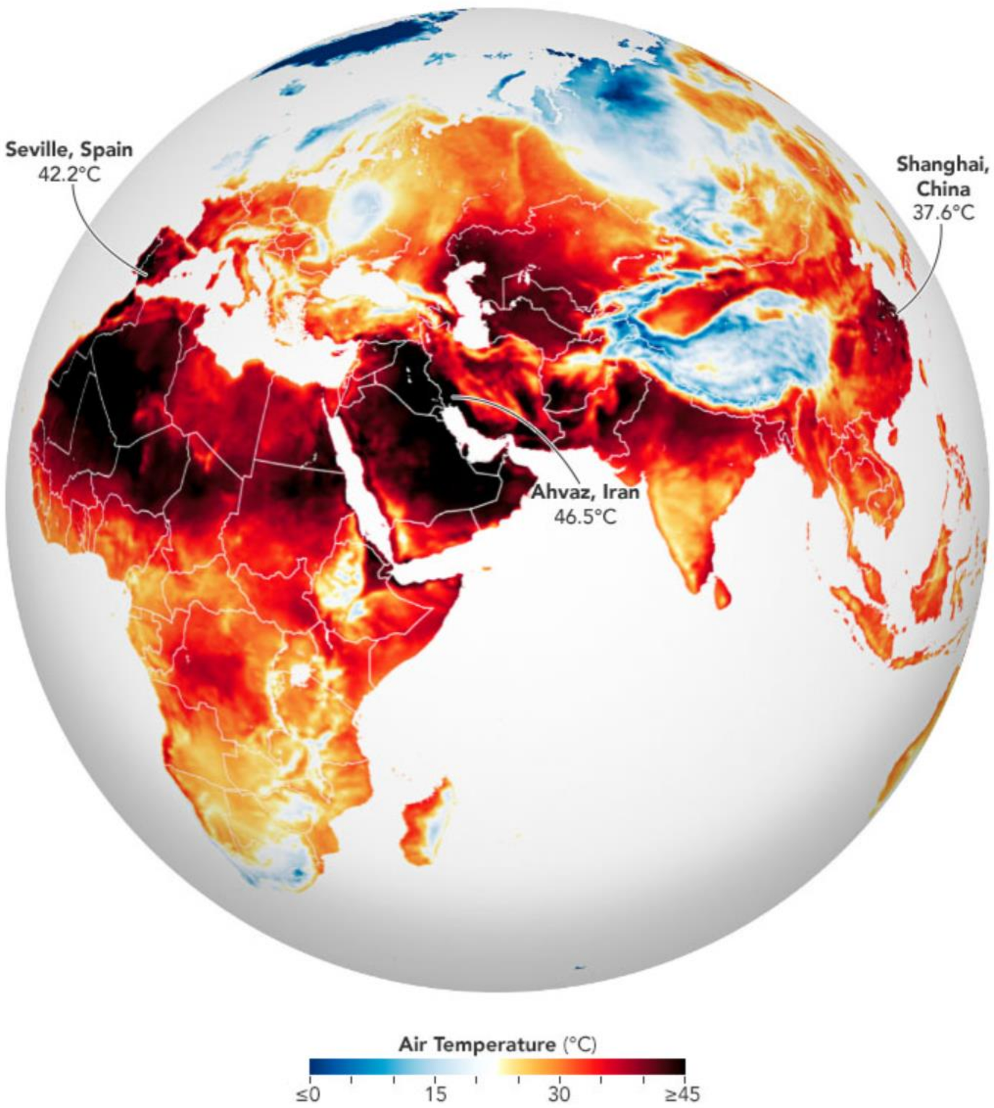
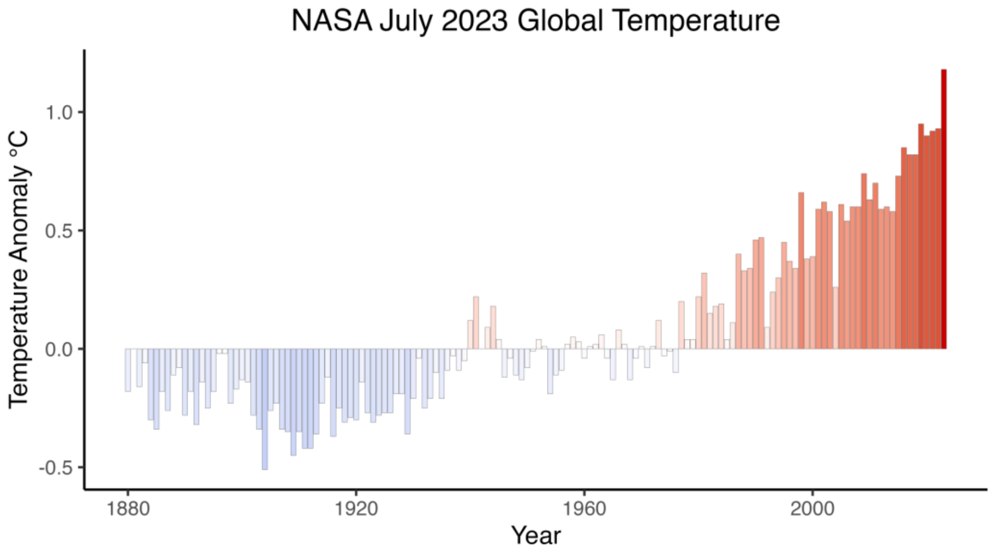
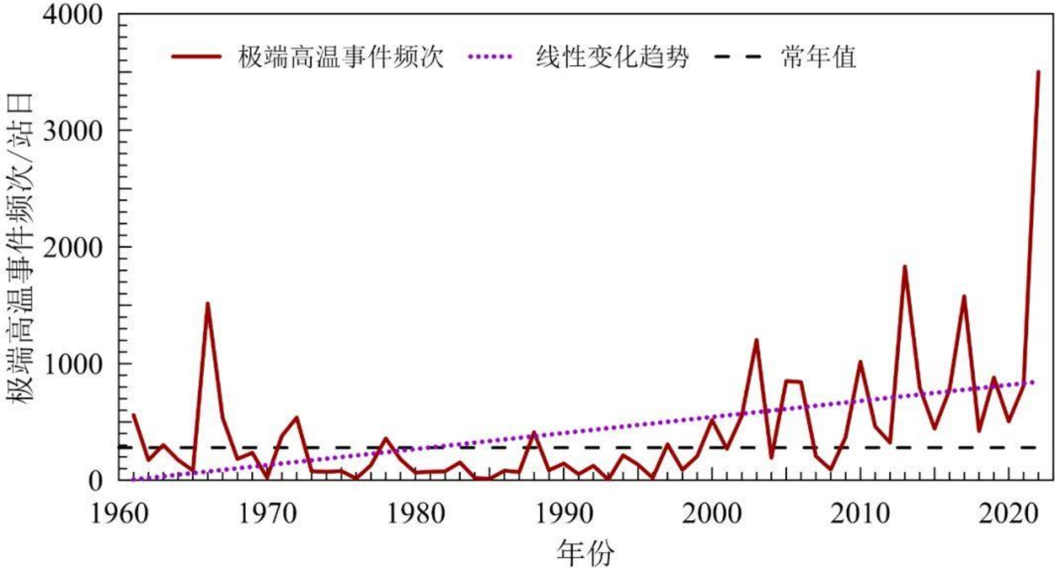
全球变暖与热浪



2022年7月13日，欧洲、非洲和亚洲大部分地区出现破纪录的极端热浪（NASA）

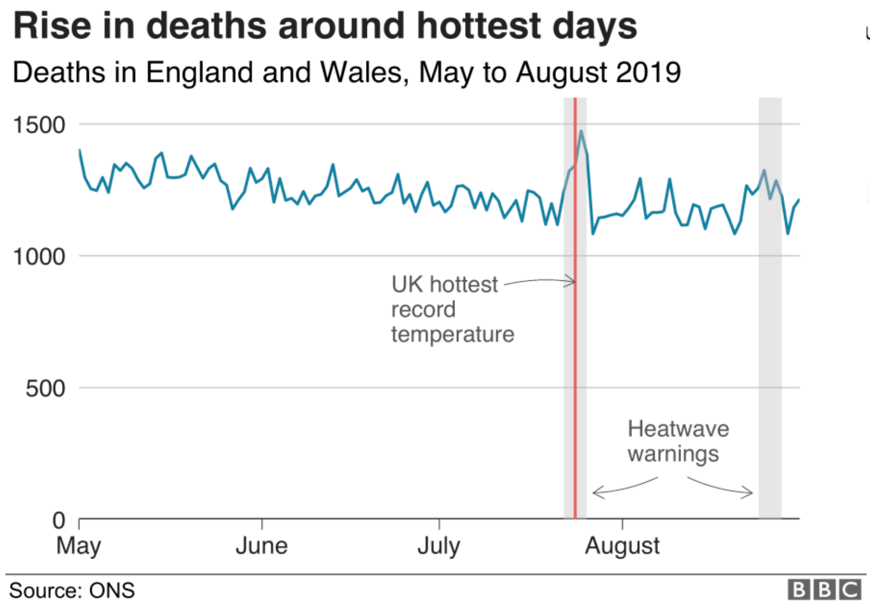


2023年7月的温度比历史任何其他7月都高0.24° C，比 1951-1980平均高1.18° C（NASA）

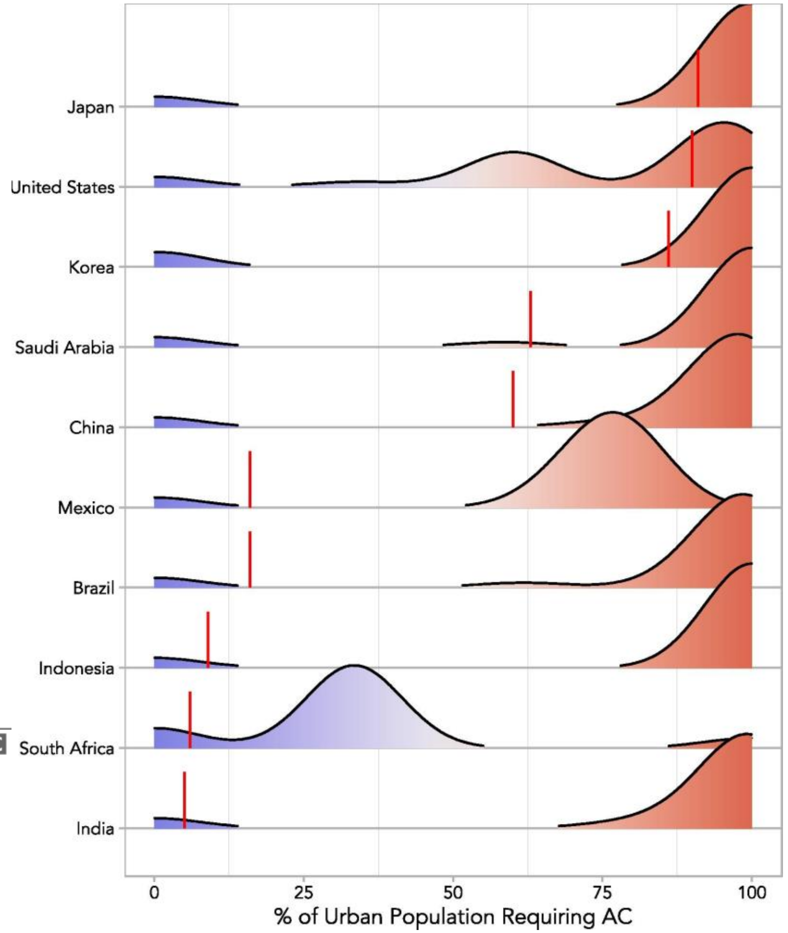


中国气候变化蓝皮书2023

热浪的危害



死亡人数在热浪天的显著增加

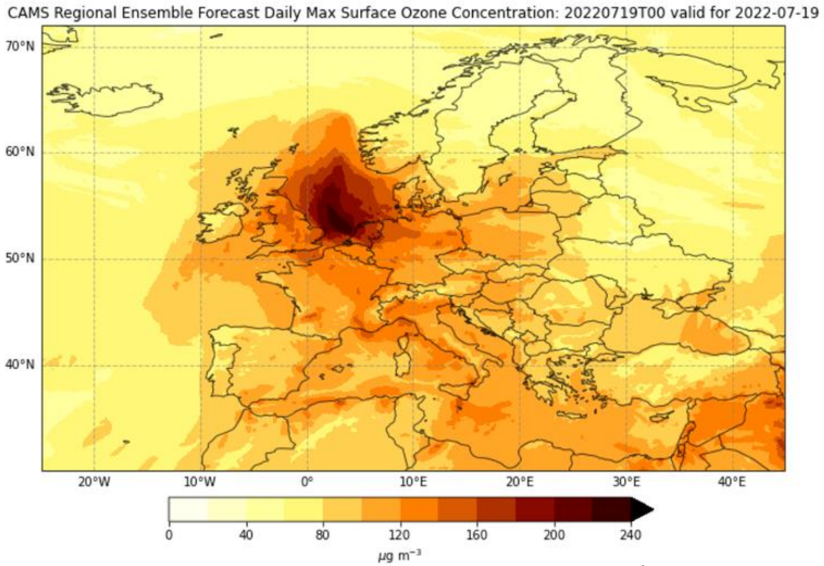


“救命”的空调在很多国家不够用（Sherman et al. 2022）

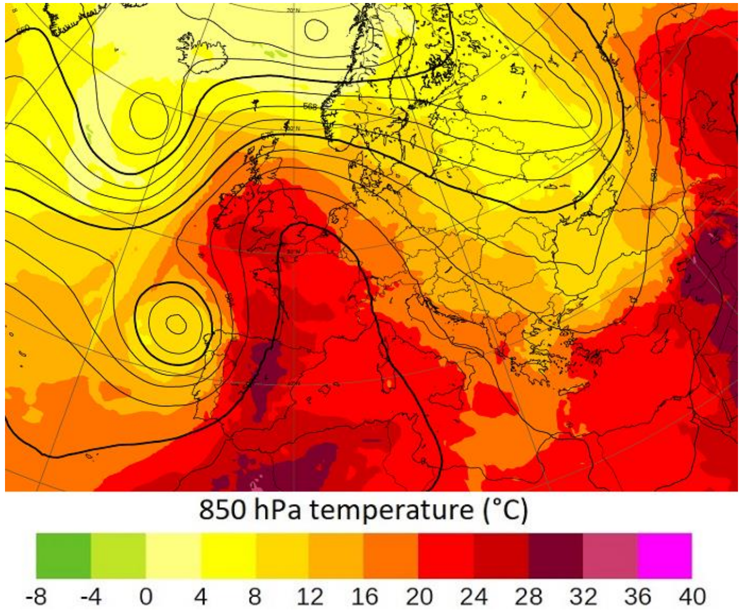
干旱、食品安全

2022年7月20日，斯洛文尼亚-意大利边境的大火

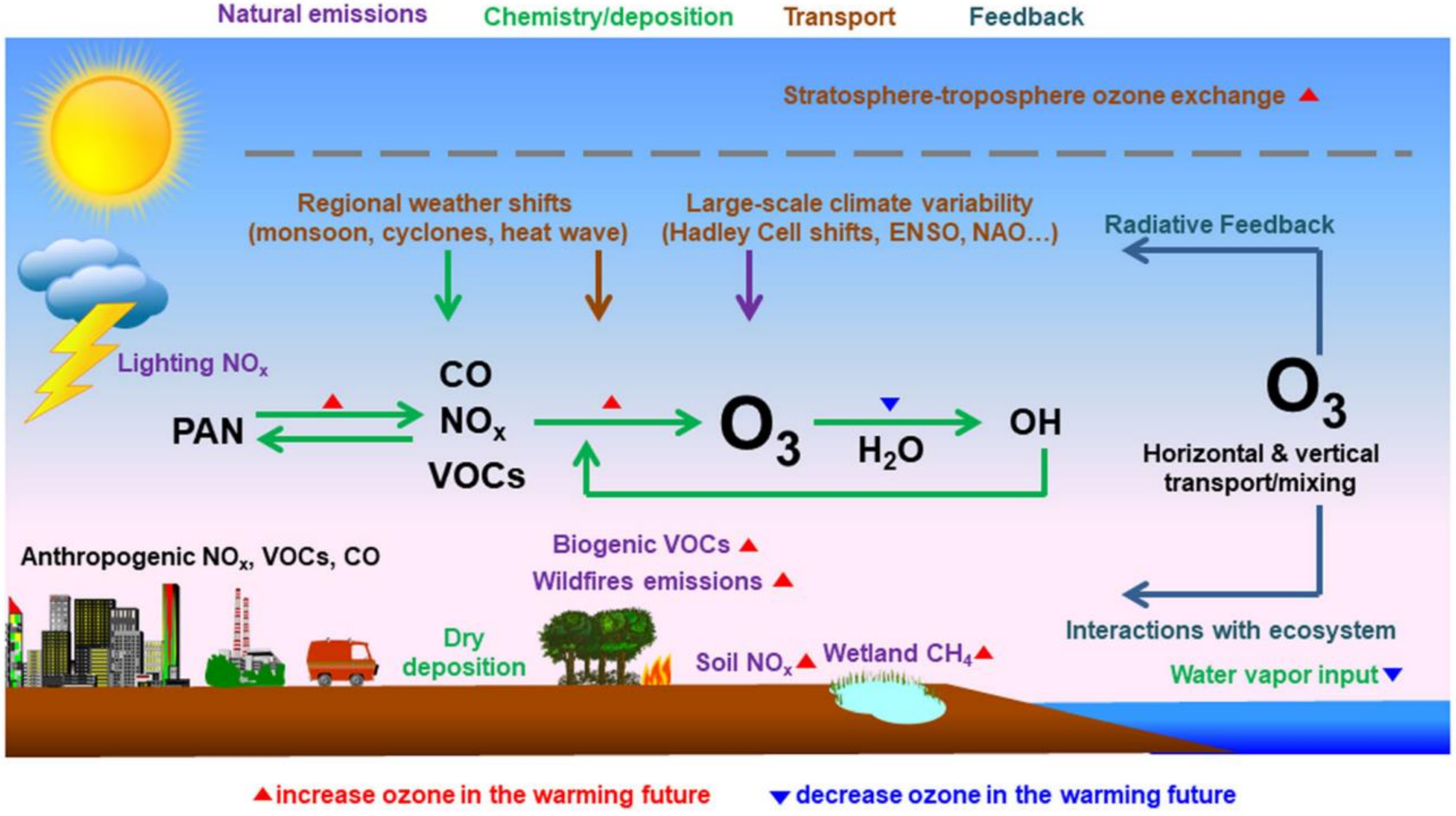
热浪与空气污染



CAMS预测2022年7月19日高臭氧浓度



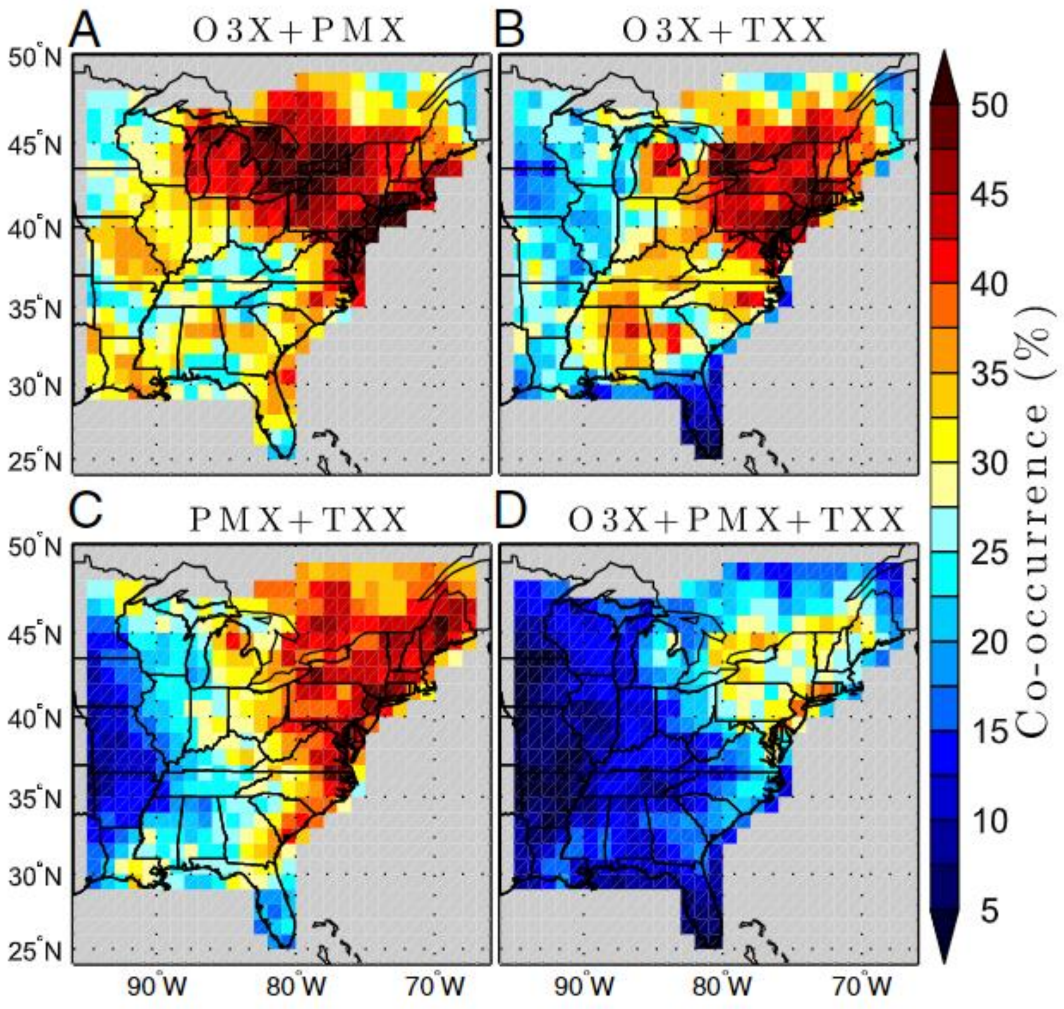
持续的高压系统影响



热浪多途径影响空气污染发展

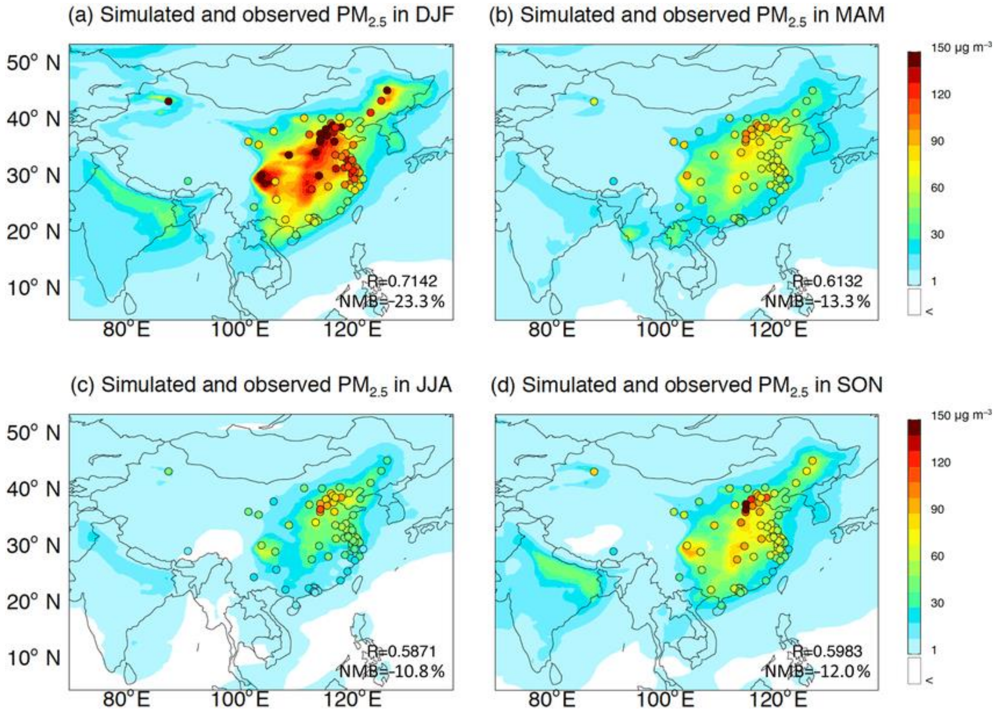
Lu et al., 2019

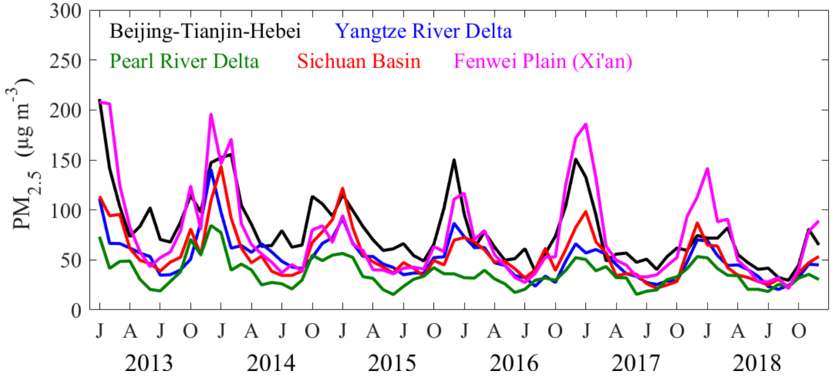
热浪与空气污染的复合事件



北美东部臭氧、颗粒物与温度复合极端事件

我国不同的污染特征





Schnell and Prather, 2017

颗粒物下降但是臭氧不断升高的趋势 Lu et al., 2018; Zhai et al., 2018

气候变化

紧密关联

空气污染

全球变暖下

全球热浪的频率、强度和持续时间将进一步增加

- 热浪与空气污染复合极端事件的历史趋势
- 同时暴露在复合极端事件下的交互健康影响
- 复合极端事件发生的季节性预测
- 世纪尺度下未来的复合极端事件与应对

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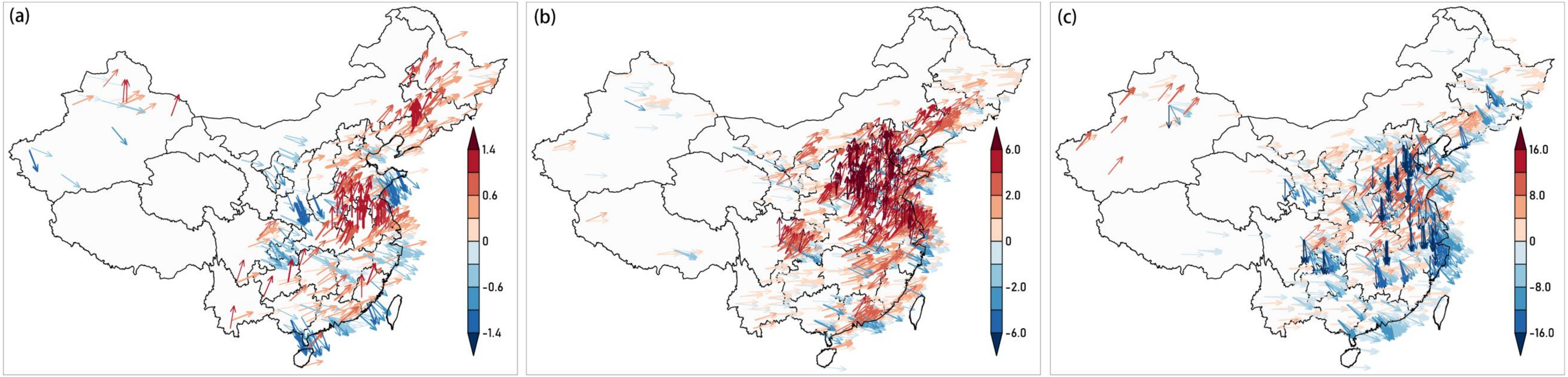
2013-2020年间湿球温度、臭氧与$PM_{2.5}$超标天数的变化



$$T_w = T\,\mathrm{atan}\left[0.151977\left(100\times\mathrm{RH}+8.313659\right)^{1/2}\right]+\mathrm{atan}\left(T+100\times\mathrm{RH}\right)-\mathrm{atan}\left(100\times\mathrm{RH}-1.676331\right)$$
$$+0.00391838\left(100\times\mathrm{RH}\right)^{3/2}\times\tan\left(0.023101\times100\times\mathrm{RH}\right)-4.686035, \quad (1)$$

Exceedance days: $T_w \geq 25$ ℃,

$PM_{2.5} \geq 75\ \mu g/m^3$,

8-hour maximum daily O_3 *(MDA8)* $\geq 160\ \mu g/m^3$

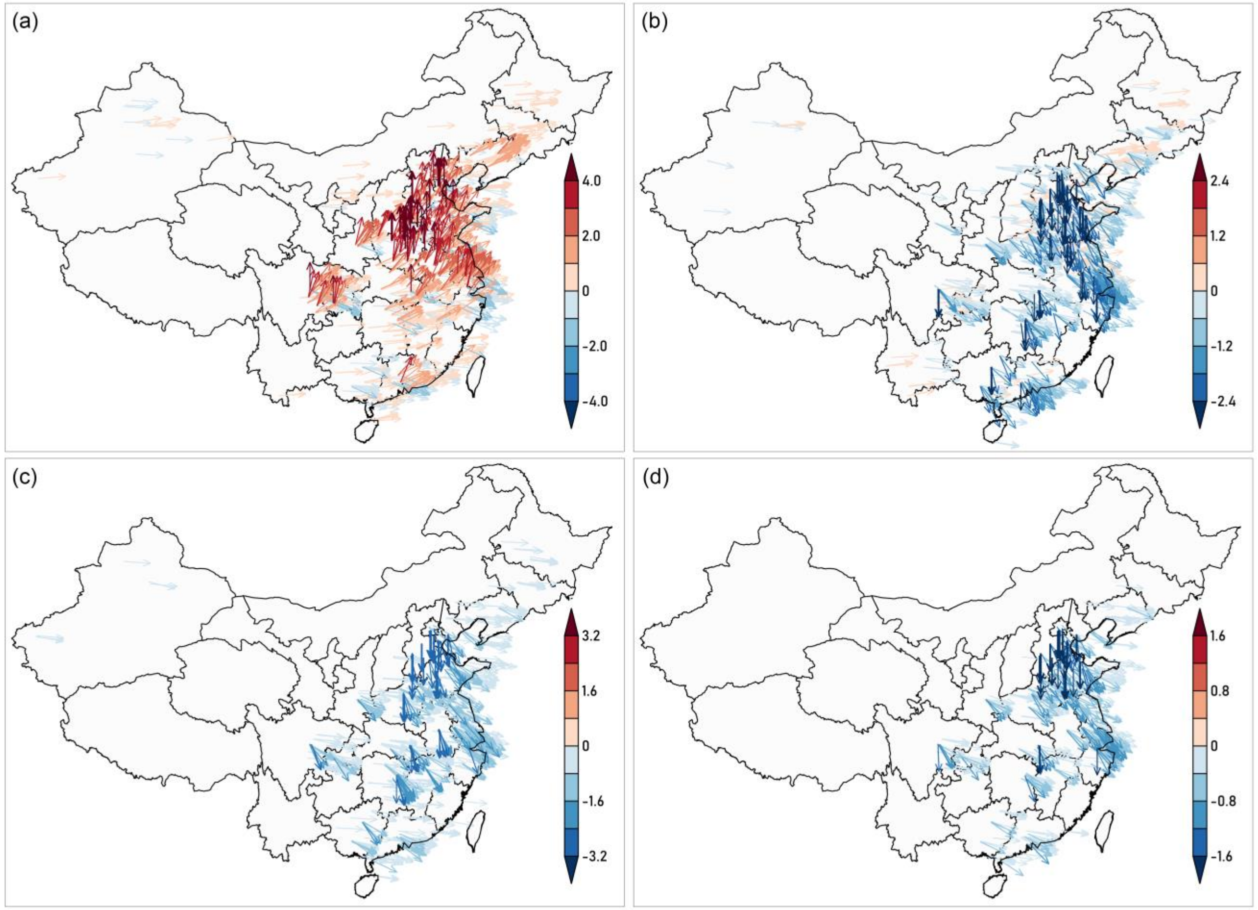
HUMAN TEMPERATURE

Relative Humidity	Air Temperature (F°) 70°	75°	80°	85°	90°	95°	100°	105°	110°	115°
	Apparent temperature									
10%	65°	70°	75°	80°	85°	90°	95°	100°	105°	111°
20%	66°	72°	77°	82°	87°	93°	99°	105°	112°	120°
30%	67°	73°	78°	84°	90°	96°	104°	113°	123°	135°
40%	68°	74°	79°	86°	93°	101°	110°	123°	137°	
50%	69°	75°	81°	88°	96°	107°	120°	135°	150°	
60%	70°	76°	82°	90°	100°	114°	132°	149°		
70%	70°	77°	85°	93°	106°	124°	144°			
80%	71°	78°	86°	97°	113°	136°	157°			
90%	71°	79°	88°	102°	122°	150°	170°			
100%	72°	80°	91°	108°	133°	166°				

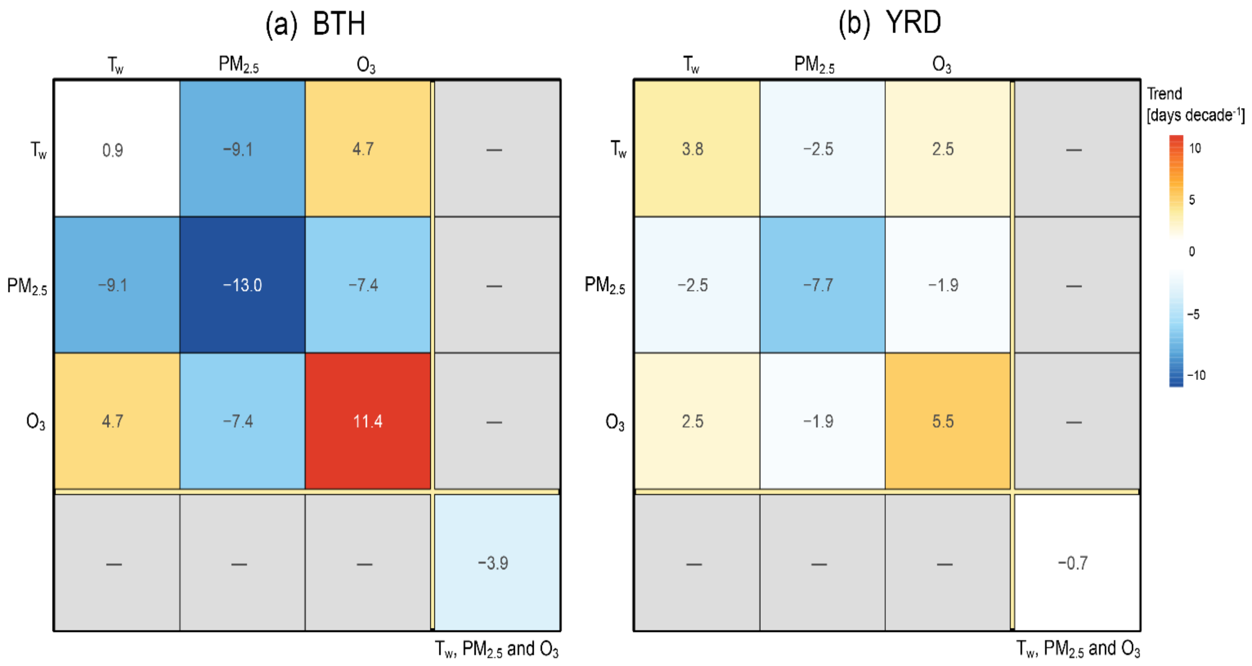
相对湿度对体感温度的影响

Xiao et al., BAMS, 2022

温度、臭氧与$PM_{2.5}$超标共同发生天数的变化



(a) Tw and O_3, (b) $PM_{2.5}$ and O_3, (c) Tw and $PM_{2.5}$, Tw, and (d) $PM_{2.5}$ and O_3



T_w and O_3 co-extremes increased by 7.0% in BTH, higher than the percentage increase of each at 0.9% and 5.5%, respectively

Xiao et al., BAMS, 2022

同时暴露于空气污染和热浪是否会放大健康影响，超出独立影响的总和？

气候变化

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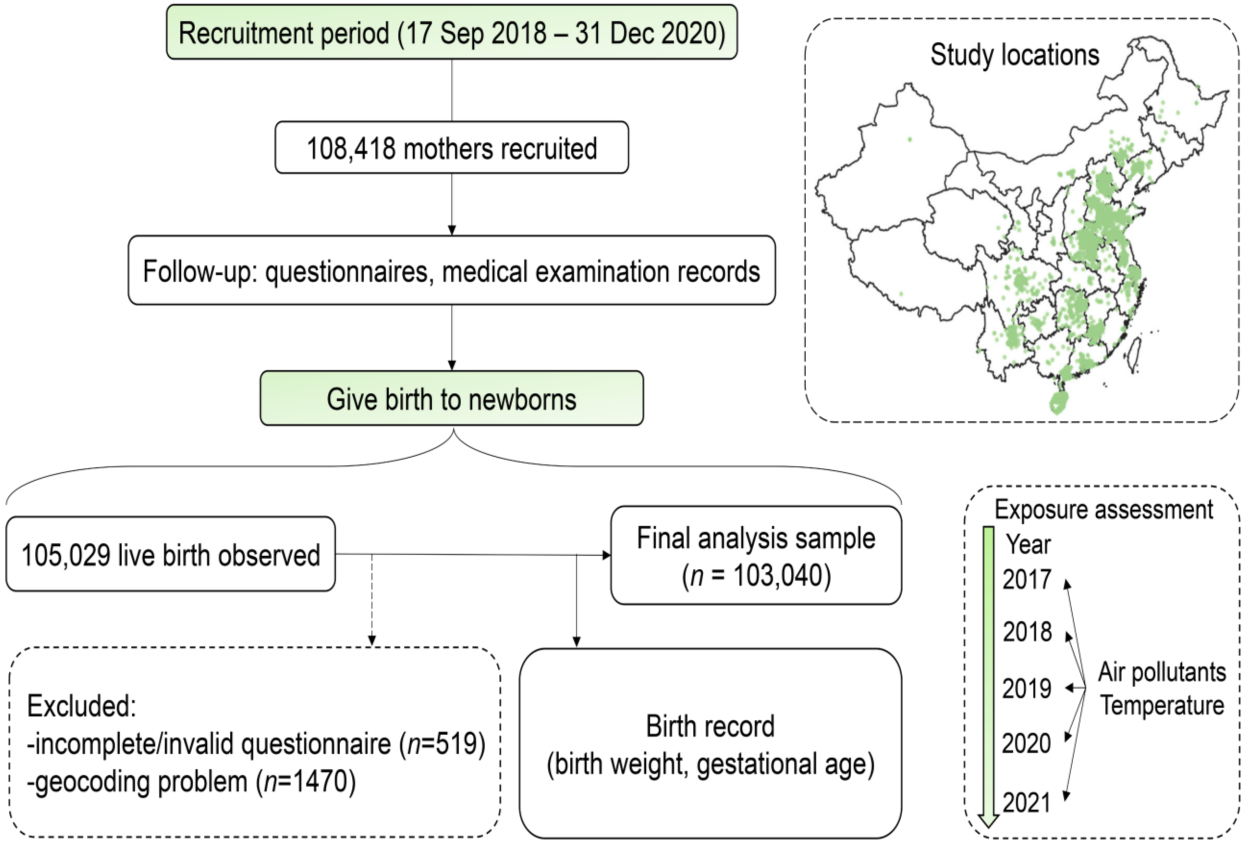
全国出生队列数据



Variable	Mean ± SD, n (%)			P
	Total (n=103040)	Term birth (n=96652)	Preterm birth (n=6388)	
Mothers				
Age (years)	30.7 (5.0)	30.7 (5.0)	31.2 (4.9)	<0.001
Pre-pregnancy BMI (kg/m^2)	21.8 (3.6)	21.8 (3.6)	22.1 (3.7)	<0.001
Gestational age (days)	274.6 (11.8)	276.6 (7.9)	243.7 (16.5)	<0.001
Ethnicity				0.16
Han	85943 (83.4)	80574 (83.4)	5369 (84.0)	
Others	17097 (16.6)	16078 (16.6)	1019 (16.0)	
Education				<0.001
Middle High school or lower	56125 (54.5)	52416 (54.2)	3709 (58.1)	
Higher education	46915 (45.5)	44236 (45.8)	2679 (41.9)	
Annual family income (CNY)				<0.001
<=100000	31415 (30.5)	29275 (30.3)	2140 (33.5)	
100000~400000	61352 (59.5)	57673 (59.7)	3679 (57.6)	
>=400000	10273 (10.0)	9704 (10.0)	569 (8.9)	
Environmental tobacco exposure	41270 (40.1)	38632 (40.0)	2638 (41.3)	0.037
Working time (hours/week)	39.9 (10.9)	39.9 (11.0)	39.6 (10.6)	0.037
Sex of newborn (Boys)	53650 (52.1)	50085 (51.8)	3565 (55.8)	<0.001
Environmental factors				
Use of air purifier (yes)	23132 (22.4)	21821 (22.6)	1311 (20.5)	<0.001
Close to main road (yes)	32685 (31.7)	30670 (31.7)	2015 (31.5)	0.764
Noise disturbance (yes)	5924 (5.7)	5558 (5.8)	366 (5.7)	0.966
$PM_{2.5}$ (μg/m^3)[a]	37.7 (17.9)	37.8 (17.7)	36.2 (20.6)	<0.001
O_3 (μg/m^3)[a]	62.2 (26.4)	62.4 (26.2)	59.1 (29.7)	<0.001
NO_2 (μg/m^3)[a]	31.6 (11.8)	31.7 (11.6)	30.2 (13.8)	<0.001
Temperature (°C)[a]	16.4 (9.4)	16.4 (9.4)	16.7 (9.7)	0.001

Xiao et al., ERL, 2023

定义与统计分析

- 定义:
  - 早产: 在妊娠37周之前分娩(Goldenberg et al. 2008).
  - 怀孕三月期:
    - 孕早期: 0 – 13 周
    - 孕中期: 14 – 27 周
    - 孕晚期: 28 – 分娩

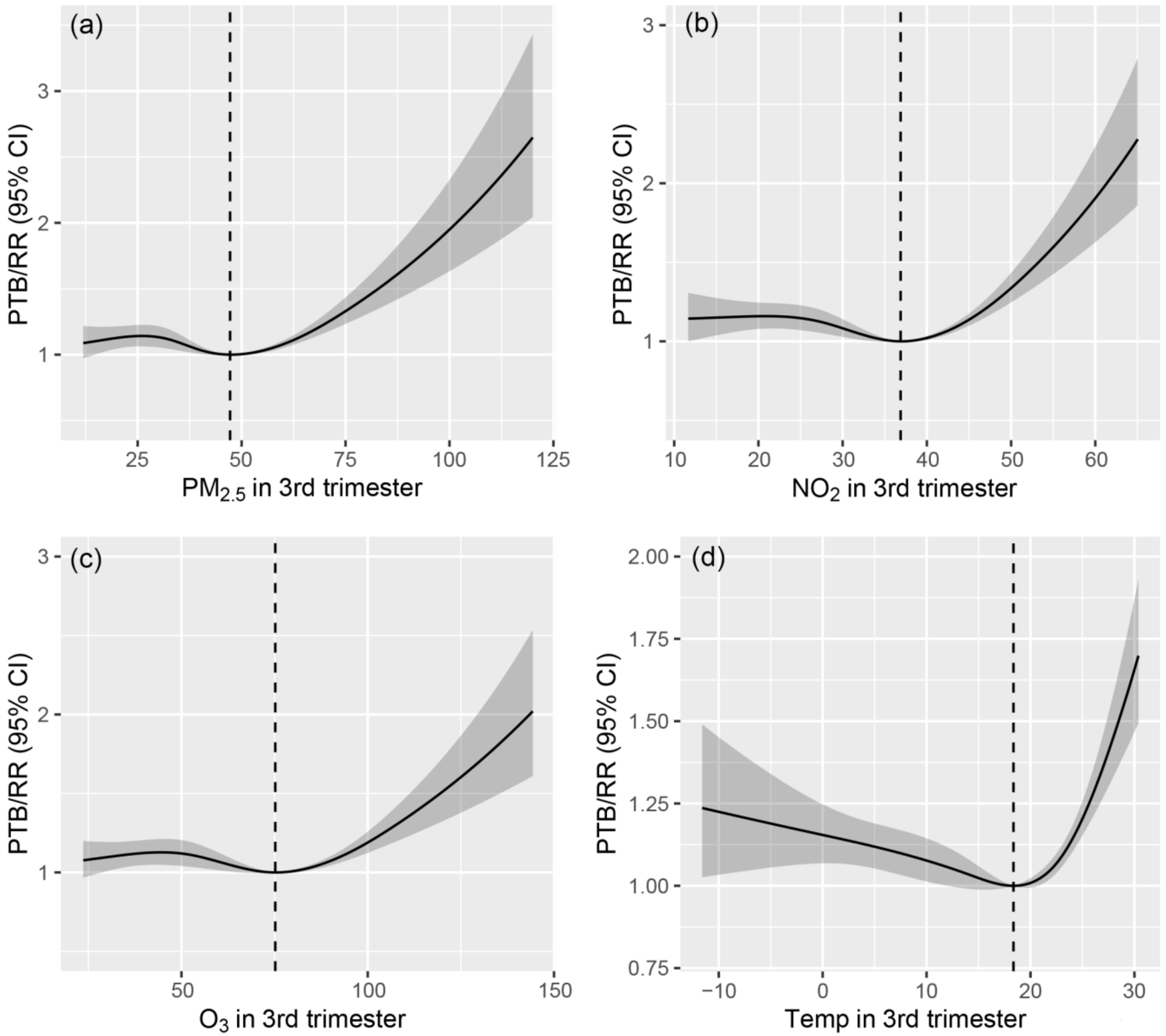
- 统计分析
  - Generalized additive models (GAMs) combined with restricted cubic spline (RCS) function
    - Potential threshold effect

  - Relative risk (RR) and 95% confidence intervals (CI) of preterm birth
    - 75th, 80th and 95th percentiles of exposure against the threshold concentration.

  - Relative excess risk due to interaction (RERI), Attributable proportion (AP) of additive effects
    - RERI > 0 indicating the combined effects were higher than that of each exposure alone

Xiao et al., ERL, 2023

孕晚期暴露重要性



- Exposures in late pregnancy showed the most significant impact on PTB
- U-shaped link between air pollutants and PTB.
- More prominent patterns were observed in associations with temperature.
  - exposure to both heat and cold temperature extremes could increase the risks of PTB
- Higher exposure, higher risk increasing rate

Xiao et al., ERL, 2023

交互健康影响

Relative excess risk (RERI, 95% CI) and attributable proportion (AP, 95% CI) due to interaction of temperature and air pollutant exposure on preterm birth.

	RERI (95% CI)		AP (95% CI)	
Variable	Adjusted[a]	Crude	Adjusted[a]	Crude
$PM_{2.5}$–HT	0.11 (0.07, 0.14)	0.06 (0.03, 0.10)	0.10 (0.07, 0.14)	0.06 (0.03, 0.10)
O_3–LT	0.16 (0.12, 0.20)	0.13 (0.09, 0.17)	0.17 (0.13, 0.21)	0.13 (0.10, 0.17)
O_3–HT	0.07 (0.03, 0.10)	0.07 (0.04, 0.11)	0.07 (0.03, 0.10)	0.07 (0.03, 0.10)

[a] Adjusted for maternal age, ethnicity, education, income, environmental tobacco exposure, residential proximity to main roads and domestic use of air purifier.

- Synergistic effects were detected for $PM_{2.5}$–High Temperature (HT), O_3–HT and O_3–Low Temperature (LT).
- PM toxicity might increase with higher temperature
- O_3 could increase oxidative and inflammatory stress, acting synergistically with low and/or high temperature extremes

Xiao et al., ERL, 2023

我们能否预见或预测空气污染和热浪的共同发生以避免交互健康损伤？

气候变化

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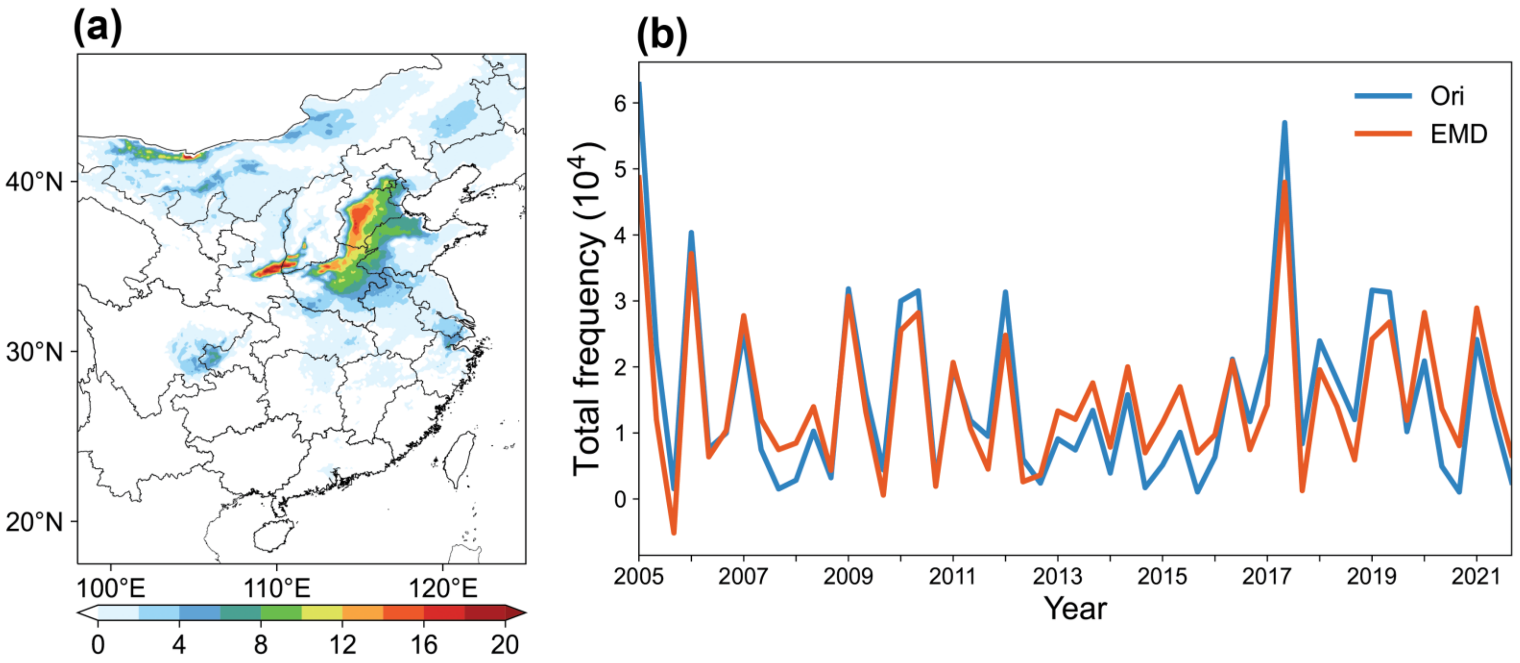
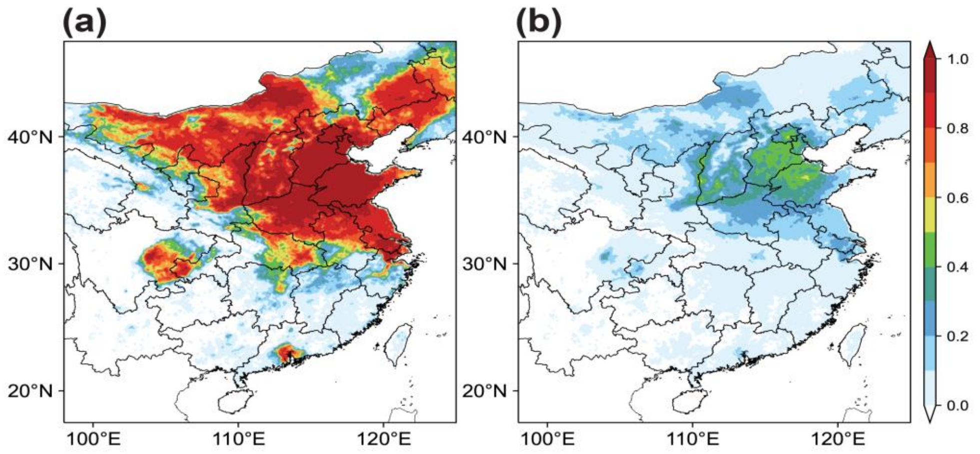
理解复合事件的共同发生意义重大

- 生态环境部标准: MDA8 $O_3 \geq 160$ μg m^{-3}
- 中国气象局热浪定义: daily maximum T2m ≥ 35 °C for at least three consecutive days
- When both heat wave and O_3 pollution occurred on the same day, that day was recorded as one co-occurrence day

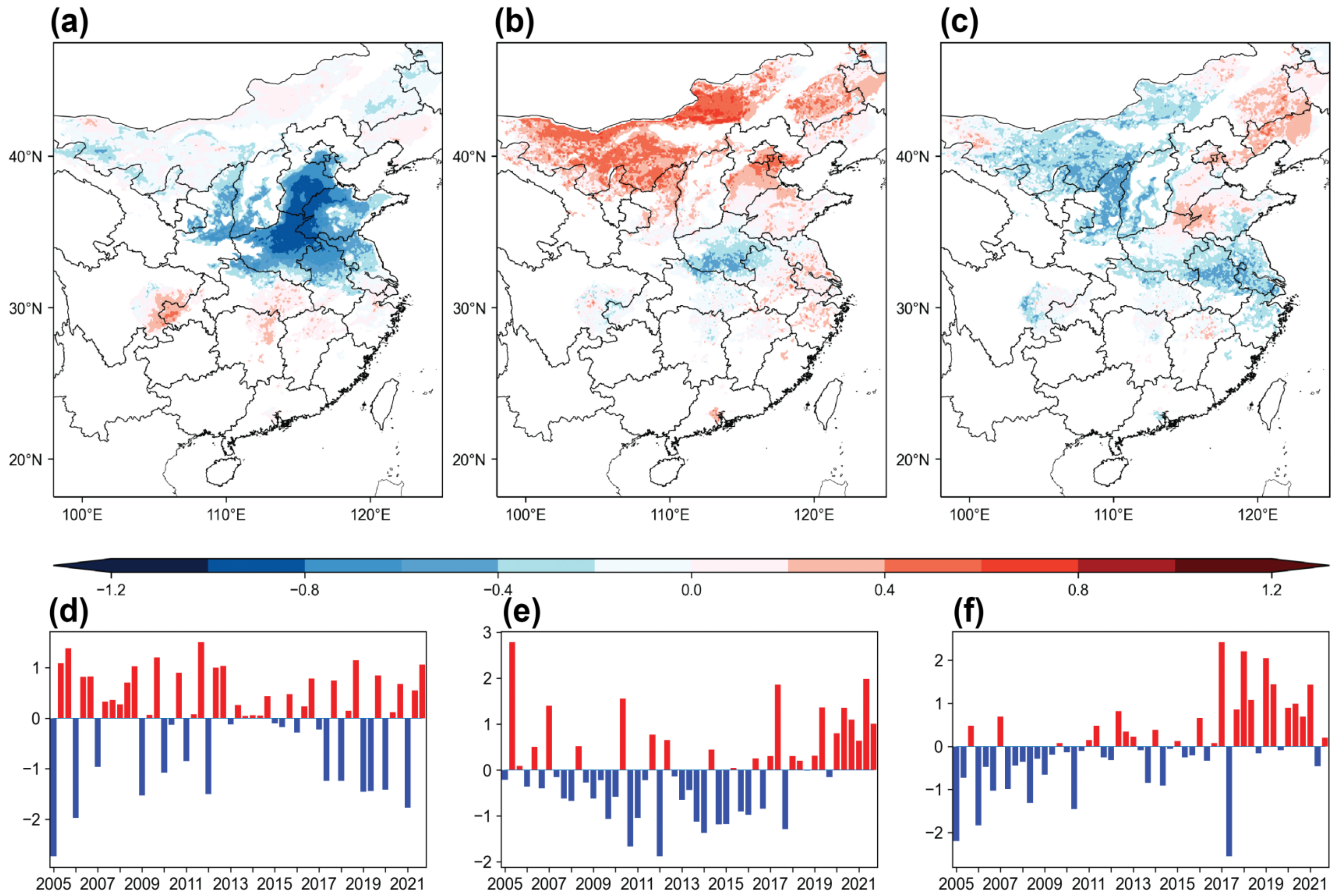




co-occurrence happens predominately (>80%) on heat wave days, while the share in all O_3 pollution days is ~50 %

Gao et al., PNAS, 2023

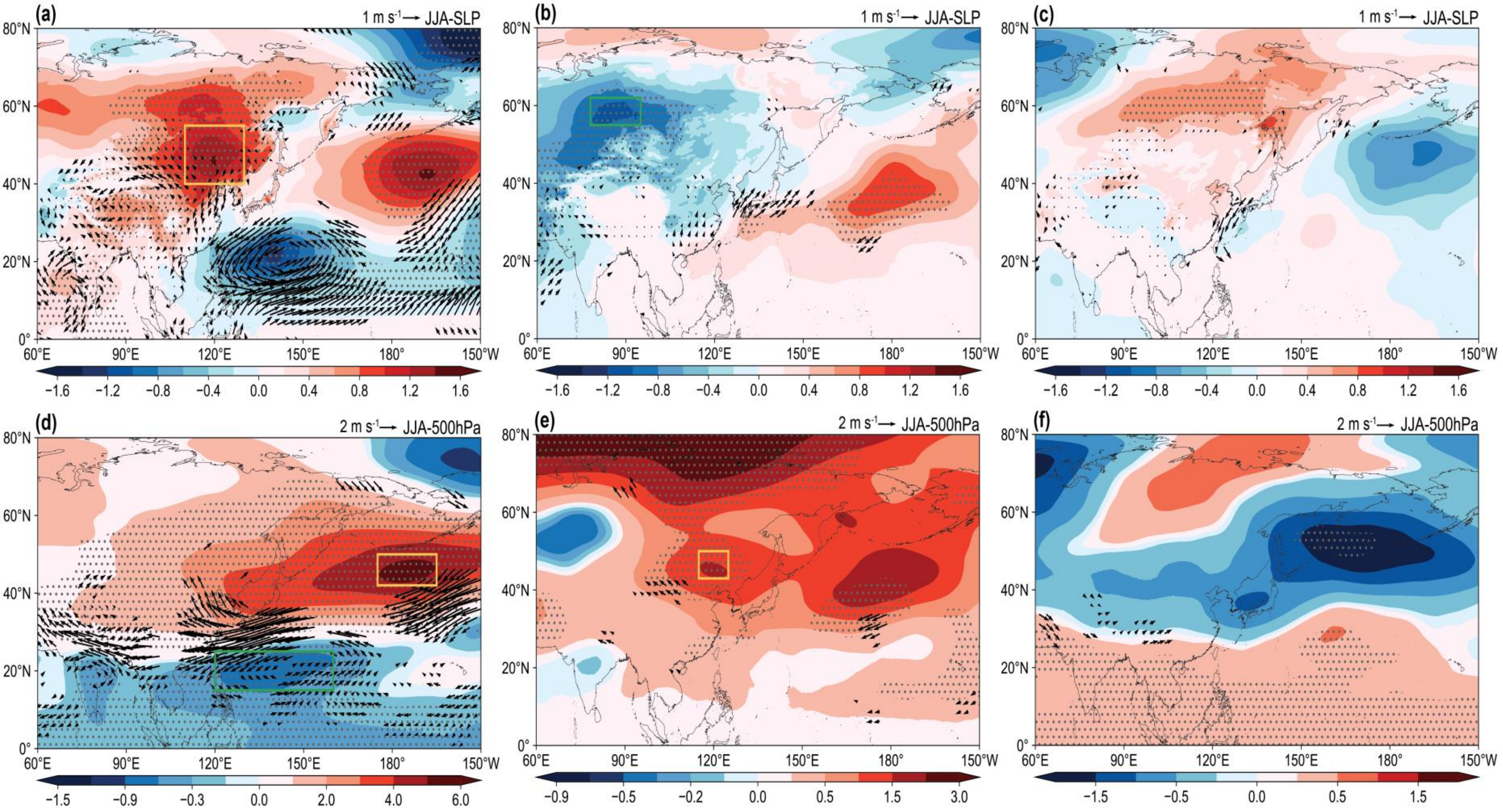
EOF分解去趋势的2005-2021年间月热浪、臭氧复合事件



- First three modes contribute 36%, 8% and 6% to the total
- EOF1: dipole feature, negative NCP but positive Yangtze River Basin
- Opposite values between June and July-August, location of the rain belt

Gao et al., PNAS, 2023

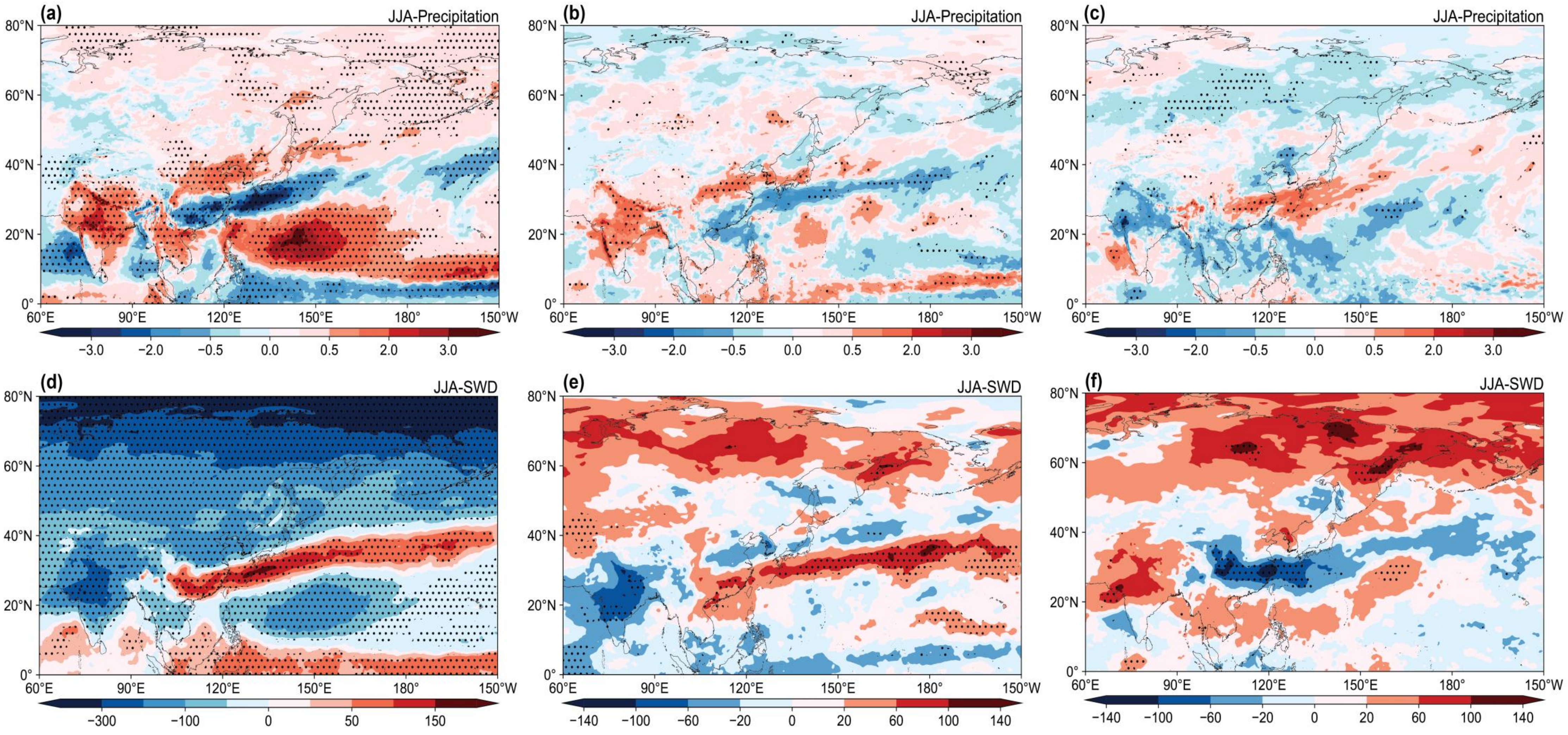
SLP, Z_{500}, winds and SST异常与主成分的回归



- PC1: weakened Western Pacific Subtropic High (WPSH) but strengthened North Pacific Subtropic High (NPSH)
- Modulates winds north and south of 30°N, leading to enhanced moisture transported to the NCP but weakened to the YRB.

Gao et al., PNAS, 2023

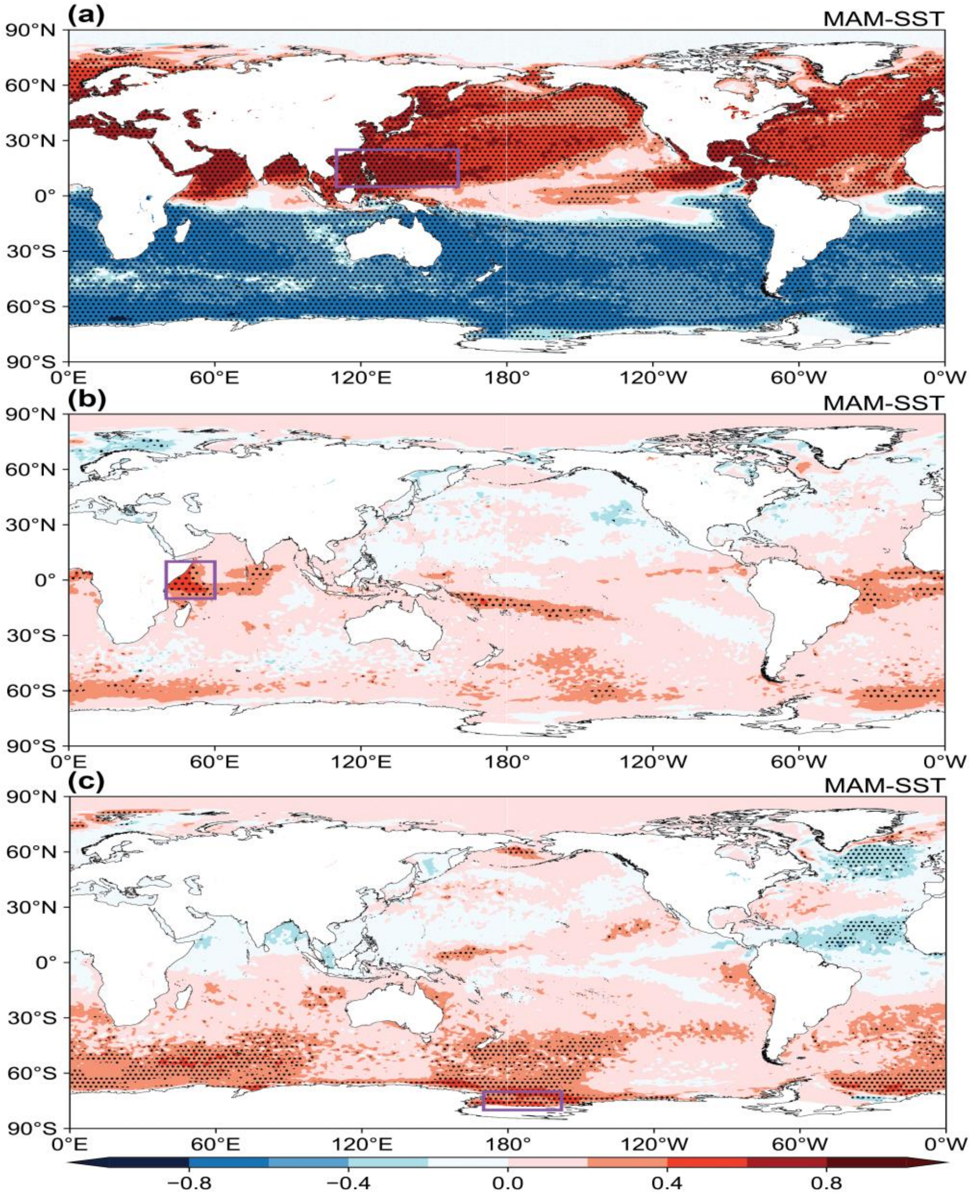
降水和向下短波辐射异常与主成分的回归

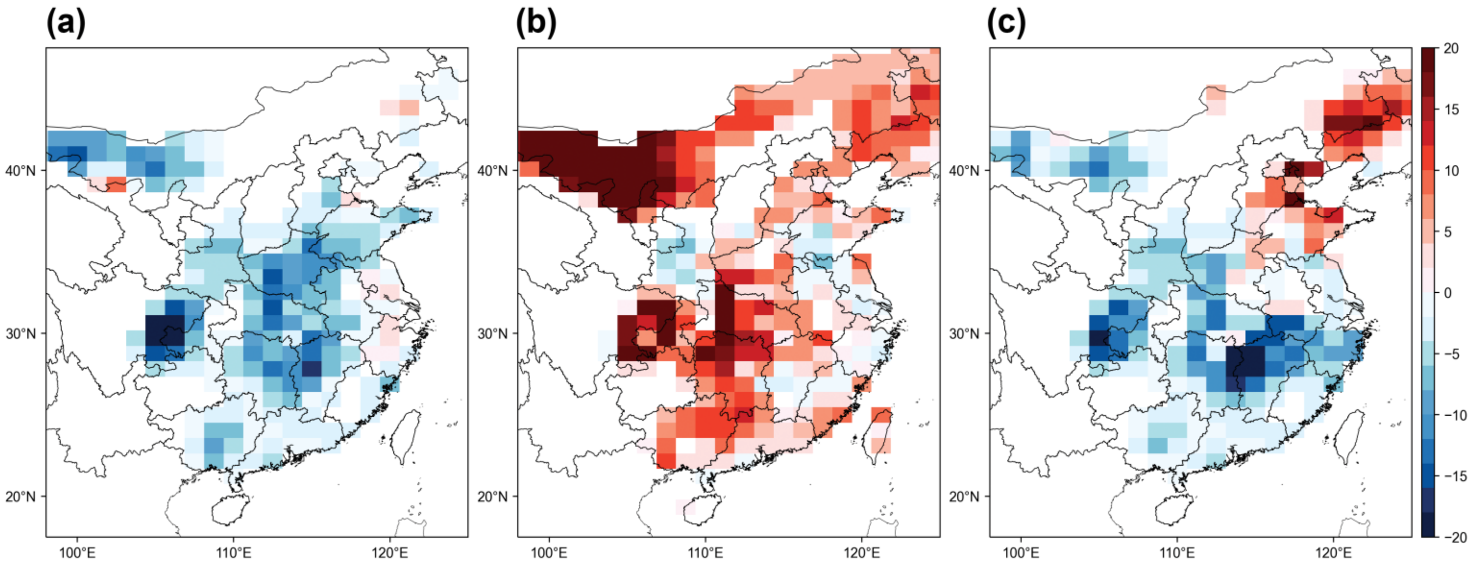


Precipitation is enhanced in the NCP but decreased in the YRB

Gao et al., PNAS, 2023

CESM模型耦合实验



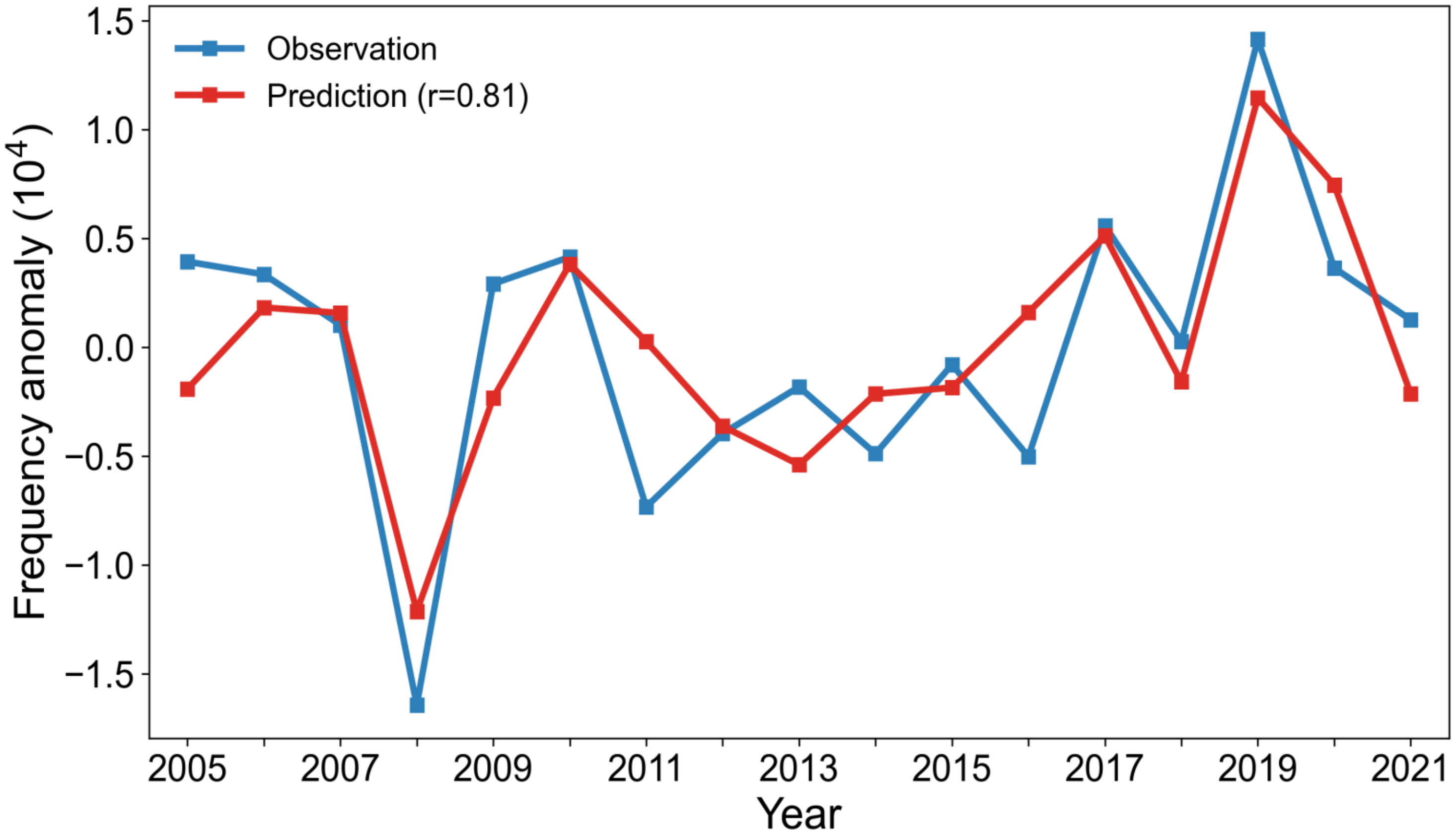


- Warming in the West India Ocean and associated northward WPSH
- Warming in the Ross Sea and associated Southward WPSH

Associated with decomposed modes, four sets of simulations were designed with SST in spring, namely $CESM_{ctrl}$, $CEMS_{wp}$, $CESM_{wi}$ and $CESM_{Ross}$. $CESM_{ctrl}$ was the control case that forced with SST data from monthly varying climatology.

Gao et al., PNAS, 2023

季节性预测模型的构建



$$HWOF = a_0 + a_1 SST_{wp} + a_2 SST_{wi} + a_3 DMI + a_4 SST_{Ross}$$

海温的记忆性

Gao et al., PNAS, 2023

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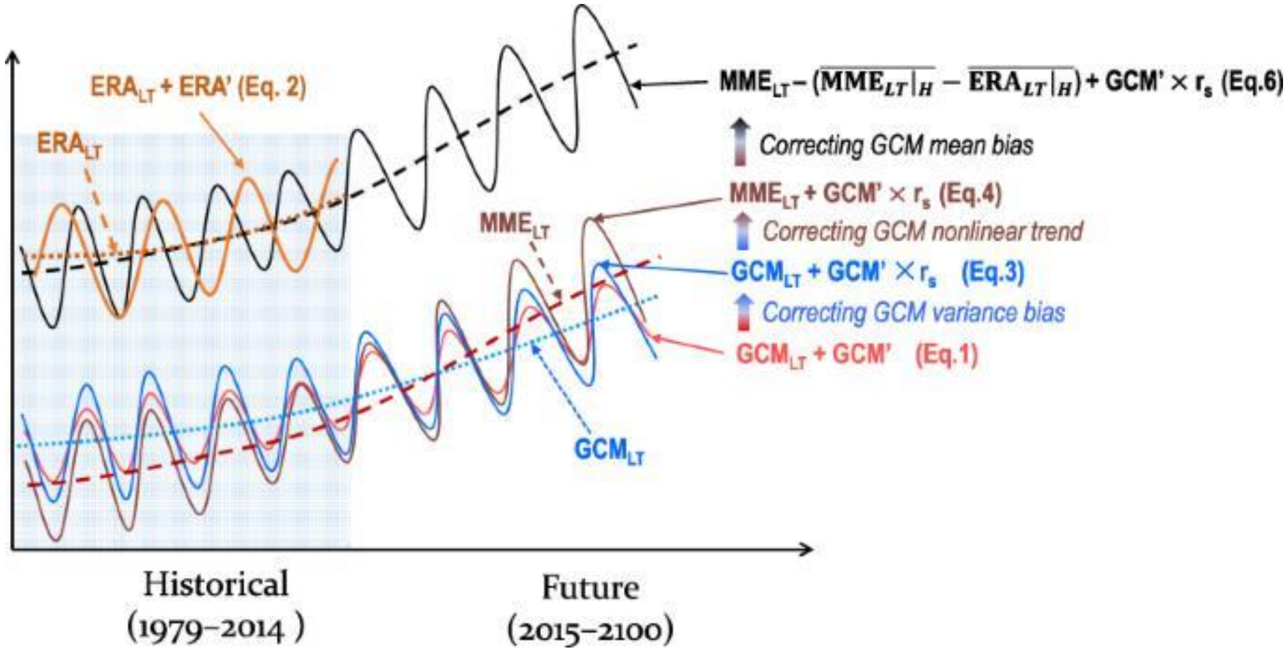
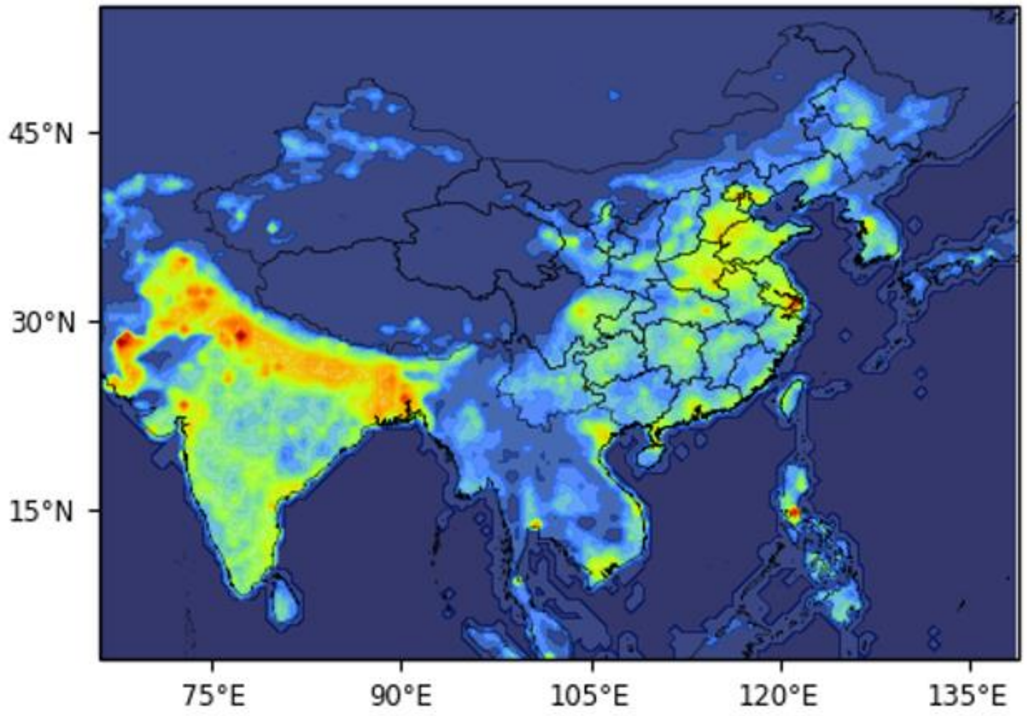
本世纪末的情形？

不同气候模式的未来预估存在较大差异



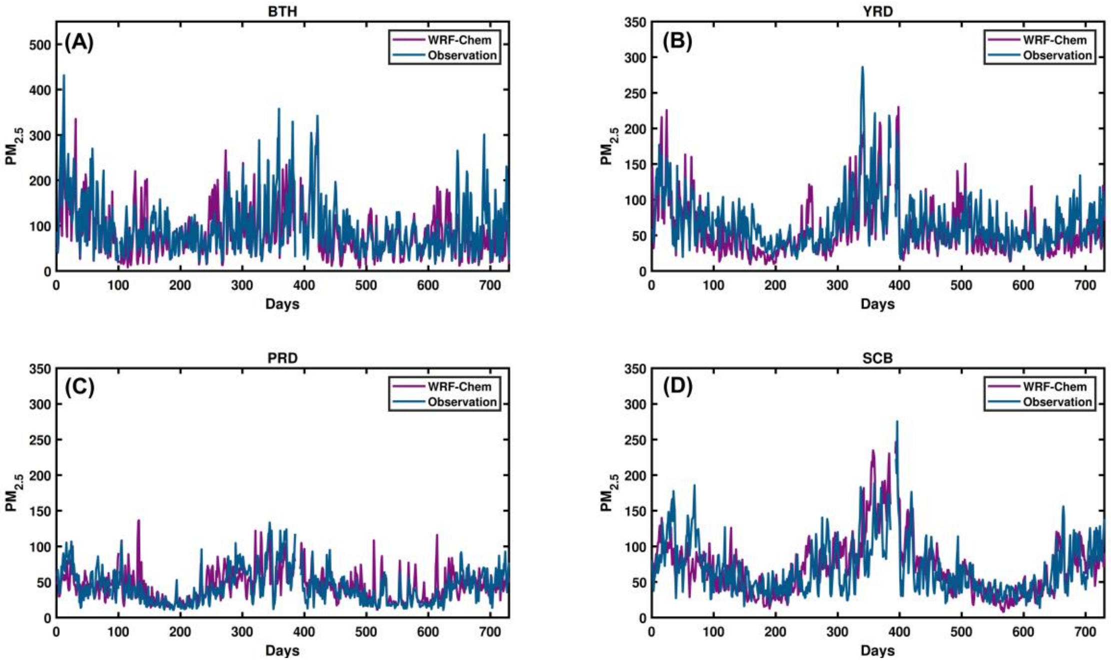
Bias-corrected CMIP6 global dataset for dynamical downscaling of the historical and future climate (1979–2100), Xu et al., 2021

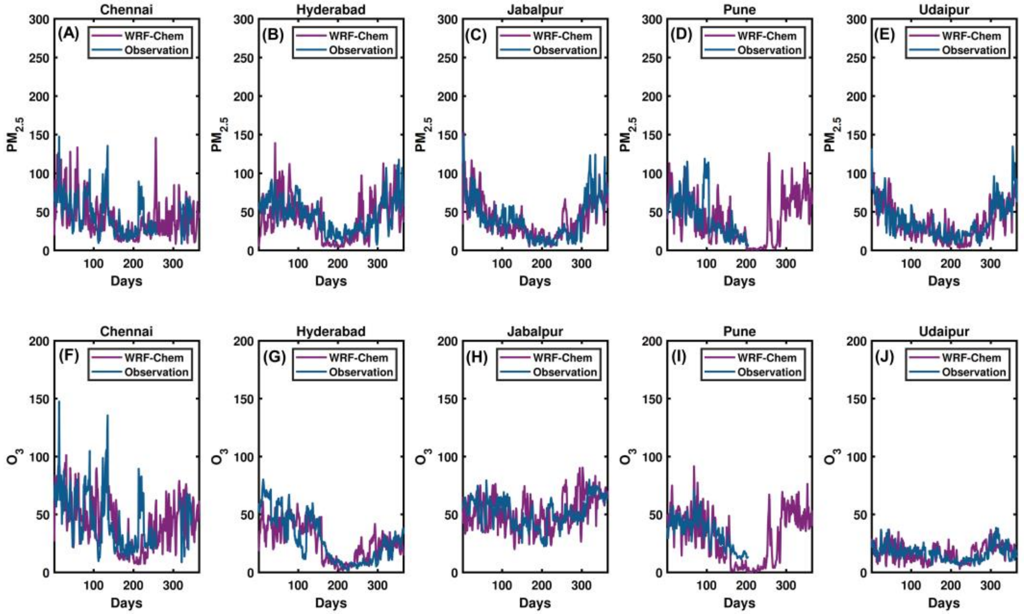


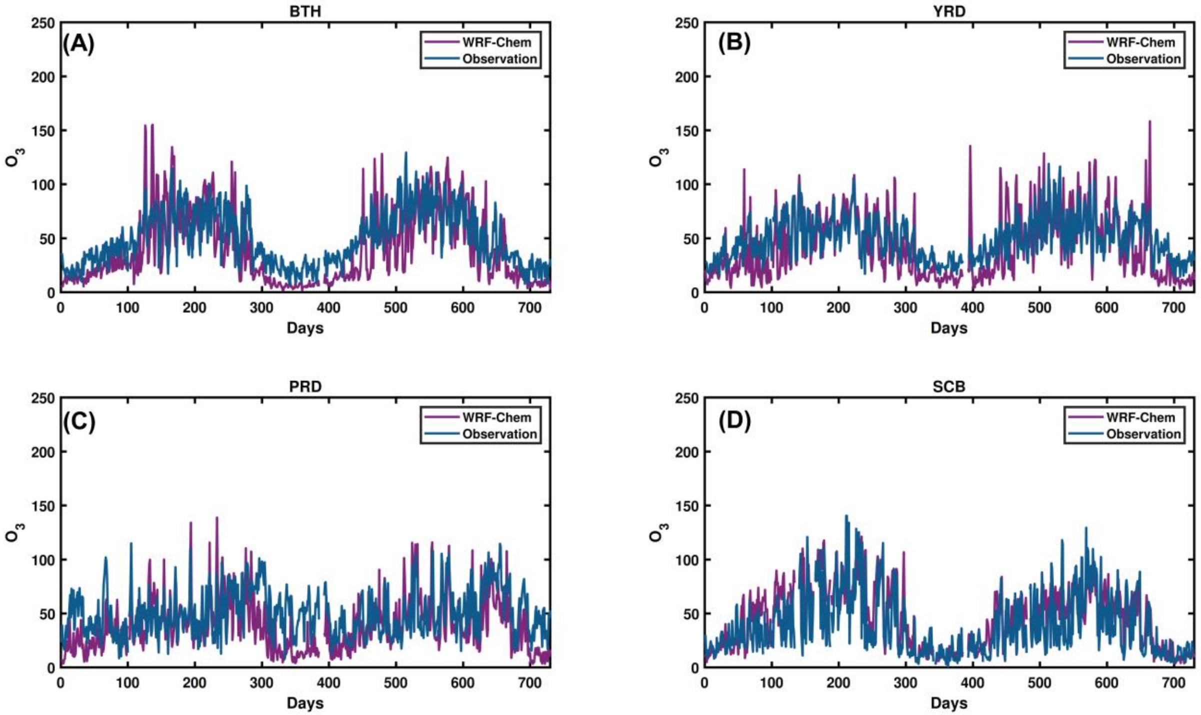
WRF-Chem downscaling
Present day: 2010-2014, five years
Future: 2096-2100, five years
SSP 245: Middle of the Road (Medium challenges to mitigation and adaptation)
SSP 585: Fossil-fueled Development – Taking the Highway

Gao et al., under review

模型验证2013-2014

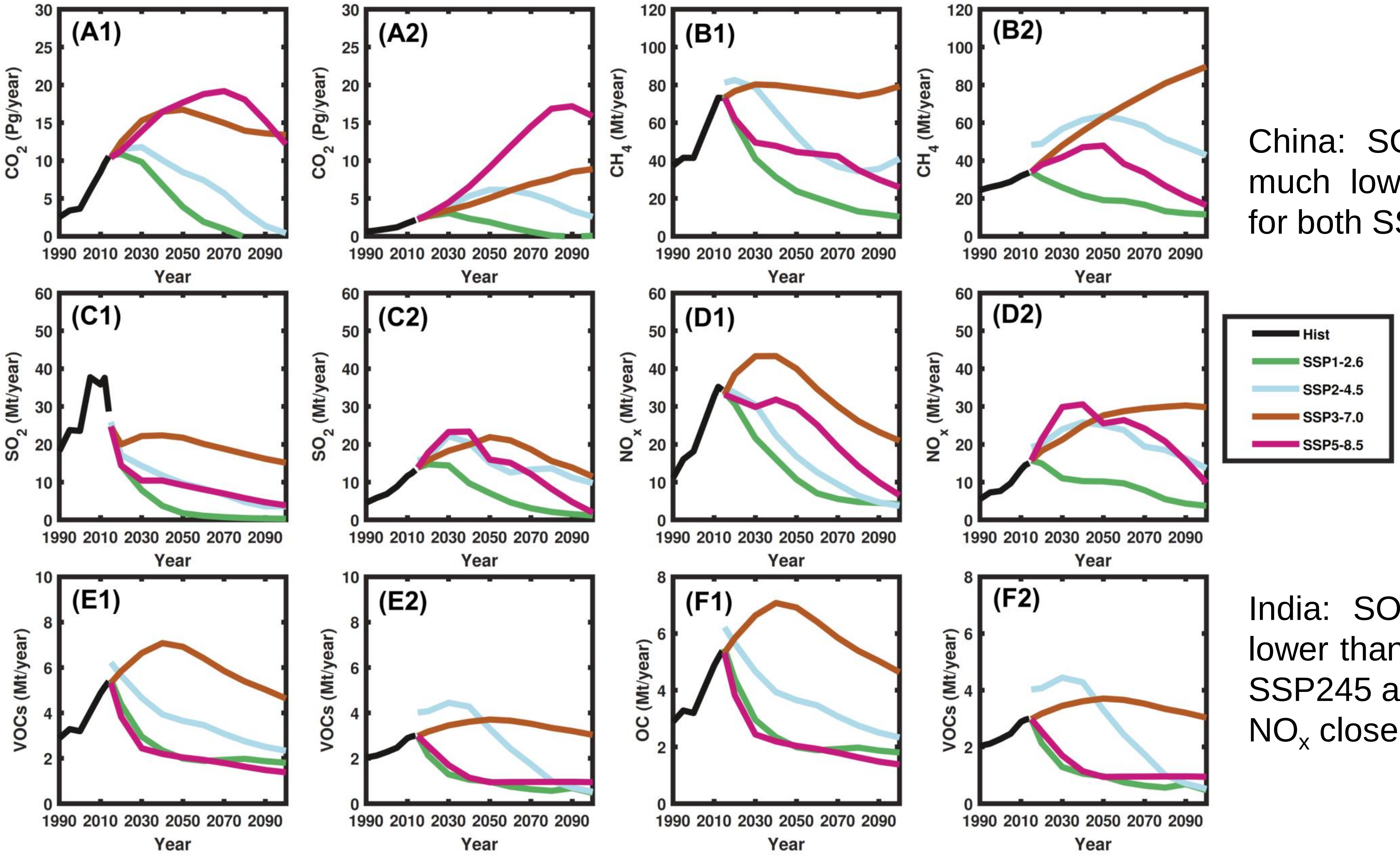






Gao et al., under review

不同SSP情景排放的变化



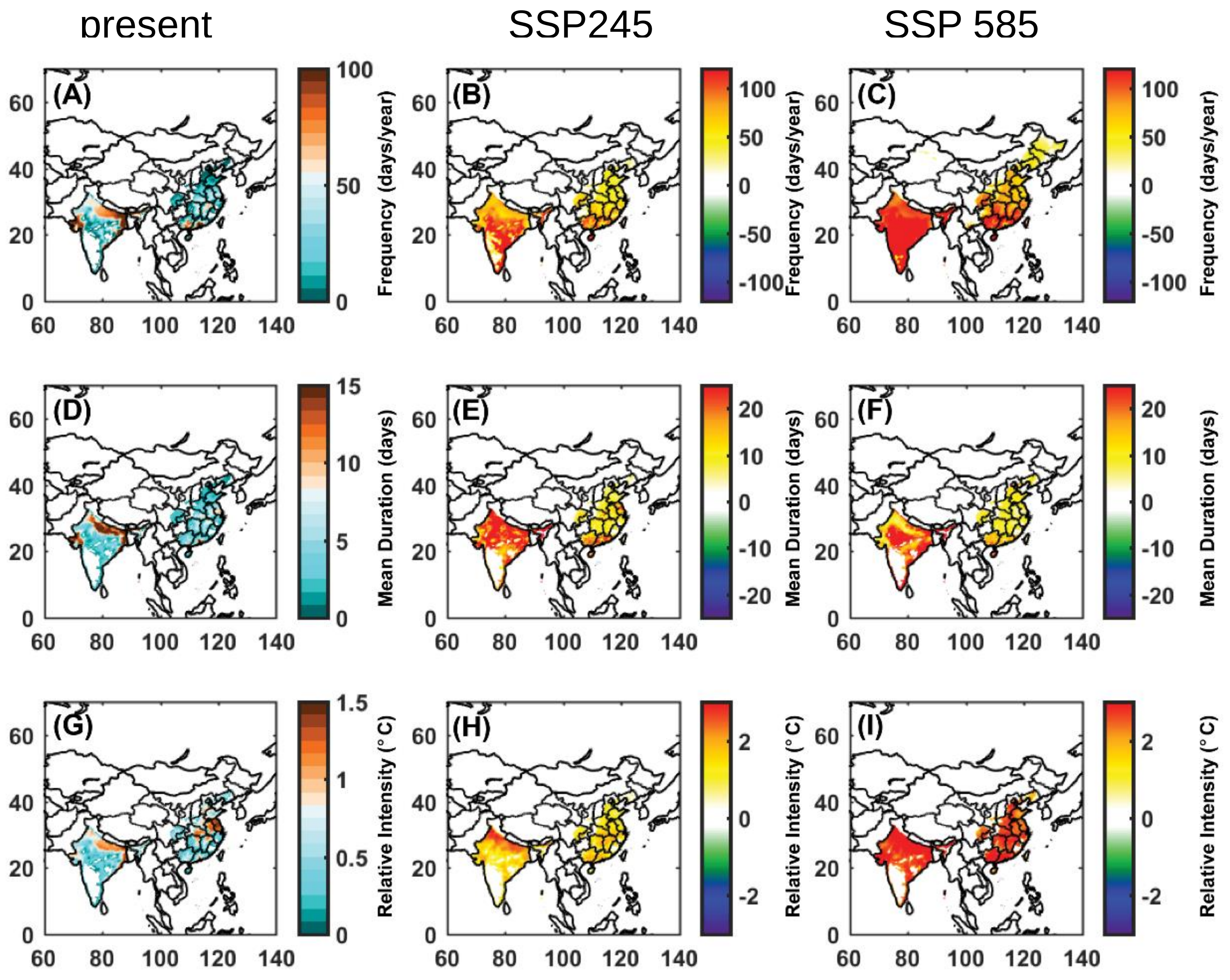
China: SO_2, NO_x, VOCs, OC much lower than present day for both SSP245 and SSP585

India: SO_2, VOCs, OC much lower than present day for both SSP245 and SSP585

NO_x close to present day

Gao et al., under review

湿球温度未来变化



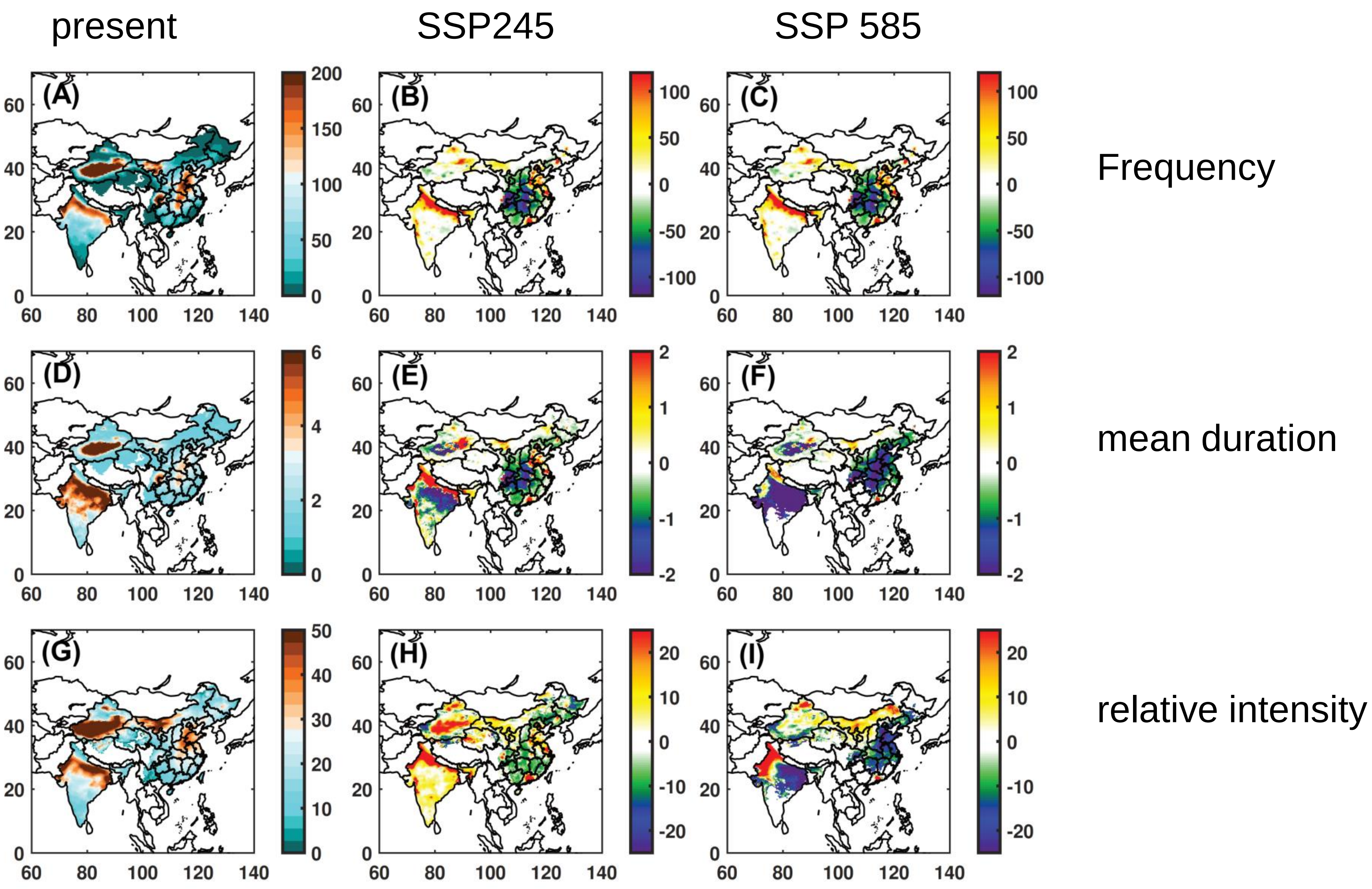
Frequency (days/year)

mean duration (number of consecutive days)

relative intensity (severity above the threshold)

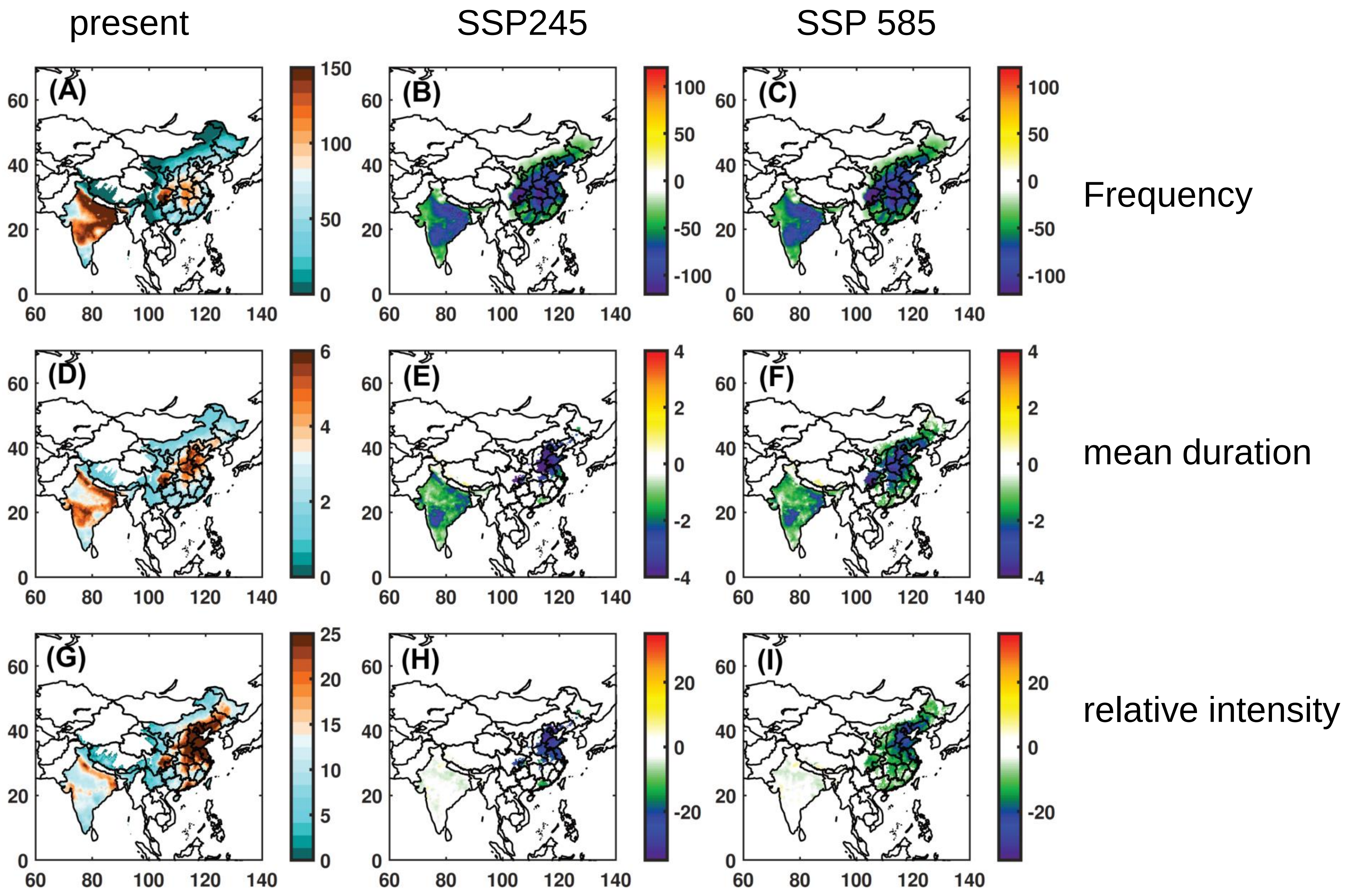
Gao et al., under review

$PM_{2.5}$未来变化



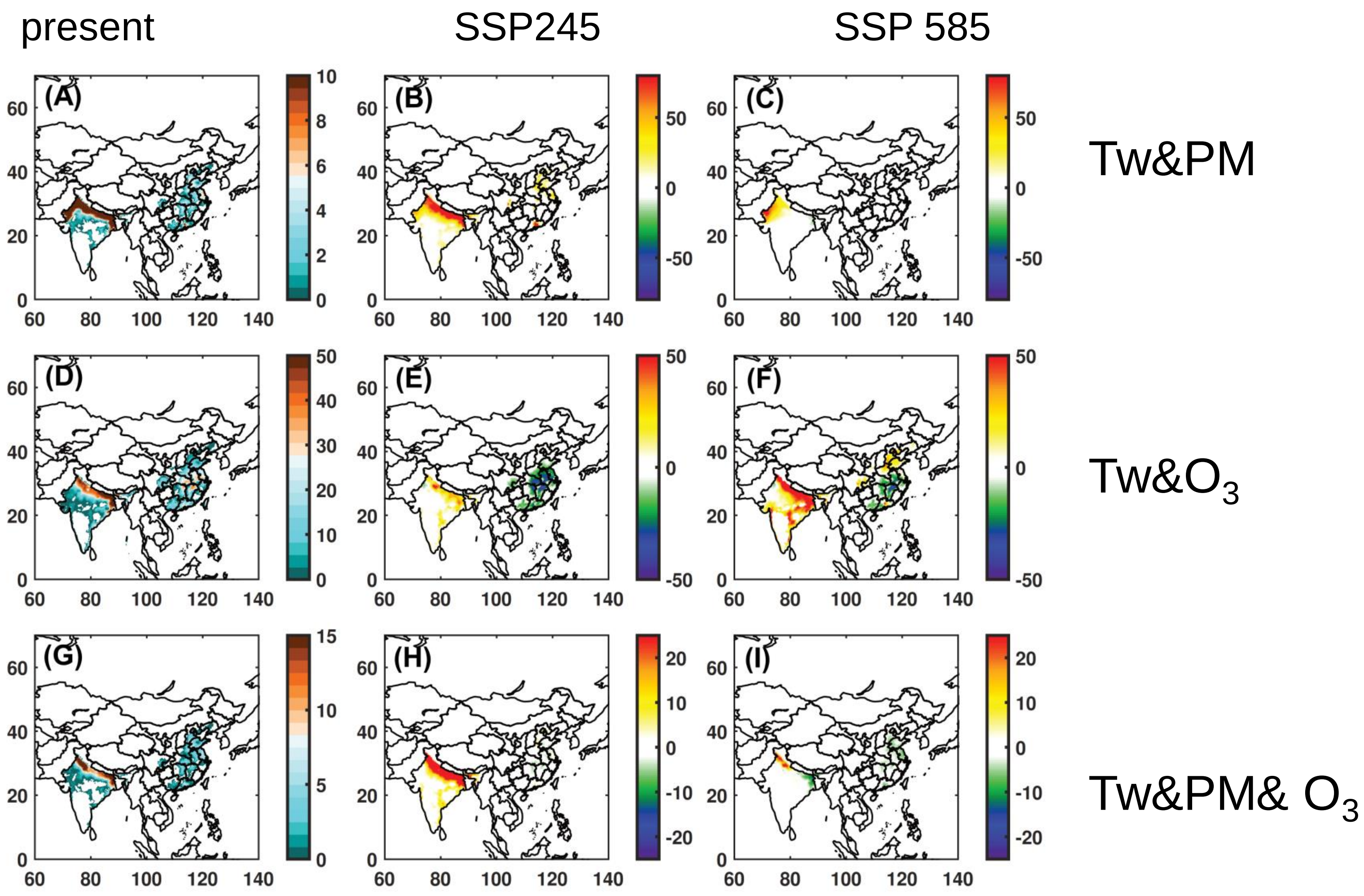
Gao et al., under review

臭氧未来变化



Gao et al., under review

大气污染与热浪复合事件未来趋势



Although levels of PM and Ozone will decline by the end of century due to emission control, co-occurrences of stressors will increase, particularly in populous NCP and IGP

Gao et al., under review

全球变暖下污染防控的挑战

全球热浪的频率、强度和持续时间将进一步增加

年均浓度下降，极端污染仍然可能发生

复合极端事件应当引起重视