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Contributions of trans-boundary transport to summertime air quality in Beijing, China

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Supplementary Information Section

The supplementary information (SI) section provides additional descriptions about the high $PM_{2.5}$ formation process in Beijing on July 8 and 11, 2015, and the model simulations for the episodes from 5 to 14 July 2015 using 2013 emission inventory (EI) and from 22 to 28 May 2015 using 2015 EI.

Section SI-1: Model Simulations on July 8 and 11, 2015

Further analyses are provided to interpret the high $PM_{2.5}$ formation in Beijing on July 8 and 11, 2015. Fig. S2 presents the haze formation process from 20:00 BJT on July 7 to 18:00 BJT on July 8 in Beijing. From 20:00 to 22:00 on July 7, the prevailing southeast winds bring the pollutants formed in Tianjin to Beijing. Meanwhile, a $PM_{2.5}$ plume in the east of Beijing has been enhanced and commenced to be transported to Beijing. From 00:00 BJT to 06:00 BJT on July 8, the formed $PM_{2.5}$ plume in the east of Beijing has been transported to the city, but only partially influenced the urban area due to the prevailing northeast winds. From 08:00 to 10:00 on July 8, the $PM_{2.5}$ pollution in the urban area of Beijing is enhanced due to rush hour emissions. After 12:00 BJT on July 8, the $PM_{2.5}$ plume formed in the urban area of Beijing has been transported to the northwest of Beijing and prevailing southeast winds continuously carry the $PM_{2.5}$ formed in Tianjin to Beijing. Fig. S3 shows the dominant role of trans-boundary transport in the haze formation in Beijing from 20:00 BJT on July 10 to 18:00 BJT on July 11. From 20:00 on July 10 to 08:00 BJT on July 11, a $PM_{2.5}$ plume formed in the east of Beijing has been transported to Beijing forced by east winds, causing continuous increase of the $PM_{2.5}$ concentration in Beijing. From 08:00 to 12:00 BJT on July 11, the transported $PM_{2.5}$ plume from outside of Beijing has been further enhanced due to rush hour emissions in Beijing, but the WRF-CHEM model overestimates the $PM_{2.5}$ concentration in the urban area due to the simulated weak or calm winds. After 12:00 BJT on July 11, the enhanced south winds commence to transport the $PM_{2.5}$ plume in the urban area to the north of Beijing.

Section SI-2: Contributions of Trans-boundary Transport to $PM_{2.5}$ and O_3 Concentrations in Beijing from 5 to 14 July 2015 Based on 2013 EI

In order to investigate the effect of APPCAP on the contribution of trans-boundary transport, sensitivity simulations for the air pollution event from 5 to 14 July 2015 have been performed using the 2013 EI. Table S3 shows the average $PM_{2.5}$ contribution in Beijing from only-Beijing emissions, non-Beijing emissions, emission interactions, and background. During the study episodes, the average $PM_{2.5}$ contribution in Beijing from only-Beijing emissions from 5 to 14 July 2015 is 13.2%, which is lower than that using 2015 EI. The non-Beijing emissions and the emission interactions contribute 65.2% and 6.5% to the $PM_{2.5}$ level in Beijing, respectively. Therefore, the $PM_{2.5}$ contribution caused by the trans-boundary transport is about 71.7% of $PM_{2.5}$ concentration in Beijing, which is higher than that with 2015 EI. The background $PM_{2.5}$ contribution to Beijing is 15.0%. Table S4 gives the average O_3 contributions from 12:00 to 18:00 BJT in Beijing from only-Beijing emissions, non-Beijing emissions, emission interactions, and background. The only-Beijing emissions contribute about 23.6% on average to the afternoon O_3 level in Beijing, varying from 16.4% to 29.7%, slightly higher than that with 2015 EI. The outside emissions contribute more than local sources, with an average of 38.0%, and the emissions interactions also decrease the O_3 level by 5.5% on average. The background also plays an important role in the O_3 level in the afternoon when using the 2013 EI, with an average contribution of 44.0%. The O_3 contribution caused by the trans-boundary transport of outside emissions is approximately 32.5% of the O_3 concentration, higher than that with 2015 EI. Hence, in general, the O_3 and $PM_{2.5}$ contribution of outside emissions has gradually decreased since implementation of the APPCAP.

Section SI-3: Contribution of Trans-boundary Transport to $PM_{2.5}$ and O_3 Concentrations in Beijing from 22 to 28 July 2015 Based on 2015 EI

The model simulations and FSA results from 5 to 14 July 2015 show that the non-Beijing emissions play an important role in the air quality in Beijing. In order to further confirm the important role of trans-boundary transport, a severe air pollution episode from 22 to 28 May 2015 in NCP is simulated using the WRF-CHEM model using 2015 EI. Table S5 shows the average $PM_{2.5}$ contribution in Beijing from only-Beijing emissions, non-Beijing emissions, emission interactions, and background. The average contribution from only-Beijing emissions is 11.5%, while the average contribution from non-Beijing emissions is 62.4%, varying from 35.4% to 73.4%, which is much higher than the contribution from local source. The emission interactions also increase the $PM_{2.5}$ level in Beijing, with average contribution of 6.3%, varying from 2.4% to 9.4%. The background contributes 17.6% to the $PM_{2.5}$ concentration in Beijing on average. Therefore, the $PM_{2.5}$ contribution induced by trans-boundary transport is about 68.7% of $PM_{2.5}$ level in Beijing during the episode from 22 to 28 May 2015, indicating the substantial impact of trans-boundary transport on the $PM_{2.5}$ concentration in Beijing. Table S6 presents the average O_3 contributions from 12:00 to 18:00 BJT in Beijing from only-Beijing emissions, non-Beijing emissions, emission interactions, and background. The local sources contribute about 17.6% on average in the afternoon to the O_3 level in Beijing. The non-Beijing emissions contribute more than local emissions, with average contribution of 42.4%, ranging from 16.9% to 51.0%. The emission interaction between only-Beijing emissions and non-Beijing emissions increase or decrease the O_3 level in Beijing in different time due to the nonlinear process of O_3 production, with contribution ranging from -2.5% to 2.1%, but the emission interactions in Beijing decrease the O_3 concentration by 0.4% on average. The background plays also an important role in the afternoon O_3 concentration, with average contribution of 40.4%. The contribution from trans-boundary transport of the outside emissions is about 42.0% during the period from 22 to 28 May 2015, also indicating that the important role of trans-boundary transport in the O_3 level in Beijing.

Table S1 Horizontal transport flux of $PM_{2.5}$, O_3, and NO_2 across Beijing boundary during the study episode.

Species	Flux intensity (μg m^{-2} s^{-1})				Flux (g s^{-1})				
	West	East	South	North	Total	West	East	South	North
$PM_{2.5}$	-331.8 ~ 273.6	-125.5 ~ 329.2	-375.9 ~ 354.8	-602.1 ~ 182.9	68.2	-42.3	25.5	103.3	-18.3
O_3	-803.6 ~ 1416.3	-470.5 ~ 770.6	-705.0 ~ 952.4	-1411.0 ~ 573.7	68.5	-111.6	55.3	244.5	-119.7
NO_2	-16.9 ~ 11.1	-11.1 ~ 103.0	-125.7 ~ 40.7	-14.2 ~ 6.1	-5.8	-8.4	1.3	2.1	-0.8

Table S2 Average NO_2 contributions (%) in Beijing from only-Beijing emissions, non-Beijing emissions, the interactions of both emissions, and background from 5 to 14 July 2015.

Emissions	Beijing	Surroundings	Interactions	Background
Date	f'_B	f'_S	f'_{BS}	f_0
5	67.6	27.0	1.7	3.7
6	76.8	21.3	-2.1	4.0
7	71.7	24.6	-0.2	3.9
8	72.2	25.8	-1.8	3.8
9	71.0	26.9	-1.2	3.3
10	64.5	27.3	4.9	3.3
11	62.8	29.2	4.5	3.5
12	74.9	23.4	-3.4	5.1
13	74.3	19.4	0.1	6.2
14	67.6	23.6	4.1	4.7
Average	70.3	24.8	0.9	4.0

Table S3 Average $PM_{2.5}$ contributions (%) in Beijing from only-Beijing emissions, non-Beijing emissions, the interactions of both emissions, and background from 5 to 14 July 2015 using 2013 emission inventory.

Emissions	Beijing	Surroundings	Interactions	Background
Date	f'_B	f'_S	f'_{BS}	f_0
5	14.2	59.6	4.0	22.2
6	14.0	64.1	1.3	20.6
7	14.6	65.8	1.3	18.2
8	13.9	66.4	4.1	15.5
9	14.2	61.0	11.1	13.6
10	11.0	67.7	8.8	12.5
11	8.9	74.3	7.9	8.8
12	13.4	66.2	10.8	9.6
13	18.7	46.3	11.0	23.8
14	16.7	56.6	7.2	19.5
Average	13.2	65.2	6.5	15.1

Table S4 Average O_3 contributions (%) from 12:00 to 18:00 BJT in Beijing from only-Beijing emissions, non-Beijing emissions, the interactions of both emissions, and background from 5 to 14 July 2015 using 2013 emission inventory.

Emissions	Beijing	Surroundings	Interactions	Background
Date	f'_B	f'_S	f'_{BS}	f_0
5	16.4	30.0	-3.7	57.3
6	19.8	32.8	-2.7	50.0
7	26.6	38.1	-5.5	40.8
8	27.4	38.2	-6.3	40.7
9	23.8	36.9	-5.2	44.5
10	19.0	41.4	-3.3	42.8
11	29.7	48.2	-8.6	30.6
12	37.3	40.8	-11.9	33.7
13	25.1	15.4	-0.9	60.4
14	21.7	34.0	-3.9	48.2
Average	23.6	38.0	-5.6	44.0

Table S5 Average $PM_{2.5}$ contributions (%) in Beijing from only-Beijing emissions, non-Beijing emissions, the interactions of both emissions, and background from 22 to 28 July 2015.

Emissions	Beijing	Surroundings	Interactions	Background
Date	f'_B	f'_S	f'_{BS}	f_0
22	25.6	35.4	2.4	36.6
23	15.0	55.4	7.7	21.9
24	9.9	63.6	8.3	18.2
25	9.9	66.8	9.4	14.0
26	8.3	70.3	5.9	15.4
27	6.9	73.4	6.7	13.0
28	9.9	72.1	4.0	14.0
Average	11.5	62.4	6.3	17.6

Table S6 Average O_3 contributions (%) from 12:00 to 18:00 BJT in Beijing from only-Beijing emissions, non-Beijing emissions, the interactions of both emissions, and background from 22 to 28 July 2015.

Emissions	Beijing	Surroundings	Interactions	Background
Date	f'_B	f'_S	f'_{BS}	f_0
22	23.7	16.9	2.1	57.3
23	22.3	31.4	-0.9	47.2
24	20.6	40.6	-1.2	40.0
25	24.2	48.5	-2.5	29.8
26	17.1	51.0	0.7	31.2
27	11.8	49.8	1.6	36.8
28	15.4	49.3	-2.0	37.3
Average	17.6	42.4	-0.4	40.4

Supplementary Figure Captions

Fig. S1 Daily variations of the average observed surface (a) temperature, (b) relative humidity, (c) wind speed, and the near-surface (d) $PM_{2.5}$ and (e) O_3 concentration in Beijing during summer of 2015. Red circles indicate the simulation episode (5-14 July 2015) in this study.

Fig. S2 $PM_{2.5}$ pattern variations in Beijing and surrounding areas from 20:00 BJT on July 7 2015 to 18:00 BJT on July 8 2015. Colored circles: $PM_{2.5}$ observations; color contour: $PM_{2.5}$ simulations; black arrows: simulated surface winds.

Fig. S3 $PM_{2.5}$ pattern variations in Beijing and surrounding areas from 20:00 BJT on July 10 2015 to 18:00 BJT on July 11 2015. Colored circles: $PM_{2.5}$ observations; color contour: $PM_{2.5}$ simulations; black arrows: simulated surface winds.

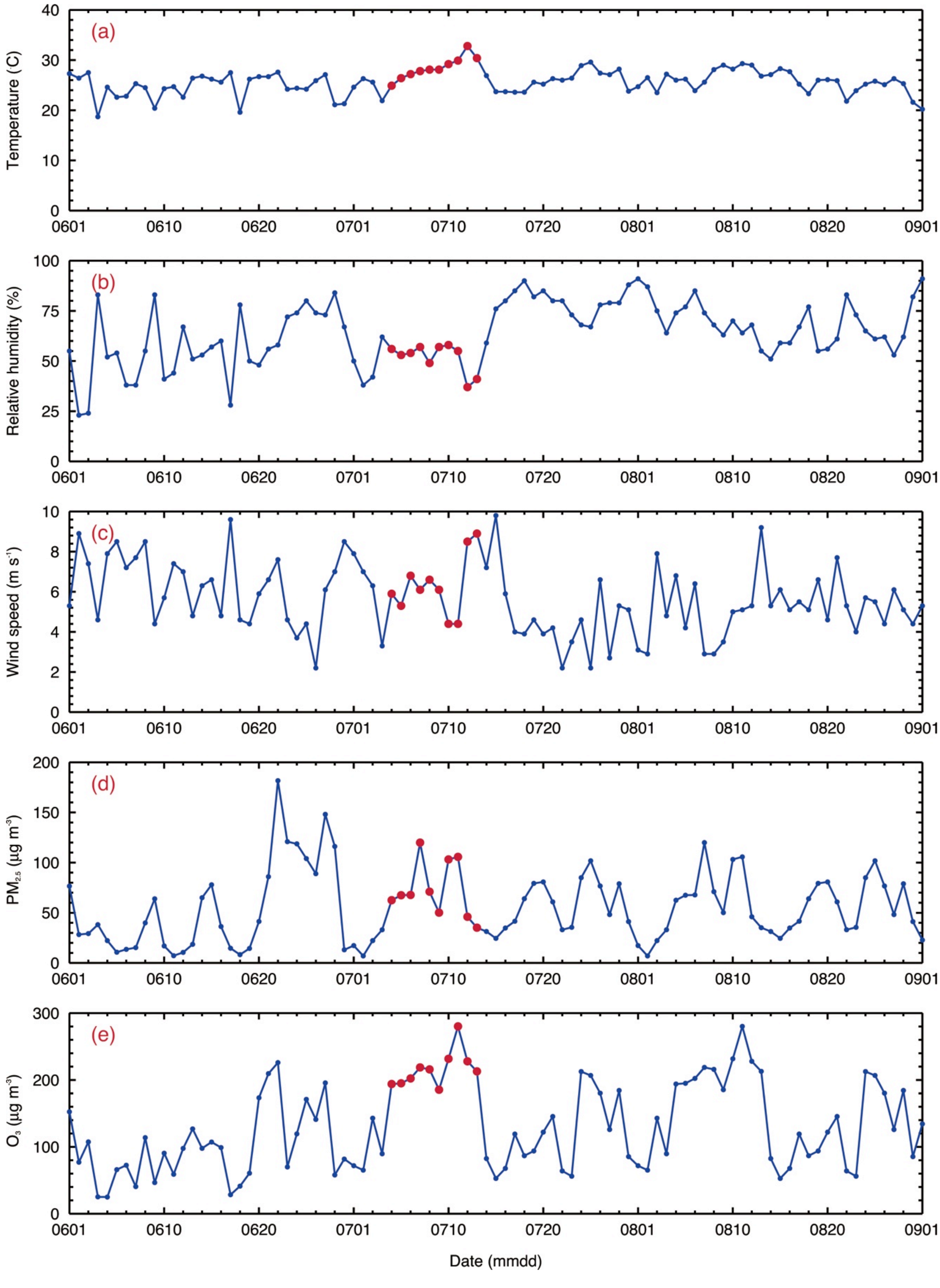

Fig. S1 Daily variations of the average observed surface (a) temperature, (b) relative humidity, (c) wind speed, and the near-surface (d) $PM_{2.5}$ and (e) O_3 Concentration in Beijing during summer of 2015. Red circles indicate the simulation episode (5-14 July 2015) in this study.

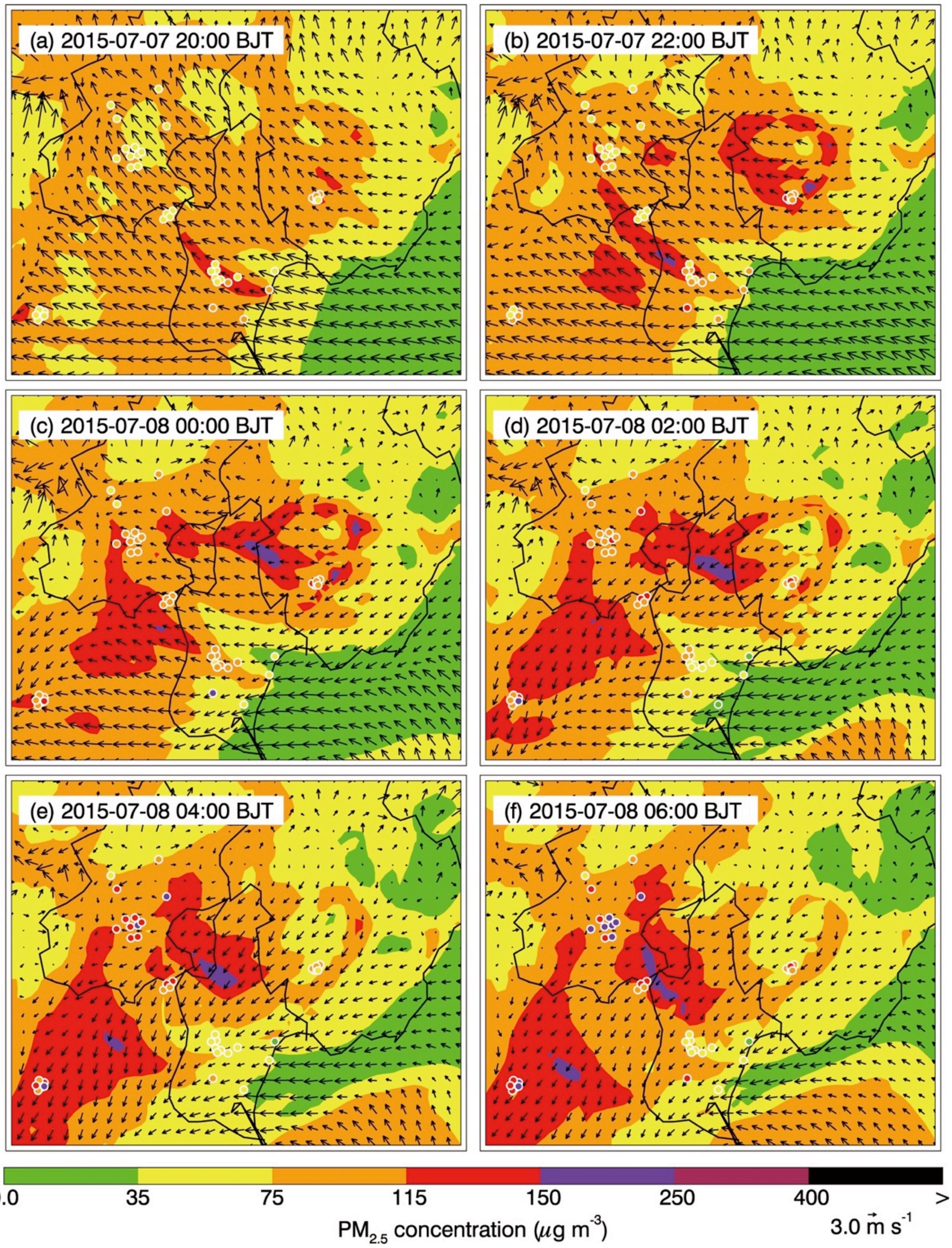

Fig. S2 $PM_{2.5}$ pattern variations in Beijing and surrounding areas from 20:00 BJT on July 7 2015 to 18:00 BJT on July 8 2015. Colored circles: $PM_{2.5}$ observations; color contour: $PM_{2.5}$ simulations; black arrows: simulated surface winds.

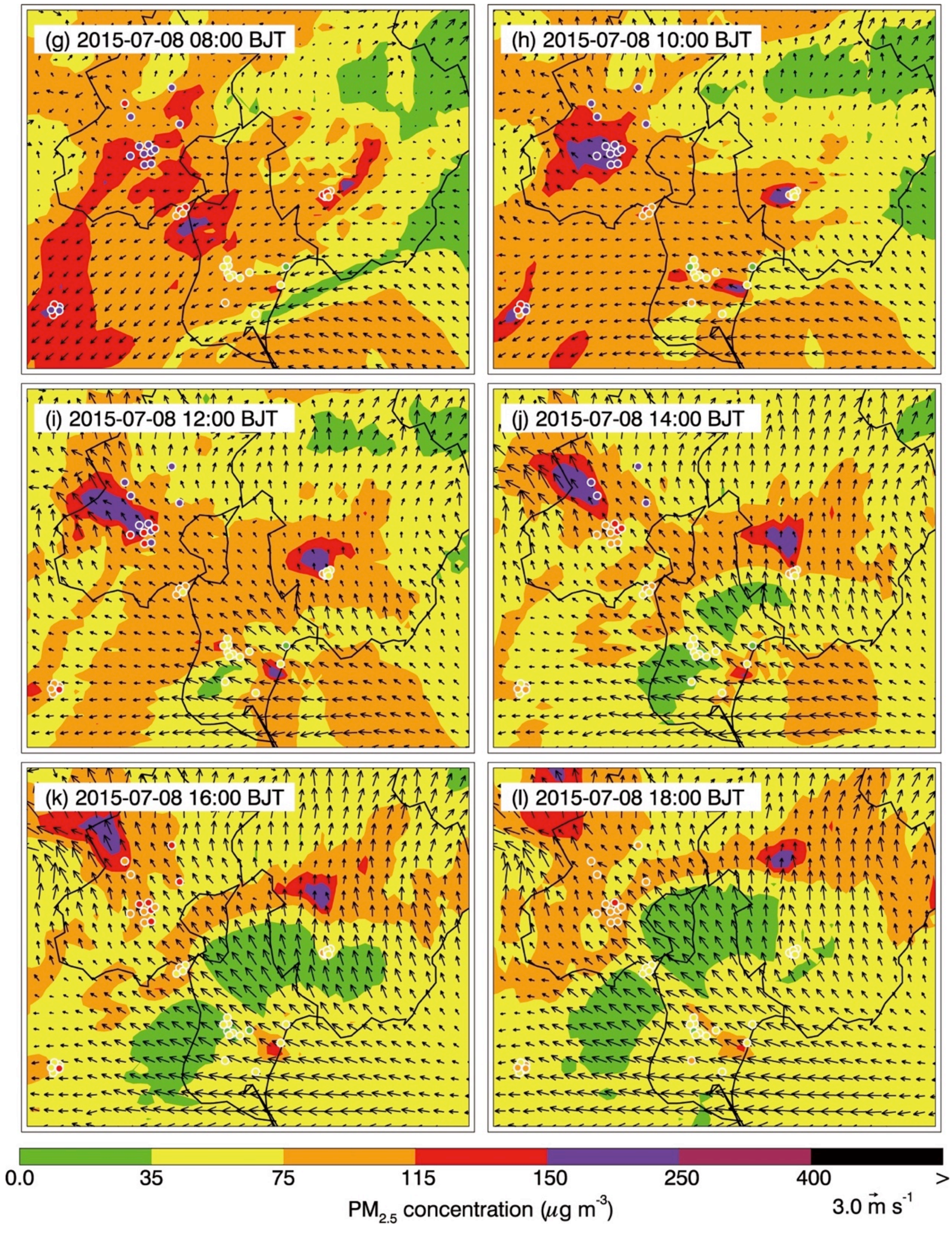

Fig. S2 Continued

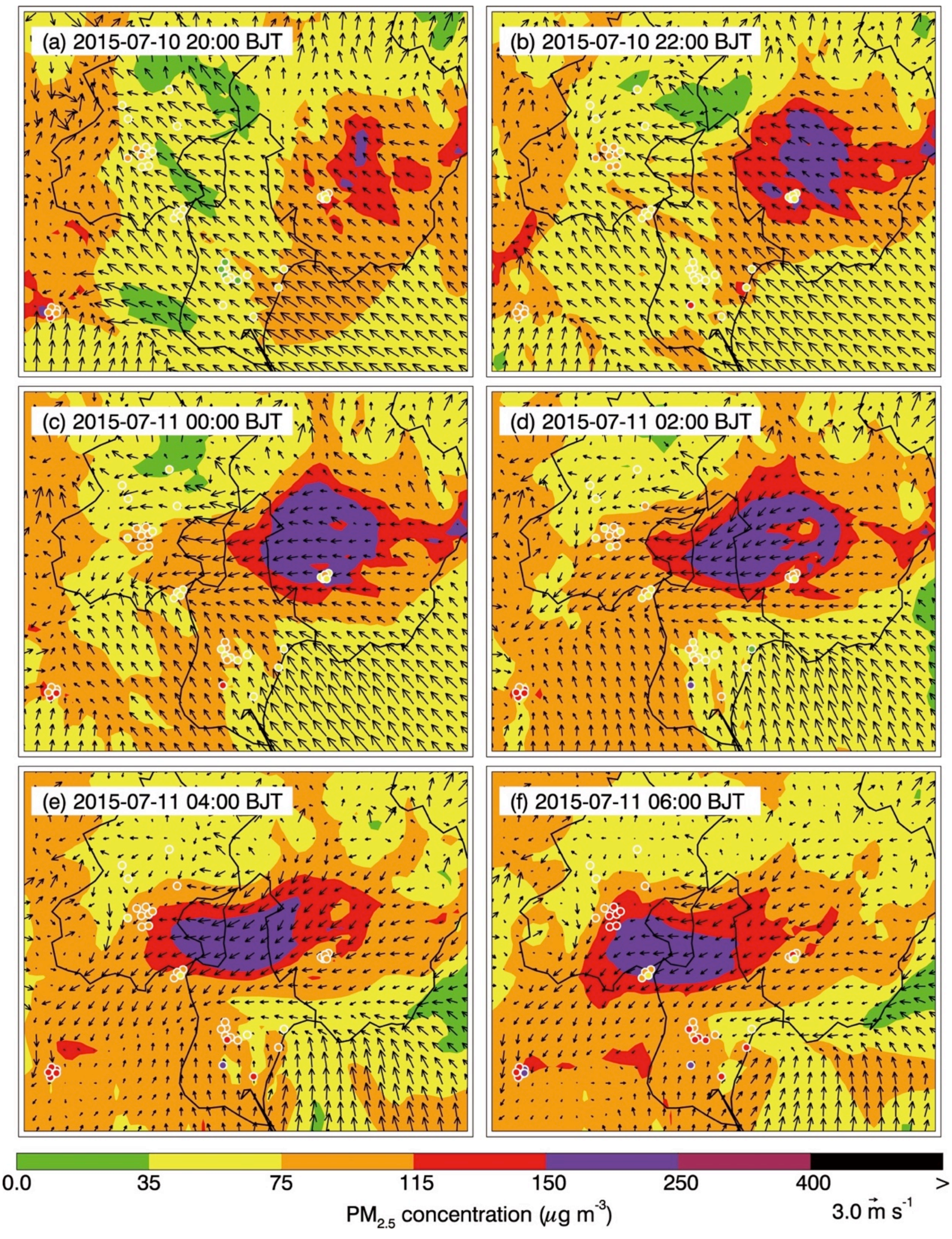

Fig. S3 $PM_{2.5}$ pattern variations in Beijing and surrounding areas from 20:00 BJT on July 10 2015 to 18:00 BJT on July 11 2015. Colored circles: $PM_{2.5}$ observations; color contour: $PM_{2.5}$ simulations; black arrows: simulated surface winds.

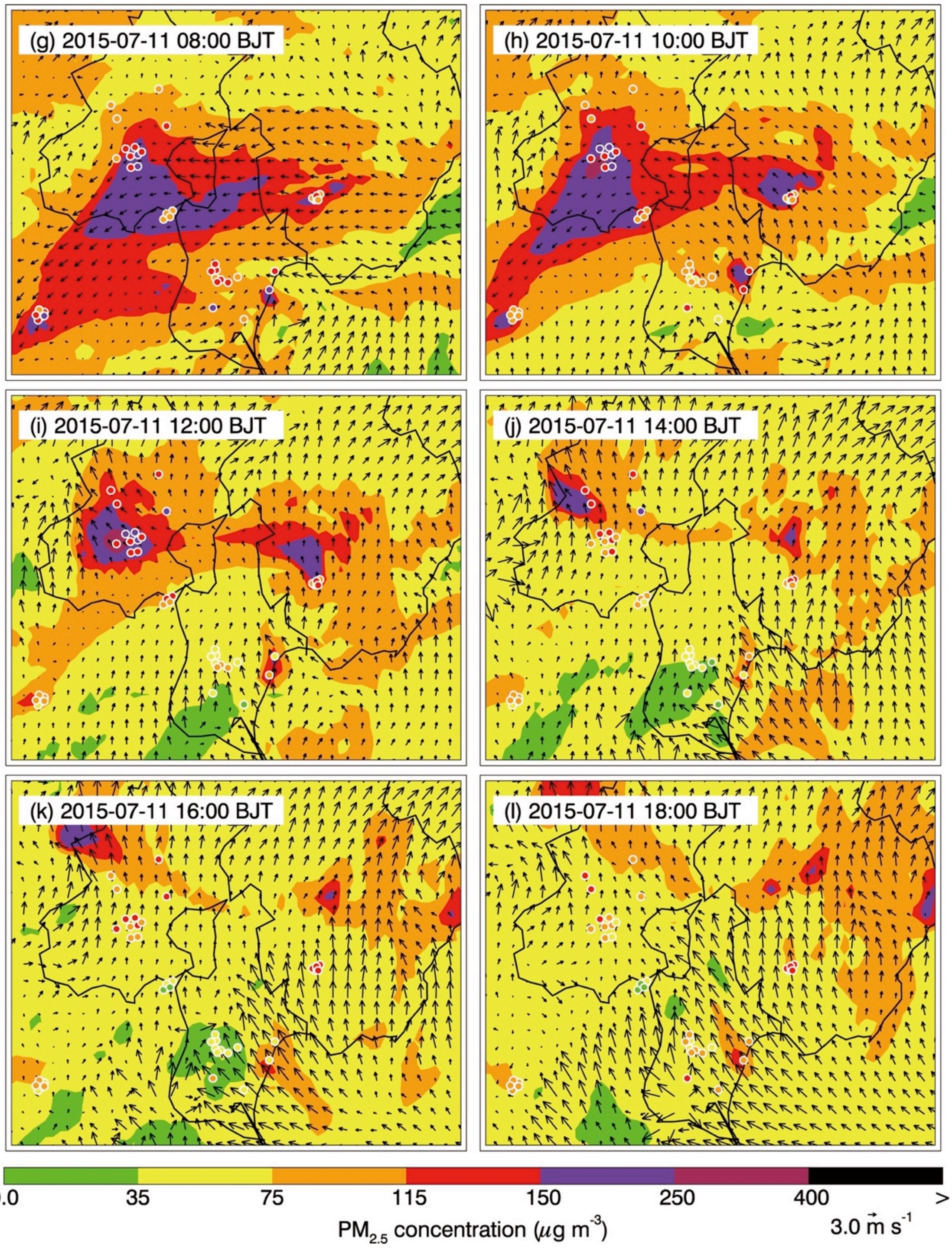

Fig. S3 Continued