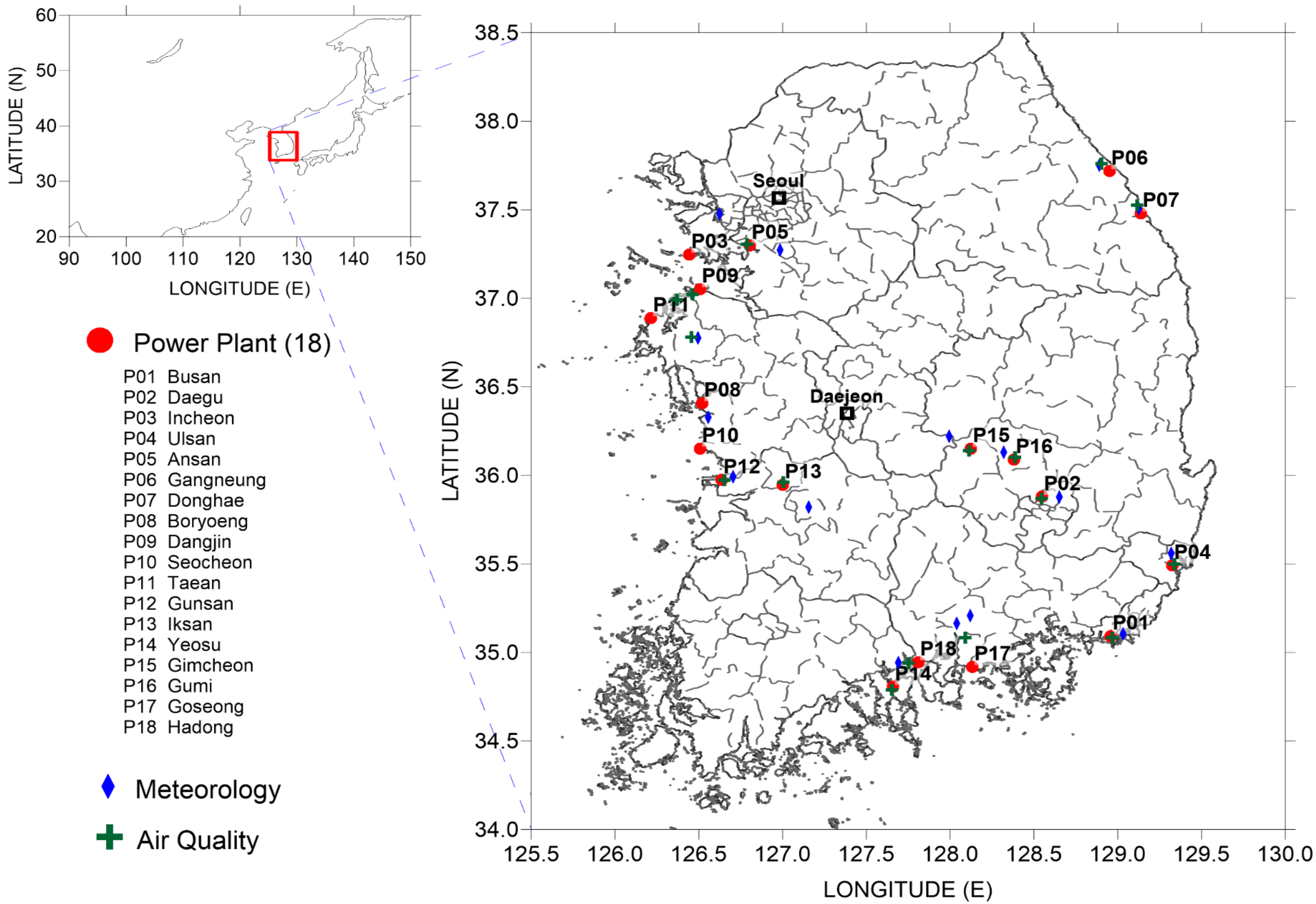
Assessing the Impact of Power Plants on PM_{10} In South Korea using a Modelling Approach

Il-Soo Park · Moon-Soo Park · Yu-Woon Jang · Woo Jeong Lee

Hankuk University of Foreign Studies
Korea-Latin America Green Convergence Center · Research Center of Asian Dust and Long-range Transboundary Air Pollutants · Weather Information Service Engine

Location of Power Plants, Meteorological and Air Quality Stations



Stack characteristics

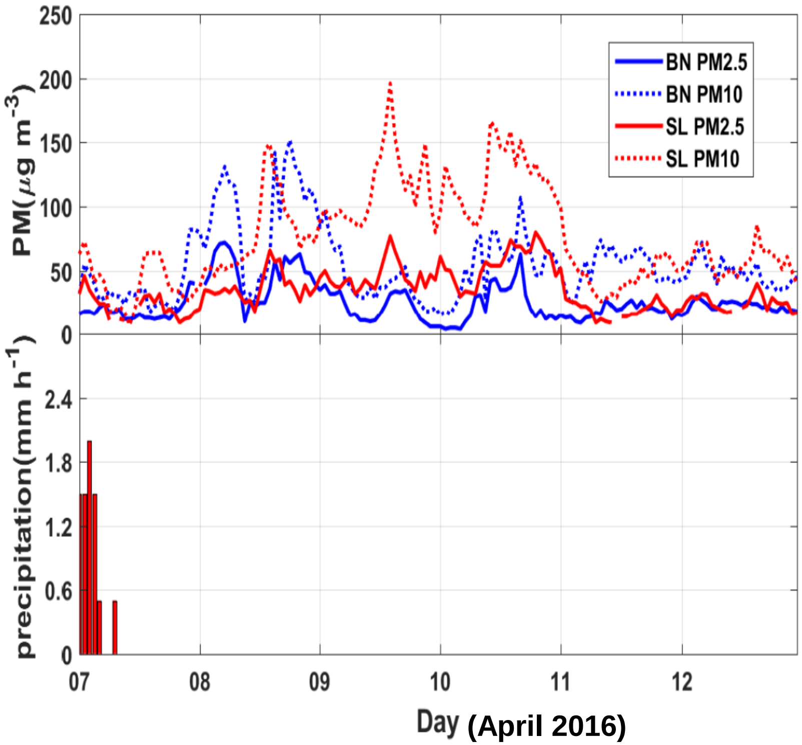
Power Plants		Latitude	Longitude	height (m)	radius (m)	exiting temp. (°K)	exiting speed (m/s)	# of stacks (ea)*	Distance from the nearest meteorological station (km)	Distance from the nearest air quality station (km)
P01	Busan	35° 05′	129° 0.5′	100.0	1.09	409.53	8.18	1	8.2	1.1
P02	Daegu	35° 53′	128° 32.50′	100.0	1.44	381.24	5.52	3	11.6	0.7
P03	Incheon	37° 14.5′	126° 26.57′	199.0	3.23	360.09	33.71	8	25.3	15.0
P04	Ulsan	35° 30.5′	129° 22.5′	153.5	1.30	371.52	17.81	8	4.9	1.6
P05	Ansan	37° 17.5′	126° 48′	123.0	1.27	363.74	4.19	18	20.3	1.7
P06	Gangneung	37° 44′	128° 58.5′	80.0	2.49	384.73	12.64	4	7.0	6.0
P07	Donghae	37° 29′	129° 8.5′	150.0	2.00	416.82	24.26	5	2.4	4.1
P08	Boryeong	36° 21′	126° 35′	41.8	2.91	362.1	20.21	10	6.7	25.6
P09	Dangjin	37° 2.5′	126° 31′	150.0	2.98	362.84	24.66	**32**	18.2	5.3
P10	Seocheon	36° 8.5′	126° 29.5′	150.0	2.05	362.25	24.23	10	12.9	19.9
P11	Taean	36° 45.5′	126° 19′	150.2	2.98	358.97	21.77	14	31.8	18.3
P12	Gunsan	35° 58.5′	126° 38′	100.0	1.34	411.44	8.57	16	7.8	1.7
P13	Iksan	35° 57′	126° 59′	80.0	0.82	428.51	14.34	8	14.6	1.0
P14	Yeosu	34° 50′	127° 41′	76.9	1.79	398.89	15.3	**25**	10.0	1.4
P15	Gimcheon	36° 9′	128° 7′	100.0	1.70	403.72	10.78	4	15.2	1.4
P16	Gumi	36° 5.5′	128° 22′	153.0	1.07	366.85	15.59	18	7.3	1.1
P17	Goseong	34° 54.5′	128° 6′	200.0	2.58	378.74	19.52	16	19.7	12.2
P18	Hadong	34° 57′	127° 49′	150.0	3.26	357.88	15.14	16	13.1	6.4

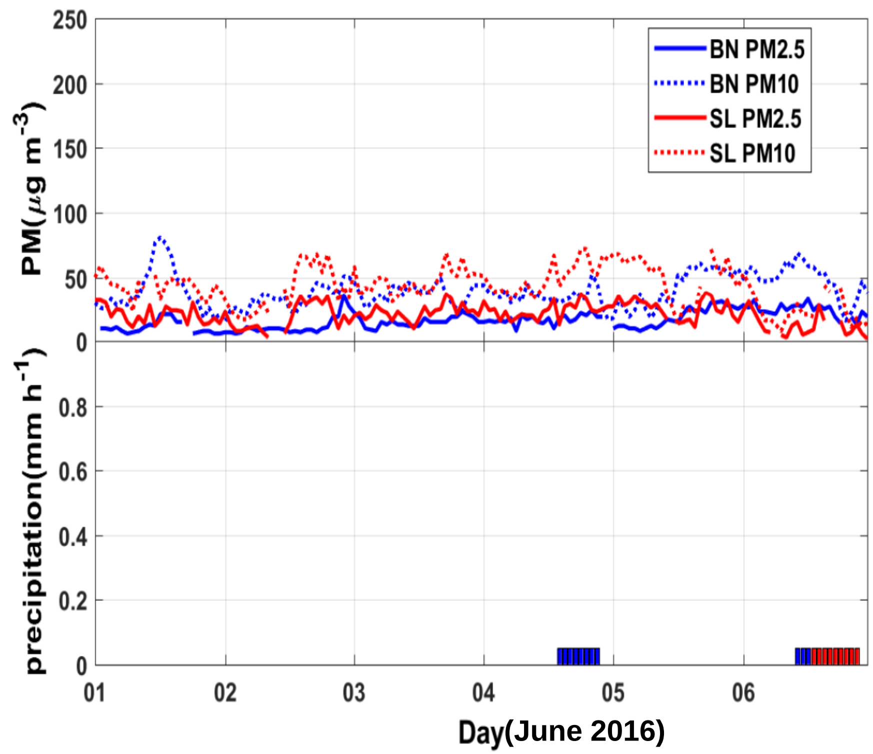
Emission rate of Power Plants

Power Plants		Emission Rate (ton/year)			
		PM_{10}	$PM_{2.5}$	NOx	SOx
P01	Busan	12.06	9.73	455.09	488.25
P02	Daegu	26.55	21.41	1042.42	1181.48
P03	Incheon	207.76	167.58	3862.97	5517.57
P04	Ulsan	14.04	11.32	905.46	847.82
P05	Ansan	14.11	11.38	686.03	324.74
P06	Gangneung	29.16	19.40	2692.47	910.16
P07	Donghae	35.59	25.21	1086.87	2406.16
P08	Boryeong	560.94	452.46	17454.32	11656.09
P09	Dangjin	319.95	111.50	17148.32	7223.25
P10	Seocheon	60.57	41.58	3613.69	1317.73
P11	Taean	835.13	673.63	22168.03	12792.28
P12	Gunsan	33.30	26.86	891.38	776.70
P13	Iksan	9.97	7.21	396.49	500.14
P14	Yeosu	229.13	178.85	6453.28	4074.51
P15	Gimcheon	2.48	2.0	83.68	69.84
P16	Gumi	29.0	23.39	2059.47	1860.64
P17	Goseong	564.47	455.32	23267.45	14531.64
P18	Hadong	470.91	379.84	13524.62	11478.44

Temporal variations of PM concentration and Precipitation

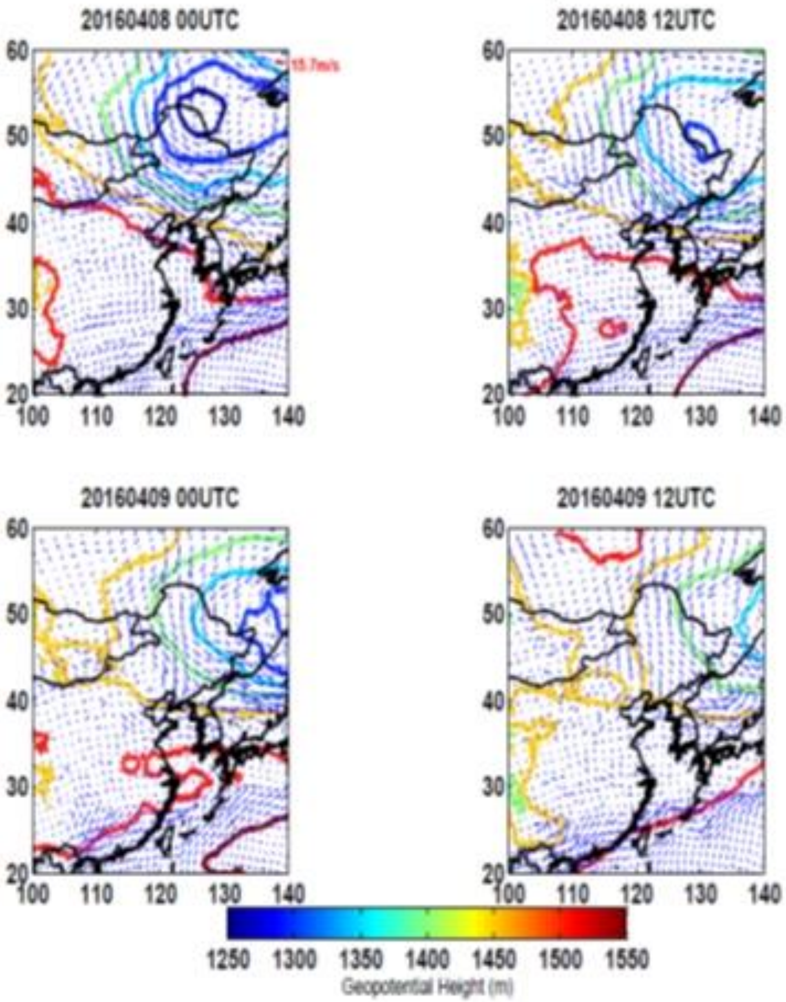
BN: Baengnyeongdo SL: Seoul





Geopotential height and wind fields at 850 hPa

00 UTC 08 – 12 LST 09 April 2016



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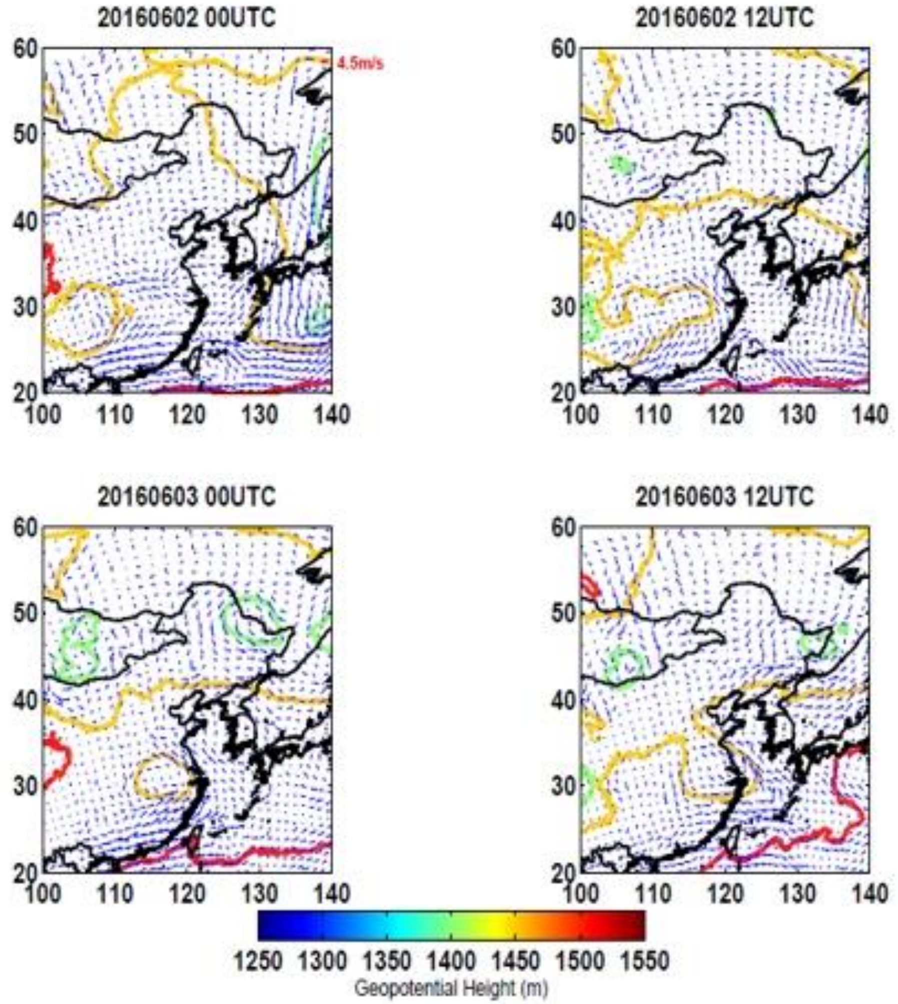
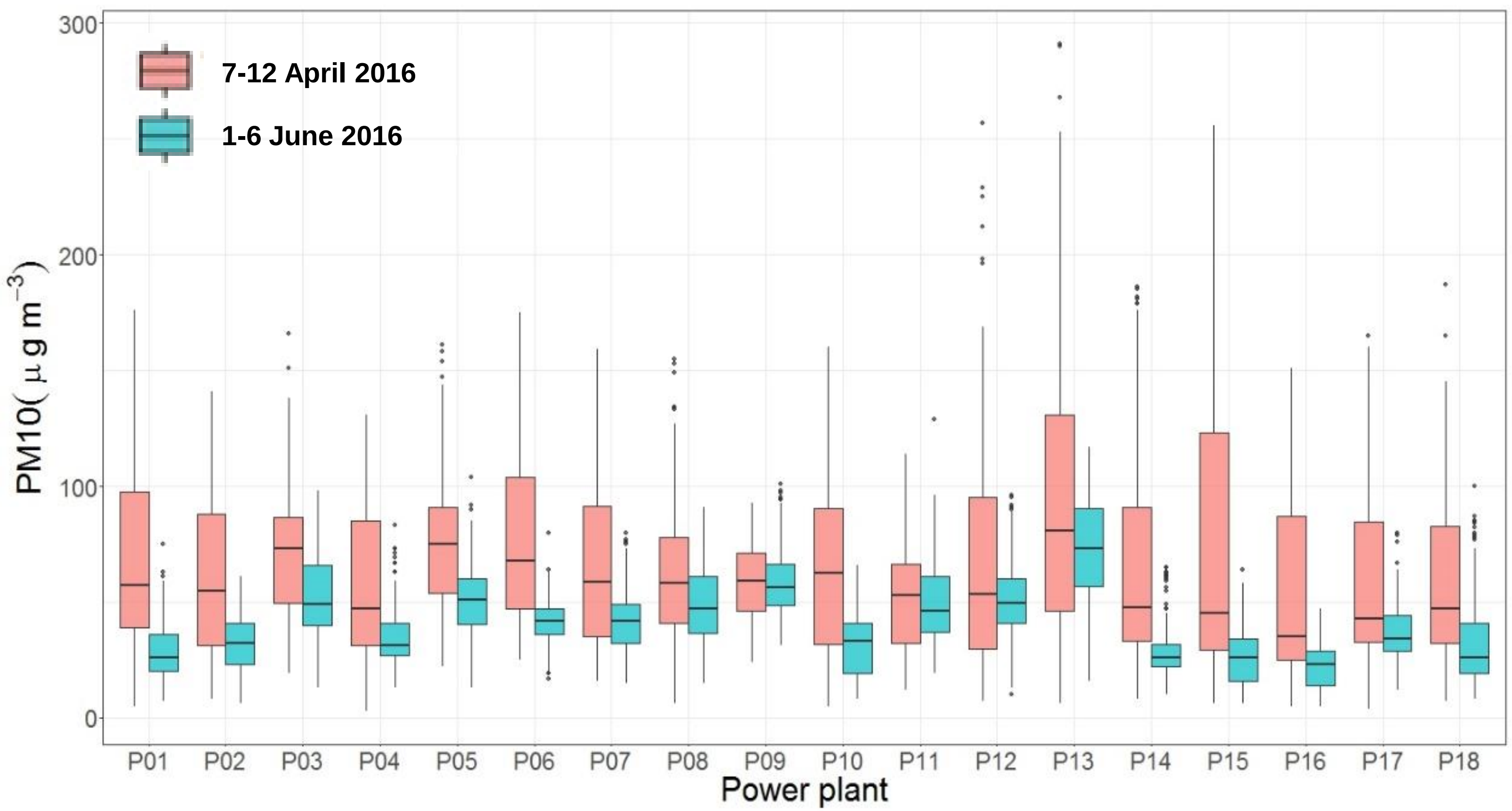


Boxplot of PM_{10} concentrations



TAPM (The Air Pollution Model)–Meteorology

$$\frac{du}{dt} = F(u) + \frac{\partial \overline{w'u'}}{\partial \sigma}\frac{\partial \sigma}{\partial z} - \theta_v\left(\frac{\partial \pi}{\partial x} + \frac{\partial \pi}{\partial \sigma}\frac{\partial \sigma}{\partial x}\right) + fv - N_s(u - u_s)$$

$$\frac{dv}{dt} = F(v) + \frac{\partial \overline{w'v'}}{\partial \sigma}\frac{\partial \sigma}{\partial z} - \theta_v\left(\frac{\partial \pi}{\partial y} + \frac{\partial \pi}{\partial \sigma}\frac{\partial \sigma}{\partial y}\right) - fu - N_s(v - v_s)$$

$$\frac{\partial \dot{\sigma}}{\partial \sigma} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + u\frac{\partial}{\partial \sigma}\left(\frac{\partial \sigma}{\partial x}\right) + v\frac{\partial}{\partial \sigma}\left(\frac{\partial \sigma}{\partial y}\right)$$

$$\frac{d\theta_v}{dt} = F(\theta_v) + \frac{\partial \overline{w'\theta_v'}}{\partial \sigma}\frac{\partial \sigma}{\partial z} + S_{\theta_v} - N_s(\theta_v - \theta_{vs})$$

$$\frac{\partial \pi_H}{\partial \sigma} = -\frac{g}{\theta_v}\left(\frac{\partial \sigma}{\partial z}\right)^{-1}$$

t : time (s)

x, y, σ: terrain-following coordinates (m)

$$\sigma = Z_T\left(\frac{Z - Z_S}{Z_T - Z_S}\right)$$

Z : Cartesian vertical coordinate (m)

Z_T: height of model top (m)

Z_S: terrain height (m)

f : Coriolis parameter

g: gravitational constant (9.81 m s^{-2})

u_s, v_s, θ_s: large scale synoptic winds and potential virtual temperature

Ns : large scale nudging coefficient (1/(24x3600))

$$S_{\theta v} = \frac{\theta_v}{T}\left(\frac{\partial T}{\partial t}\right)_{RADIATION} - \frac{\lambda}{c_p}S_{qv}$$

λ: latent heat of water vapor (2.5×10^6 J kg^{-1})

c_p: specific heat at const pressure (1006 J kg^{-1} K^{-1})

$$\frac{\partial \sigma}{\partial x} = \left(\frac{\sigma - z_T}{z_T - z_s}\right)\frac{\partial z_s}{\partial x}, \quad \frac{\partial \sigma}{\partial y} = \left(\frac{\sigma - z_T}{z_T - z_s}\right)\frac{\partial z_s}{\partial y}, \quad \frac{\partial \sigma}{\partial z} = \left(\frac{z_T}{z_T - z_s}\right)$$

TAPM – Air pollutant concentration

$$\frac{d\chi}{dt} = \frac{\partial}{\partial x}\left(K_\chi \frac{\partial \chi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_\chi \frac{\partial \chi}{\partial y}\right) - \left(\frac{\partial \sigma}{\partial z}\right)\frac{\partial}{\partial \sigma}\left(\overline{w'\chi'}\right) + S_\chi + R_\chi.$$

$$\overline{w'\chi'} = -K_\chi \frac{\partial \chi}{\partial \sigma}\frac{\partial \sigma}{\partial z} + \frac{(1-c_{\chi 3})}{c_{\chi 1}}\frac{E}{\varepsilon}\frac{g}{\theta_v}\overline{\theta_v'\chi'}$$

- χ : concentration by prognostic equation
- S*x* : pollutants emissions
- R*x* : chemical reactions
- K*x*, K*y* : diffusion coefficient

TAPM-Chemical Reactions

Reactions	**Reaction Rates**
$R_{smog} + hv \rightarrow RP + R_{smog} + \eta SNGOC$	$R_1 = k_1[R_{smog}]$
$RP + NO \rightarrow NO_2$	$R_2 = k_2[RP][NO]$
$NO_2 + hv \rightarrow NO + O_3$	$R_3 = k_3[NO_2]$
$NO + O_3 \rightarrow NO_2$	$R_4 = k_4[NO][O_3]$
$RP + RP \rightarrow RP + \alpha H_2O_2$	$R_5 = k_5[RP][RP]$
$RP + NO_2 \rightarrow SGN$	$R_6 = k_6[RP][NO_2]$
$RP + NO_2 \rightarrow SNGN$	$R_7 = k_7[RP][NO_2]$
$RP + SO_2 \rightarrow SNGS$	$R_8 = k_8[RP][SO_2]$
$H_2O_2 + SO_2 \rightarrow SNGS$	$R_9 = k_9[H_2O_2][SO_2]$
$O_3 + SO_2 \rightarrow SNGS$	$R_{10} = k_{10}[O_3][SO_2]$

$$\alpha = \max\left(0.03\exp\left(-0.0261\frac{[R_{smog}]}{[NO_x]}\right)\right)$$

η : 0.1

k_1 : $k_3 f$

k_2 : $3580/(60T)$

k_3 : $0.0001\delta TSR/60$

k_4 : $(924/60T)\exp(-1450/T)$

$$k_5 = (10/60),$$

$$k_6 = (0.12/60),$$

$$k_7 = k_6,$$

$$k_8 = (0.003/60),$$

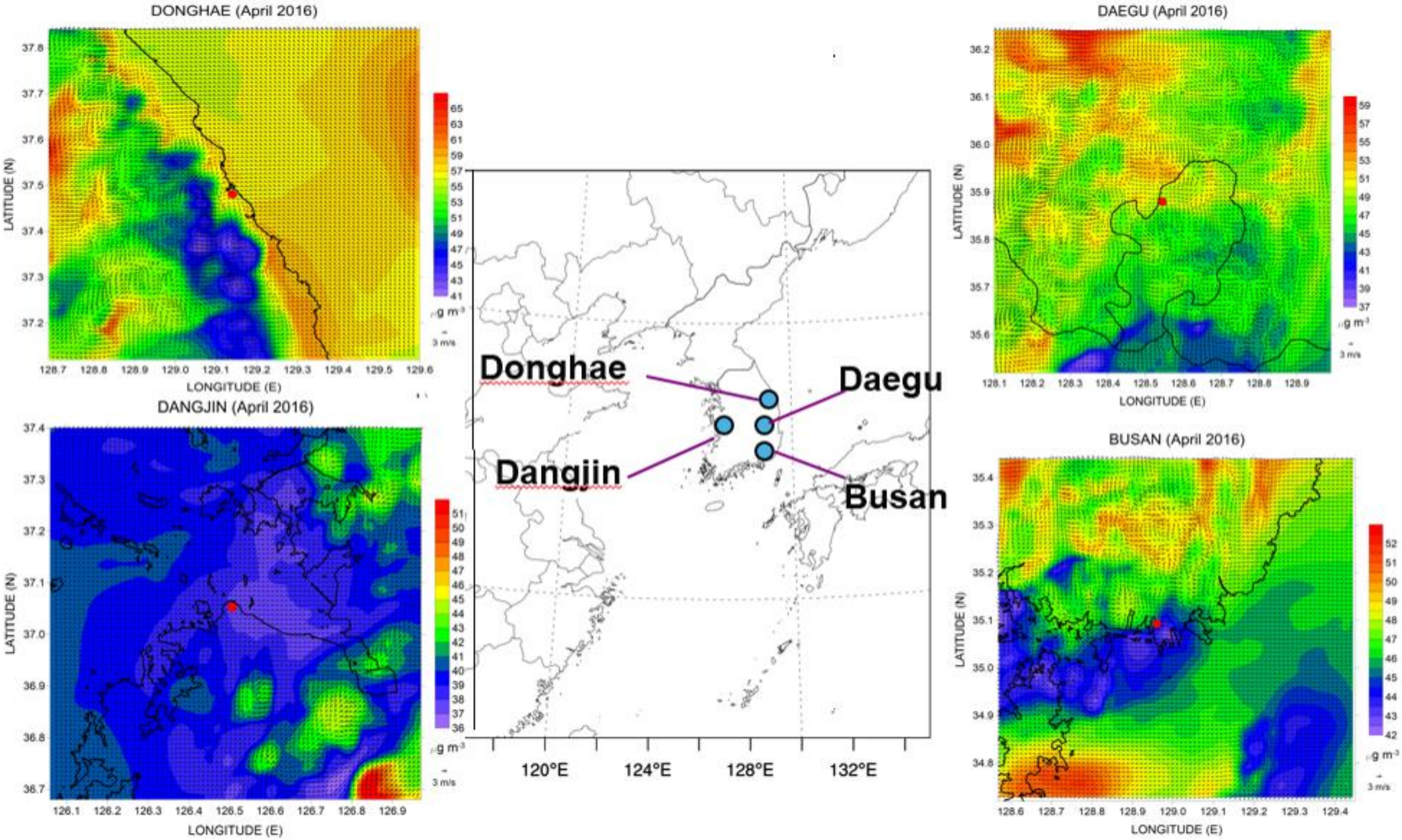
$$k_9 = \frac{7.45\times10^7[H^+]\alpha_1}{1+13[H^+]}K_{H\_S(IV)}K_{H\_H_2O_2}L\cdot R\cdot T\cdot 10^{-9},$$

$$k_{10} = (2.4\times10^4\alpha_0 + 3.7\times10^5\alpha_1 + 1.5\times10^9\alpha_2)K_{H\_S(IV)}K_{H\_O_3}L\cdot R\cdot T\cdot 10^{-9}$$

Observed period mean concentration

Power Plants		7-12 April 2016					1-6 June 2016				
		SO_2 (ppm)	CO (ppm)	O_3 (ppm)	NO_2 (ppm)	PM_{10} (㎍/㎥)	SO_2 (ppm)	CO (ppm)	O_3 (ppm)	NO_2 (ppm)	PM_{10} (㎍/㎥)
P01	**Busan**	0.00728	0.54326	0.03452	0.01300	**70.7**	0.00660	0.39881	0.03603	0.02394	**29.0**
P02	**Daegu**	0.00416	0.41268	0.02755	0.02108	**68.8**	0.00371	0.29573	0.04087	0.01280	**33.3**
P03	**Incheon**	0.00498	0.48112	0.04188	0.01748	**70.6**	0.00511	0.34910	0.04998	0.01454	**52.5**
P04	**Ulsan**	0.01318	0.66667	0.03115	0.03288	**68.6**	0.00980	0.41667	0.03985	0.02434	**36.6**
P05	**Ansan**	0.00517	0.52657	0.02715	0.03108	**68.7**	0.00442	0.51265	0.03023	0.02975	**40.8**
P06	**Gangneung**	0.00309	0.34132	0.04478	0.01334	**76.9**	0.00204	0.29881	0.04507	0.01343	**42.1**
P07	**Donghae**	0.00230	0.27048	0.03717	0.01386	**71.4**	0.00261	0.32901	0.03988	0.01869	**38.2**
P08	**Boryeong**	0.00310	0.45874	0.04657	0.01538	**62.0**	0.00392	0.40595	0.05785	0.01491	**49.0**
P09	**Dangjin**	0.00330	0.24545	0.04312	0.01470	**58.4**	0.00656	0.31078	0.05484	0.01723	**58.4**
P10	**Seocheon**	0.00170	0.40786	0.04705	0.00802	**62.8**	0.00174	0.25067	0.05374	0.00717	**31.8**
P11	**Taean**	0.00548	0.49021	0.04291	0.04279	**51.7**	0.00783	0.35210	0.04290	0.02204	**50.9**
P12	**Gunsan**	0.00513	0.48881	0.04210	0.01840	**71.1**	0.00523	0.42635	0.05195	0.01402	**50.9**
P13	**Iksan**	0.00614	0.53472	0.04482	0.01685	**90.5**	0.00660	0.46587	0.05471	0.01321	**67.7**
P14	**Yeosu**	0.00943	0.32378	0.03518	0.02048	**77.9**	0.01399	0.54970	0.03781	0.04084	**33.8**
P15	**Gimcheon**	0.00158	0.60214	0.04526	0.01439	**71.9**	0.00135	0.41786	0.04474	0.01107	**26.6**
P16	**Gumi**	0.00371	0.50280	0.04864	0.02723	**54.7**	0.00311	0.24286	0.04948	0.01324	**22.5**
P17	**Goseong**	0.00525	0.30000	0.03657	0.02857	**61.2**	0.00524	0.33413	0.04533	0.01663	**37.8**
P18	**Hadong**	0.01205	0.52286	0.03246	0.02381	**60.4**	0.01061	0.43631	0.03382	0.01595	**32.9**

Simulated wind and PM_{10} concentration (April 2016)



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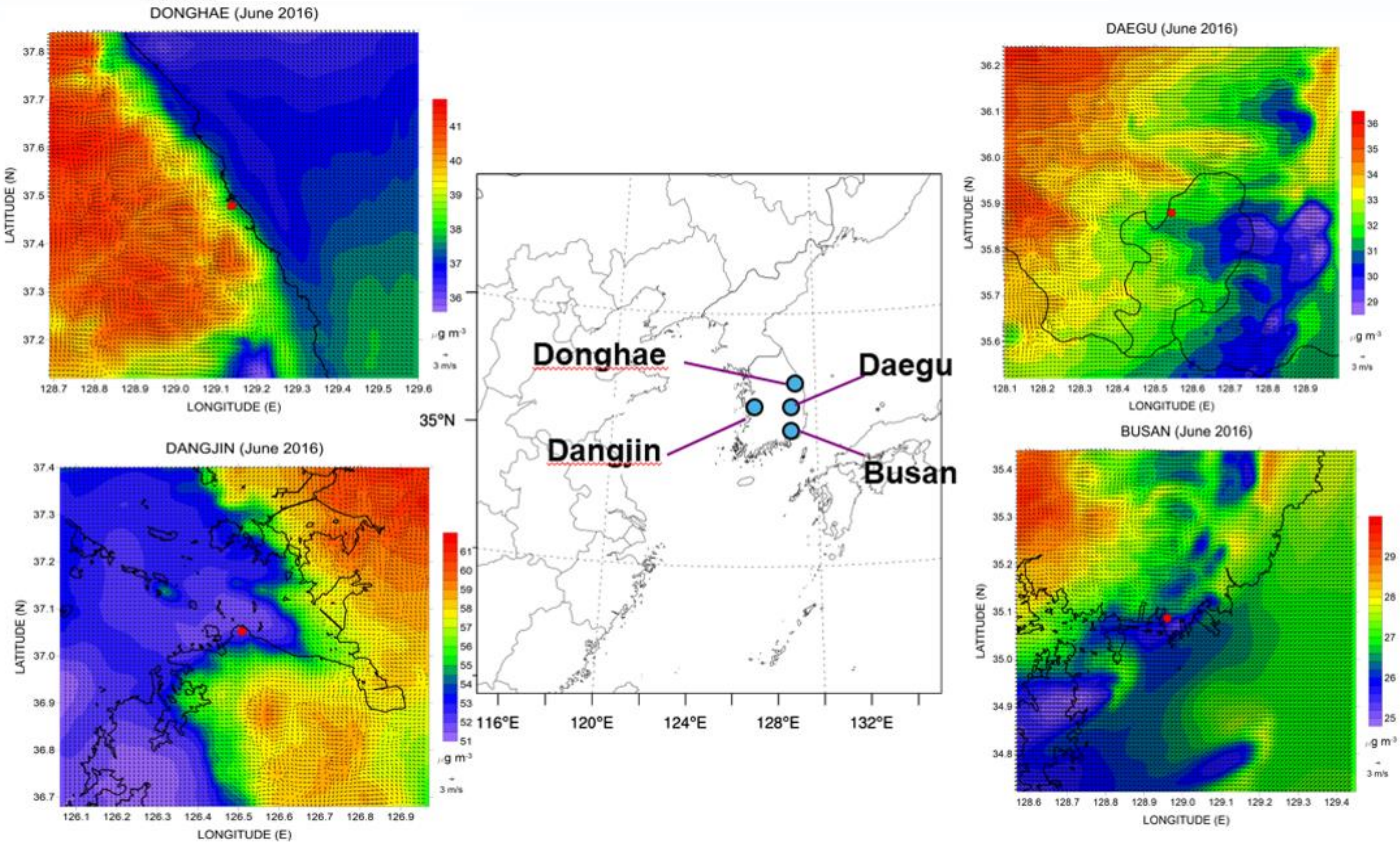
Simulated wind and PM_{10} concentration (June 2016)



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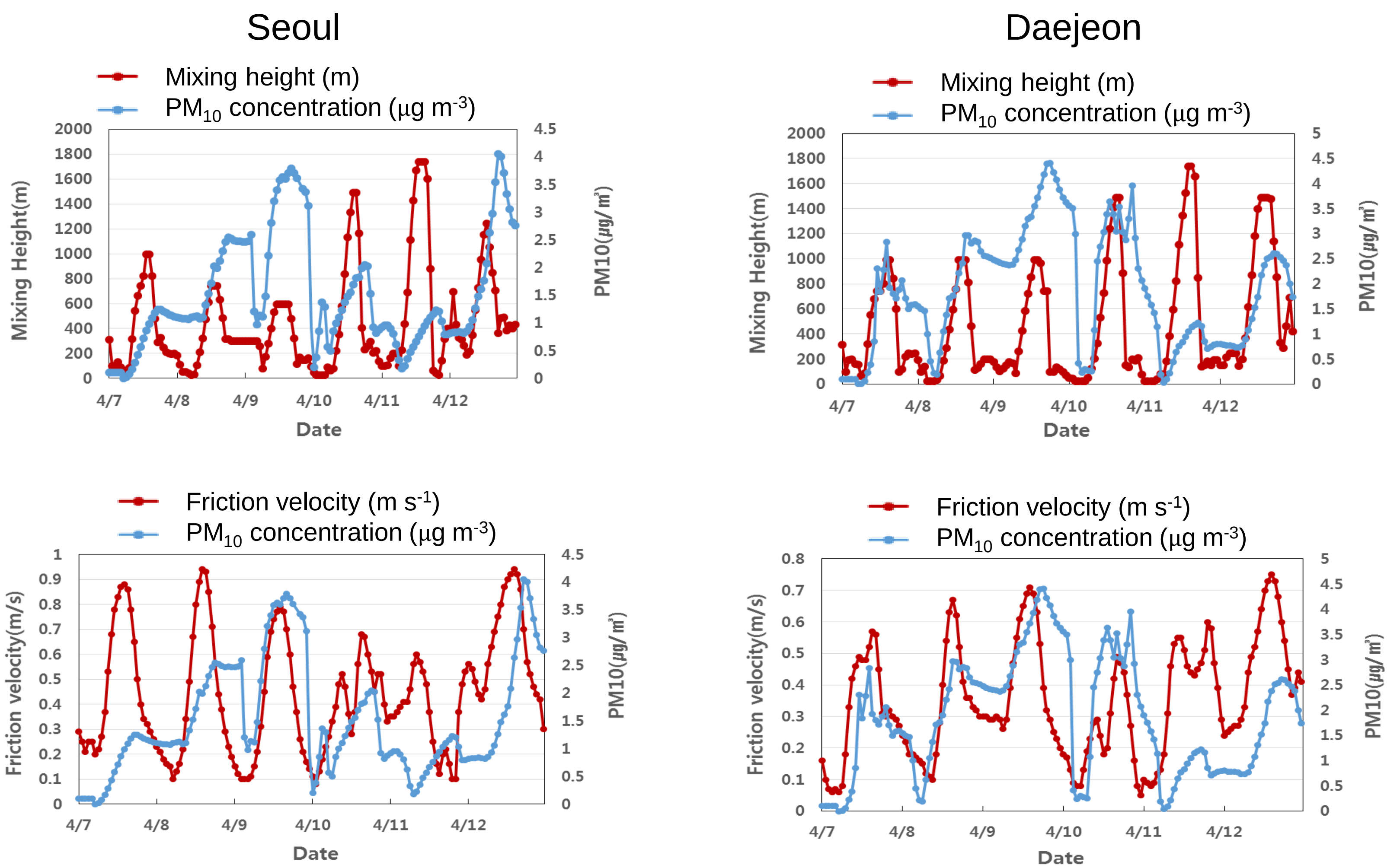
IOA between simulated and observed variables

Period	7-12 April 2016				1-6 June 2016			
Power Plant	PM_{10}	WS	WD	Temp.	PM_{10}	WS	WD	Temp.
P01	0.63	0.59	0.91	0.81	0.56	0.53	0.69	0.74
P02	0.58	0.73	0.72	0.92	0.50	0.78	0.68	0.88
P03	0.35	0.64	0.66	0.86	0.48	0.68	0.75	0.88
P04	0.60	0.63	0.68	0.82	0.48	0.70	0.46	0.90
P05	0.37	0.54	0.80	0.88	0.56	0.50	0.60	0.47
P06	0.24	0.49	0.51	0.89	0.25	0.42	0.56	0.92
P07	0.32	0.43	0.60	0.85	0.32	0.59	0.55	0.93
P08	0.36	0.39	0.66	0.91	0.28	0.41	0.62	0.91
P09	0.41	0.58	0.67	0.88	0.46	0.64	0.65	0.91
P10	0.37	0.38	0.63	0.81	0.42	0.40	0.58	0.84
P11	0.41	0.58	0.66	0.93	0.33	0.66	0.80	0.95
P12	0.27	0.72	0.60	0.94	0.27	0.73	0.63	0.89
P13	0.32	0.76	0.53	0.95	0.28	0.77	0.56	0.89
P14	0.47	0.59	0.86	0.81	0.45	0.71	0.55	0.84
P15	0.45	0.64	0.73	0.93	0.45	0.73	0.48	0.85
P16	0.51	0.32	0.65	0.94	0.45	0.28	0.66	0.90
P17	0.58	0.61	0.55	0.92	0.43	0.41	0.46	0.87
P18	0.54	0.63	0.87	0.83	0.42	0.71	0.74	0.86

Simulated maximum and averaged PM_{10} concentration

Power Plant #	April 2016						June 2016					
	max. (㎍/㎥)	Direction/Distance (km) from PP		avg. (㎍/㎥)	Direction/Distance (km) from PP		max. (㎍/㎥)	Direction/Distance (km) from PP		avg. (㎍/㎥)	Direction/Distance (km) from PP	
P01	4.3	SE	223.5	1.65	SSE	166.5	6.68	WNW	181.1	3.39	WNW	181.1
P02	4.15	ESE	210.0	1.63	SSE	175.3	7.93	NW	217.8	4.07	NW	223.5
P03	4.09	SSE	215.1	1.55	SSE	167.0	10.8	ESE	31.6	4.86	NW	130.9
P04	4.03	SE	220.6	1.6	SSE	192.5	5.93	NNW	157.2	2.69	N	79.0
P05	3.79	SSE	217.9	1.46	SSE	129.5	9.59	WNW	137.1	4.73	WNW	144.1
P06	5.94	WNW	12.6	1.38	SE	220.6	7.48	WSW	158.5	3.52	WSW	156.8
P07	5.89	WSW	5.7	1.42	SW	220.6	7.38	WSW	156.1	3.49	WNW	156.1
P08	12.1	NE	2.8	3.08	NE	2.8	15.32	NE	2.8	5.9	NE	2.8
P09	4.93	ESE	45.6	1.68	SSE	132.5	12.84	ESE	21.5	5.06	NW	181.0
P10	6.19	ESE	155.8	1.91	SSE	172.6	9.17	SSW	121.5	4.94	WNW	190.9
P11	8.3	NE	11.7	2.23	NE	2.8	17	NE	2.8	5.46	NE	2.8
P12	4.2	ENE	8.6	1.77	ESE	43.6	9.03	SSW	67.7	4.88	NW	190.3
P13	7.43	ESE	108.3	1.89	SW	203.7	8.73	SW	203.7	4.72	WNW	197.2
P14	5.41	WSW	50.1	2.07	ENE	5.7	8.82	WNW	101.0	4.26	NW	192.0
P15	4.14	SE	220.6	1.64	SE	212.4	8.33	NNW	204.1	4.26	WNW	162.6
P16	4.15	SSE	217.9	1.66	SSE	217.9	8.01	NW	212.1	4.16	WNW	177.0
P17	6.03	NE	8.5	2..05	NE	2.8	15.18	NE	2.8	4.24	WNW	180.4
P18	6.09	NE	2.8	2.03	SE	212.1	12.98	WNW	106.6	4.30	WNW	154.0

Comparison of PM_{10} concentration with mixing height and friction velocity (7–12 April 2016)



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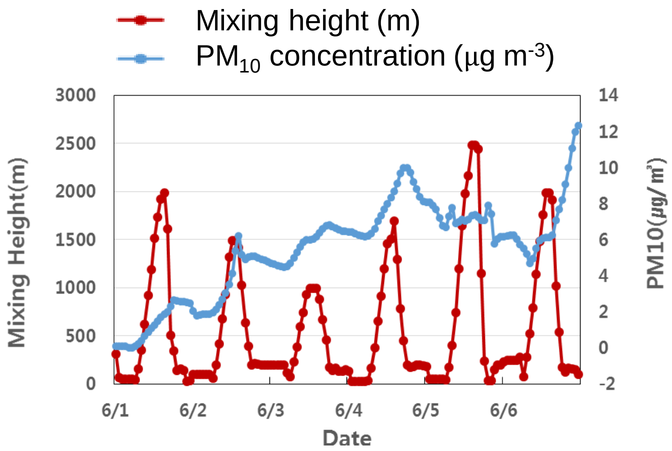
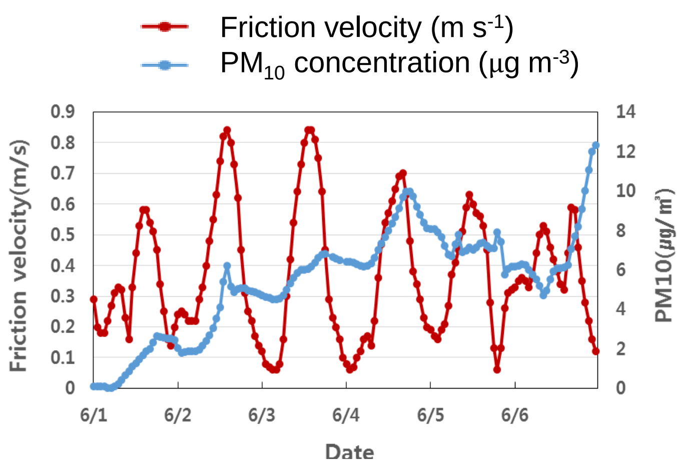
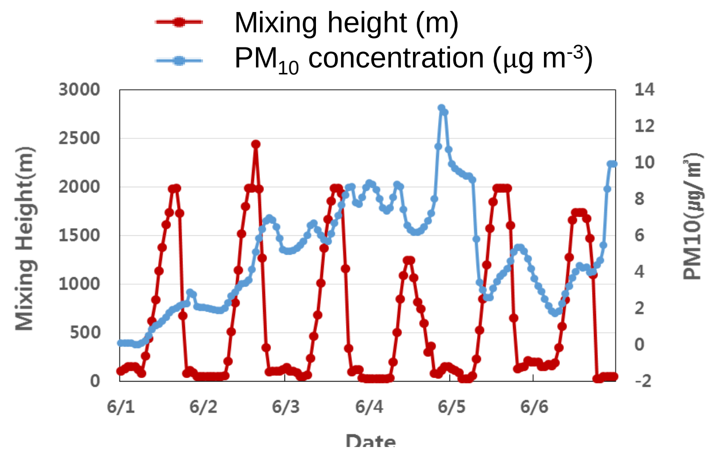
Comparison of PM_{10} concentration with mixing height and friction velocity (1–6 June 2016)

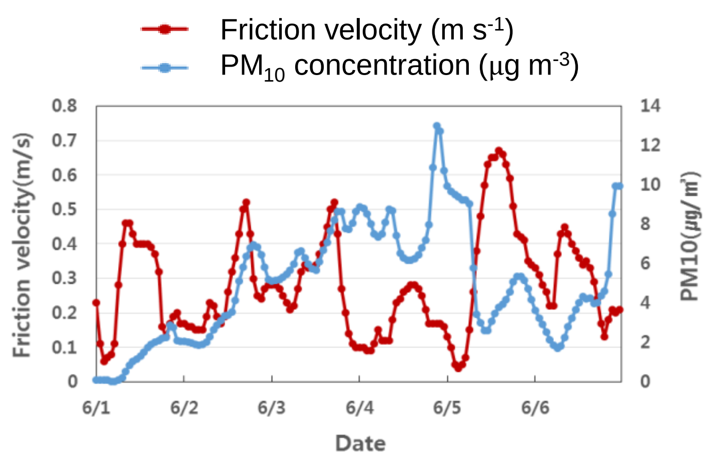
Seoul



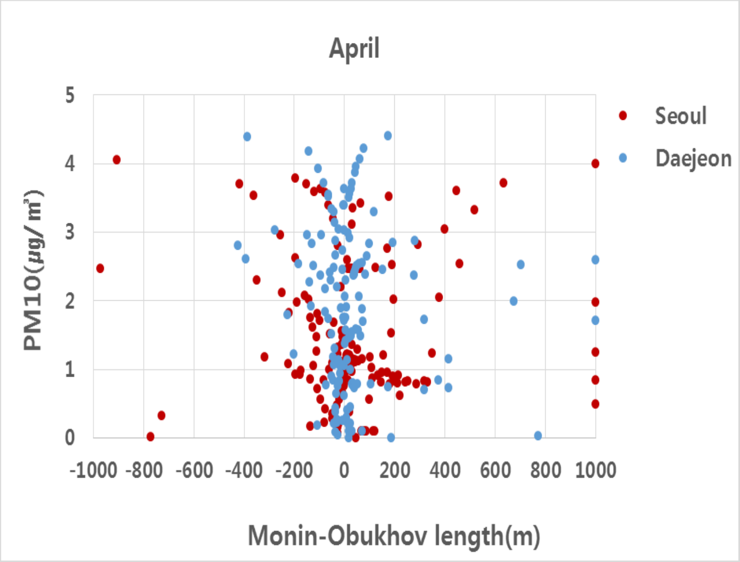


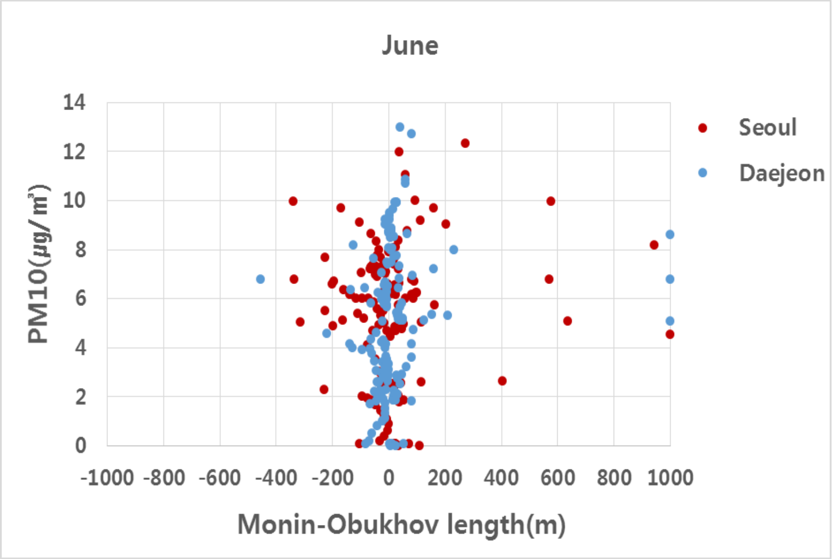
Daejeon



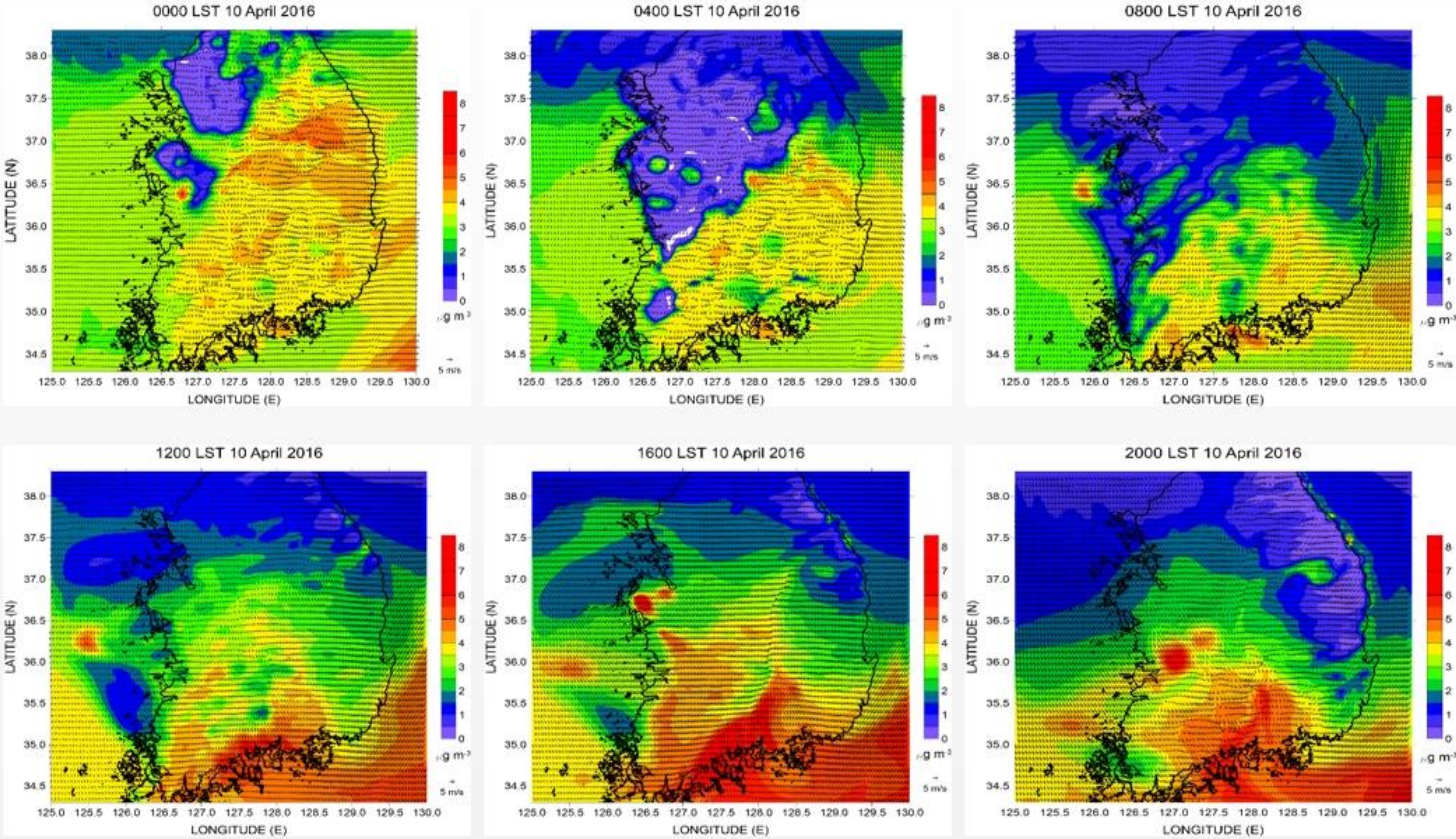


Scatter diagram between PM_{10} and Obukhov length

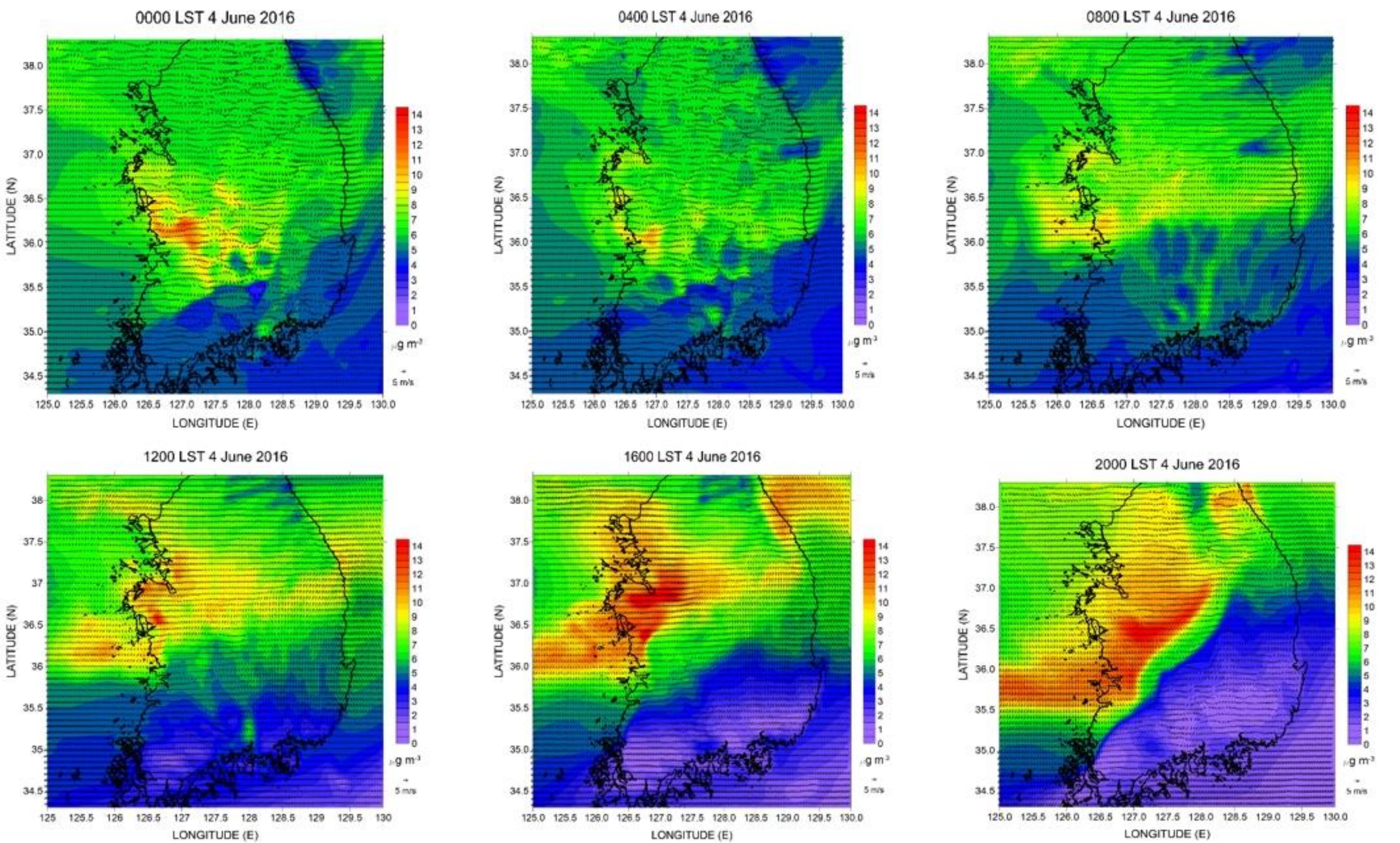




Simulated PM_{10} concentration and wind on 10 April 2016



Simulated PM_{10} concentration and wind on 4 June 2016



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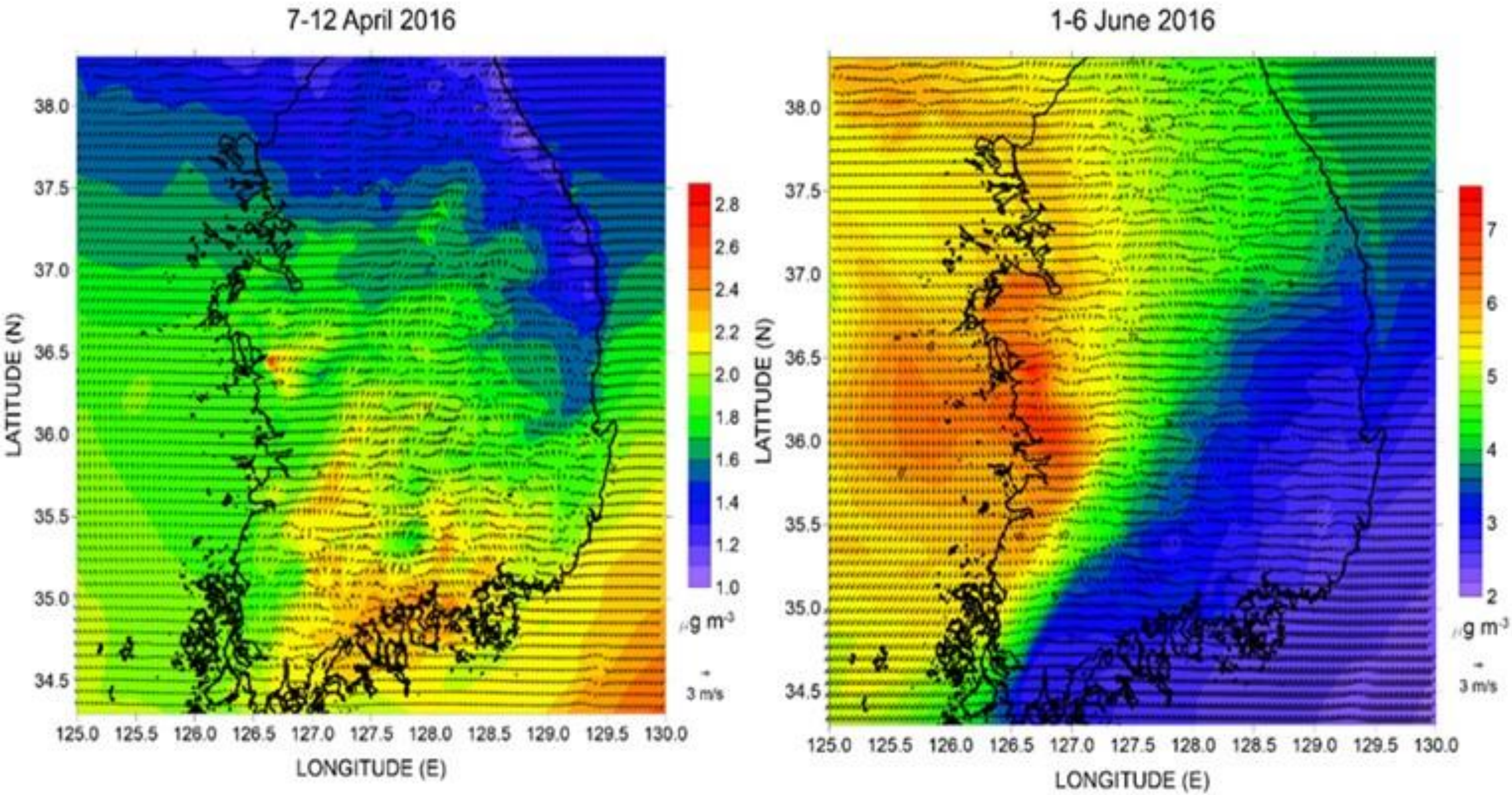
Period mean simulated PM_{10} concentration and wind



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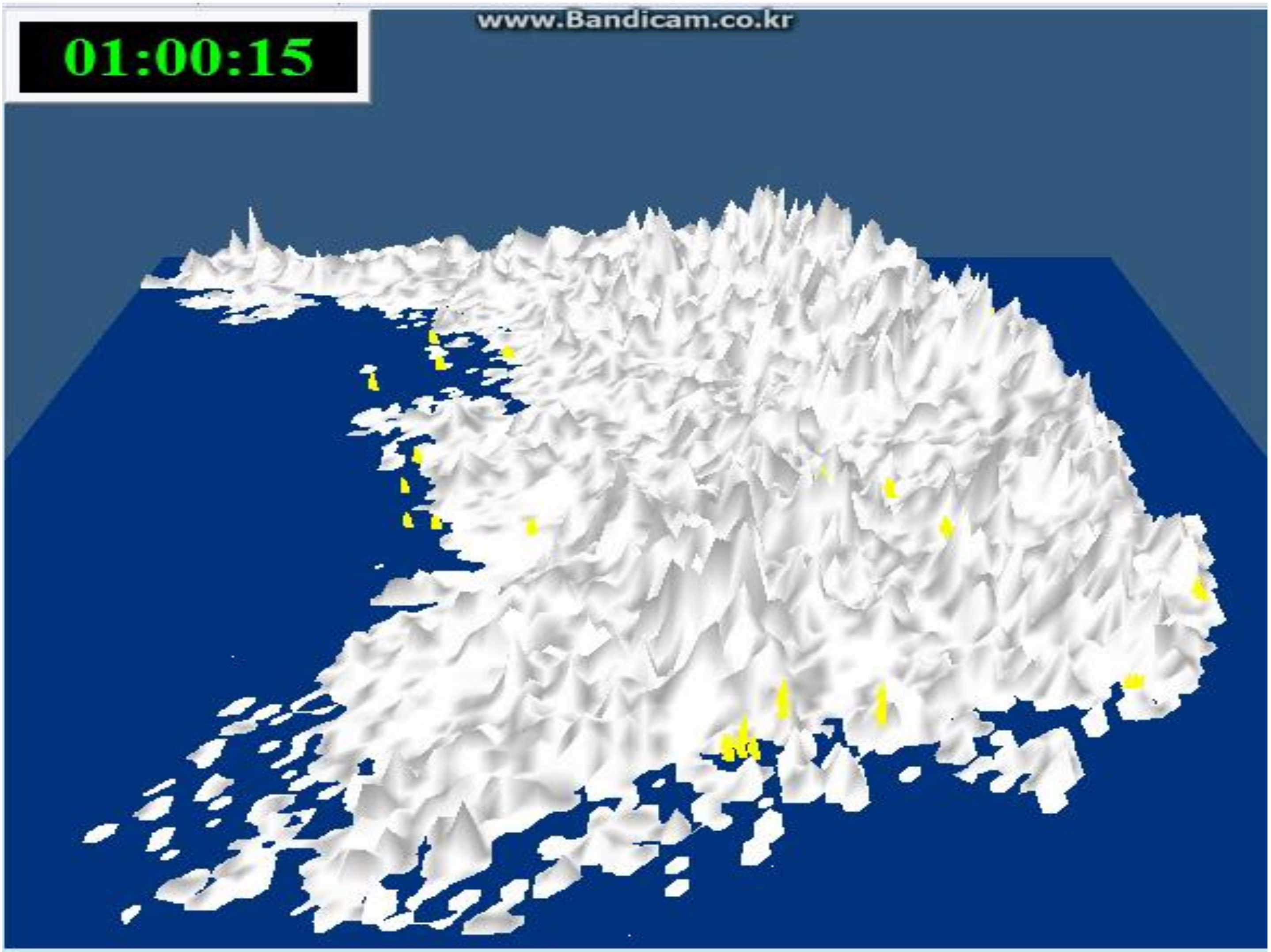
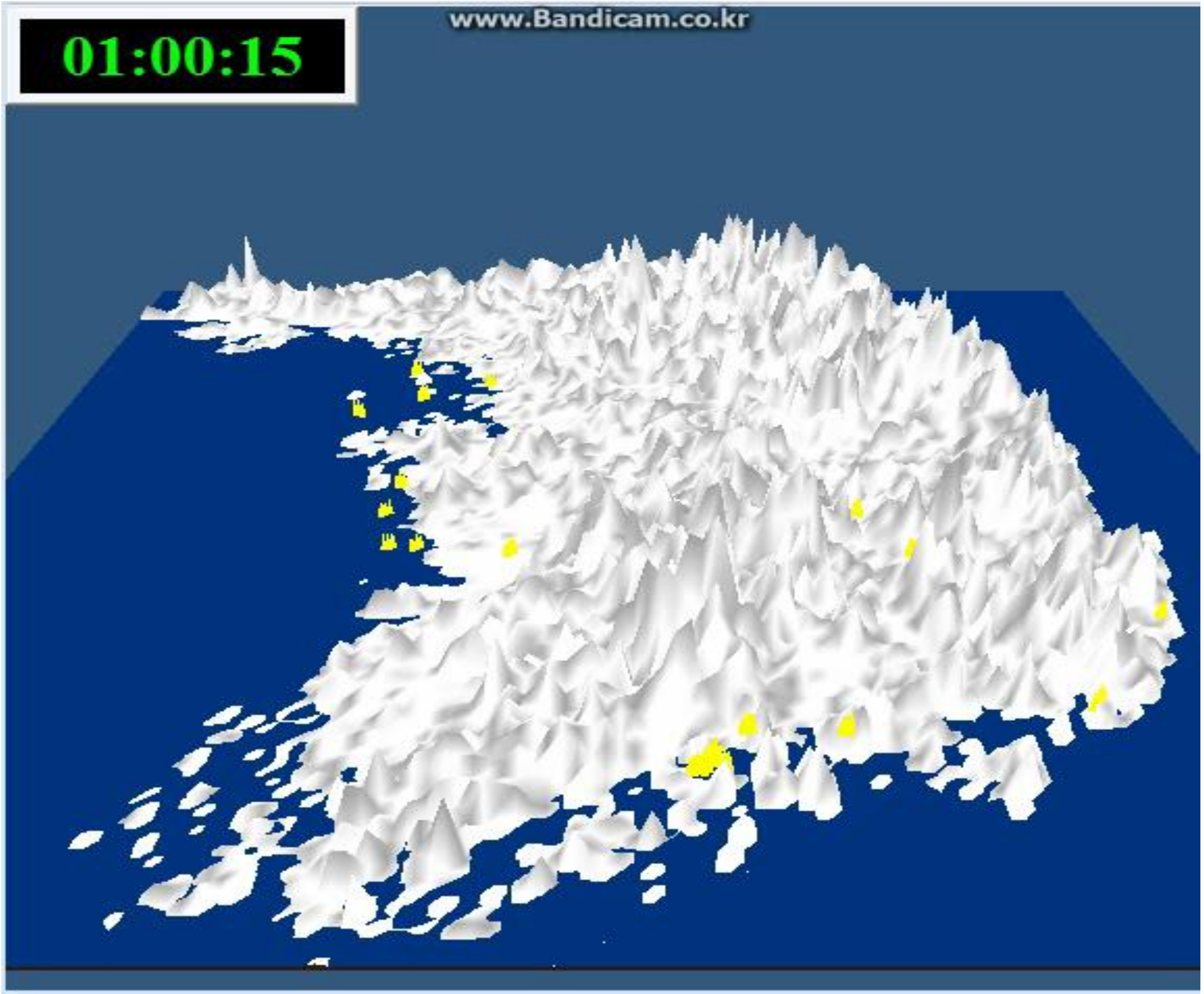
Animated PM_{10} concentration on April 2016



Animated PM_{10} concentration on June 2016



Emission reduction scenarios

Scenarios	Shut-Down Efficiencies			Reduction Emission (ton)				Target Areas of Impact Assessments
	Power Plants		Operation Rate(%)	PM10	PM2.5	NOx	SOx	
Scenario I	P08	Boryeong	0.0 %	560.94	452.46	17,454.32	11,656.09	Seoul, Daejeon
Scenario II	P03	Incheon	0.0 %	207.76	167.58	3862.97	5,517.57	Seoul, Daejeon
	P05	Ansan	0.0 %	14.11	11.38	686.03	324.74	
	P09	Dangjin	0.0 %	319.95	111.50	17,148.32	7,223.25	
	P11	Taean	0.0 %	835.13	673.63	22,168.03	12,792.28	
Scenario III	P17	Goseong	81.3 %	105.73	85.28	9,497.16	3,275.97	Seoul, Daejeon, P06, P17, P08, P10
	P08	Boryeong	74.6 %	142.37	114.84	4,935.66	3,549.51	
	P06	Gangneung	0.0 %	188.28	151.87	2,741.27	3,394.57	
	P10	Seocheon	0.0 %	60.57	41.58	3,613.69	1,317.73	
Scenario IV	P01~P18		0.00 0.00 58,896.02 38,978.72 Having the emissions of NOx and SO_2 only with no reduction of particulate emissions for all 18 power plants					Seoul, Daejeon, P06, P17, P08, P10

Hourly and period-averaged maximum Concentration

Scenarios	Period	Hourly Max. Con. (μg m^{-3})	Direction from Daejeon	Distance from Daejeon (km)	Averaged Max. Con. (μg m^{-3})	Direction from Daejeon	Distance from Daejeon (km)
BAU	April	16.98	WNW	78.2	2.87	WNW	78.2
	June	25.64	WNW	78.2	7.61	WNW	74.2
Scenario I	April	11.81	SSE	158.6	2.62	SSE	157.7
	June	22.34	SW	127.9	6.77	WSW	72.5
Scenario II	April	17.03	WNW	78.2	2.75	WNW	78.2
	June	23.82	WNW	78.2	6.73	WNW	74.2
Scenario III	April	11.59	WNW	78.2	2.54	SSE	158.6
	June	21.57	SSE	127.9	7.21	W	78.2
Scenario IV	April	14.94	WNW	78.2	2.69	WNW	78.2
	June	20.58	WNW	78.2	6.95	WNW	78.2

Reduced PM_{10} concentration ($\mu g\ m^{-3}$)

Scenarios	Period	Seoul	Daejeon	P06	P17	P08	P10
		Max (△fraction) Avg (△fraction)	Max (△fraction) Avg (△fraction)	Max (△fraction) Avg (△fraction)	Max (△fraction) Avg (△fraction)	Max (△fraction) Avg (△fraction)	Max (△fraction) Avg (△fraction)
BAU	April	max. 4.05 avg. 1.52	max. 4.41 avg. 1.86	max. 4.50 avg. 1.46	max. 6.95 avg. 2.45	max. 16.99 avg. 2.88	max. 3.57 avg. 1.87
	June	max. 12.33 avg. 5.44	max. 12.99 avg. 4.97	max. 9.76 avg. 3.88	max. 16.96 avg. 3.78	max. 25.64 avg. 7.55	max. 16.17 avg. 6.99
Scenario I	April	4.05 (-0.0 %) 1.51 (-0.7 %)	4.41 (-0.0 %) 1.82 (-2.2 %)	-	-	-	-
	June	11.79 (-4.4 %) 5.39 (-0.9 %)	12.24 (-5.8 %) 4.78 (-3.8 %)	-	-	-	-
Scenario II	April	3.79 (-6.4 %) 1.46 (-4.0 %)	4.40 (-0.2 %) 1.74 (-6.5 %)	-	-	-	-
	June	10.00 (-18.9 %) 5.26 (-3.3 %)	9.89 (-23.9 %) 4.59 (-7.6 %)	-	-	-	-
Scenario III	April	4.00 (-1.2 %) 1.51 (-0.7 %)	4.07 (-7.7 %) 1.82 (-2.2 %)	4.21 (-6.4 %) 1.44 (-1.4 %)	6.22 (-10.5 %) 2.35 (-4.7 %)	11.59 (-31.8 %) 2.48 (-13.9 %)	3.56 (-0.3 %) 1.82 (-2.7 %)
	June	11.97 (-2.9 %) 5.39 (-0.9 %)	12.57 (-3.2 %) 4.85 (-2.4 %)	9.39 (-3.8 %) 3.85 (-0.8 %)	13.68 (-19.3 %) 3.47 (-8.2 %)	20.21 (-21.2 %) 7.15 (-5.3 %)	15.39 (-4.8 %) 6.81 (-2.6 %)
Scenario IV	April	3.79 (-6.4 %) 1.49 (-2.0 %)	4.35 (-1.4 %) 1.81 (-2.7 %)	4.05 (-10.0 %) 1.44 (-1.4 %)	6.22 (-10.5 %) 2.35 (-4.1 %)	14.94 (-12.1 %) 2.69 (-6.6 %)	3.65 (-0.3 %) 1.81 (-3.2 %)
	June	11.06 (-10.3 %) 5.27 (-3.1 %)	11.70 (-9.9 %) 4.63 (-6.8 %)	8.45 (-13.4 %) 3.75 (-3.4 %)	15.12 (-10.7 %) 3.55 (-6.1 %)	20.58 (-19.7 %) 6.81 (-9.8 %)	14.33 (-11.4 %) 6.32 (-9.6 %)

Conclusions

- High emissions and low stack heights can cause high levels of ground maximum concentration.
- The location of the plant (coast or inland) is critical for determining how far the ground maximum concentration can be occurred from the plant.
- In order to decrease the concentration of Seoul Metropolitan area, it is expected that direct emission reduction of power plants located in West Sea could be essential

Conclusions

- It should be noted that reducing emissions of gaseous air pollutant, precursors of the secondary production of PM_{10}, could be very effective as like reducing the primary emission of PM_{10} directly.

- The reduction effectiveness in June under unstable condition is higher than one in April under stagnant synoptic condition. This implies that the plume from stack of power plant is significantly influenced by turbulent motion as convection and friction velocity.

Thank to co-authors :

Yu-Woon Jang[a], Sang-Sub Ha[a], Su-Hwan Jang[a], Kyung-Won Chung[a], Sang-kyun Kim[c], Byung-Gon Kim[d], Chang-Keun Song[e], Cheol-Hee Kim[f]

[a] Korea-Latin America Green Convergence Center, Hankuk University of Foreign Studies

[b] Weather Information Service Engine, Hankuk University of Foreign Studies

[c] Div. of Global Environmental Research, National Institute of Environmental Research

[d] Dept. of Atmospheric Environmental Sciences, Gangneung-Wonju National University

[e] School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology

[f] Dept. of Atmospheric Sciences, Pusan National University