Ensemble Forecast of $PM_{2.5}$ During The 2018 Camp Fire Event Using The HYSPLIT Model

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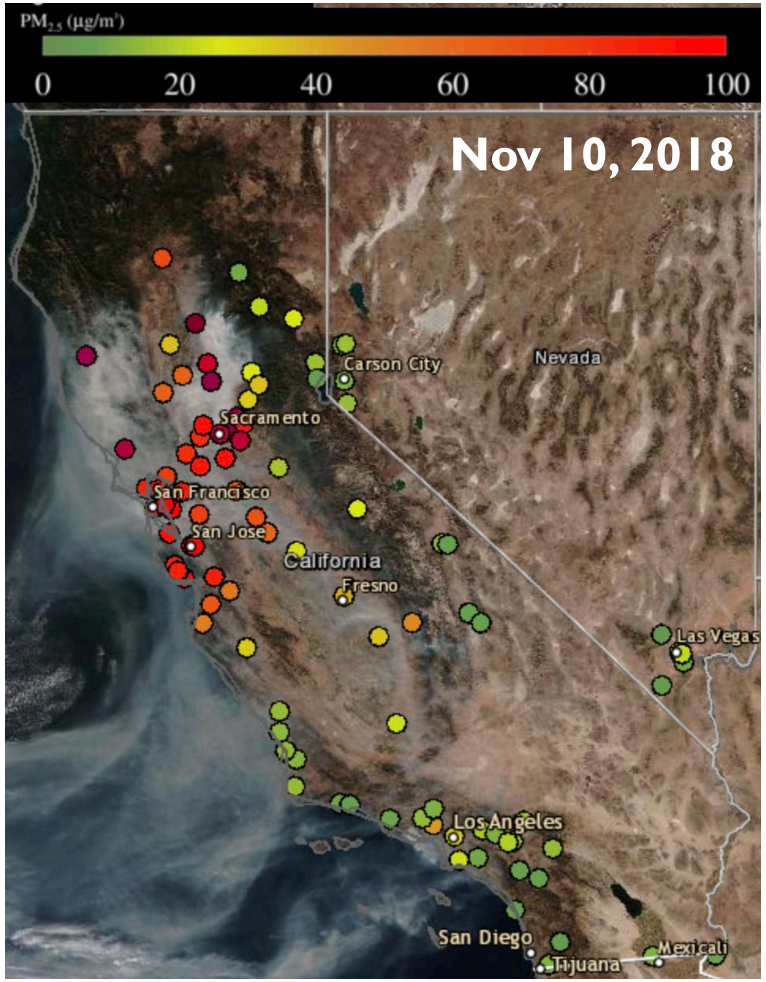
BACKGROUND

- Biomass burning releases a large amount of aerosols and trace gases into the atmosphere, often leading to severe air quality and health problems.
- However, the aerosols from biomass burning emissions are poorly predicted by global and regional models.
  - Great uncertainty in injection height, meteorological field, emission rate, emission source, transport model, etc.
  - Large gradient of the pollution concentration between affected and unaffected region
- Ensemble forecast is considered to be a good approach in reducing forecast uncertainty.
- Camp Fire: Nov 8-25 in North California
- In this study, we focus on $PM_{2.5}$



(Source: NOAA AerosolWatch)

ENSEMBLE SETUP I

- We use different plume rise schemes, meteorology inputs, PBL options, vertical motion options, and emission data seta to create the ensemble.
  - Plume rise scheme:

    1. Default: Briggs (1969) with updates by SP Arya (1999)

$$FB = 8.8 \times 10^{-6} \times HEAT$$

$$H_p = \begin{cases} 1.3FB\ U^{-1}\ x^{*-2}) & neutral, unstable \\ 2.6(FB\ U^{-1}\ s^{-1})^{\frac{1}{3}} & stable, U > 0.5\ m\ s^{-1} \\ 5.3FB^{\frac{1}{4}}\ s^{-\frac{3}{8}} & stable, U \leq 0.5\ m\ s^{-1} \end{cases}$$

FB: Buoyancy Flux
U: wind speed
x^*: friction velocity
s: static stability

2. Newly added to HYSPLIT: Sofiev (2012)

$$H_p = \alpha H_{PBL} + \beta \left(\frac{FRP}{P_{f0}}\right)^{\gamma} \exp(-\frac{\delta N_{FT}^2}{N_0^2})$$

α, β, γ, δ: parameters
H_{PBL}: PBL Height
FRP: Fire Radiative Power
P_{f0}: reference FRP (Pf0=10 W)
N_{FT}: Brunt–Vaisala frequency at Free Troposphere;
N_0: reference N

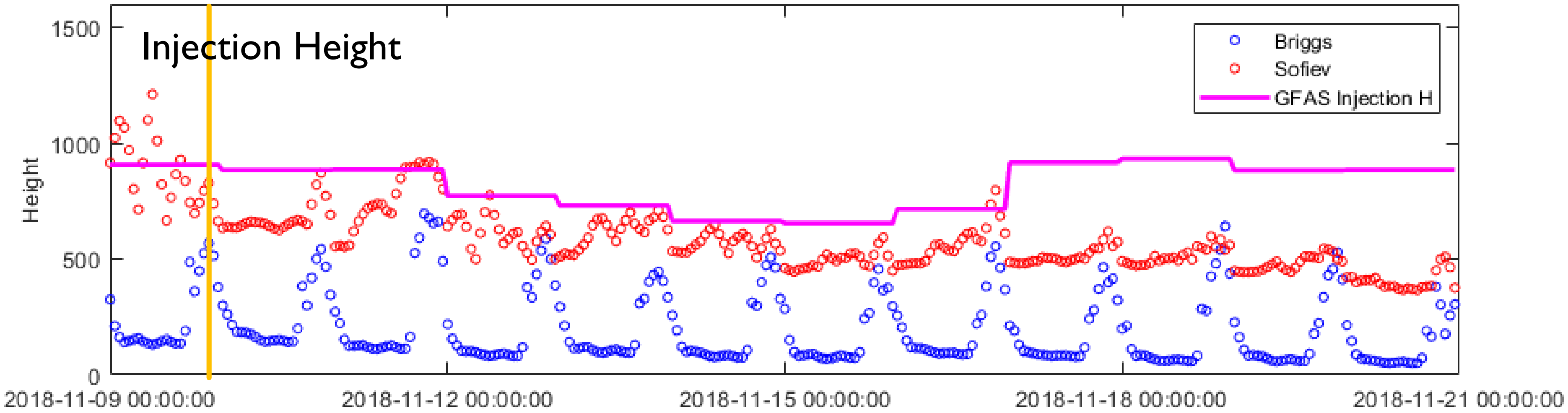
Step 1: using parameter set 1 (α=0.15; β=102; γ=0.49; δ=0) to calculate a temporary injection height (H_t).
Step 2: If H_t < PBL_h then use parameter set 2 (α=0.24; β=170; γ=0.35; δ=0.6) to calculate H_p; if H_t > PBL_h, then use parameter set 3 (α=0.93; β=298; γ=0.13; δ=0.7) to calculate H_p.

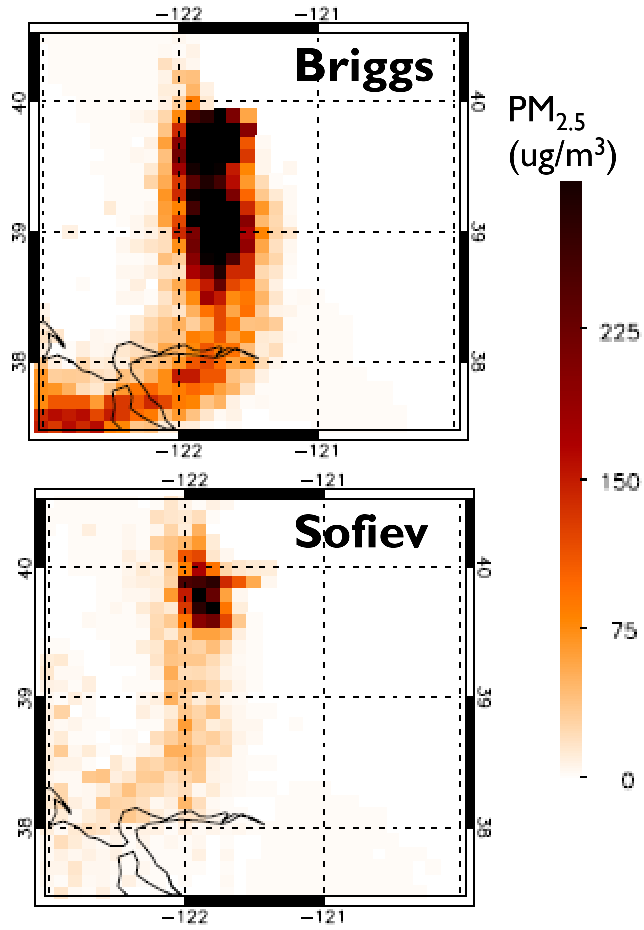
3. GFAS injection height

ENSEMBLE SETUP II

- We use different plume rise schemes, meteorology inputs, PBL options, vertical motion options, and emission data sets to create the ensemble.
  - **Plume rise schemes:** Briggs 1969, Sofiev 2012, and using GFAS injection height
  - **Meteorology inputs**: GDAS, NAM12, NARR, WRF
  - **PBL Options**:
    - CONTROL: using PBL height from input data;
    - KMIXD: PBL height derived from temperature profile;
  - **Emission data**: GFAS, FEER, GBBEPx, FLAMBE
  - **Vertical motion options**:
    - Option 0: using the meteorological model's vertical velocity fields
    - Option 5: compute vertical motion from the velocity divergence (for GDAS)
    - Option 6: adjusting the vertical velocity according to the slope of the terrain (for complex terrain)
- Totally more than 200 experiments

THE IMPACTS OF DIFFERENT PLUME RISE SCHEMES

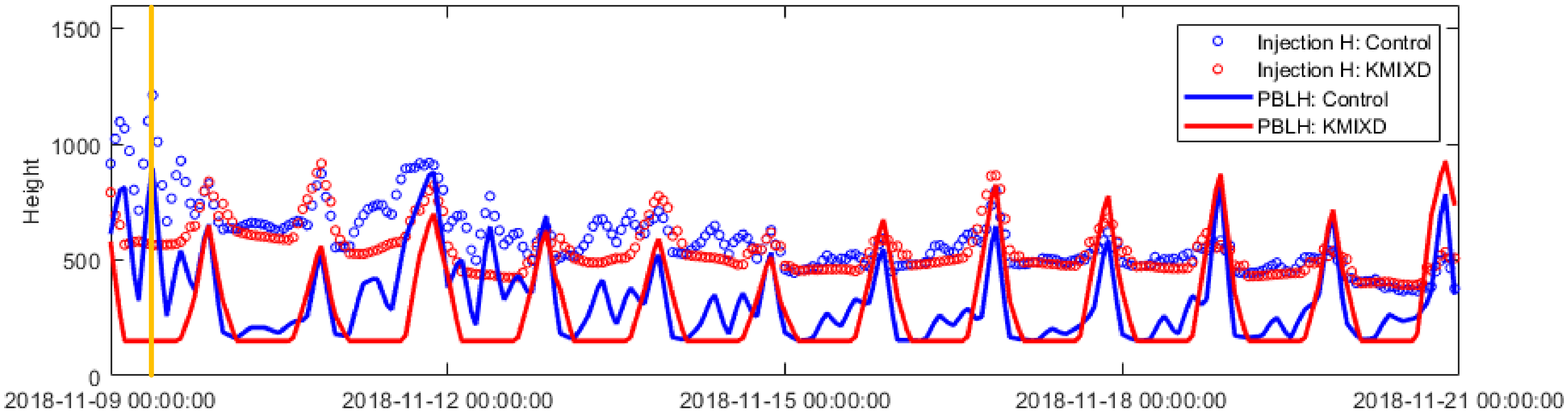


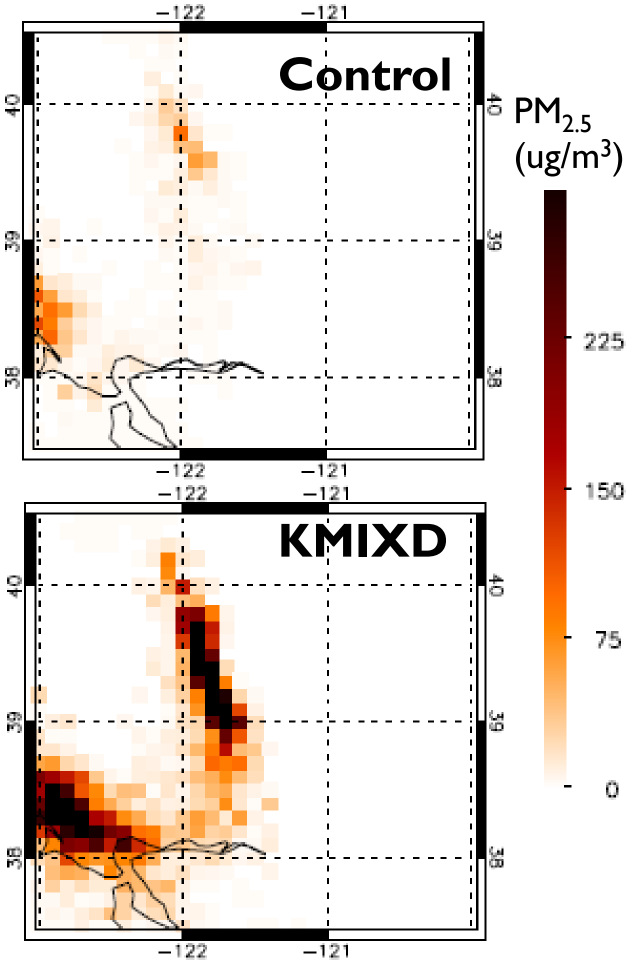


	Plume rise	Met data	Vertical motion	PBL option	Emission data
Run 01	Briggs	NAM12	Opt=0, using W from input	Opt=0, using PBL from input	GFAS
Run 02	Sofiev				

- The injection height calculated by different plume rise schemes are very different, which results in the difference in the $PM_{2.5}$ concentration forecast.
- Usually, a higher injection height will reduce the concentration of the ground pollution.
- The daily GFAS injection height data fails to show the diurnal change of the PBL height.

THE IMPACTS OF DIFFERENT PBL OPTIONS





	Plume rise	Met data	Vertical motion	PBL option	Emission data
Run 01	Sofiev	NAM12	Opt=0, using W from input	Control: PBL from Input	GFAS
Run 02				KMIXD: calculate PBL from T	

- The injection height calculated by Sofiev 2012 scheme depends on PBL height.
- If the injection height is higher than the PBL height, the pollution would be injected to the free troposphere where horizontal wind speed is much higher, which will increase the impacted area.

THE IMPACTS OF DIFFERENT METEOROLOGY INPUTS

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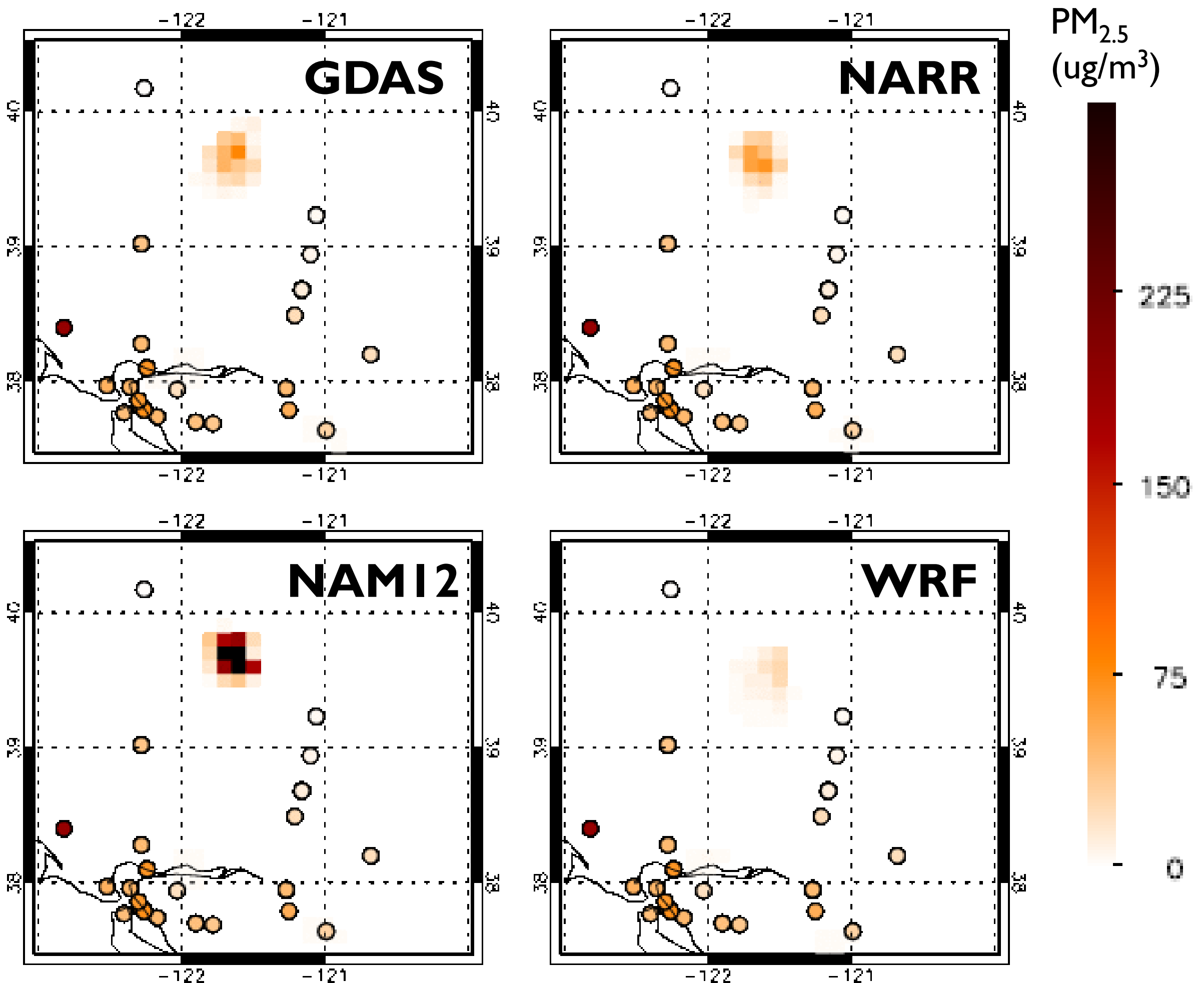
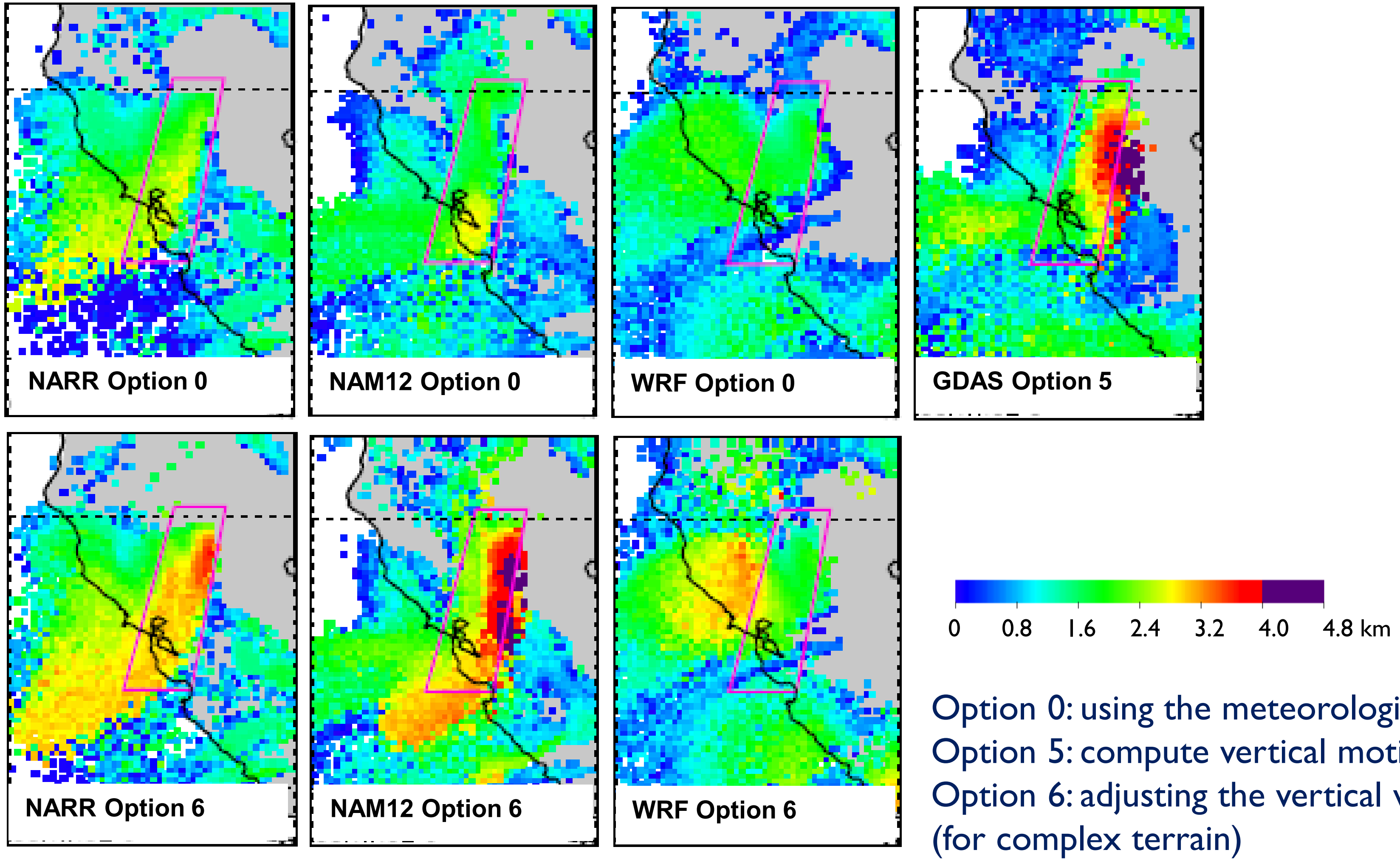


Run #	Plume rise	Met data	Vertical motion	PBL option	Emission data
01	Briggs	GDAS	5 (div)	Control: PBL from Input	GFAS
02		NARR	0 (input)		
03		NAM12			
04		WRF			

- Different meteorology inputs have different:
  - **Horizontal wind speed field:** controls the horizontal transport of the pollution and the impacted region
  - **Vertical wind speed field:** controls the vertical transport pattern
  - **PBL height**: controls the injection height and the vertical transport pattern
  - **Humidity & precipitation**: affects the wet deposition

THE IMPACTS OF DIFFERENT VERTICAL MOTION OPTIONS



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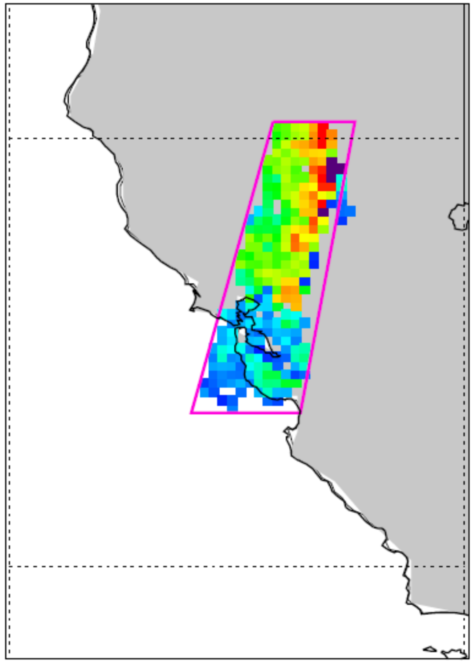
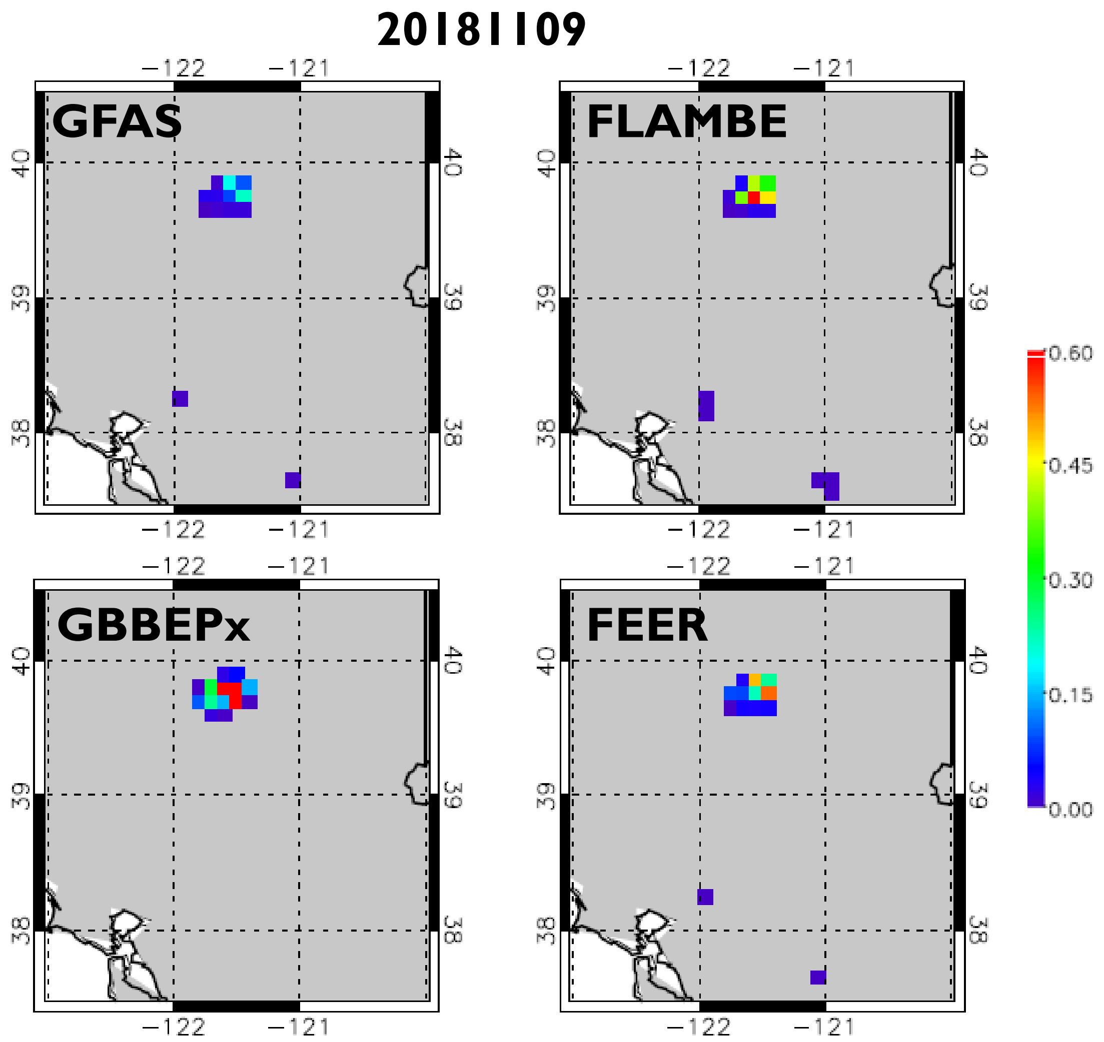
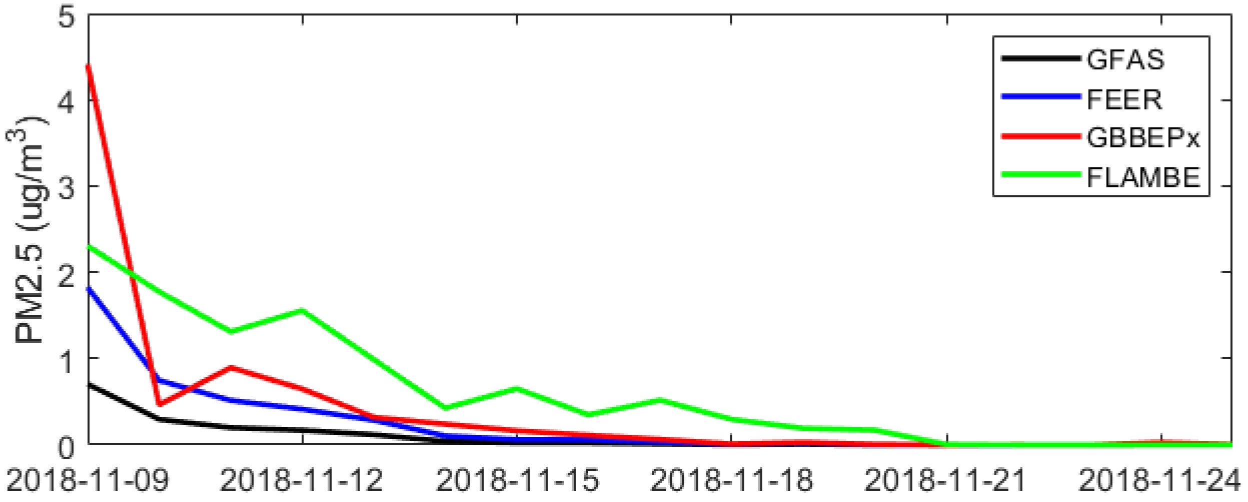
MISR Plume Height



Option 0: using the meteorological model's vertical velocity fields
Option 5: compute vertical motion from the velocity divergence (for GDAS)
Option 6: adjusting the vertical velocity according to the slope of the terrain (for complex terrain)

THE IMPACTS OF DIFFERENT EMISSION DATA





- Different emission data sets provide different emission amount, temporal/spatial variations, and FRPs.

ENSEMBLE REDUCTION

- We use different plume rise schemes, meteorology inputs, PBL options, vertical motion options, and emission data sets to create the ensemble.
  - **Plume rise schemes:** Briggs 1969, Sofiev 2012, ~~and using GFAS injection height~~
  - **Meteorology inputs**: GDAS, NAM12, NARR~~, WRF~~
  - **PBL Options**:
    - CONTROL: using PBL height from input data;
    - KMIXD: PBL height derived from temperature profile;
  - **Emission data**: GFAS, FEER, GBBEPx, FLAMBE
  - **Vertical motion options**:
    - Option 0: using the meteorological model's vertical velocity fields
    - Option 5: compute vertical motion from the velocity divergence (for GDAS)
    - Option 6: adjusting the vertical velocity according to the slope of the terrain (for complex terrain)
- Totally 80 experiments

EXP #	Plume Rise	Met Input	Vertical Motion	PBL Option	Emission Data
1	Briggs	GDAS	5	Control	FLAMBE
2				KMIXD	
3		NARR	0	Control	
4				KMIXD	
5			6	Control	
6				KMIXD	
7		NAM12	0	Control	
8				KMIXD	
9			6	Control	
10				KMIXD	
11	Sofiev	GDAS	5	Control	
12				KMIXD	
13		NARR	0	Control	
14				KMIXD	
15			6	Control	
16				KMIXD	
17		NAM12	0	Control	
18				KMIXD	
19			6	Control	
20				KMIXD	
21	Briggs	GDAS	5	Control	GFAS
22					FEER
23					GBBEPx
24				KMIXD	GFAS
25					FEER
26					GBBEPx
27		NARR	0	Control	GFAS

EXP #	Plume Rise	Met Input	Vertical Motion	PBL Option	Emission Data
28	Briggs	NARR	0	Control	FEER
29					GBBEPx
30				KMIXD	GFAS
31					FEER
32					GBBEPx
33			6	Control	GFAS
34					FEER
35					GBBEPx
36				KMIXD	GFAS
37					FEER
38					GBBEPx
39		NAM12	0	Control	GFAS
40					FEER
41					GBBEPx
42				KMIXD	GFAS
43					FEER
44					GBBEPx
45			6	Control	GFAS
46					FEER
47					GBBEPx
48				KMIXD	GFAS
49					FEER
50					GBBEPx
51	Sofiev	GDAS	5	Control	GFAS
52					FEER
53					GBBEPx
54				KMIXD	GFAS

EXP #	Plume Rise	Met Input	Vertical Motion	PBL Option	Emission Data
55	Sofiev	GDAS	5	KMIXD	FEER
56					GBBEPx
57		NARR	0	Control	GFAS
58					FEER
59					GBBEPx
60				KMIXD	GFAS
61					FEER
62					GBBEPx
63			6	Control	GFAS
64					FEER
65					GBBEPx
66				KMIXD	GFAS
67					FEER
68					GBBEPx
69		NAM12	0	Control	GFAS
70					FEER
71					GBBEPx
72				KMIXD	GFAS
73					FEER
74					GBBEPx
75			6	Control	GFAS
76					FEER
77					GBBEPx
78				KMIXD	GFAS
79					FEER
80					GBBEPx

STATISTICAL ANALYSIS OF EACH EXPERIMENTS

- We calculated the following 6 statistical variables to evaluate the simulation results of the 80 members:
  - Correlation coefficient (P=99%) $r_{xy} = \frac{S_{xy}}{S_x S_y}$
  - Normalized mean square error $NMSE = \frac{1}{N}\sum_{i}^{N}\frac{(x_i - y_i)^2}{\overline{xy}}$
  - Fractional bias [2B/(C+M)] $FB = 2 \times \left(\frac{\bar{x} - \bar{y}}{\bar{x} + \bar{y}}\right)$
  - Figure of merit in space (%) $FMS = \frac{A_x \cap A_y}{A_x \cup A_y} \times 100\%$
  - Kolmogorov-Smirnov Parameter $D = \sup_{-\infty < x < \infty} |F_n(x) - G_m(x)|$
  - Root mean square error $RMSE = \left(\frac{1}{N}\sum_{i}^{N}(\mathrm{x_i} - y_i)^2\right)^{\frac{1}{2}}$

Overlap of the impact area between observation and simulation

Distribution differences between observation and simulation

- $Rank = CORR * CORR + (1.0 - |\frac{FB}{2.0}|) + (\frac{FMS}{100.0}) + (1.0 - \frac{KSP}{100.0})$

EXP #	Corr	NMSE	|FB|	FMS	KSP	RMSE	Rank
1	0.38	4.05	0.36	79.7	21	72.93	2.55
2	0.42	3.12	0.33	80.69	21	62.83	2.61
3	0.22	13.1	0.51	81.75	17	139.07	2.44
4	0.23	15.83	0.68	81.62	19	169.29	2.34
5	0.28	19.49	0.73	82.02	19	194.05	2.34
6	0.2	46.21	1.04	81.09	24	366.07	2.09
7	0.53	15.53	1.06	77.22	23	208.06	2.29
8	0.56	14.71	1.13	77.86	23	215.35	2.3
9	0.43	3.98	0.79	79.01	35	39.44	2.23
10	0.45	3.41	0.5	78.27	34	43.04	2.39
11	0.25	3.17	0.14	80.2	24	49.54	2.56
12	0.25	3.13	0.23	81.28	24	47.38	2.52
13	0.18	8.98	0.04	81.68	18	92.31	2.65
14	0.25	10.5	0.49	82.8	18	124.56	2.47
15	0.18	9.46	0.15	79.85	29	85.26	2.46
16	0.25	17.83	0.62	81.39	24	176.39	2.33
17	0.4	3.48	0.23	77.78	21	61.55	2.61
18	0.47	3.98	0.39	77.54	22	71.74	2.58
19	0.37	14.19	1.54	77.45	54	40.8	1.61
20	0.43	9.99	1.42	78.61	51	39.63	1.75
21	0.47	6.27	1.19	78.74	37	37.28	2.04
22	0.47	2.16	0.42	78.74	31	34.95	2.48
23	0.45	2.86	0.22	77.83	28	56.71	2.59
24	0.41	3.71	0.29	75.93	27	67.51	2.51
25	0.45	6.43	1.2	78.4	37	37.57	2.02
26	0.45	2.24	0.44	78.4	31	35.47	2.46
27	0.16	5.77	0.81	82.4	34	46.64	2.11
28	0.16	7.74	0.08	82.4	20	86.31	2.61
29	0.14	13.9	0.7	80.84	19	161.1	2.29
30	0.18	5.66	0.75	81.71	33	47.71	2.14
31	0.18	8.38	0.15	81.71	22	92.74	2.55
32	0.14	14.63	0.76	80.34	20	170.53	2.25
33	0.29	4.94	0.4	80.1	38	52.91	2.31
34	0.29	10.98	0.52	80.1	27	126.3	2.36
35	0.28	26.27	1.13	80.53	21	285.53	2.11
36	0.27	6.43	0.21	78.18	35	66.64	2.4
37	0.27	16.2	0.7	78.18	28	169.53	2.22
38	0.27	32.71	1.26	76.92	24	352.32	1.97
39	0.57	2.54	0.67	78.73	36	33.49	2.41
40	0.56	3.77	0.22	78.73	33	64.73	2.66
41	0.52	9.19	0.8	76.98	26	139.52	2.38

EXP #	Corr	NMSE	|FB|	FMS	KSP	RMSE	Rank
42	0.58	2.35	0.61	77.13	38	33.09	2.42
43	0.58	3.93	0.29	77.13	33	67.96	2.63
44	0.53	9.62	0.85	75.31	26	146.69	2.35
45	0.42	12.13	1.49	78.61	53	40.41	1.69
46	0.42	4.21	0.91	78.61	44	38.16	2.07
47	0.33	5.75	0.16	75.12	39	67.26	2.4
48	0.38	10.61	1.43	77.67	52	40.21	1.69
49	0.38	4.27	0.8	77.67	46	40.93	2.06
50	0.31	7.28	0.06	75.75	43	79.62	2.39
51	0.28	13.43	1.5	79.46	47	41.36	1.66
52	0.29	4.48	0.92	79.46	32	38.42	2.1
53	0.31	2.77	0.26	78.52	28	43.92	2.47
54	0.29	13.28	1.49	80.2	46	41.28	1.68
55	0.3	4.43	0.91	80.2	32	38.33	2.12
56	0.3	2.86	0.23	78.57	25	45.17	2.51
57	0.27	7.11	1.14	81.16	41	40.97	1.91
58	0.28	5.53	0.36	81.16	26	57.73	2.45
59	0.37	5.67	0.28	80.79	19	82.14	2.62
60	0.22	5.2	0.83	82.2	31	43.63	2.15
61	0.22	6.31	0.06	82.2	19	76.83	2.65
62	0.19	10.81	0.69	81.37	18	140.94	2.32
63	0.17	12.83	1.44	80.29	50	42.53	1.62
64	0.18	7.27	0.82	80.29	39	51.15	2.03
65	0.23	5.48	0.18	80.39	25	64.02	2.52
66	0.3	4.66	0.58	79.71	38	47.77	2.22
67	0.3	8.9	0.35	79.71	28	106.02	2.43
68	0.33	18.63	1.04	79.76	24	228.53	2.15
69	0.56	6.74	1.25	77.54	40	36.71	2.06
70	0.56	2.16	0.54	77.54	29	32.69	2.53
71	0.58	1.93	0	76.85	25	41.77	2.85
72	0.62	3.57	0.98	77.45	36	33.11	2.31
73	0.62	1.8	0.15	77.45	28	37.2	2.8
74	0.56	4.36	0.46	77.42	24	79.79	2.62
75	0.47	113.2	1.93	78.25	72	44.76	1.32
76	0.47	42.14	1.82	78.25	64	43.51	1.46
77	0.48	28.07	1.74	72.29	61	42.86	1.48
78	0.54	64.16	1.87	76.94	68	44.21	1.45
79	0.54	22.27	1.69	76.94	56	42.02	1.65
80	0.43	11.71	1.48	75.44	53	40.27	1.67
Mean	0.49	2.59	0.08	79.86	15	46.62	2.85

Plume Rise	Met Input	Vertical Motion	PBL Option	Emission Data	Rank
mean					2.85
Sofiev	NAM12	0	Control	GBBEPx	2.85
Sofiev	NAM12	0	KMIXD	FEER	2.8
Briggs	NAM12	0	Control	FEER	2.66
Sofiev	NARR	0	Control	FLAMBE	2.65
Sofiev	NARR	0	KMIXD	FEER	2.65
Briggs	NAM12	0	KMIXD	FEER	2.63
Sofiev	NARR	0	Control	GBBEPx	2.62
Sofiev	NAM12	0	KMIXD	GBBEPx	2.62
Briggs	GDAS	5	KMIXD	FLAMBE	2.61
Sofiev	NAM12	0	Control	FLAMBE	2.61
Briggs	NARR	0	Control	FEER	2.61

Top 1

Top 5

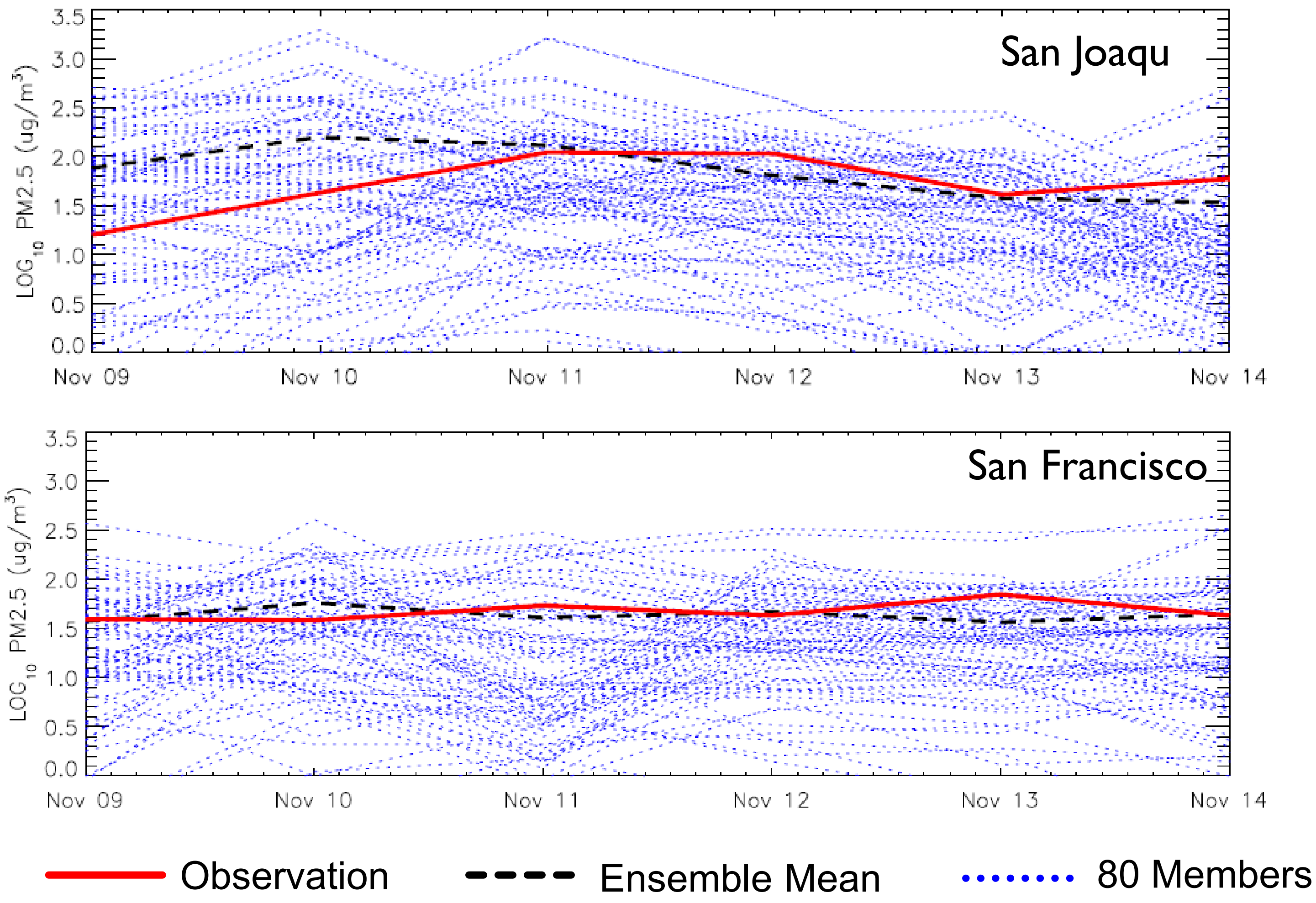
Top 10

Bottom 1

Bottom 5

Bottom 10

HYSPLIT ENSEMBLE RESULTS VS. EPA GROUND OBSERVATION



- The difference among 80 ensemble members are large, which shows the uncertainty of wildfire emission forecast
- The ensemble mean is close to the ground observation.

CONCLUSION & FUTURE

- Conclusion:
  - The wildfire pollution forecast is of great uncertainty.
  - We conducted 80 member ensemble forecasts with different combinations of meteorology inputs, plume rise schemes, PBL options, vertical motion options and emission data. The ensemble spread of the 80 is very large. The ensemble mean shows the best performance.
  - Using ensemble mean can reduce the uncertainty of the wildfire generated PM2.5 forecast.

- Future:
  - Reduce the size of the ensemble
  - Implement the Sofiev 2012 scheme in CMAQ


Thank you!