Application of WRF/Chem-MADRID for real-time air quality forecasting over the Southeastern United States

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Outline

- 1 Background
- 2 Objective
- 3 Method
- 4 Analysis
- 5 Conclusion

Background

- A Real-Time Air Quality Forecast (RT-AQF) system that is based on a three-dimensional air quality model provides a powerful tool to forecast air quality and advise the public with proper preventive actions.
- This model exits the overpredictions of O_3 and underprediction of PM2.5are likely due to uncertainties in emissions, inaccuracies in simulated meteorological variables such as 2-m temperature, 10-m wind speed, and precipitation, and uncertainties in the boundary conditions.
- WRF/Chem-MADRID demonstrates good forecasting skill that is consistent with current RT-AQF models

Objectives

- The objectives of this study are to evaluate the forecasting skill of WRF/Chem-MADRID in RT-AQF applications and to identify likely causes of model biases as well as the areas of the improvement.

Methods

- Existing AQF tools include simple rules of thumb in which thresholds of forecasted meteorological variables can indicate future high pollutant concentrations based on their correlation derived from observed and forecasted meteorological and air quality data,
- An RT-AQF system based on an online-coupled meteorology-chemistry model has a potential to better represent the real atmosphere and thus provides more accurate AQF.
- WRF/Chem for RT-AQF is based on the modal approach, MADRID uses a sectional representation for particle size distribution and more advanced model treatments.

Analysis

- Fig. 1 Flowchart of the RT-AQF system based on WRF/Chem-MADRID

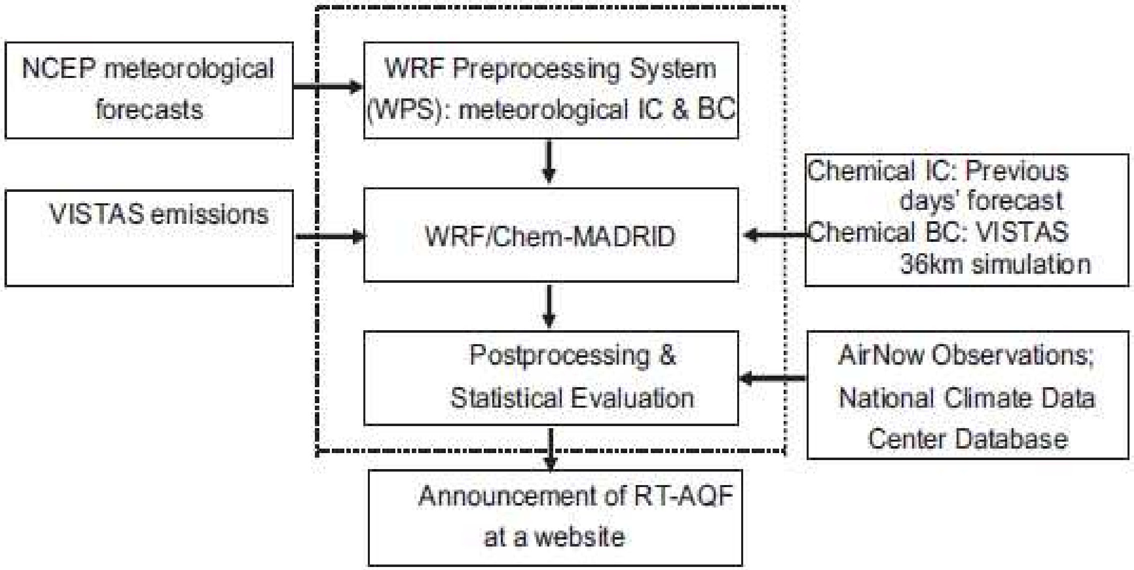

Fig. 1. Flowchart of the RT-AQF system based on WRF/Chem-MADRID (VISTAS denotes the Visibility Improvement State and Tribal Association of the Southeast).

- Fig. 2. Simulated domain for RT-AQF. Numbers of 1-9 indicate geographical regions(separated by dash lines) to be evaluated.

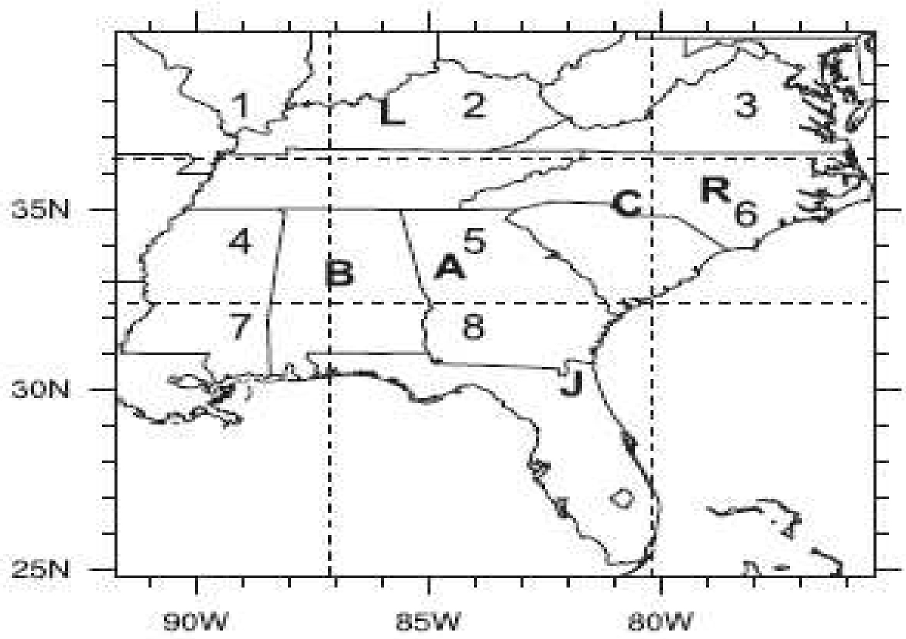

Fig. 2. Simulated domain for RT-AQF. Numbers of 1–9 indicate geographical regions (separated by dash lines) to be evaluated; letters indicate the locations of the selected six urban sites for detailed analyses: A-Atlanta city in Georgia; B-Birmingham city in Alabama; C-Charlotte city in North Carolina; J-Jacksonville city in Florida; L: Louisville city in Kentucky, and R: Raleigh city in North Carolina.

- Table 1 Summary of discrete evaluation for meteorological and chemical variables in May-September of 2009.

$$\text{Accuracy}\ (A) = \left(\frac{b+c}{a+b+c+d}\right) \times 100\% \quad (1)$$

$$\text{Critical Success Index}\ (\text{CSI}) = \left(\frac{b}{a+b+d}\right) \times 100\% \quad (2)$$

$$\text{Probability Of Detection}\ (\text{POD}) = \left(\frac{b}{b+d}\right) \times 100\% \quad (3)$$

$$\text{Bias}\ (B) = \left(\frac{a+b}{b+d}\right) \quad (4)$$

$$\text{False Alarm Ratio}\ (\text{FAR}) = \left(\frac{a}{a+b}\right) \times 100\% \quad (5)$$

where a, b, c, and d, are the numbers of simulated and observed data pairs at one site at a specific time in the four regions (see Fig. S1 in the supplementary material). They represent forecast

Summary of discrete evaluation for meteorological and chemical variables in May–September of 2009.

		Mean Obs	Mean Sim	MB	RMSE	NMB (%)	NME (%)
hourly T2 (°C)	May	19.8	20.1	0.3	2.7	1.8	7.6
	June	23.9	24.2	0.3	2.5	1.5	5.9
	July	24.1	24.4	0.3	2.4	1.4	5.9
	August	24.4	25.0	0.6	2.4	2.6	6.5
	September	21.5	21.6	0.1	2.3	0.3	6.7
	May–September	22.7	23.1	0.4	2.5	1.5	6.8
hourly WS10 ($m\ s^{-1}$)	May	5.6	4.3	−1.3	3.4	−23.9	35.6
	June	4.7	3.6	−1.1	3.1	−22.6	38.9
	July	4.5	3.5	−1.0	2.9	−21.8	42.1
	August	4.1	3.3	−0.8	2.9	−20.4	41.6
	September	4.5	3.5	−1.0	3.3	−22.5	42.8
	May–September	4.7	3.7	−1.0	3.2	−22.3	40.9
Total daily Precip ($mm\ day^{-1}$)	May	3.5	4.5	1.0	16.1	29.4	175.0
	June	2.4	2.3	−0.1	11.7	−5.7	161.9
	July	2.8	3.8	1.0	15.5	35.7	197.7
	August	2.5	2.9	0.4	14.3	15.5	184.5
	September	3.1	3.3	0.2	16.2	7.9	166.2
	May–September	2.9	3.4	0.5	14.9	18.7	178.0
Max 1-h O_3 (ppb)	May	45.9	49.7	3.8	17.4	8.4	28.3
	June	52.8	53.7	0.9	17.5	1.6	25.2
	July	48.5	54.3	5.8	16.9	12.0	25.9
	August	46.3	54.2	7.9	16.4	17.1	26.7
	September	43.2	47.3	4.0	15.6	9.2	27.5
	May–September	47.3	51.8	4.4	16.8	9.4	26.6
Max 8-h average O_3 (ppb)	May	41.5	43.9	2.4	13.9	5.7	26.1
	June	47.4	47.6	0.2	13.9	0.4	23.2
	July	43.5	47.9	4.4	13.3	10.2	23.6
	August	41.2	48.2	7.0	13.6	17.0	25.7
	September	38.7	42.7	4.0	13.5	10.3	27.3
	May–September	42.5	46.0	3.5	13.6	8.5	25.0
24-h average $PM_{2.5}$ ($\mu g\ m^{-3}$)	May	9.2	8.2	−1.0	4.5	−10.7	36.0
	June	13.5	11.3	−2.2	6.3	−16.2	34.8
	July	12.5	11.4	−1.1	6.0	−8.8	35.9
	August	12.4	12.0	−0.4	6.4	−3.2	36.9
	September	10.2	11.8	1.7	5.9	16.5	42.0
	May–September	11.5	10.0	−0.6	5.9	−5.2	37.0

Note: T2: Temperature at 2 m; WS: Wind Speed; Precip: Precipitation; MB: Mean Bias; RMSE: Root Mean Square Error; NMB: Normalized Mean Bias; NME: Normalized Mean Error.
Mean Bias (MB) $= 1/N \sum_1^N (\text{Sim} - \text{Obs})$,
Root Mean Square Error (RMSE) $= \sqrt{1/N \sum_1^N (\text{Sim} - \text{Obs})^2}$,
Normalized Mean Bias (NMB) $= \sum_1^N (\text{Sim} - \text{Obs}) / \sum_1^N (\text{Obs}) \times 100\%$,
Normalized Mean Error (NME) $= \sum_1^N |\text{Sim} - \text{Obs}| / \sum_1^N (\text{Obs}) \times 100\%$ where Sim, Obs, and N are simulated values, observated values, and the number of observations, respectively.

- Fig. 3 shows the overlay plots of 5-month mean daily max 8-h average O_3 and 24-h average $PM_{2.5}$ with AIRNow observations.

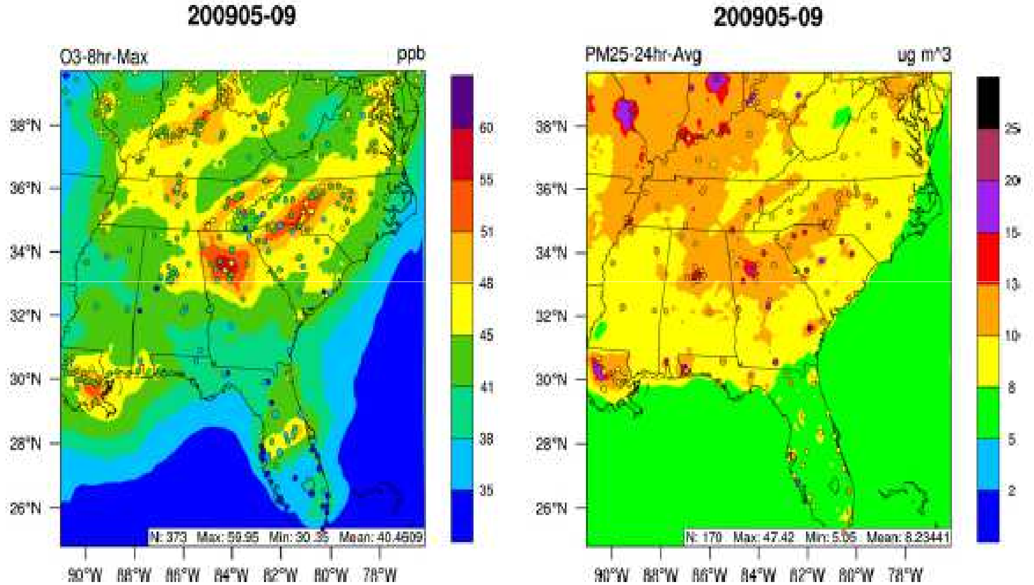

Fig. 3. Five-month (May–September 2009) mean spatial distribution of concentrations of max 8-h average O_3 (left), and 24-h average $PM_{2.5}$ (right) (circles indicate observations from AIRNow, http://www.epa.gov/airnow).

O_3 overpredictions are most apparent in most areas of Kentucky and Tennessee, southern areas of Indiana, Illinois, and Ohio, and the Appalachian Mountains region.

- Fig. 5 shows simulated and observed daily max 8-h average O_3 mixing ratios at the six urban sites.

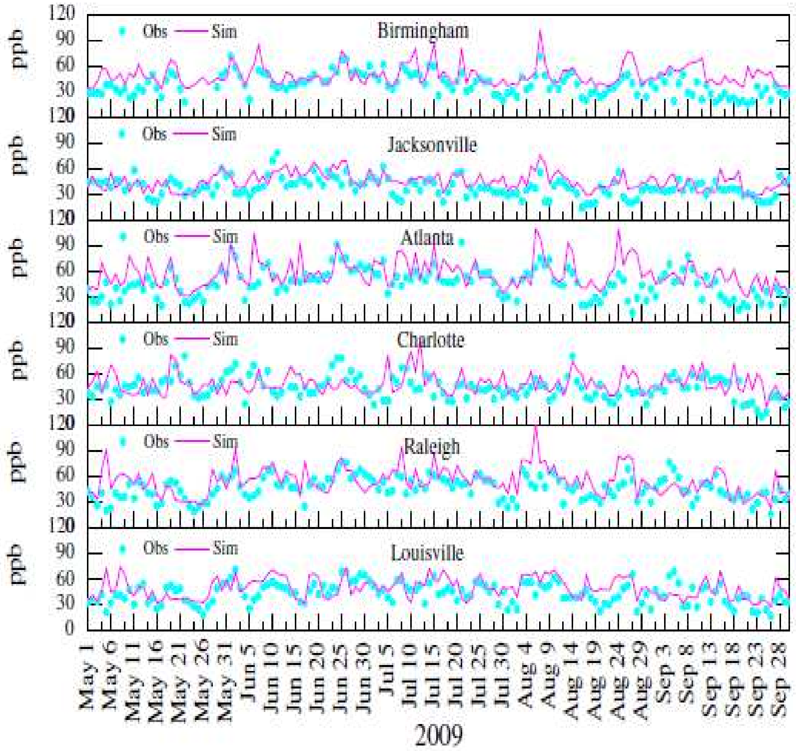

Fig. 5. Simulated and observed daily max 8-h average O_3 mixing ratios at representative urban sites during May–September 2009 (see site locations in Fig. 2). The observational data were obtained from AIRNow, http://www.epa.gov/airnow. Louisville is in Region 2, Atlanta, Birmingham, and Charlotte are in Region 5, Raleigh is in Region 6, Jacksonville is in Region 8.

Fig. 6 shows simulated and observed 24-h average $PM_{2.5}$ concentrations at urban sites.

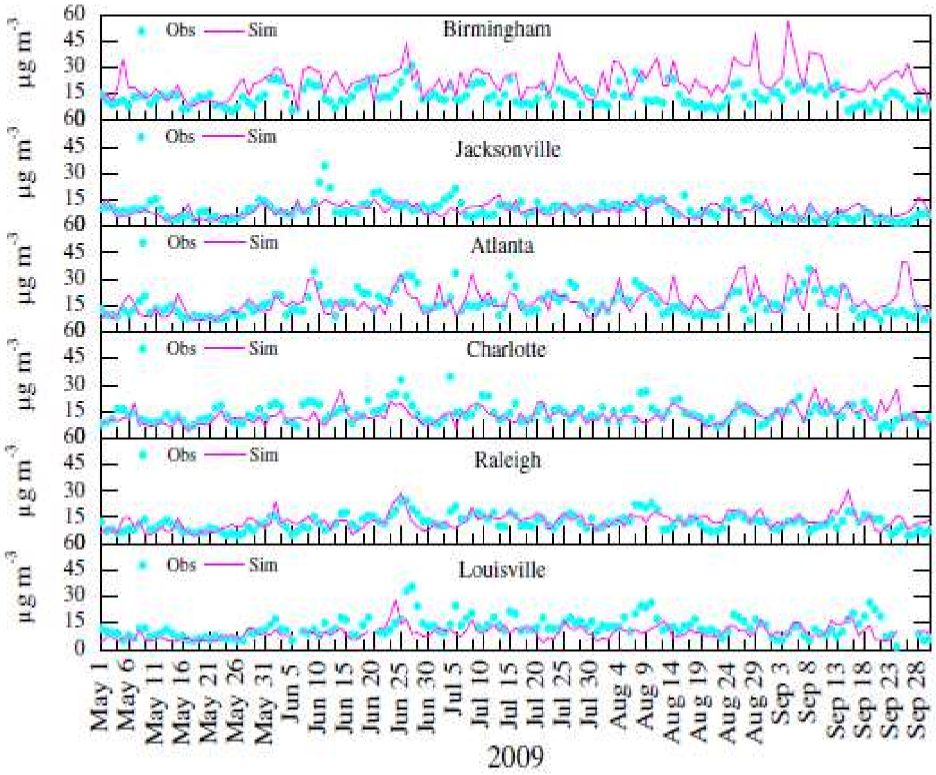

Fig. 6. Simulated and observed 24-h average $PM_{2.5}$ concentrations at representative urban sites for May–September 2009 (see site locations in Fig. 2). The observational data were obtained from AIRNow, http://www.epa.gov/airnow. Louisville is in Region 2, Atlanta, Birmingham, and Charlotte are in Region 5, Raleigh is in Region 6, Jacksonville is in Region 8.

Table 2 summarizes categorical evaluation results.

Table 2
Summary of categorical evaluation for O_3 and $PM_{2.5}$ in May–September of 2009.

	Threshold	Period	*A* (%)	CSI (%)	POD (%)	*B*	FAR (%)	*a*	*b*	*c*	*d*
Max 1-h O_3 (ppb)	80 ppb	May	94.6	2.0	22.0	10.0	97.7	576	13	10,914	46
		June	92.3	7.7	25.5	2.5	90.0	658	73	10,332	213
		Jul	92.9	6.0	40.8	6.2	93.4	754	53	10,766	77
		August	92.2	4.8	43.0	8.3	94.8	844	46	10,707	61
		September	97.9	0.4	5.6	11.9	99.5	218	5	11,024	22
		May–September	94.0	5.2	31.3	5.3	94.1	3050	190	53,743	419
Max 8-h average O_3 (ppb)	60 ppb	May	88.3	12.5	29.1	1.6	82.0	863	189	9813	460
		June	80.0	15.1	26.0	1.0	73.5	1100	395	8470	1123
		Jul	83.9	14.8	41.7	2.2	81.4	1389	318	9278	444
		August	84.5	17.5	56.8	2.8	79.7	1474	374	9179	285
		September	91.8	2.5	7.2	1.9	96.2	594	27	9901	300
		May–September	85.6	14.0	33.3	1.7	80.6	5420	1303	46,641	2612
24-hraverage $PM_{2.5}$ ($\mu g\ m^{-3}$)	15 $\mu g\ m^{-3}$	May	91.9	10.8	16.0	0.6	74.7	160	54	4655	284
		June	69.9	26.7	32.1	0.5	38.6	341	541	2904	1143
		Jul	70.8	19.2	27.1	0.7	60.1	539	358	3282	965
		August	69.9	21.1	30.0	0.7	58.2	571	409	3137	955
		September	78.8	25.8	47.8	1.3	64.1	643	362	3482	395
		May–September	76.2	22.3	31.5	0.7	56.6	2254	1724	17,460	3742

1. *A*: Accuracy; CSI: Critical success index; POD: probability of detection; *B*: bias: FAR: False alarm ratio.
2. *a*, *b*, *c*, *d*, are the number of simulated and observed data pairs at one site for a specific time in the four regions shown in Fig. S1.

Table 3 compares model performance using offline and online BVOC emissions in July 2009.

Table 3
Comparison of discrete evaluation of the baseline RT-AQF with offline biogenic emissions and the sensitivity simulations with online biogenic emissions based on the modified Guenther scheme, and modified boundary conditions in July 2009.

		Mean Obs	Mean Sim	MB	RMSE	NMB (%)	NME (%)
Max 1-h O_3 (ppb)	Offline BVOCs	48.5	54.4	5.9	16.9	12.1	25.9
	Online BVOCs		54.4	5.9	16.9	12.1	26.0
	Modified LBCs		50.3	1.8	15.6	3.7	24.3
Max 8-h average O_3 (ppb)	Offline BVOCs	43.5	47.9	4.4	13.3	10.2	23.6
	Online BVOCs		48.1	4.6	13.4	10.5	23.9
	Modified LBCs		44.4	0.9	12.6	2.0	22.3
24-h average $PM_{2.5}$ ($\mu g\ m^{-3}$)	Offline BVOCs	12.5	11.4	−1.1	6.0	−8.9	35.9
	Online BVOCs		12.3	−0.3	6.0	−1.7	35.4
	Modified LBCs		12.8	0.3	6.1	2.8	36.5

Obs: Observation; Sim: Simulation; MB: Mean Bias; RMSE: Root Mean Square Error; NMB: Normalized Mean Bias; NME: Normalized Mean Error; BVOCs: Biogenic Volatile Organic Carbons; LBCs: Lateral Boundary Conditions.

Fig. 7. July 2009 monthly-mean bias of concentrations of daily max 8-h average O3 (upper) and 24-h average PM2.5 (lower) from simulations with offline (baseline) and online (Guenther scheme) biogenic volatile compound emissions, and modified boundary condition

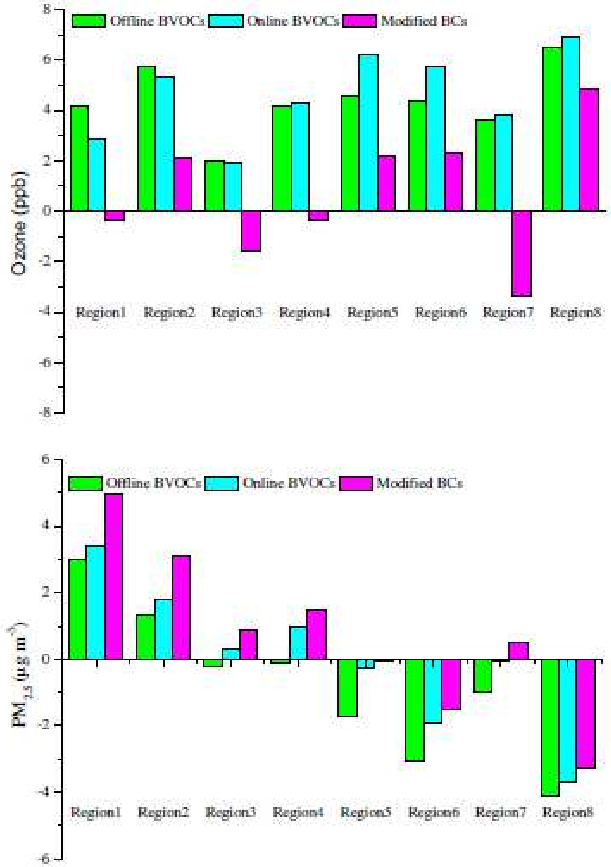

Fig. 7. July 2009 monthly-mean bias of concentrations of daily max 8-h average O_3 (upper) and 24-h average $PM_{2.5}$ (lower) from simulations with offline (baseline) and online (Guenther scheme) biogenic volatile compound emissions, and modified boundary condition (labeled as offline BVOCs, online BVOCs, and modified BCs, respectively).

Conclusion

- 1. Even though this system exists lots of uncertainties and inaccuracies, the RT-AQF model based on WRF/Chem-MADRID demonstrates a promising forecasting skill that is consistent with current RT-AQF models.
- 2. These bias correction approaches may be explored to further improve the model’s forecasting skill.

Thank you