Upgrades to the Canadian Operational Regional Air Quality Deterministic Prediction Systems in 2021

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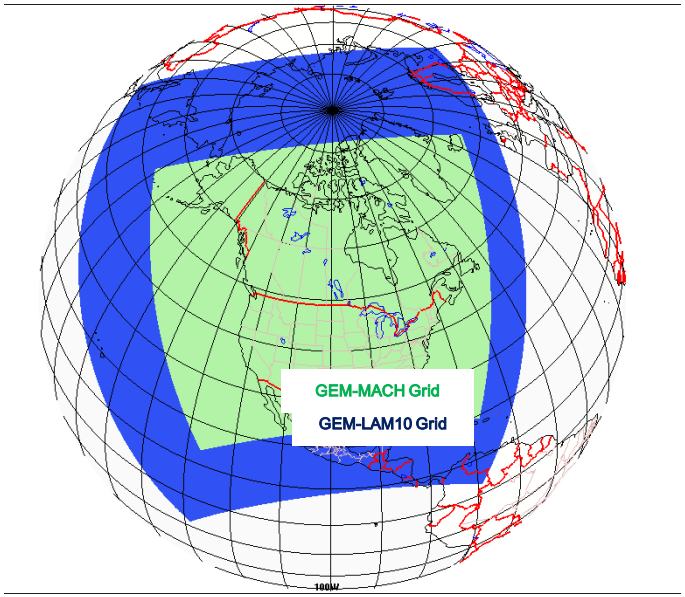
2021 CMAS Conference (Virtual) *2 Nov. 2021*

Outline

- Introduction and background
- Features of the new versions (v023) of ECCC's two operational AQ forecast systems: RAQDPS and RAQDPSFW ("FireWork")
- Selected predictions and evaluation results from pre-2021 final cycling runs (development tests) and spring-summer 2021 parallel runs (acceptance tests)
- Summary and next steps

ECCC Operational AQ Forecast Systems: RAQDPS (Regional AQ Deterministic Prediction System) and RAQDPSFW ("FireWork")

- GEM-MACH **in-line** chemical weather model is used by **both** of ECCC's AQ forecast systems: *RAQDPS* (since **2009**; no wildfire emissions) and *FireWork* (since **2016**; RAQDPS+wildfire emissions)
- Limited-area (LAM) configuration
- Meteorology provided by **GEM** numerical weather prediction model (initial and boundary conditions)
- **10**-km horizontal grid spacing, **84** vertical levels up to 0.1 hPa
- **72**-hour runs launched **twice** daily (00, 12 UTC)
- **One-way** coupling (meteorology affects chemistry)
- **2-bin** sectional representation of PM size distribution (i.e., 0-2.5 μm and 2.5-10 μm) with **8** chemical PM components (SO4, NO3, NH4, BC, POM, SOM, CM, SS)
- Full process representation of oxidant and aerosol chemistry:
  - gas-, aqueous- & heterogeneous chemistry mechanism
  - aerosol dynamics
  - dry and wet deposition



https://weather.gc.ca/aqfm/index_e.html

Emissions Inventories	In operations since Sept. 2018	Proposed for Autumn 2021
Canada	2013	Proj 2020
U.S.A.	Proj 2017	Proj 2023
Mexico	2008	Proj 2023

Major Updates to the Operational RAQDPS from 2009 to 2020

Version	Release Date	Short Description
001	Nov. 2009	Emission Inventories [EIs]: 2006 CA, 2005 US, 1999 MX)
004	Oct. 2011	New emissions (EIs: 2006 CA, projected 2012 US, 1999 MX)
007	Oct. 2012	New model version, new grid (15 km → 10 km, L58 → L80)
009	Feb. 2013	3 bug fixes, including one to near-surface vertical diffusion
013	Jun. 2015	New emissions (EIs: 2010 CA, 2011 US, 1999 MX)
015/ 016	Apr. 2016/ Sep. 2016	First operational implementation of FireWork/ New model code, new vertical discretization (→ staggered)
020	Sep. 2018	New emissions (EIs: 2013 CA, projected 2017 US, 2008 MX)
021	Jul. 2019	New model code, new vertical discretization (80 → 84 levels)

RAQDPS Innovations for 2021

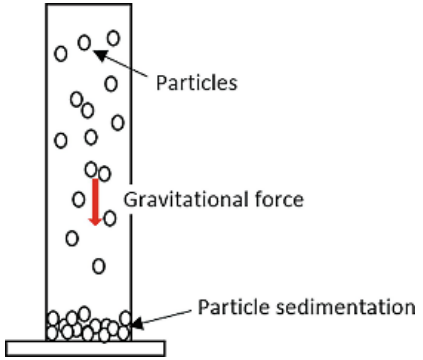
(1) New anthropogenic emissions files (SET4)

Update anthropogenic emissions inventories used to prepare emission files

- Canada: **2013** Air Pollutant Emission Inventory (APEI) → **2020** *projected* APEI
- U.S.: **2017** *projected* National Emissions Inventory → **2023** *projected* NEI
- Mexico: **2008** National Emissions Inventory (NEI) → **2023** *projected* NEI

(2) Improved representation of particle sedimentation

- More accurate numerical solution, reduces rate of PM removal



(3) New meteorological and chemical libraries

- Meteorology: GEM 5.0.2 → GEM 5.1.0
- Chemistry: GEM-MACH 3.0.0.2 → GEM-MACH 3.1.0.0
  - Code optimization and some bug fixes
  - LINOZ scheme for ozone stratospheric chemistry is now part of GEM libraries. It was removed from the MACH chemistry library

Percentage Changes in National Annual Gridded Emissions of Criteria Air Contaminants Between Current (SET3.1.2) and New (SET4) Emissions Files

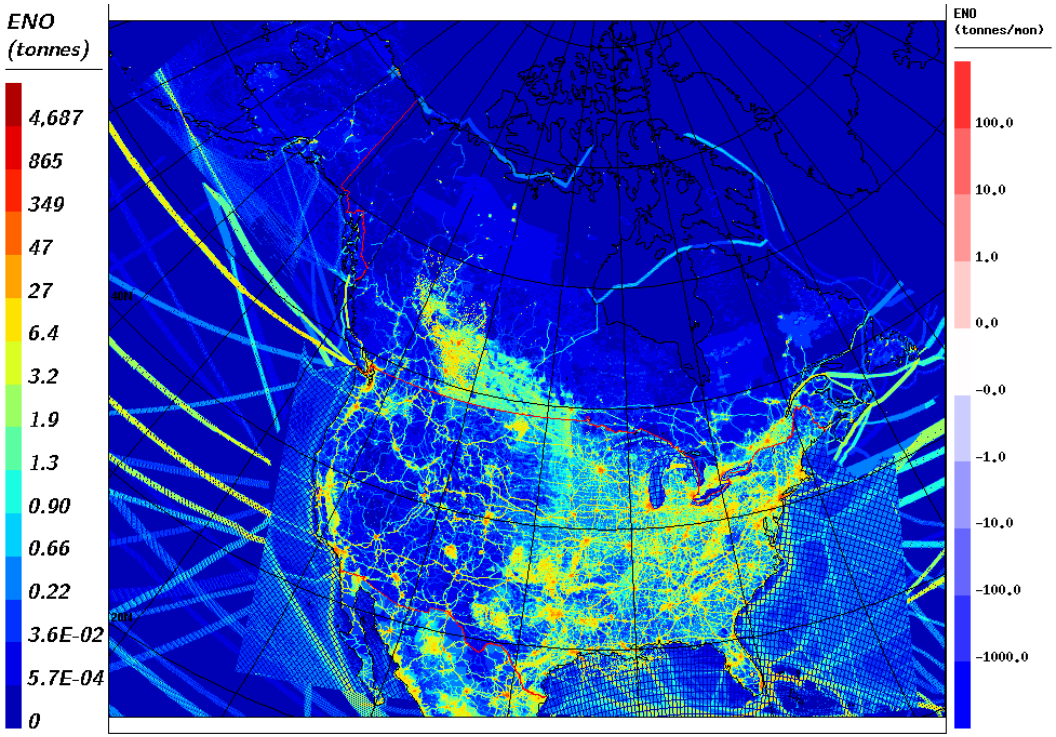
Country	SO_2	NO_x	VOC	NH_3	CO	$PM_{2.5}$	PM_{10}
Canada (%)	-36	-19	-25	12	-25	-26	-21
U.S. (%)	-31	-30	-11	10	-11	-7	-6

- Emissions changes are large and are mainly decreases
- This is the first time that we have had access to a suitable *projected* Canadian emissions inventory (*cf*. Moran et al., 2017)
- New inventory base years (2020, 2023) are better aligned with current forecast year (2021)
- Spatial distributions of emissions changes are complex (see next 3 slides)

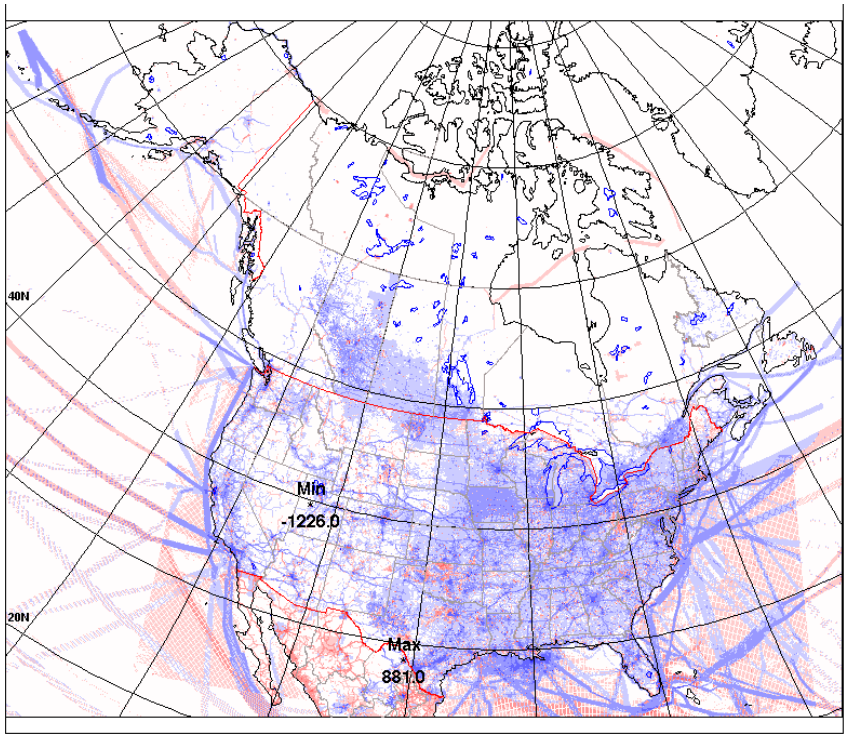
Moran, M.D., Q. Zheng, J. Zhang, R. Pavlovic, and M. Sassi, 2017. Impact on recent North American AQ forecasts of replacing a retrospective U.S. emissions inventory with a projected inventory. *16th CMAS Conference*, 23-25 Oct., Chapel Hill, North Carolina [see https://www.cmascenter.org/conference//2017/slides/moran_impact_recent_2017.pptx]

Spatial Distribution of New NO Emissions (July) & Changes vs. Current Emissions (New – Current; tonnes/grid cell)

SET4



SET4 – SET3.1.2

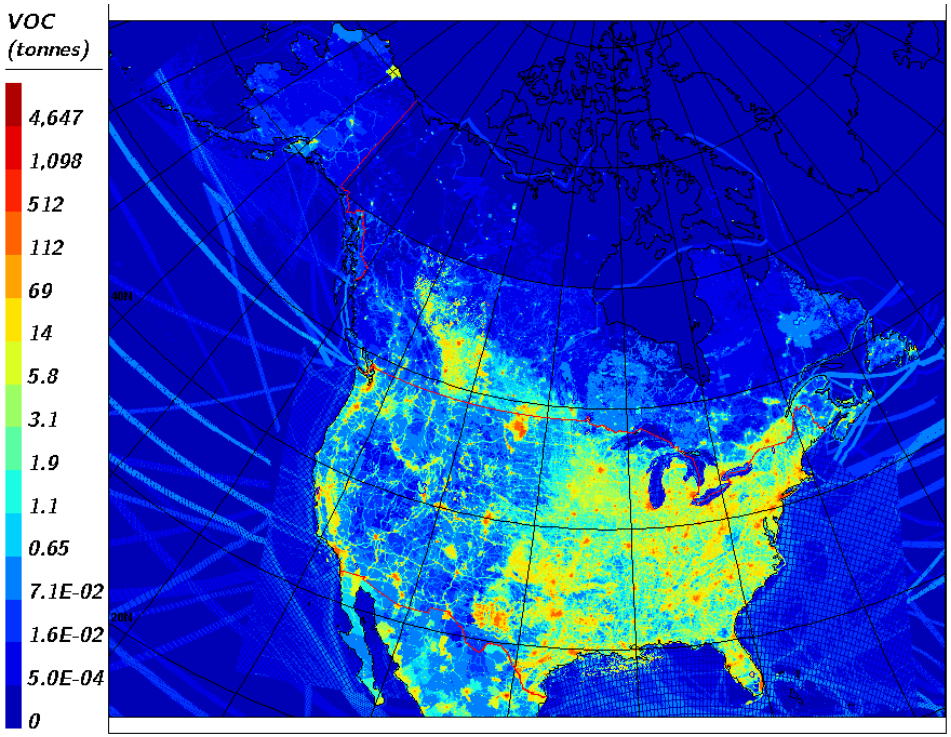


Main source sectors:

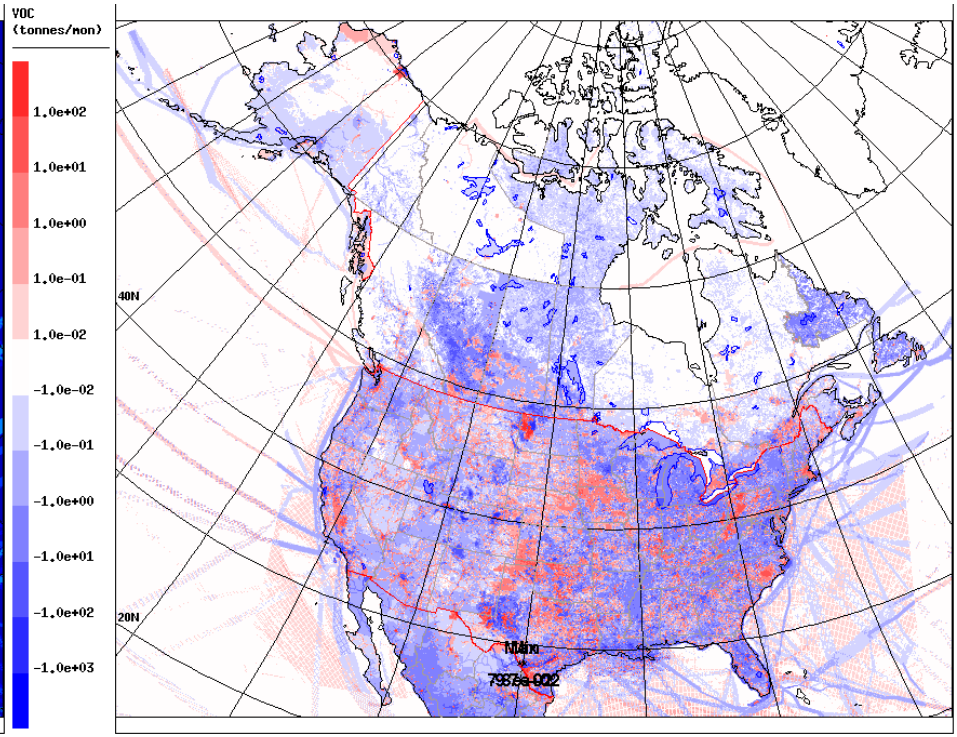
On-road and off-road vehicles, power generation, industry, oil & gas

Spatial Distribution of New VOC Emissions (July) & Changes vs. Current Emissions (New – Current; tonnes/grid cell)

SET4



SET4 – SET3.1.2

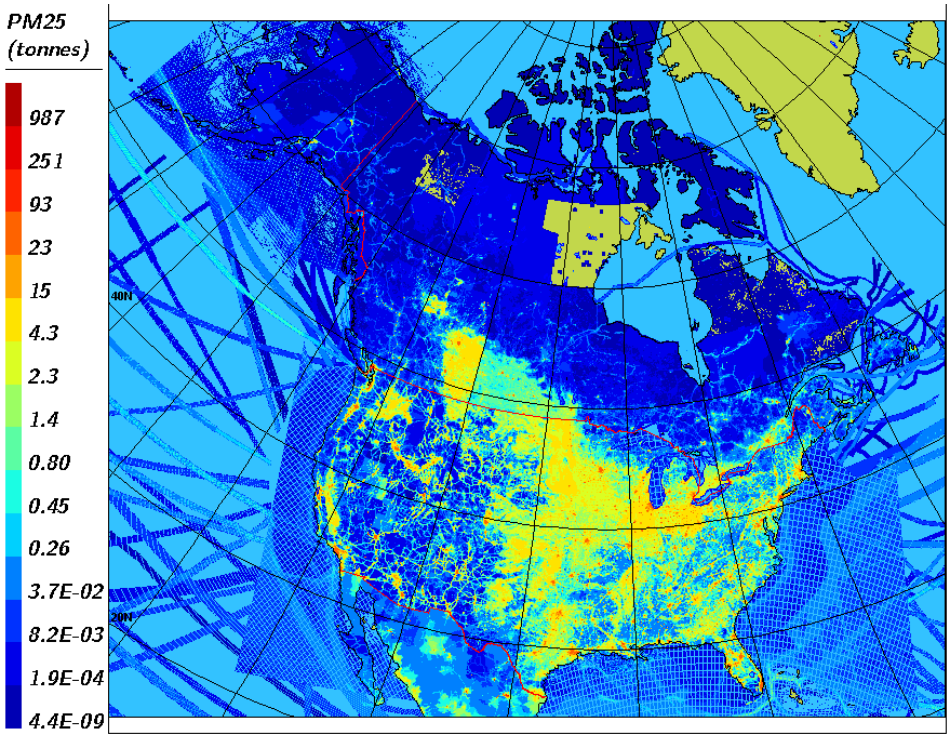


Main source sectors:

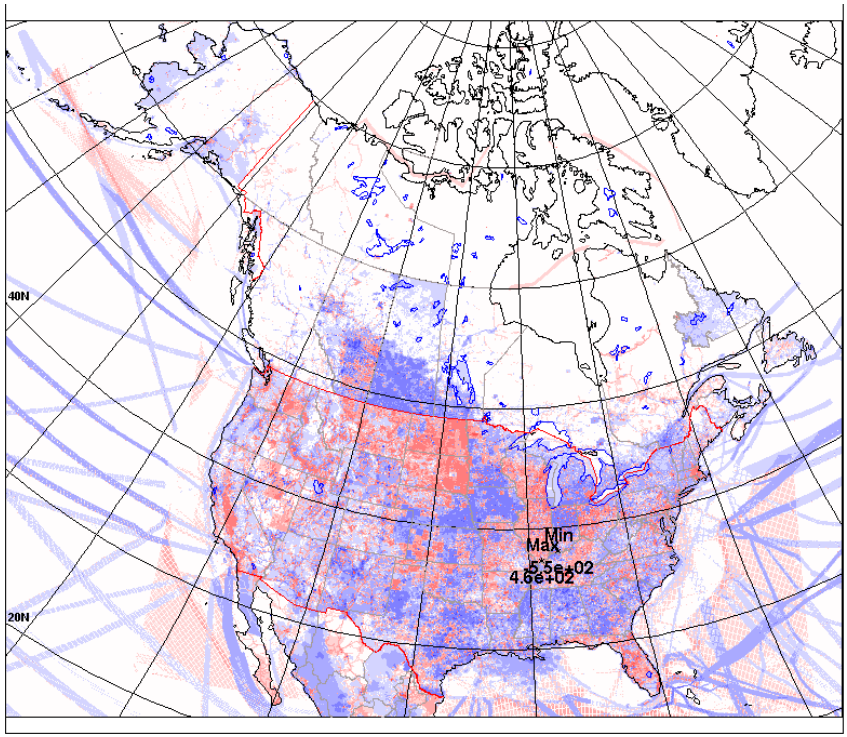
transport, wood burning, solvent use, oil & gas

Spatial Distribution of New $PM_{2.5}$ Emissions (July) & Changes vs. Current Emissions (New – Current; tonnes/grid cell)

SET4



SET4 – SET3.1.2



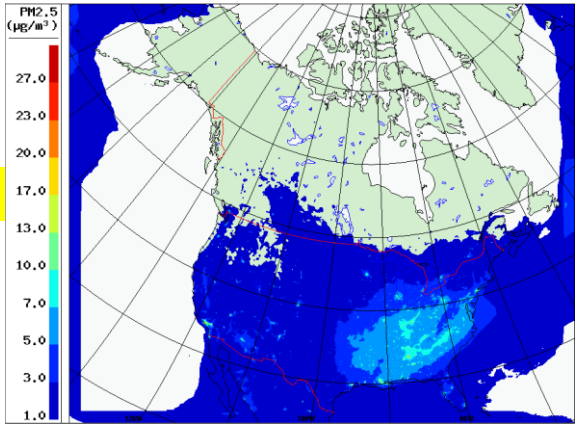
Main source sectors:

Road dust, construction, agriculture, wood burning

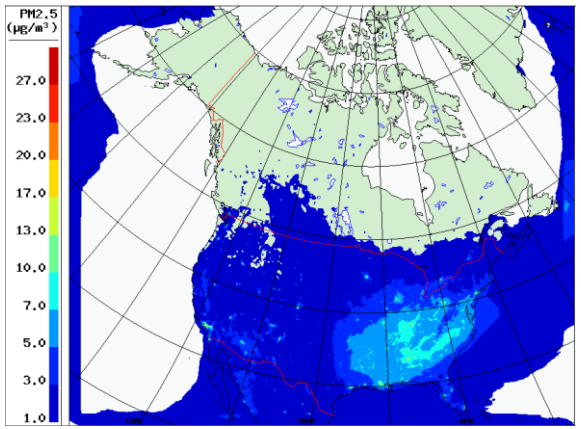
Impact of Revised Numerical Solution for Particle Sedimentation Scheme

(2-Month Mean Surface $PM_{2.5}$ Concentration Without Sea Salt)

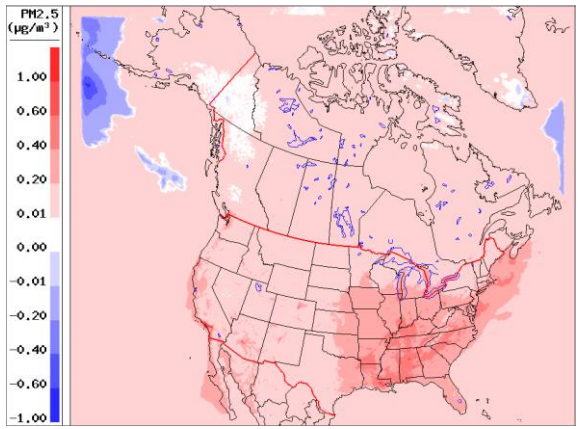
summer



base

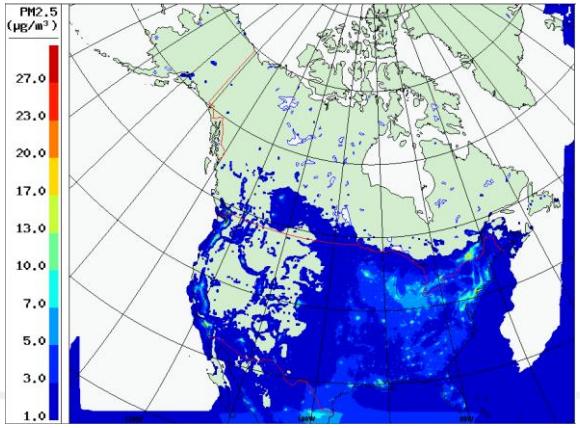


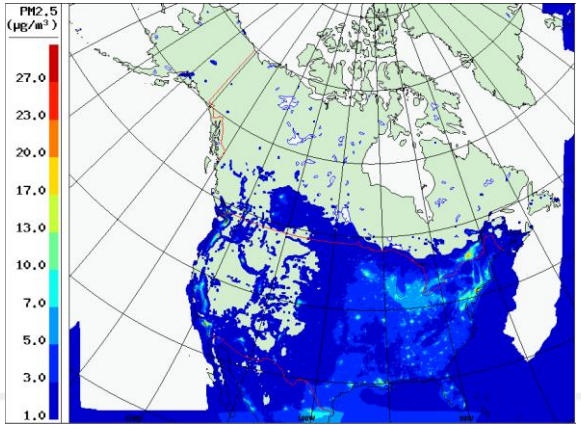
test

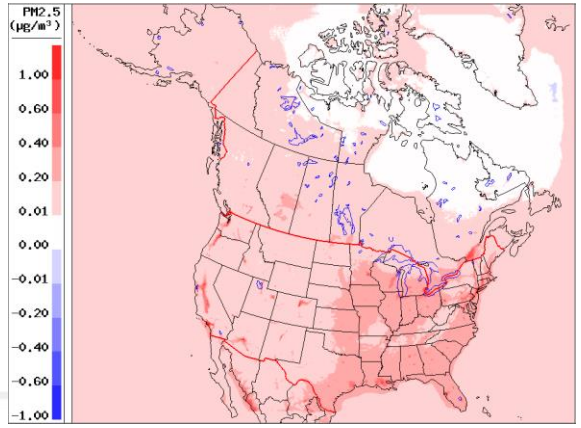


Mean Difference (test – base)

winter







Revised numerical solution for gravitational settling process scheme reduces net rate of removal and hence increases near-surface PM concentrations

FireWork (RAQDPSFW) Innovations for 2021

Upgrade of Canadian Forest Fire Emission Prediction System (CFFEPS) from v2.06 to v4

- CFFEPS code ported from original NRCan C language to Fortran
- New flexibility for on-line and off-line fire emissions calculations
- Uniform Maestro suite: CFFEPS emissions processing merged into GEM-MACH module (no more separate module)

Innovations for CFFEPSv4-offline

- Use all model layers for wildfire plume-rise parameterization (instead of pre-defined 5 pressure levels) and account for latent heat impact on plume rise
- Introduce more detailed forest fuel parameters (@250 m, e.g., crown/surface fuel loads, elevation, slope, stand density…)
- Diurnal fuel consumption based on modelled fire rate of spread (instead of default climatological diurnal profile)

CPOP Role and CPOP Standards

The **C**omité des **p**asses **o**pérationnelles et **p**arallèles (Committee for Operational and Parallel Runs) is an internal change-management (i.e., "gatekeeping") committee at the Meteorological Service of Canada Branch of ECCC that must approve operational implementations of new forecast model versions

Step 1. To be accepted by CPOP for a simultaneous run in "parallel" with the current operational forecast model, the applicants must demonstrate that the proposed new model version outperformed the current version for a past summer and winter season ("final cycling runs")
[**summer 2019** and **winter 2020** for this delivery]

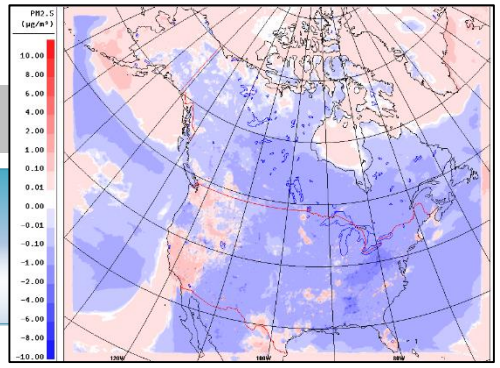
Step 2. To be accepted by CPOP for operational implementation, the applicants must demonstrate that the new model version also outperformed the current version during the parallel run period
[**May 25 to August 11, 2021** for this delivery]

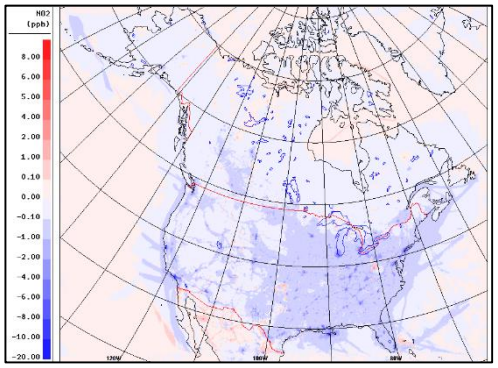
RAQDPS: Spatial Differences In Average Summer Surface Concentrations in 2019 and 2021

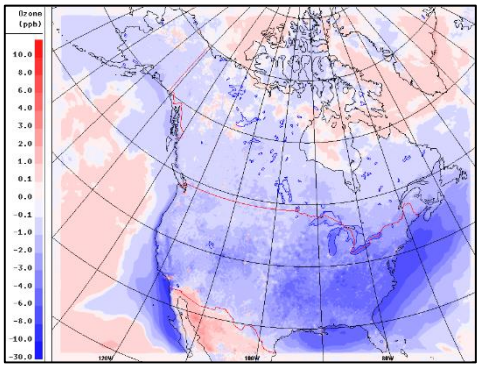
Final cycle

SUMMER 2019

Difference RAQDPS023 - RAQDPS022





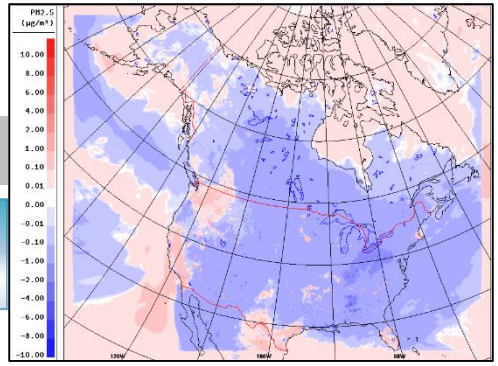


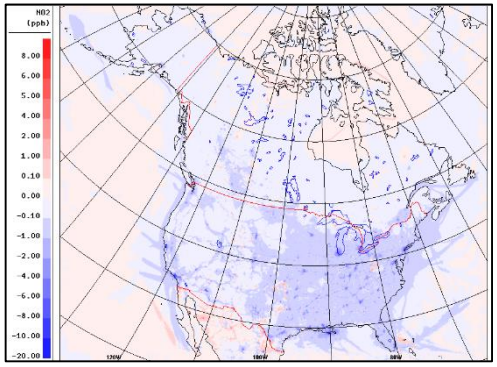
$\Delta PM_{2.5}$ ΔNO_2 ΔO_3

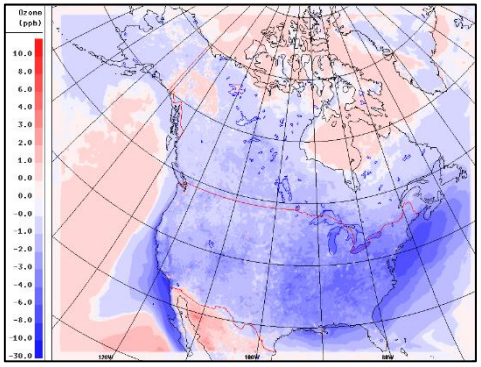
Parallel/Operational run

SUMMER 2021

Difference PAR - OPS



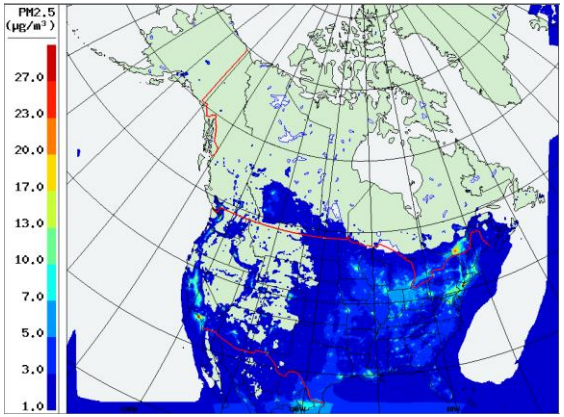




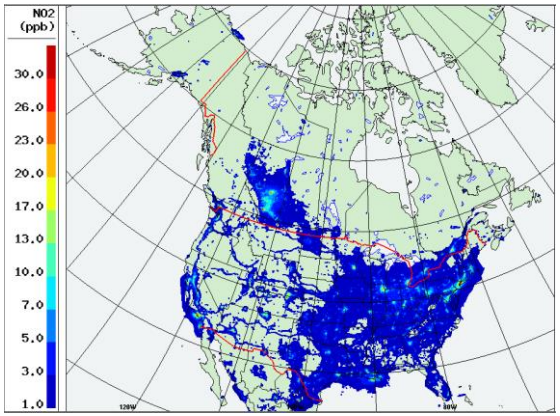
Spatial Differences In Mean Winter 2020 Surface Concentrations of $PM_{2.5}$, NO_2, and O_3

RAQDPS022 Averages

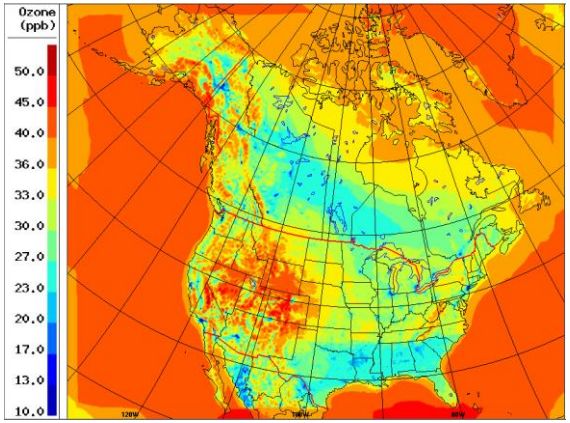
$PM_{2.5}$



NO_2

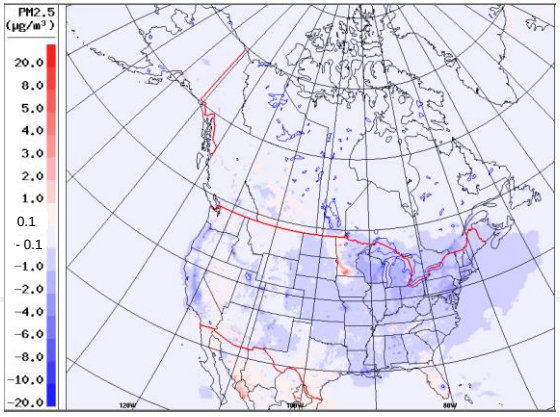


O_3

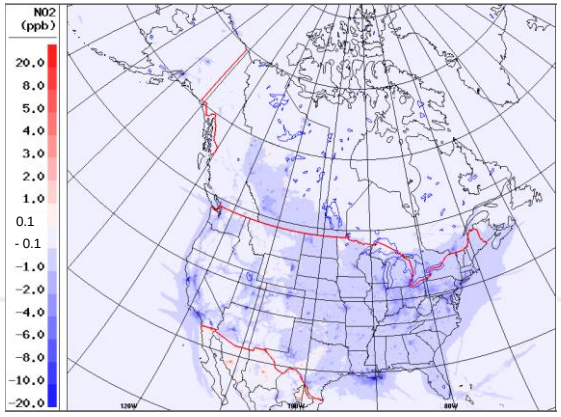


Difference RAQDPS023 Minus RAQDPS022

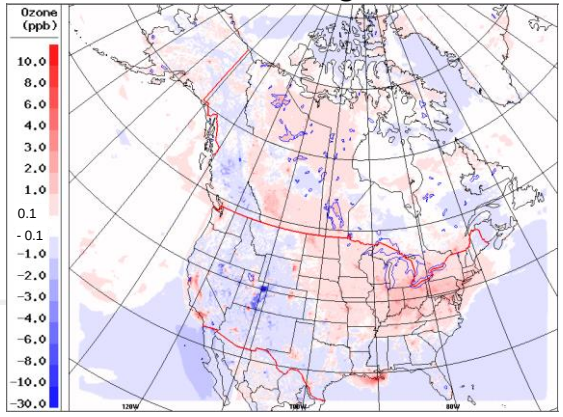
$\Delta PM_{2.5}$



ΔNO_2

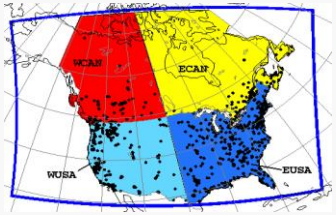


ΔO_3



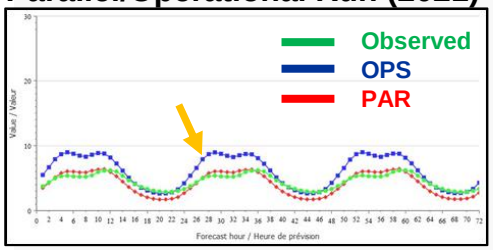
Objective Scores for Predicted Maximum Daily Values for Summer 2019 and Summer 2021

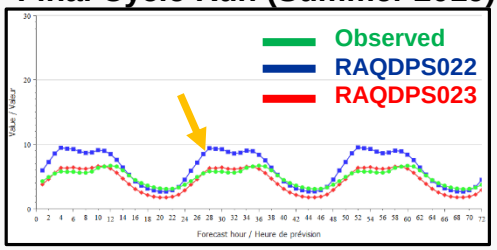
RAQDPS Domain



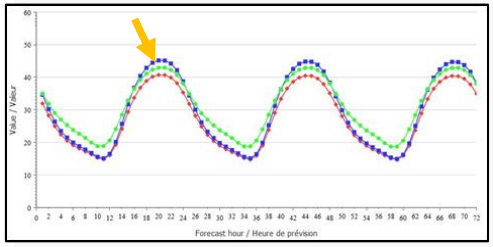
Parallel/Operational Run (2021) | **Final Cycle Run (Summer 2019)**

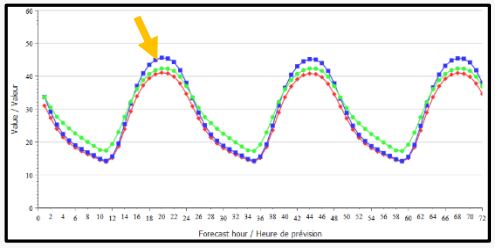
NO_2 [ppb]



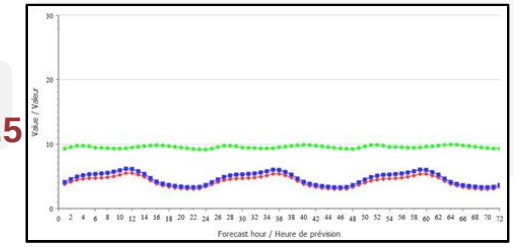


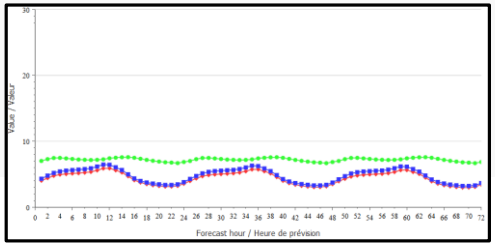
O_3 [ppb]





$PM_{2.5}$ [µg/m³]





Parallel/Operational Run (2021)

		WCAN		ECAN		WUSA		EUSA	
		raqdps OP	raqdps PAR	raqdps OP	raqdps PAR	raqdps OP	raqdps PAR	raqdps OP	raqdps PAR
NO2	MB	2,15	0,21	4,18	1,31	3,75	-1,39	5,56	-1,37
	R	0,52	0,52	0,57	0,58	0,55	0,52	0,56	0,58
	RMSE	8,68	7,34	9,74	6,81	11,63	8,86	12,78	7,94
O3	MB	-2,38	-4,03	0,61	-3,05	0,05	-4,15	8,57	1,98
	R	0,68	0,69	0,67	0,68	0,71	0,74	0,64	0,65
	RMSE	11,35	11,16	11,18	10,61	14,08	13,52	16,52	12,44
PM2.5	MB	-12,45	-13,91	-4,79	-6,11	-10,19	-10,32	-5,46	-7,29
	R	0,08	0,08	0,22	0,18	0,06	0,09	0,12	0,14
	RMSE	34,57	34,58	15,06	15,75	26,31	26,17	16,64	16,37

Final Cycle Run (2019)

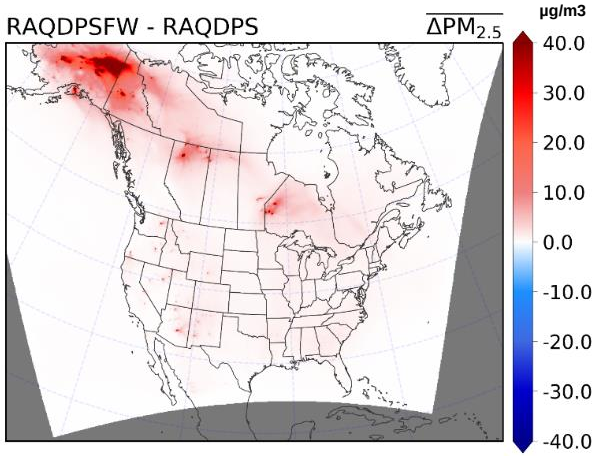
		WCAN		ECAN		WUSA		EUSA	
		RAQDPS022	RAQDPS023	RAQDPS022	RAQDPS023	RAQDPS022	RAQDPS023	RAQDPS022	RAQDPS023
NO2	MB	2,27	0,54	3,75	0,96	3,09	-2,06	5,95	-1,61
	R	0,49	0,50	0,61	0,64	0,58	0,53	0,66	0,66
	RMSE	7,99	6,85	9,34	6,81	10,91	8,91	12,56	7,23
O3	MB	-2,79	-3,75	2,09	-1,15	0,07	-3,83	10,25	3,20
	R	0,52	0,53	0,72	0,72	0,72	0,74	0,64	0,64
	RMSE	9,29	9,45	10,72	9,56	12,96	12,56	17,65	12,75
PM2.5	MB	-2,93	-4,15	-1,83	-2,99	-4,47	-4,44	-2,29	-4,01
	R	0,07	0,03	0,22	0,18	0,12	0,16	0,17	0,17
	RMSE	13,77	12,34	12,17	12,82	13,28	13,02	12,60	11,65

Periods : PAR 2021-05-25 to 2021-08-11
Final Cycle 2019-06-15 to 2019-08-31

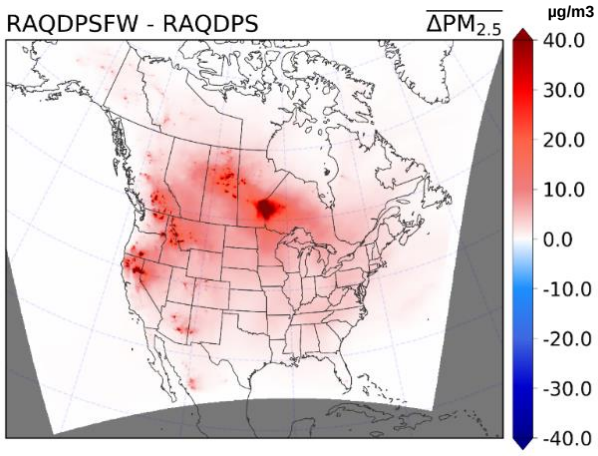
Pink shading indicates new model score is better, light blue indicates old model score is better, and yellow indicates equivalent score

RAQDPSFW: Mean Summertime Surface $PM_{2.5}$ Concentrations from Wildfire Smoke

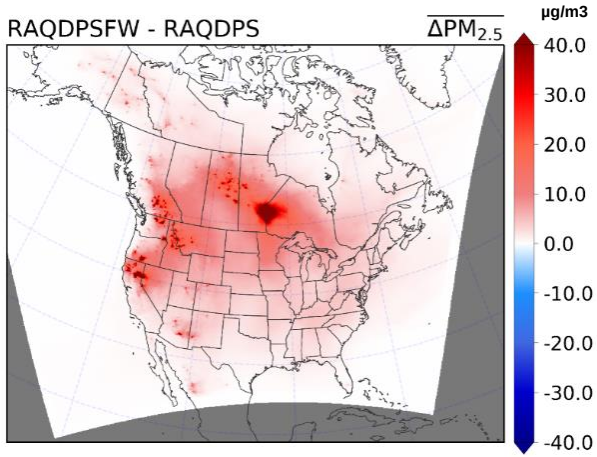
Final cycle run (June 15 to August 31, 2019)



Operational run (May 25 to August 11, 2021)

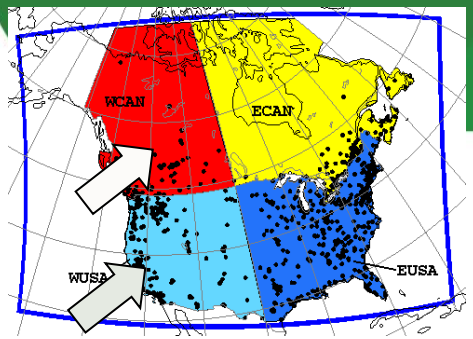


Parallel run (May 25 to August 11, 2021)



- 2019 and 2021 wildfire seasons were very different
- Switch from CFFEPS v2.06 to CFFEPS v4 has a small but visible impact on surface $PM_{2.5}$ for summer 2021

RAQDPSFW Regional Evaluation: Western Canada (WCAN) and Western United States (WUSA) for Summer 2019 and Summer 2021



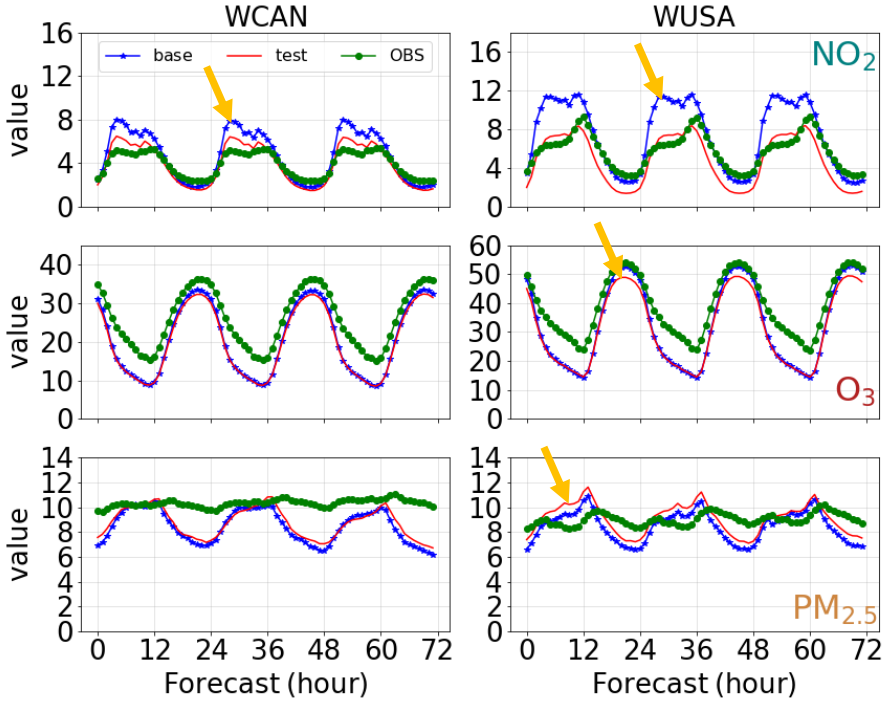
Final Cycle 2019

Bootstrapping	WCAN-BASE	WCAN-TEST	WUSA-BASE	WUSA-TEST
NO2_bias	0.876	0.119	1.295	-1.285
NO2_corr	0.498	0.507	0.561	0.567
NO2_rmse	4.916	4.295	7.197	5.621
O3_bias	-5.035	-5.337	-6.97	-8.11
O3_corr	0.67	0.679	0.77	0.787
O3_rmse	10.087	9.972	13.976	13.758
PM2.5_bias	-1.106	-1.554	-1.88	-1.859
PM2.5_corr	0.327	0.346	0.289	0.321
PM2.5_rmse	7.46	6.495	6.734	6.475

Parallel Run 2021

Bootstrapping	WCAN-BASE	WCAN-TEST	WUSA-BASE	WUSA-TEST
NO2_bias	0.749	-0.036	1.575	-0.988
NO2_corr	0.501	0.509	0.516	0.533
NO2_rmse	5.279	4.513	7.623	5.796
O3_bias	-5.34	-5.906	-6.733	-7.99
O3_corr	0.679	0.7	0.756	0.776
O3_rmse	12.132	11.82	14.826	14.468
PM2.5_bias	-1.848	-1.534	-0.976	0.044
PM2.5_corr	0.545	0.619	0.41	0.405
PM2.5_rmse	19.747	18.081	22.365	27.726

Parallel Run 2021



Hourly average values as a function of forecast lead time
-- RAQDPSFW022 (base) -- RAQDPSFW023 (test) -- Observations (OBS)

Hourly statistical scores (subjected to bootstrap test for statistical significance): red shading indicates score of new version is better, blue shading indicates score of old version better, and yellow shading indicates equivalent scores

Summary and Next Steps

- New versions of ECCC's RAQDPS and RAQDPSFW operational regional air quality forecast modelling systems were developed, delivered to the Canadian Meteorological Centre (CMC) of the Meteorological Service of Canada, and underwent parallel tests over the spring-summer 2021 period
- Innovations in these new versions include a major update to the anthropogenic emission files, an improved numerical solution for PM sedimentation, an upgraded version of the Canadian Forest Fire Emission Prediction System (CFFEPS), and new versions of the GEM and MACH computer codes
- Overall, the new versions predict lower atmospheric concentrations for 3 key pollutants (NO_2, O_3, $PM_{2.5}$) due largely to significant emissions decreases in the new emissions files that better match current conditions
- Overall, the new versions outperformed the current operational AQ forecast systems during the spring-summer 2021 parallel run period
- Operational implementation of the new v023 versions at CMC is tentatively scheduled for November 2021

Thank You For Your Interest

Some GEM-MACH and FireWork References

Munoz-Alpizar, R., R. Pavlovic, M.D. Moran, J. Chen, S. Gravel, S.B. Henderson, S. Ménard, J. Racine, A. Duhamel, S. Gilbert, P.-A. Beaulieu, H. Landry, D. Davignon, S. Cousineau, and V. Bouchet, 2017. Multi-year (2013–2016) $PM_{2.5}$ wildfire pollution exposure over North America as determined from operational air quality forecasts. *Atmosphere*, **8**, 179, https://doi.org/10.3390/atmos8090179, 24 pp.

Pendlebury, D., S. Gravel, M.D. Moran, and A. Lupu, 2018. The impact of chemical lateral boundary conditions in a regional air quality forecast model on surface ozone predictions during stratospheric intrusions. *Atmos. Environ*., **174**, 148-170, https://doi.org/10.1016/j.atmosenv.2017.10.052.

Chen, J., K. Anderson, R. Pavlovic, M.D. Moran, P. Englefield, D.K. Thompson, R. Munoz-Alpizar, and H. Landry, 2019. The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions Prediction System v2.03. *Geosci. Model Dev*., **12**, 3283-3310, https://doi.org/10.5194/gmd-12-3283-2019.