Routine Multi-Model Performance Analysis Over North America For Three Operational Air Quality Forecast Systems

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Fourth MAC-MAQ Conference *11-13 Sept. 2019* *Davis, California, U.S.A.*

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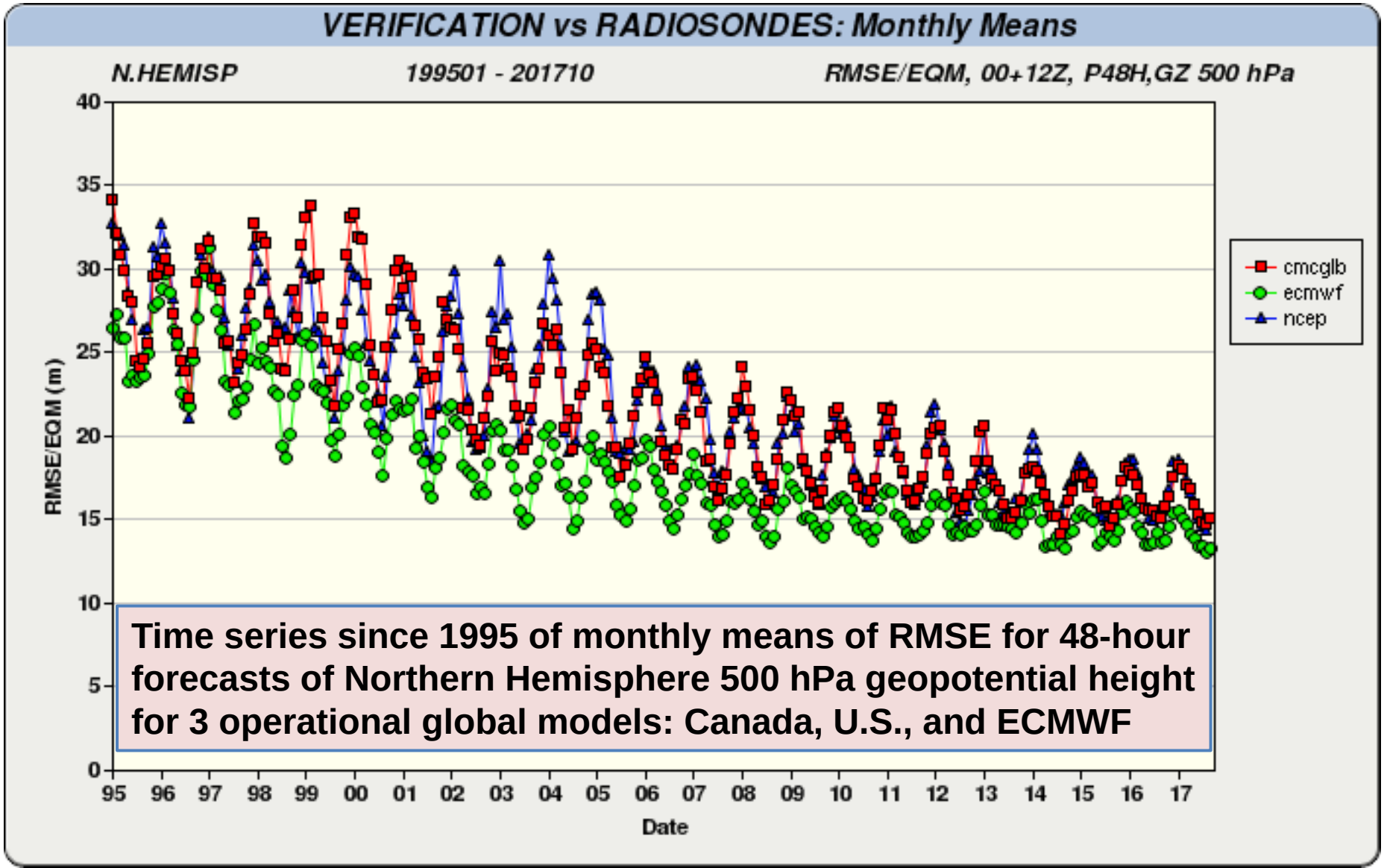
BACKGROUND: OPERATIONAL NUMERICAL WEATHER PREDICTION (NWP) CENTRES HAVE SHARED AND COMPARED FORECASTS ROUTINELY FOR DECADES



INTRODUCTION

- Seven groups in Europe making operational regional AQ forecasts have shared and compared their forecasts since 2009 under the MACC-I, -II, and -III projects (e.g., Marécal et al., 2015)
- In North America, while operational regional AQ forecasts have been made for over a decade in both Canada and the U.S., no comparable routine side-by-side evaluation and comparison of forecasts had taken place until recently
- ECCC, NOAA, and ECMWF are now collaborating to exchange operational AQ forecasts for North America starting from January 2017, and ECCC has built an automated verification system to receive, ingest, and compare these forecasts
- The rest of this presentation will describe this new North American effort and present some results from different available analyses

PARTICIPATING AQ FORECAST SYSTEMS

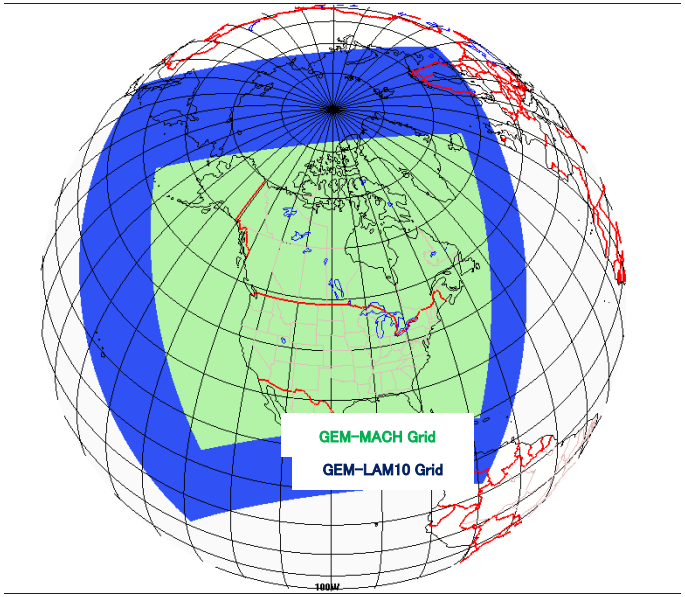
The following four operational AQ systems have been used for regular multi-model performance analyses for North America since January 2017

AQ Modelling System	Origin	Type	Grid Size	Pollutants	Wildfire Emissions	Chemical Data Assimilation	Forecast Availability
RAQDPS	**Canada** (ECCC)	Regional	10 km	O_3 $PM_{2.5}$ **NO_2**	**No**	No	Hourly
FireWork*	**Canada** (ECCC)	Regional	10 km	**$PM_{2.5}$**	Yes	No	Hourly
NAQFC	**U.S.A.** (NOAA)	Regional	12 km	O_3 $PM_{2.5}$	Yes	No	Hourly
CAMS-IFS	**Europe** (CAMS-ECMWF)	**Global**	**40** km	O_3 $PM_{2.5}$ **NO_2**	Yes	**Yes**	**3-Hourly**

FireWork *is a seasonal (April-October) system identical to RAQDPS except for the inclusion of near-real-time wildfire emissions. Since NAQFC and CAMS-IFS both include wildfire emissions, FireWork* $PM_{2.5}$ *forecasts are considered as ECCC* $PM_{2.5}$ *forecasts for multi-model performance analysis in warm season.*

ECCC OPERATIONAL AQ SYSTEM:
RAQDPS (Regional AQ Deterministic Prediction System)

- GEM-MACH **in-line** chemical transport 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 the **GEM** NWP model (initial and boundary conditions)
- **10**-km horizontal grid spacing, **80** vertical levels up to 0.1 hPa
- **48**-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
- 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

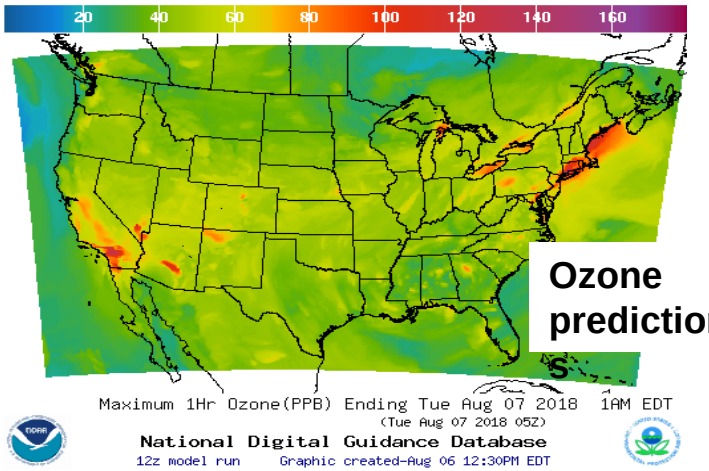
Emissions Inventories	In operations until Sept. 2018	In operations since Sept. 2018
Canada	2010	**2013**
U.S.A.	2011	**2017***
Mexico	1999	**2008**

* Projected from 2011

NOAA OPERATIONAL AQ SYSTEM:
NAQFC (National Air Quality Forecast Capability)

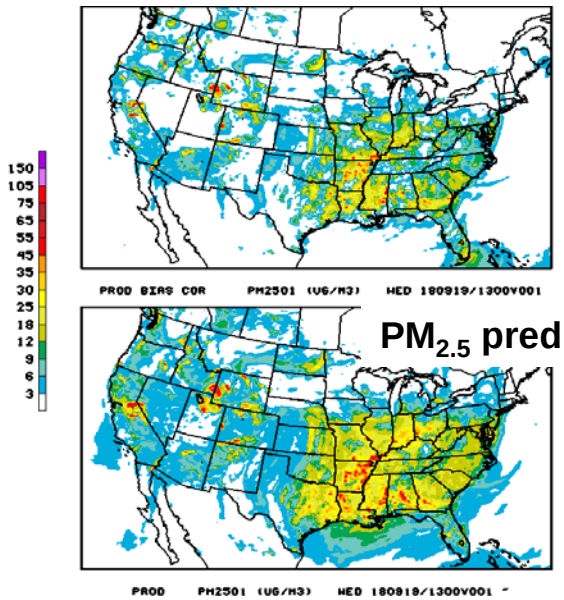
- Operationally integrated system at NOAA: North American Mesoscale forecast system (**NAM**) meteorology as input to the Community Multiscale Air Quality modeling system (**CMAQ**)
- Regional model with **12** km horizontal resolution
- Hourly predictions for **48**-hour simulations
- EPA's **CMAQ** version 5.0.2 with CB05 chemical mechanism and AERO-6 aerosol module
- Emissions inventories: U.S. NEI 2014v2 (**with adjustments**), Canada 2011, Mexico 2012
- Wildfire locations from NESDIS satellite detections; particulate emissions modeled using USFS BlueSky
- AQ predictions from this system are operational over the U.S.A.
  - ozone since **2010** (for 48 contiguous states since 2007)
  - $PM_{2.5}$ since **2016**

http://airquality.weather.gov/



Ozone prediction

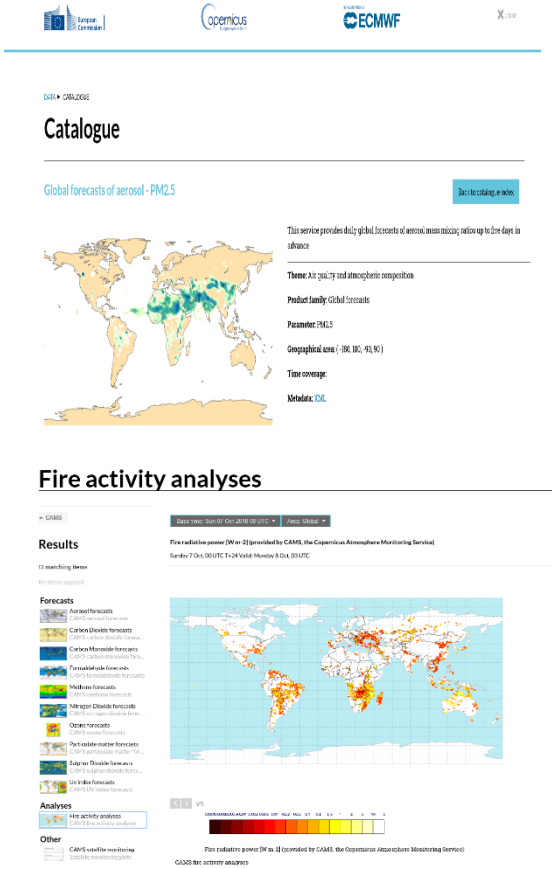
http://www.emc.ncep.noaa.gov/mmb/aq/cmaqbc/web/html/



$PM_{2.5}$ predictions

CAMS OPERATIONAL AQ SYSTEM

- Part of ECMWF's **Integrated Forecasting System** (**IFS**)
- Global forecast with **40** km (T511) horizontal resolution and **137** levels up to 0.1 hPa
- **Two** forecasts daily (00 and 12 UTC) over **5** days
- Modules for chemistry and aerosol (not coupled)
  - CB05 chemical mechanism, Cariolle stratospheric ozone
  - LMDz aerosol module (3xDD, 3xSS, 2xOM, 2xBC, SO_4, SO_2)
- **Data assimilation** (4DVAR) of O_3, NO_2, CO and AOD to improve initial conditions
- Emissions:
  - Anthropogenic: MACCITY extended to 2017/18
  - Biogenic: MEGAN monthly mean
  - Biomass burning: GFAS (made CAMS) based on MODIS FRP
- AQ predictions since **2007** and with DA since **2008**
- Control forecast (0 UTC) without DA
- Reanalysis of atmospheric composition from 2003-present day



(https://atmosphere.copernicus.eu)

Copernicus Europe's eyes on Earth

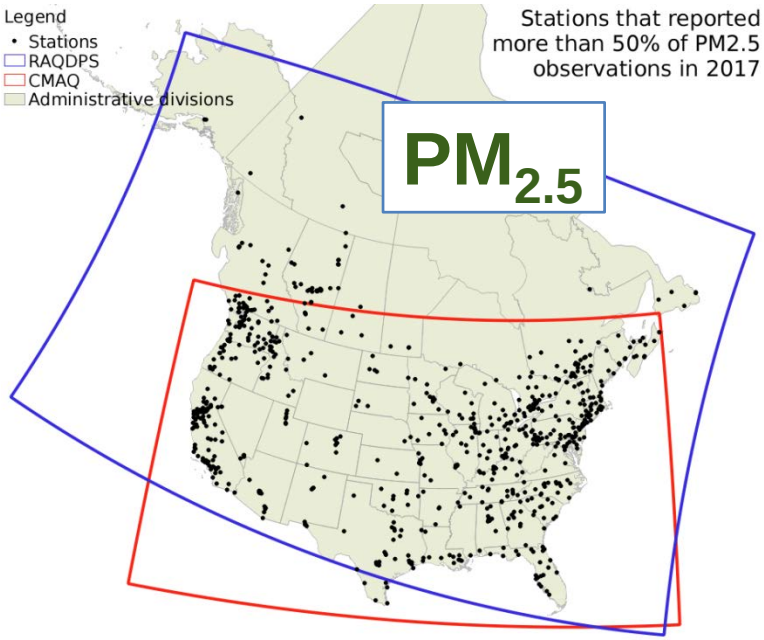
European Commission

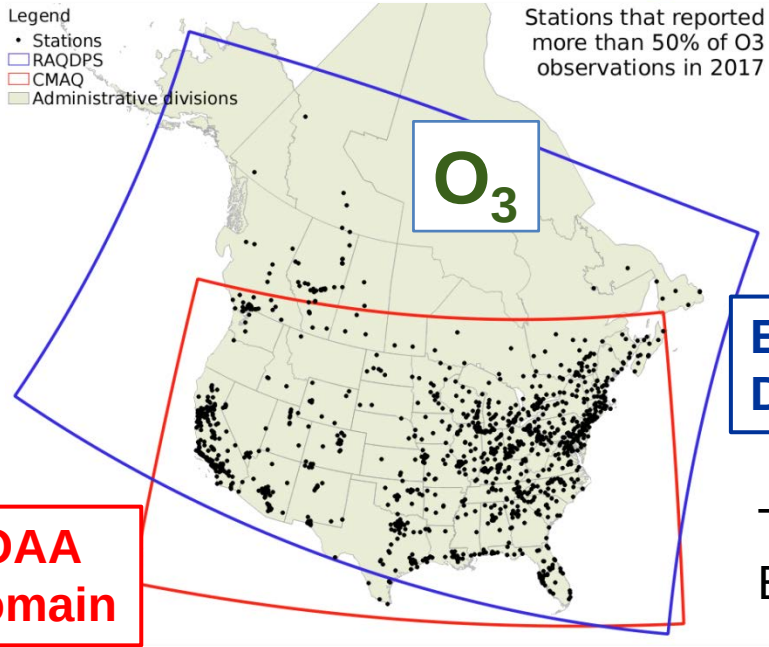
ECMWF

RECENT OR PLANNED IMPROVEMENTS

NOAA/NWS	ECCC	CAMS-ECMWF
NAM-CMAQ (20181216) ▪ Updated $PM_{2.5}$ bias correction ▪ New bias-corrected O_3 product ▪ Updated anthropogenic emissions (NEI2014v2) Emissions Update (20190501) • Wildfire emissions back on • New EGU point source emissions <u>Current testing includes:</u> • CMAQ driven by meteorology from the new GFS system with FV3 dynamical core • CMAQ predictions to 72 hours • Updates to fire emissions • Potentially other emissions improvements	RAQDPS020 (20180918) • New IAU-based meteorological initialization • Faster meteorological spin-up • New emissions (2013 Cdn, projected 2017 U.S., 2008 MX) FireWork020.2 (20190412) New wildfire module (CFFEPS) with: ▪ modelled fire spread and growth using forecasted meteorology ▪ plume injection height based on fire energy thermodynamics RAQDPS021 (20190703) • New GEM version (GEM5) and physical parameterizations • More vertical levels (80 → 84) • New SOA formation pathway • Meteorological modulation of fugitive dust emissions • AQ forecast extended to 72 h	45r1 upgrade (20180626) • Passive monitoring of Sentinel 5P O3 and NO2 • GOME-2 NO2 assimilation • New sea salt scheme • Prognostic ozone and aerosol input to NWP radiation 46r1 upgrade (20190712) • Assimilation of S5P data • 137 vertical levels • Nitrate and SOA aerosol representation • 24 h GFAS biomass burning data • Upgrade to global CAMS emissions • New online dust emission scheme (Nabat et al., 2012)

AQ Measurement Stations Available in Near-Real Time





ECCC Domain

NOAA Domain

Number of stations by pollutant that reported at least 50% of all hourly observations in 2017

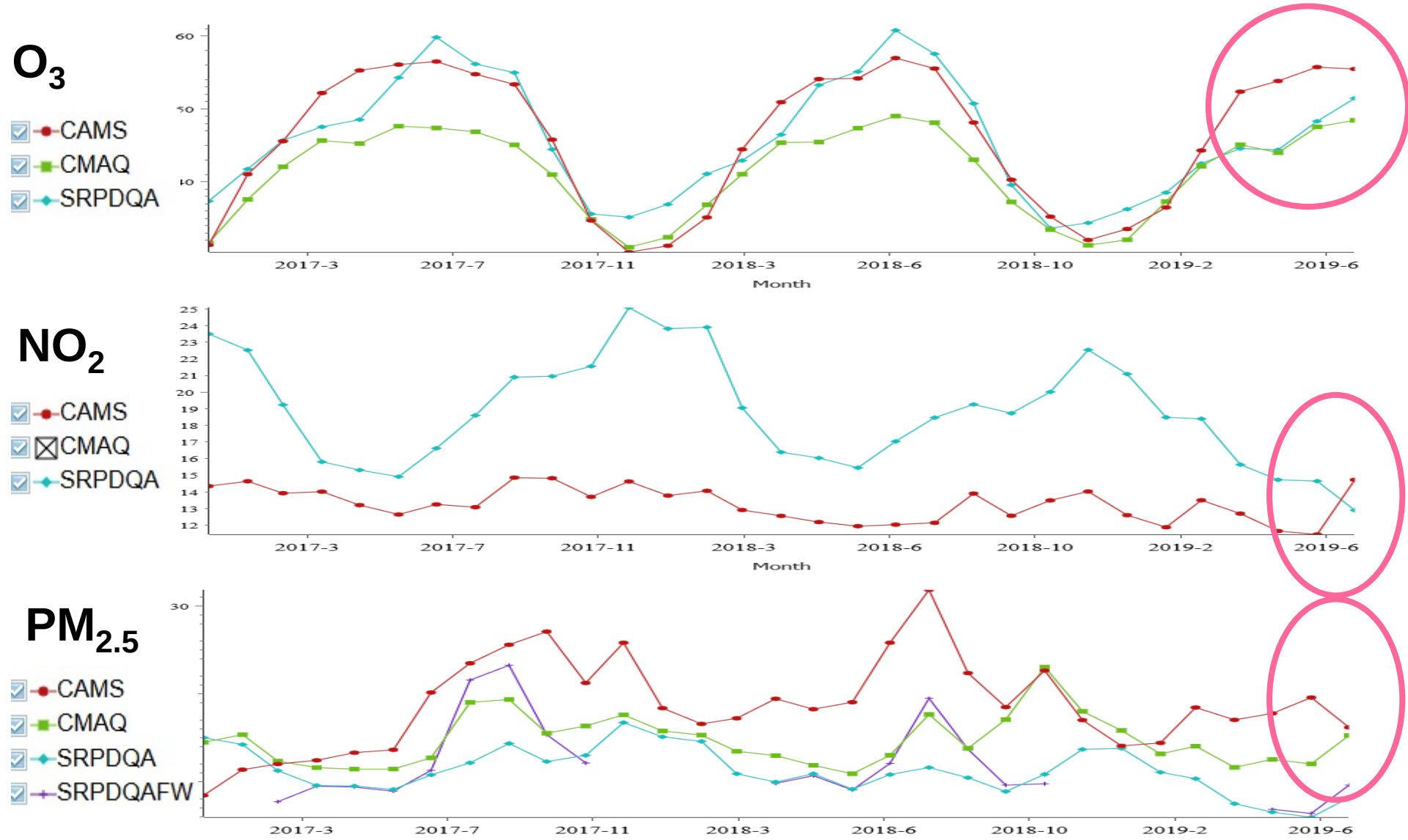
NO_2	317
O_3	1,196
$PM_{2.5}$	789

Two NRT AQ measurement data feeds are U.S. EPA AIRNow system and ECCC ADE system

AUTOMATED VERIFICATION SYSTEM

- Monthly evaluation statistics for each AQ modelling system are calculated automatically early in the following month for 7 regions (domain, Canada, U.S., WCAN, ECAN, WUSA, EUSA)
- Statistics are calculated for forecast O_3, NO_2, and $PM_{2.5}$ for the 12 UTC runs
- Since AQ episodes and acute health impacts are of greatest concern, most monthly statistics are calculated based on observed and predicted *daily maximum* values (paired by day but not necessarily by hour)
- The standard statistics are *n, $\bar{Y}$, MB, MFB, NMB, R, FAC2, NMGE, RMSE, URMSE, sigma Y, and var Y* (where *n* is the number of model-measurement pairs and *Y* is the predicted species concentration)
- A new non-dimensional summary statistic, AQPI (AQ Performance Index), which is based on 3 standard non-dimensional statistics (R, FAC2, MFB), is also calculated, where AQPI = 100 * [**FAC2** + **R** + (1-ABS(**MFB**/2))] / 3
- Hour-of-day-specific statistics are also calculated for every *third* hour (to align with IFS outputs) to examine the variation of model errors by time of day

Time Series of O_3, NO_2, and $PM_{2.5}$ Mean Monthly Values for 4 Forecast Systems: 2017/01–2019/07, Continental Domain

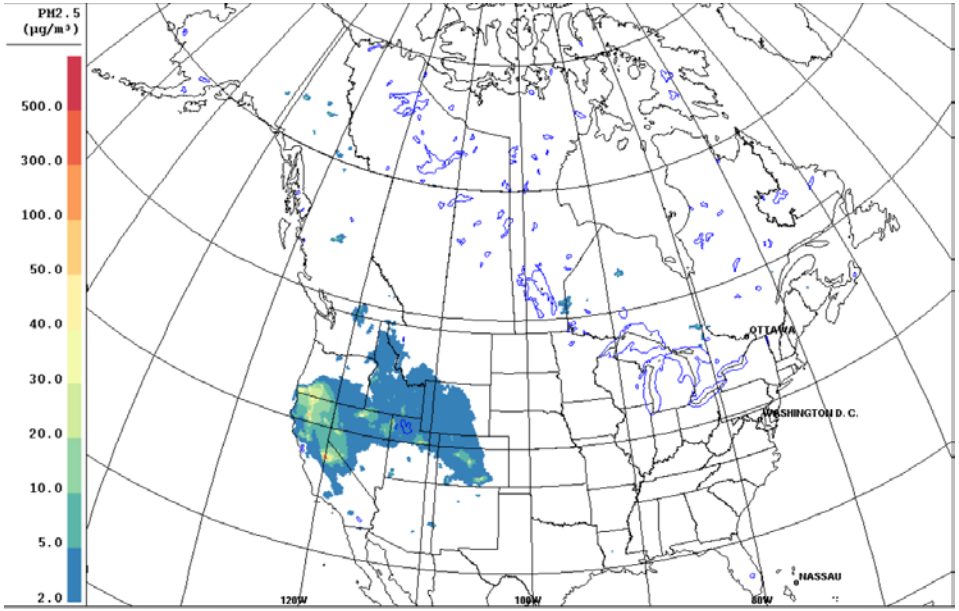


*Statistics are calculated using **daily MAX** observed and forecasted concentrations*

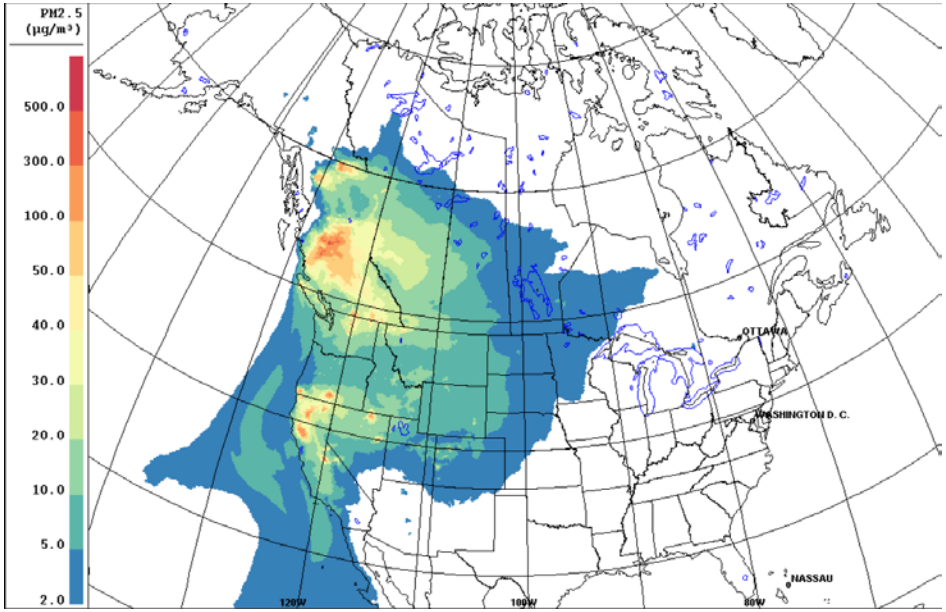
Time Series of O_3, NO_2, and $PM_{2.5}$ Mean Monthly Values for Factor-of-2 and Correlation: 2017/01–2019/07, Continental Domain

*Statistics are calculated using **daily MAX** observed and forecasted concentrations*

Mean Monthly Surface Fire-$PM_{2.5}$ Concentrations from FireWork-FEPS (μg m^{-3} ; source: Chen et al., 2019)

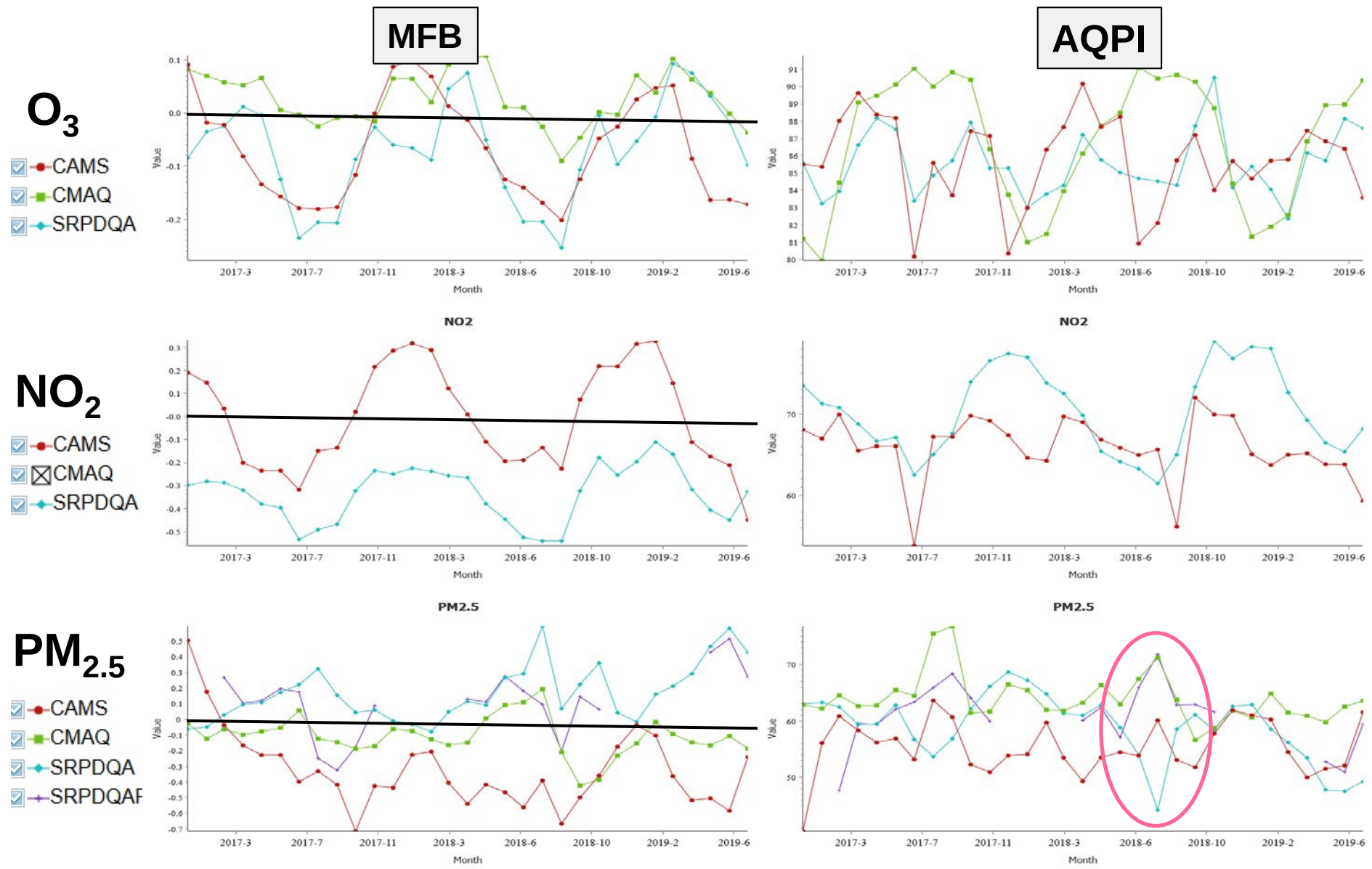


July 2018



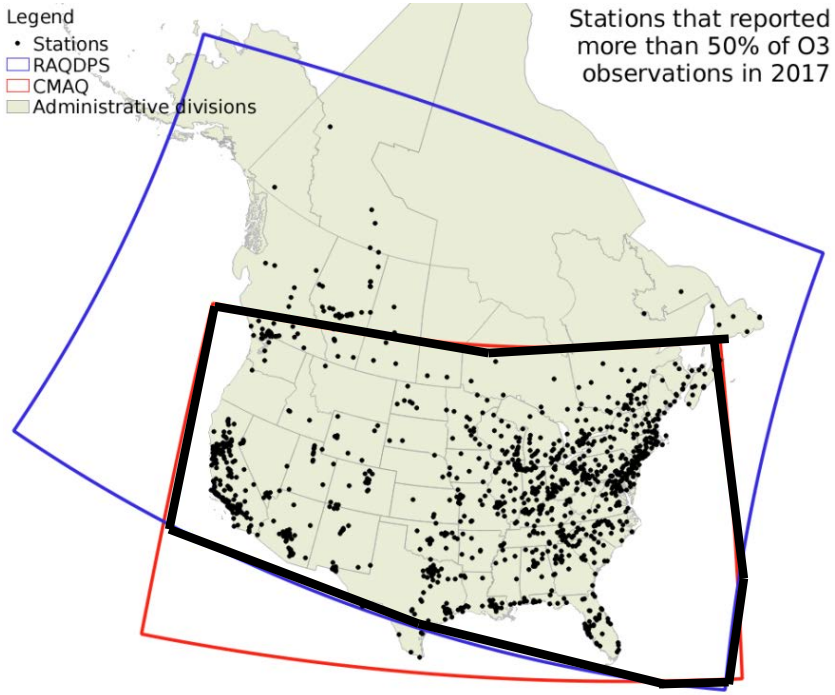
August 2018

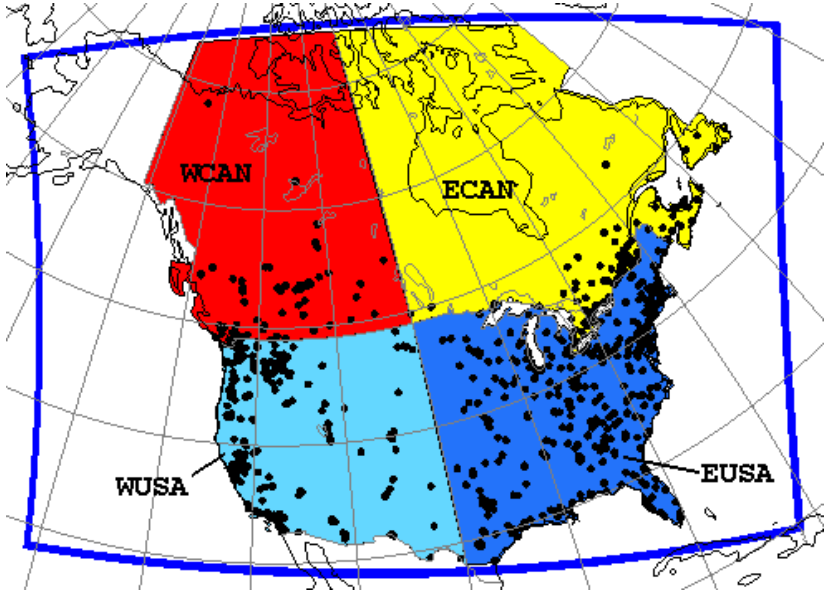
Time Series of O_3, NO_2, and $PM_{2.5}$ Mean Monthly Values for Mean Fractional Bias and AQPI: 2017/01–2019/07, Continental Domain



*Statistics are calculated using **daily MAX** observed and forecasted concentrations*

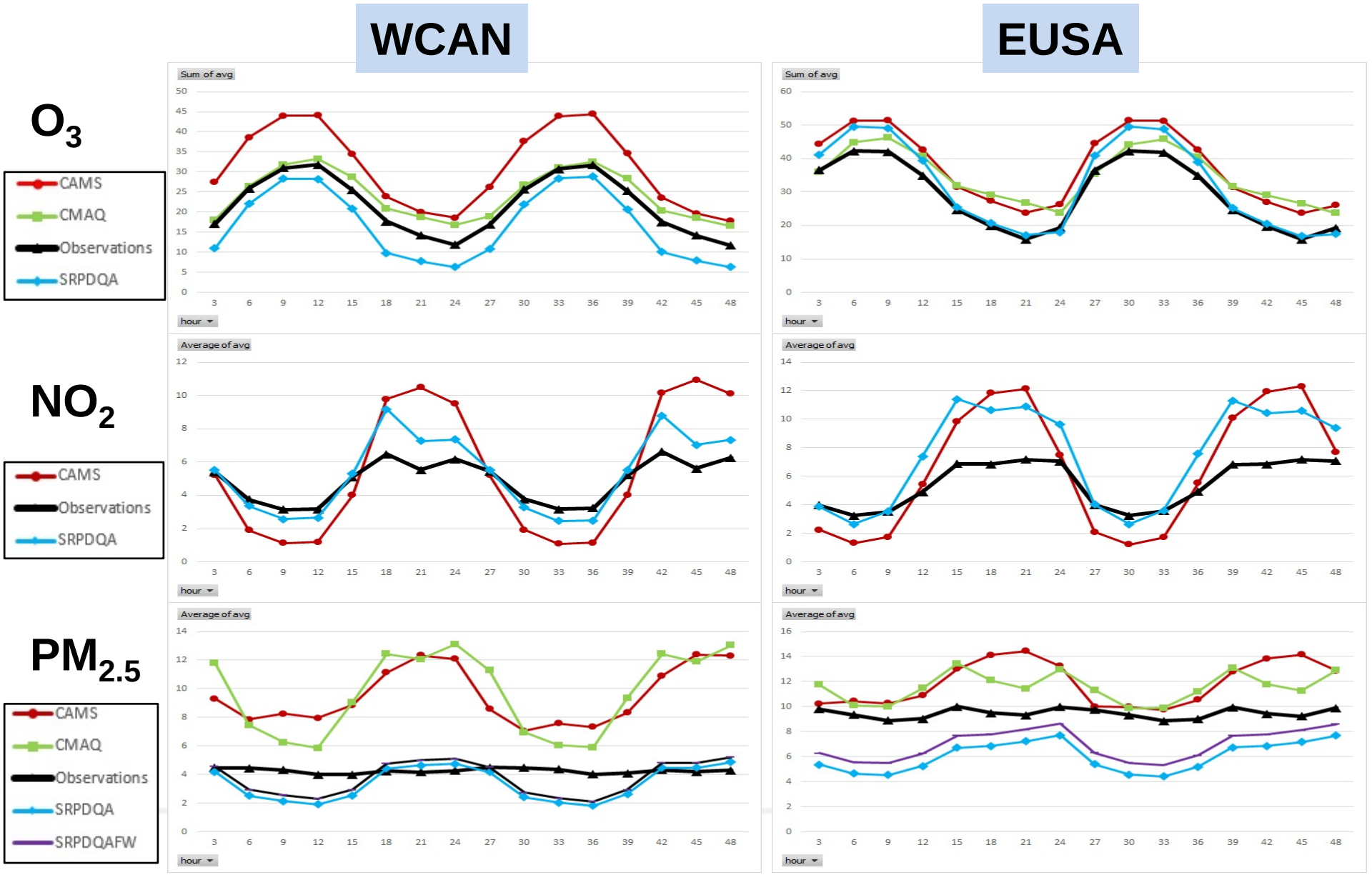
FOUR GEOGRAPHIC ANALYSIS REGIONS





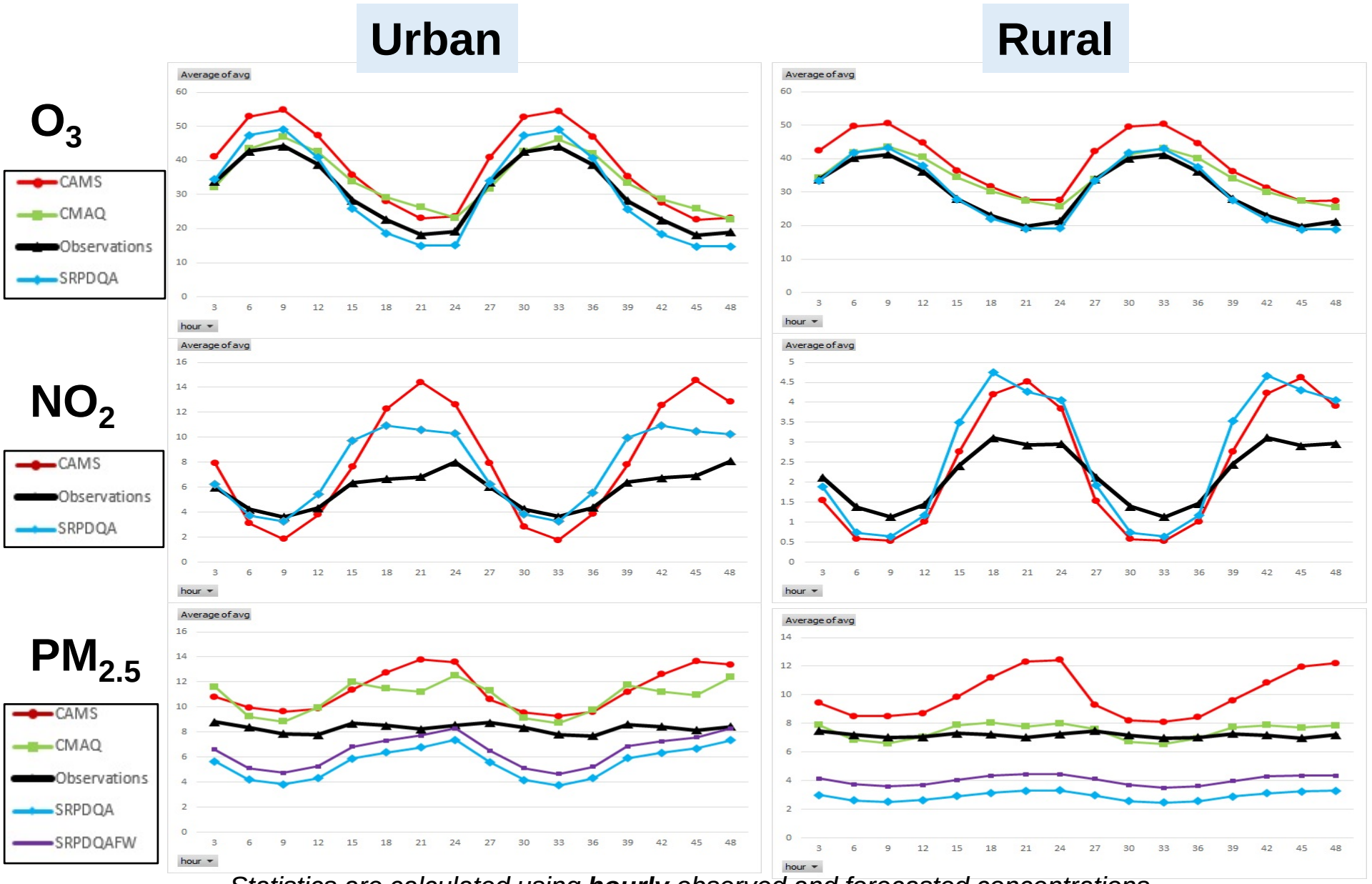
100°W

Time Series of O_3, NO_2, and $PM_{2.5}$ Mean *Hourly* Values for Western Canada and Eastern U.S. Regions, July 2019, 12Z Forecasts



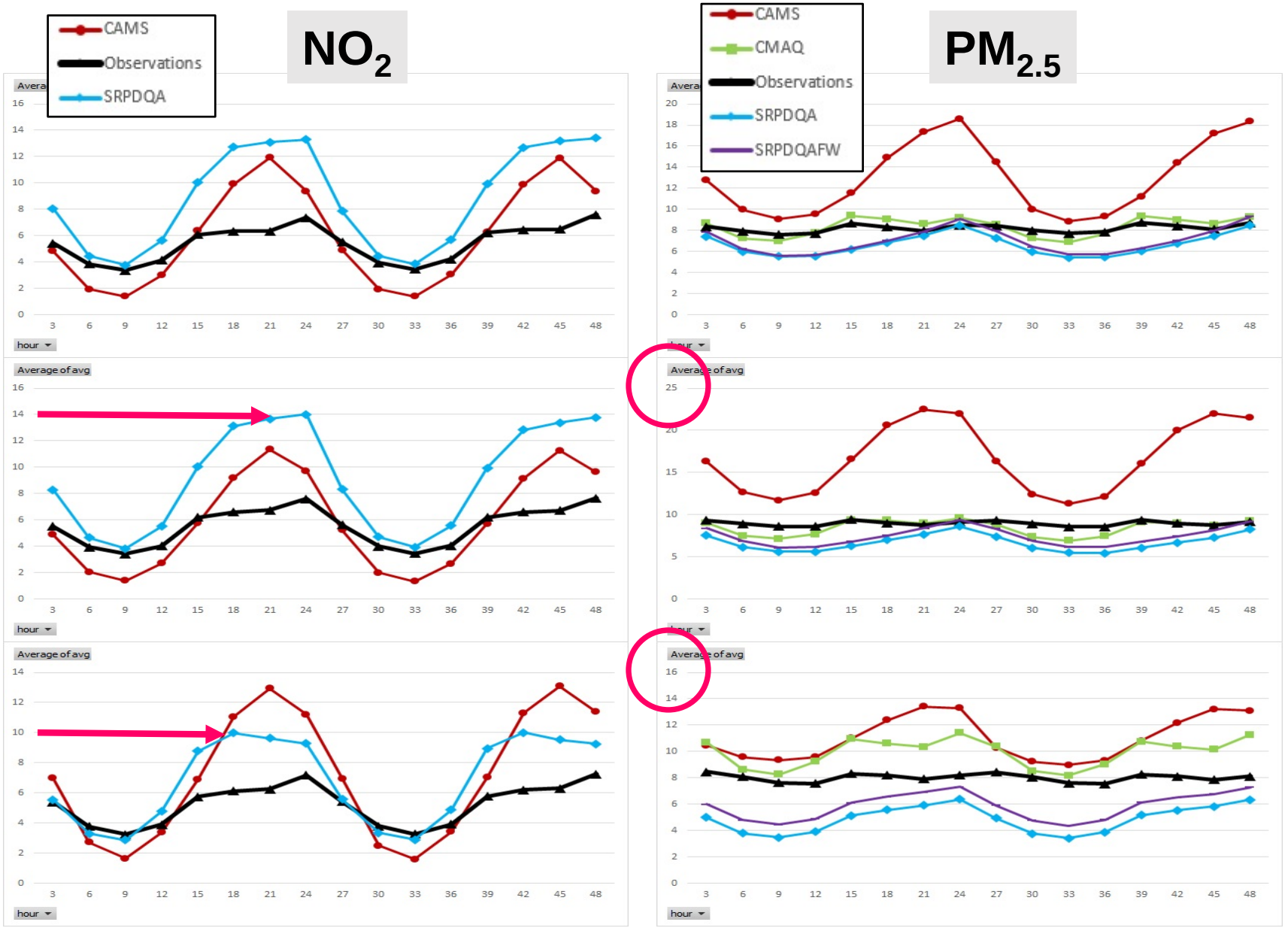
*Statistics are calculated using **hourly** observed and forecasted concentrations*

Time Series of O_3, NO_2, and $PM_{2.5}$ Mean *Hourly* Values for Urban vs. Rural Stations: July 2019, Continental Domain, 12Z Forecasts



*Statistics are calculated using **hourly** observed and forecasted concentrations*

Time Series of NO_2 and $PM_{2.5}$ Mean *Hourly* Values for July 2017, July 2018, and July 2019, Continental Domain, 12Z Forecasts



SUMMARY AND CONCLUSIONS (1)

To date nearly 3 years of operational AQ forecasts for North America from 2 regional AQ forecast models and one global AQ forecast model have been collected for 3 species: O_3, NO_2, and $PM_{2.5}$

This new evaluation database allows the performance of these 3 AQ forecast systems (RAQDPS/FireWork, NAQFC, and CAMS-IFS) to be examined and compared for multiple statistics from multiple perspectives, including:

- Time trends
- Time of year (month or season) and time of day (hour)
- Regional differences (e.g., west vs. east, north vs. south)
- Urban vs. rural differences
- Impacts of modelling system upgrades

SUMMARY AND CONCLUSIONS (2)

Evaluation results can help each forecast centre by showing similarities and differences in error patterns, which may be understood in part by comparing such primary modelling system characteristics as

- model inputs (e.g, anthropogenic emissions, natural emissions)
- AQ process representations
- chemical boundary conditions
- chemical data assimilation

This side-by-side analysis suggests that even though these 3 AQ forecast systems have many differences (e.g., meteorological and chemical representations, inputs, numerics, domains and grids), they are all affected by similar issues and uncertainties and no model consistently outperforms the others; impacts of some model upgrades can also be seen from sudden changes in some evaluation statistics

FUTURE WORK

Further refinements to the current analysis suite are possible, including the construction and evaluation of ensemble forecasts

A set of standard evaluation products needs to be chosen for routine dissemination amongst the forecast centres

Other AQ operational systems could be added to this North American multi-model performance analysis

Additional evaluations could be considered, such as spatial pattern analysis, diagnostic evaluations, and case studies

Thank You

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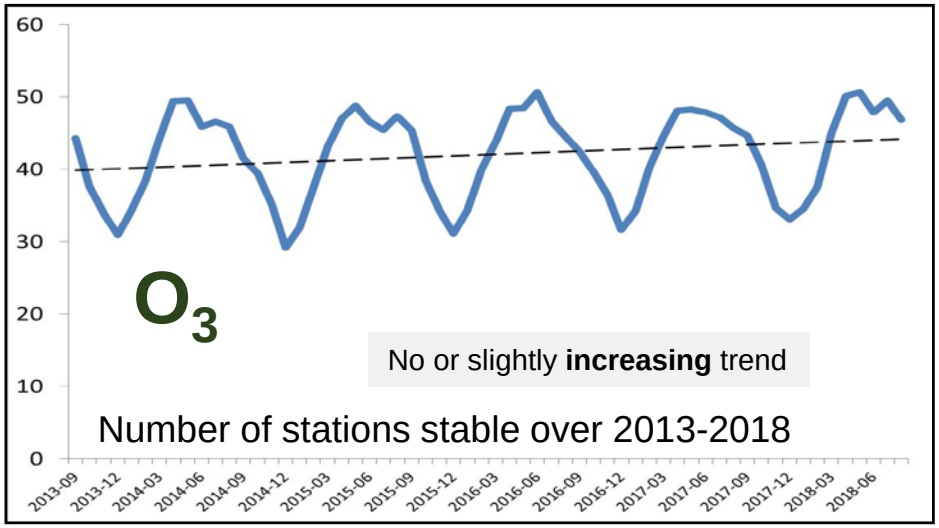
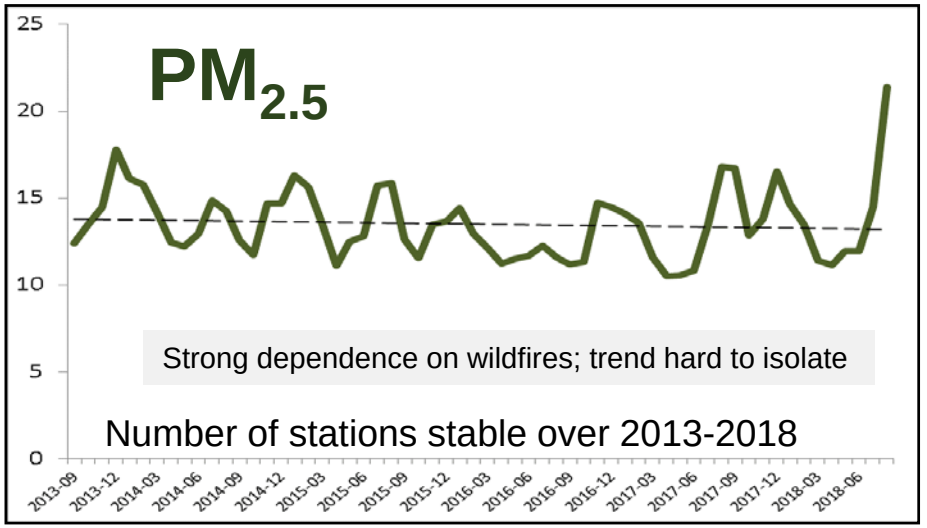
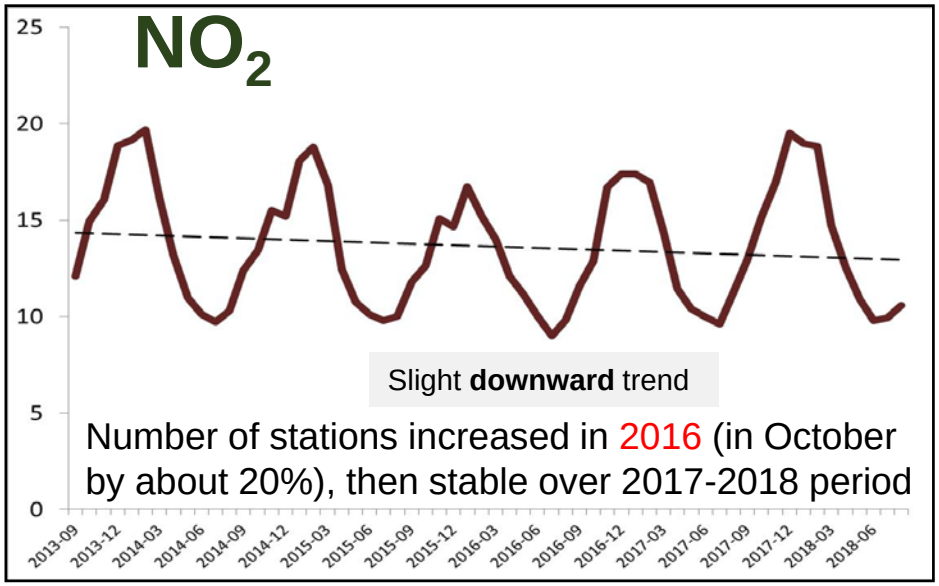
2013-18 OBSERVED POLLUTION TRENDS FOR THE INTERSECTION OF THE ECCC, NOAA, AND CAMS MODEL DOMAINS







O_3: Summertime concentrations without trend, while wintertime concentrations with slight increasing trend

NO_2: Decreasing trend over 2013-2016, replaced by increasing trend over 2017-2018

$PM_{2.5}$: Wildfires have an important contribution. August 2018 was the most extreme month, with an average concentration of 21.4 µg/m^3 due to extreme wildfires in W Can and W USA.

A NEW AIR QUALITY PERFORMANCE INDEX (AQPI)

Many statistical metrics are available. However, a review of recent publications suggested that several statistics are frequently used by various modelling groups for AQ performance analyses of multiple species: FAC2, NMB, MFB, R

The following statistics were selected for ECCC's AQPI analysis:

- Factor-of-2 Fraction **FAC2** (**measure of error or scatter**)
  - ✓ Provides fraction (0-1) of modelled & observed pairs meeting this criterion (M_i are modelled and O_i are observed concentrations); dimensionless statistic, not sensitive to outliers
- Correlation Coefficient **R** (**measure of linearity of relationship**)
  - ✓ Dimensionless, values between -1 and 1
- Mean Fractional Bias **MFB** (**measure of bias or offset**)
  - ✓ Where MFB=2 x $[(M_i-O_i)/(M_i+O_i)]$ and 1-ABS(MFB/2) provides values in range 0-1
  - ✓ Dimensionless, symmetric and bounded statistic (vs. NMB, which is asymmetric and unbounded)

Pollutant-Specific Performance Index (PI) Equation:

PI$[O_3,NO_2,PM_{2.5}]$= 100*AVG [**FAC2** + **R** + (1-ABS(**MFB**/2))]

- Provides values ranging from -**33** to **0** (**no skill**) to **100** (**perfect model**)

Note: Statistics are calculated using maximum daily concentrations (observed and forecasted)

Objective: ECCC would like to analyse overall AQ system performance taking into account different statistical properties. These statistics are presented every month to an internal steering committee (Comité des passes opérationnelles et parallèles).

MONTHLY (2017/09–2018/08) AQPI VALUES

	O_3	NO_2	$PM_{2.5}$	O_3	NO_2	$PM_{2.5}$
	2017-09			2018-03		
CAMS-ECMWF	83.7	67.2	60.7	**87.6**	69.7	53.5
NOAA	**90.8**	n/a	**76.8**	84.0	n/a	**61.8**
ECCC	85.7	**67.6**	68.4	84.3	**72.5**	61.3
	2017-10			2018-04		
CAMS-ECMWF	87.4	69.8	52.3	**90.2**	69.0	49.3
NOAA	**90.4**	n/a	61.4	86.1	n/a	**63.2**
ECCC	87.9	**73.9**	**64.1**	87.2	**69.9**	61.0
	2017-11			2018-05		
CAMS-ECMWF	**87.1**	69.2	51.0	**87.7**	**66.9**	53.5
NOAA	86.4	n/a	61.7	87.7	n/a	**66.4**
ECCC	85.3	**76.6**	**66.1**	**85.8**	65.4	62.4
	2017-12			2018-06		
CAMS-ECMWF	80.3	67.4	53.9	88.3	**65.9**	54.5
NOAA	83.7	n/a	66.5	**88.5**	n/a	**63.0**
ECCC	**85.3**	**77.5**	**68.7**	85.0	64.2	57.1
	2018-01			2018-07		
CAMS-ECMWF	**83.0**	64.6	54.1	80.9	**65.0**	53.9
NOAA	81.0	n/a	65.4	**91.1**	n/a	**67.4**
ECCC	**83.0**	**77.0**	**67.2**	84.7	63.3	65.9
	2018-02			2018-08		
CAMS-ECMWF	**86.3**	64.3	59.7	82.1	**65.7**	60.1
NOAA	81.5	n/a	62.0	**90.5**	n/a	71.2
ECCC	83.8	**73.8**	**64.8**	84.5	61.5	**71.8**

Number of months with the best AQPI values (indicated by red bold font in table):

O_3: NOAA (5), ECMWF(6) and ECCC (3). NOAA is the best in summer months.

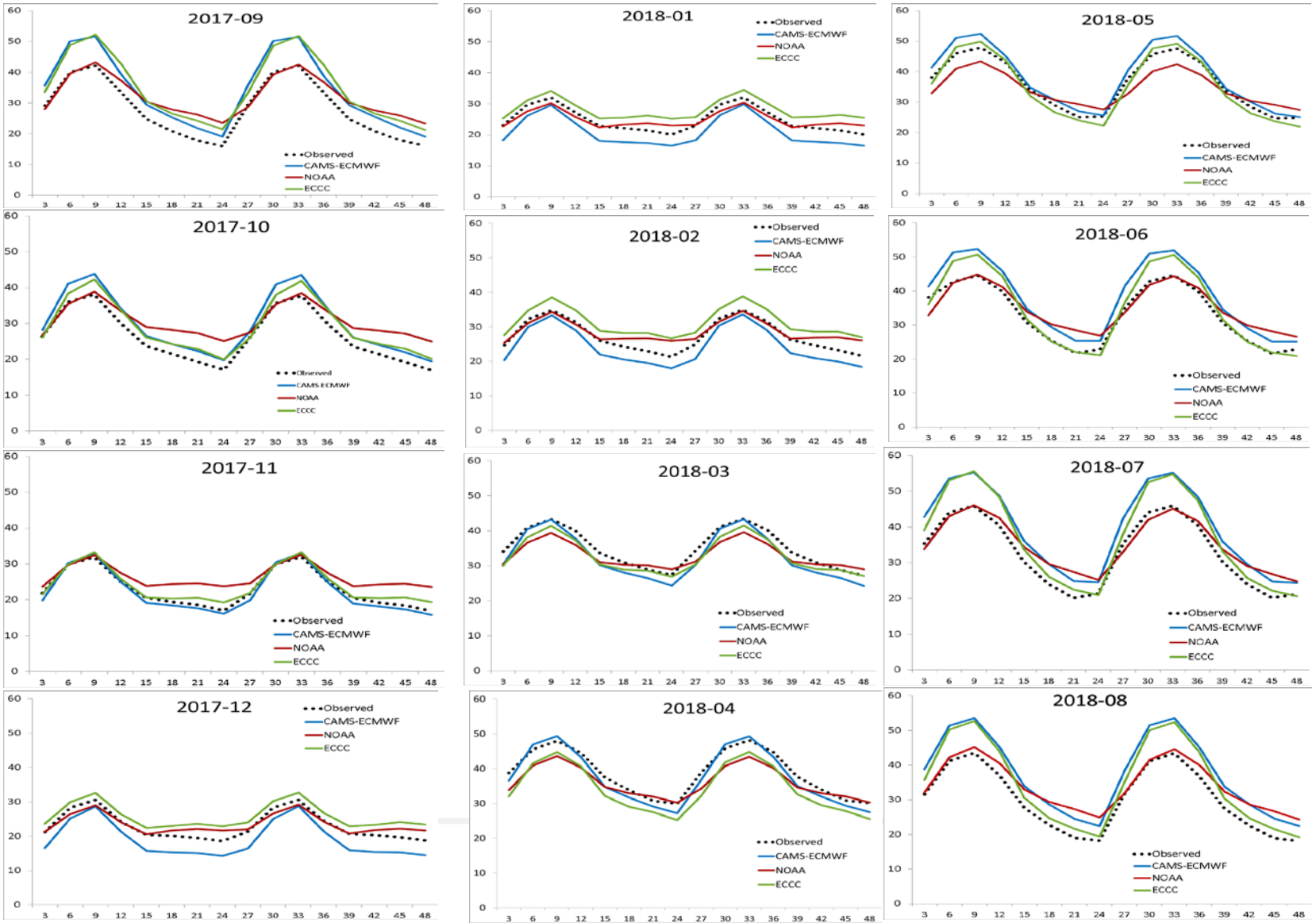
NO_2: ECMWF (4) and ECCC (8). ECMWF is better in the summer and ECCC in other months.

$PM_{2.5}$: NOAA (6), ECMWF (0) and ECCC (6).

PI	Legend
90%-100%	Excellent
80%-90%	Very Good
70%-80%	Good
60%-70%	Acceptable
50%-60%	Poor
<50%	Very Poor

Note: Only first day [0-24h] forecasts are considered
Forecasts at lowest model level are considered: NOAA (40 m), ECCC (40 m) and ECMWF (20 m)

Monthly Per-Forecast Hour Mean Observed And Forecasted O_3 (ppbv), Sept. 2017–Aug. 2018

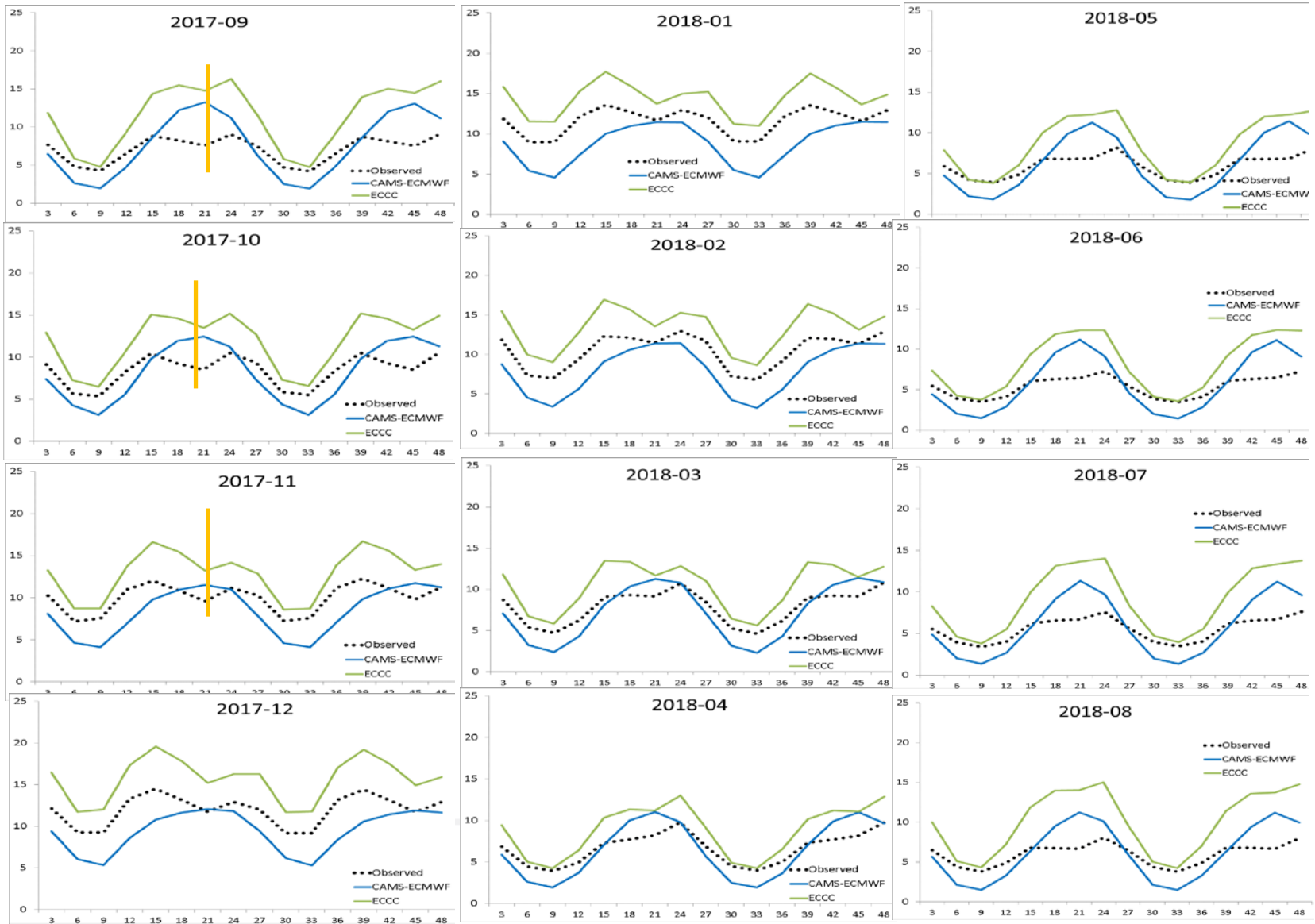


NOAA performs the best in forecasting summer MAX concentrations. However, it over-predicts night-time minima

ECMWF over-predicts summer MAX concentrations, but in winter / spring (ex. Apr., Nov.) ECMWF has the best performance

ECCC over-predicts summer MAX concentrations, but in some months (ex. May) this system has the best forecasts.

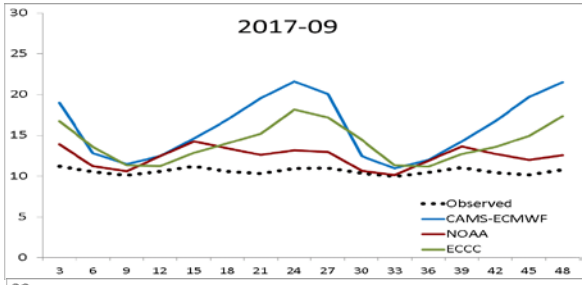
Monthly Per-Forecast-Hour Mean Observed and Forecasted NO_2 (ppbv), Sept. 2017–Aug. 2018

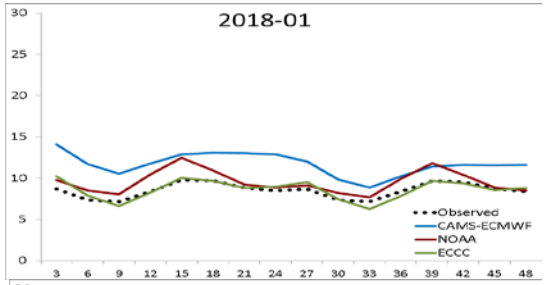


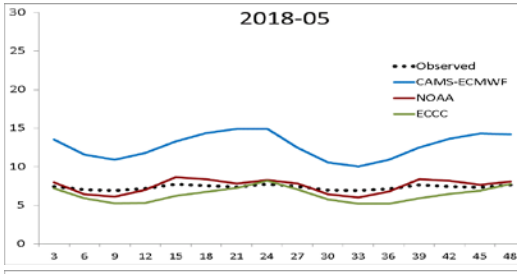
ECMWF forecasts concentrations closer to observations vs. ECCC. Issues with timing of maximum (21h) – forecasted when secondary minima is occurring (see yellow lines)

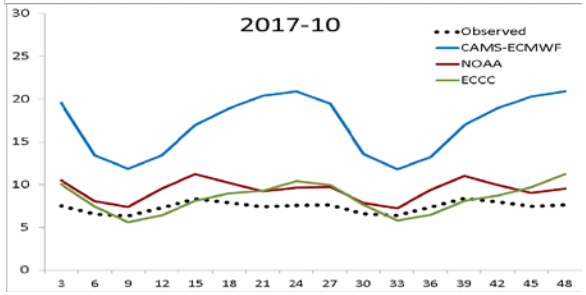
ECCC over-predicts NO_2 concentration, especially in summer months.

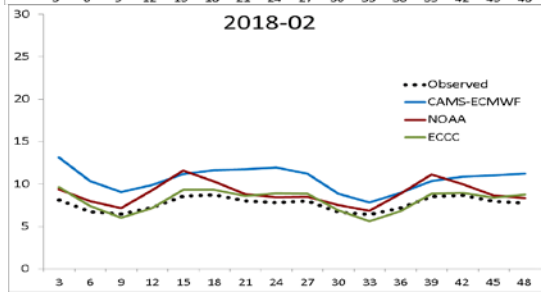
Monthly Per-Forecast-Hour Mean Observed and Forecasted $PM_{2.5}$ (μg/m³), Sept. 2017–Aug. 2018

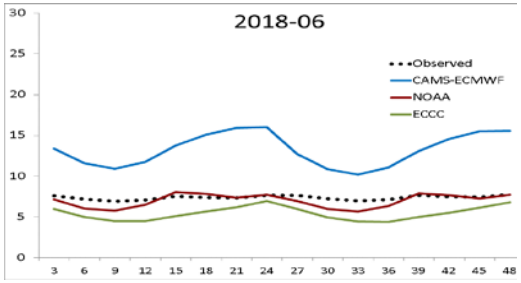


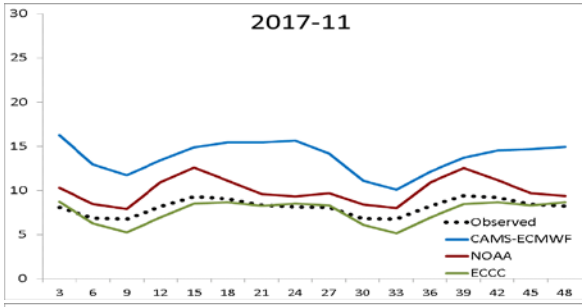


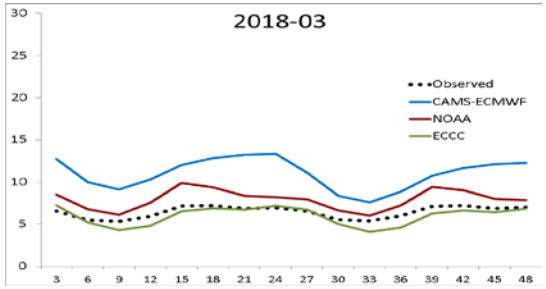


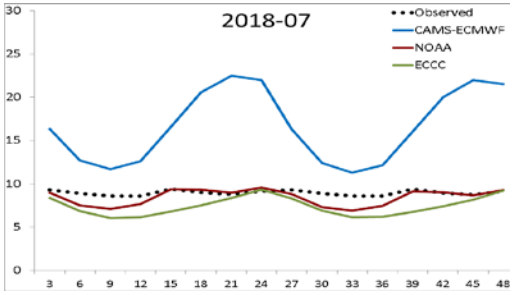


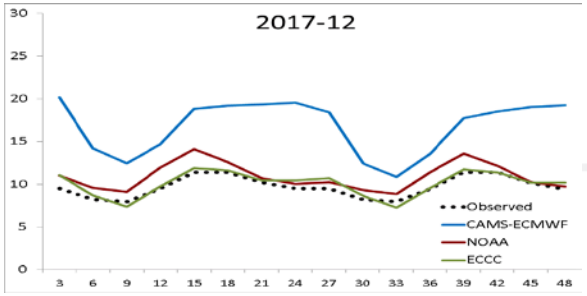


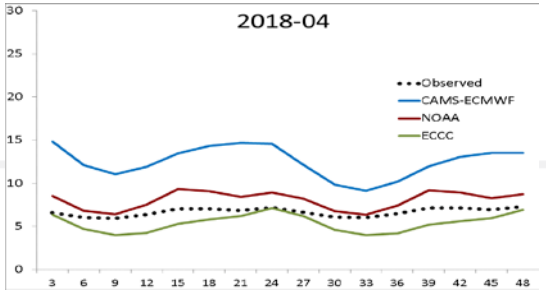


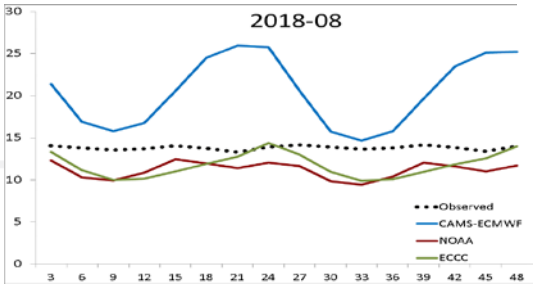












NOAA and **ECCC** have comparable performance, with **NOAA** out-performing in spring-summer (May to July) and **ECCC** outperforming in colder months.

ECMWF has an important positive bias, especially during the wildfire season.