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Research Needs from Environment Canada's Perspective

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International Workshop on Air Quality Forecasting Research

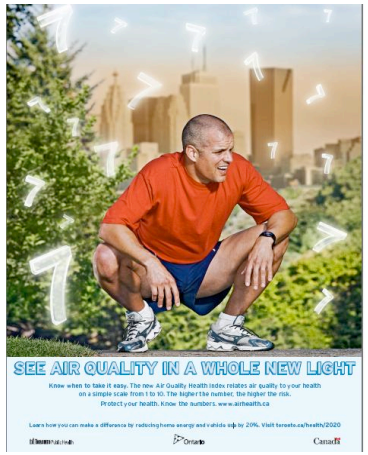
Boulder, December 2-3, 2009

Outline

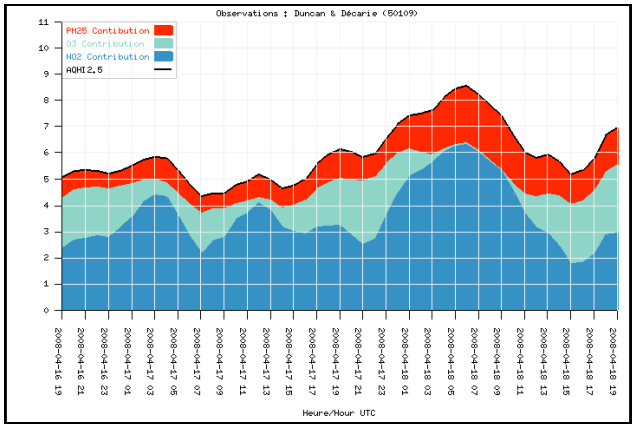
- Overview of the Canadian AQ forecasting program
- Science developments to date in support of the program
  - GEM-MACH15
- Active research areas to strengthen forecast accuracy
  - Process analyses
  - Missing sources
  - Program-driven challenges
  - Data assimilation
- Future areas of interest
  - Canadian satellites
  - Two-way interactions
  - Ensemble forecasts
- Summary

Overview of the Canadian AQ forecast program

- Ten year old program that has evolved from an O_3-only forecast in Eastern Canada to a Canada-wide O_3, NO_2, $PM_{2.5}$ forecast program
- Forecast is communicated in most areas as an Air Quality Health Index (AQHI)



AQHI = 10/10.4*100*[(exp(0.000871*NO_2)-1) +(exp(0.000537*O_3) -1)+(exp(0.000487*$PM_{2.5}$) -1)]

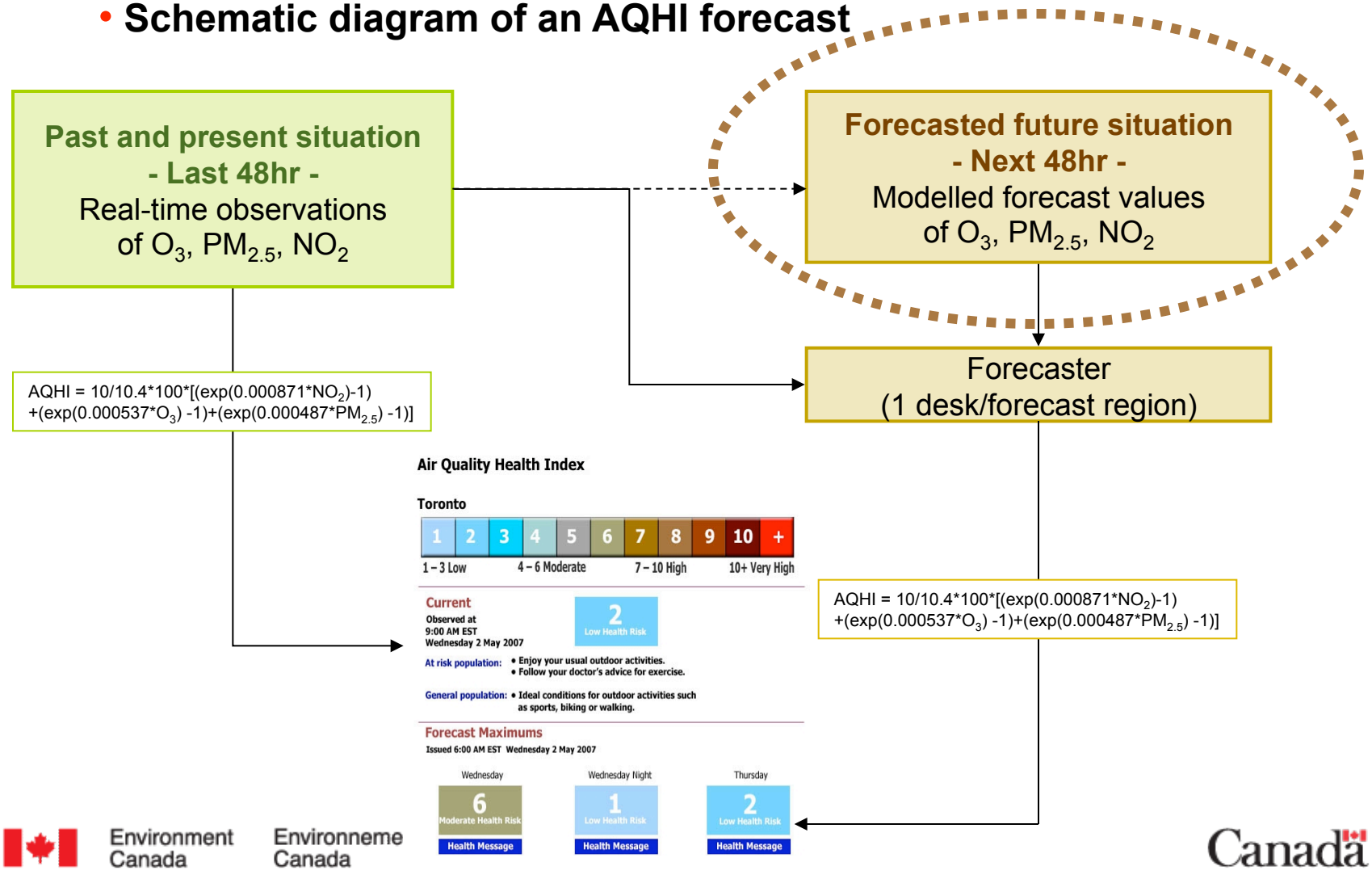


- 10 point scale that links air quality to the health risk associated with exposure to a pollutant mix

- Developed by Health Canada from Canadian multi-city mortality/morbidity studies of short term health effects and AQ data from the Canadian National Air Pollution Surveillance Network (NAPS)

Overview of the Canadian AQ forecast program

- **Schematic diagram of an AQHI forecast**



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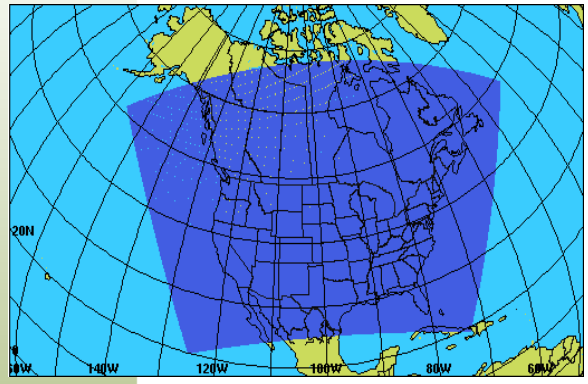
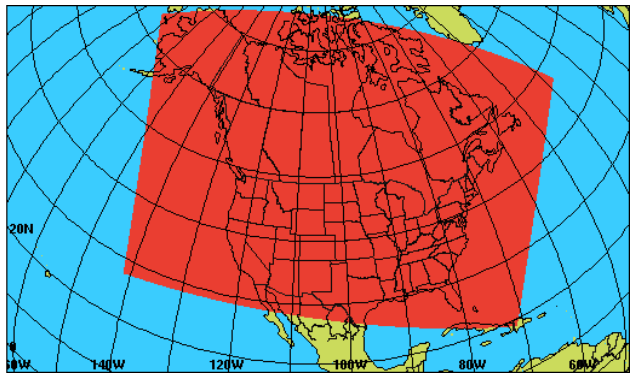
Science developments to date in support of the program



CHRONOS

Major phases of the numerical capacity development

- **Summer 1999**: First experimental ground-level O_3 forecast
  - Eastern North America, 21km spatial res., CHRONOS based
  - Extended to full continental domain in 2001
- **Summer 2003**: Implementation of bulk aerosol scheme
- **Summer 2004**: Year-long forecasts of O_3 and PM
- **Fall 2005**: Initiation of complete redesign of modelling platform as science improvements were hampered by technical limitations
  - Need to move to MPI capable framework
  - Also recognizing
    - Interpolation of meteorological field for off-line system leads to errors
    - Constant increase in meteorological fields requirements
  - **Chosen concept:** Use GEM Canadian Weather Forecast model as the host model and introduce chemistry processes on-line
- **November 2009**: Operational implementation of GEM-MACH15 producing 48h forecast, 2x daily, for O_3, $PM_{2.5}$ and NO_2



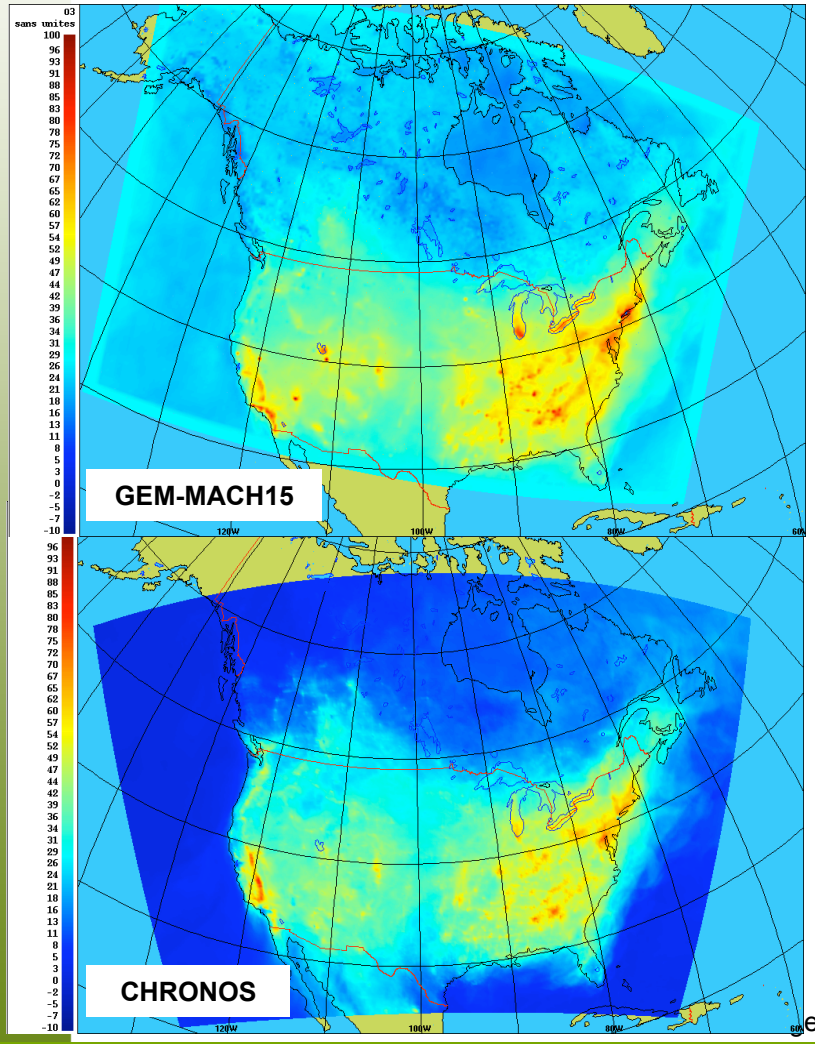
GEM-MACH15

Canada

Science developments to date: GEM-MACH15

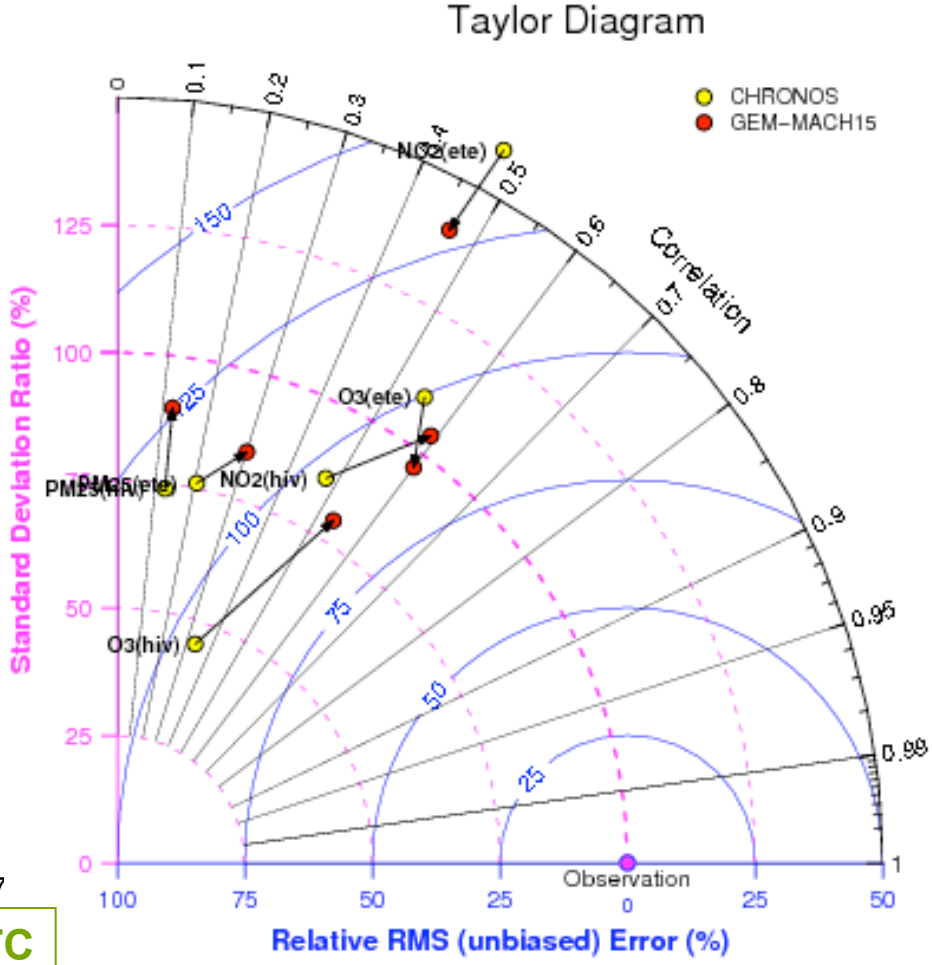
- **GEM-MACH15: Summary of major improvements**
  - Improved PM representation
    - Full representation of aerosol dynamics (vs bulk treatment)
    - Inclusion of aqueous-phase chemistry and cloud to rain transfer processes for gases and aerosols
    - Extended chemical species list (SO_4, NO_3, NH_4, EC, pOC, sOC, CM, SS) and associated emissions of species and/or precursors
  - Improved representation of boundary conditions
  - On-line treatment of meteorology and chemistry (vs off-line)
  - Improved resolution and coverage
    - 15km horizontal res (vs 21km), lid up to 0.1hPa from 6km
  - Improved temporal resolution (15min vs 1h)
  - Updated emission fields
  - Improved timeliness of execution and good scalability through multiprocessor computing

Science developments to date: GEM-MACH15



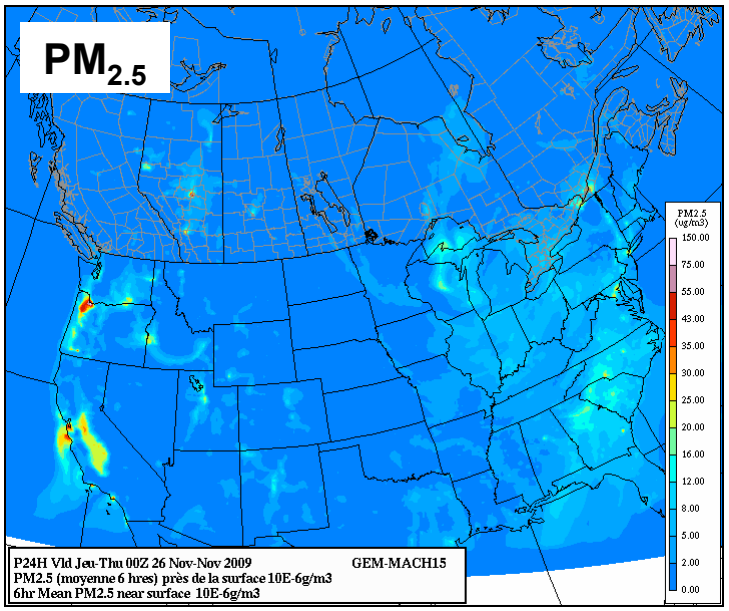
Averaged O_3 2008 summer fields at 20 UTC

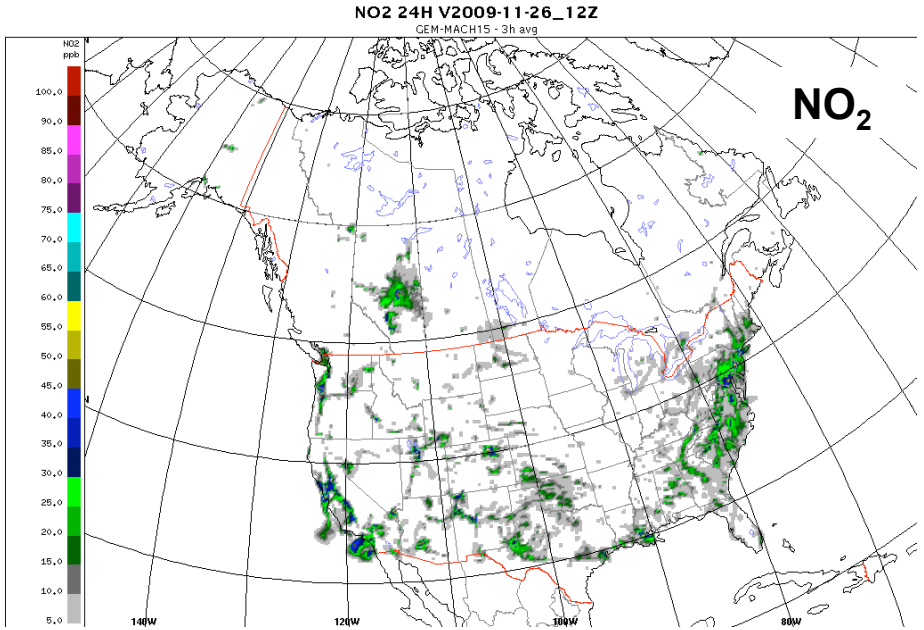
Overall GEM-MACH15 performance Summer 08 & Winter 09 (Canada)



Science developments to date: GEM-MACH15

- GEM-MACH15 O_3 and $PM_{2.5}$ model forecasts now publically available (NO_2 available internally)
  - www/weatheroffice.gc.ca (Analyses& Modelling)
    - *labelled as CHRONOS for the next month*





- **For details see presentations and posters in Theme 1**

Active areas of research to strengthen forecast accuracy

Current accuracy challenges:

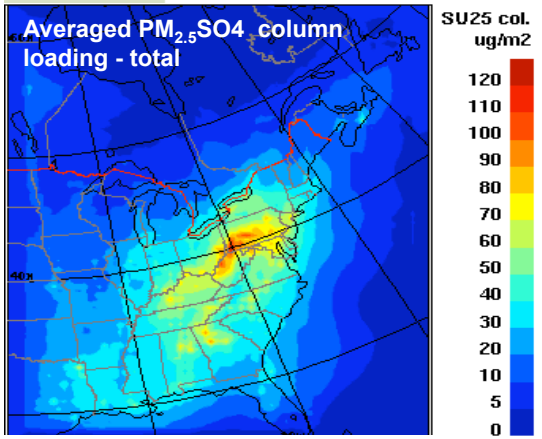
- PM forecasting
  - Good performance on directional change, magnitude an issue
    - GEM-MACH15 has a tendency to overestimate PM levels
    - Winter PM levels specific area of lower performance
- Still issues with over-forecasting of O_3

Are process parameterizations working as expected?

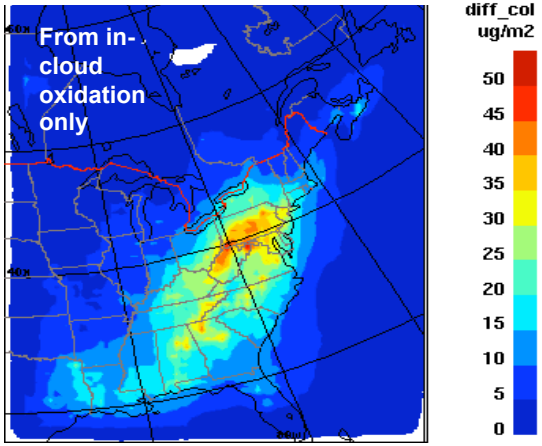
Research Area: PM forecast accuracy/ challenges

Process analyses using measurement intensives

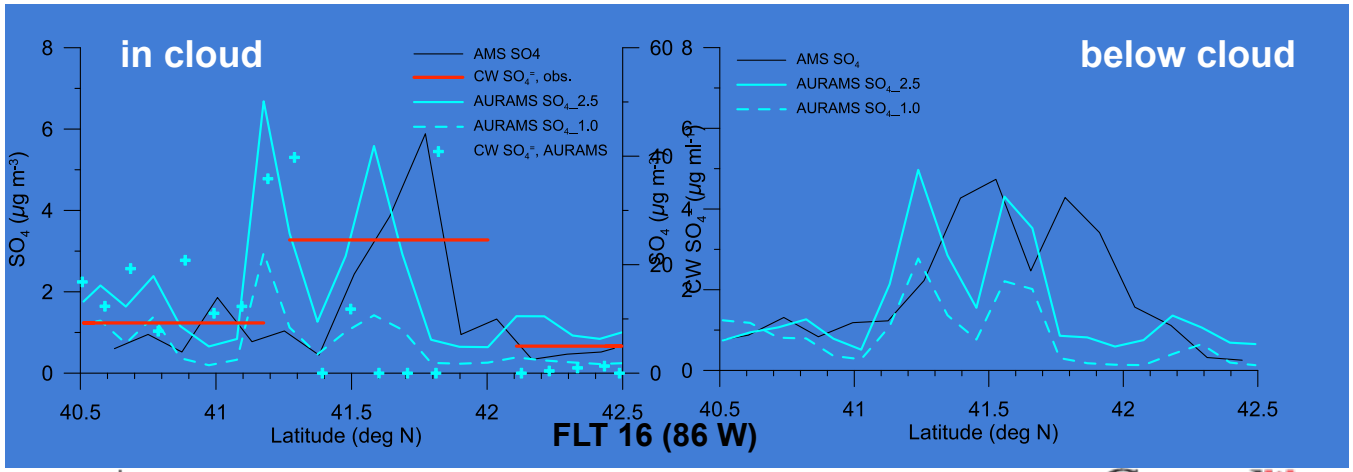
- Canadian component of ICARTT 2004 focused on cloud processes



July 14 – August 18, 2004



- During campaign, in-cloud oxidation contributed 30-40% to sulfate column loading over eastern N.A. using the aqueous phase module shared by GEM-MACH15 and AURAMS
- Analysis of Chicago urban/industrial plume on August 10, 2004 provides insights on in-cloud versus below cloud processing representation



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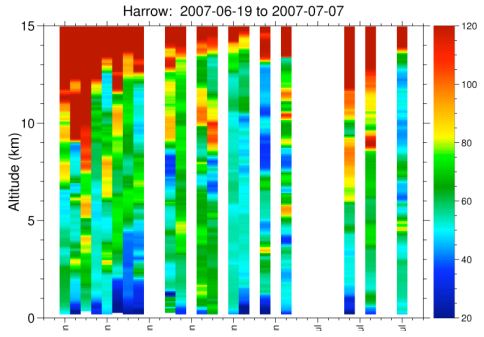
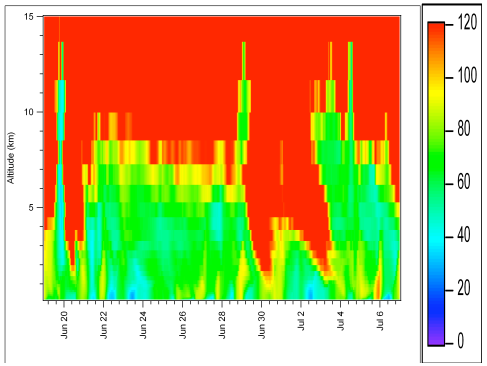
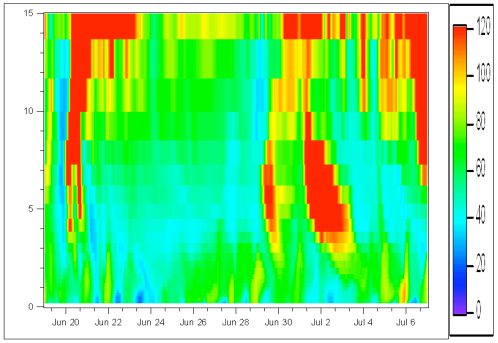
Research Area: PM forecast accuracy/ challenges



Ozonesonde

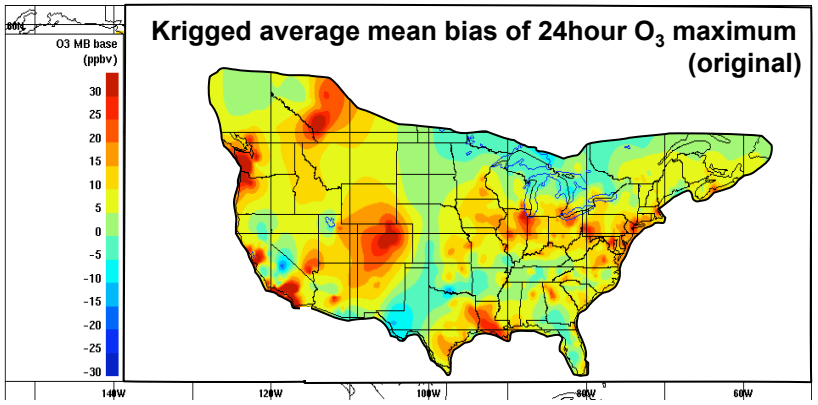


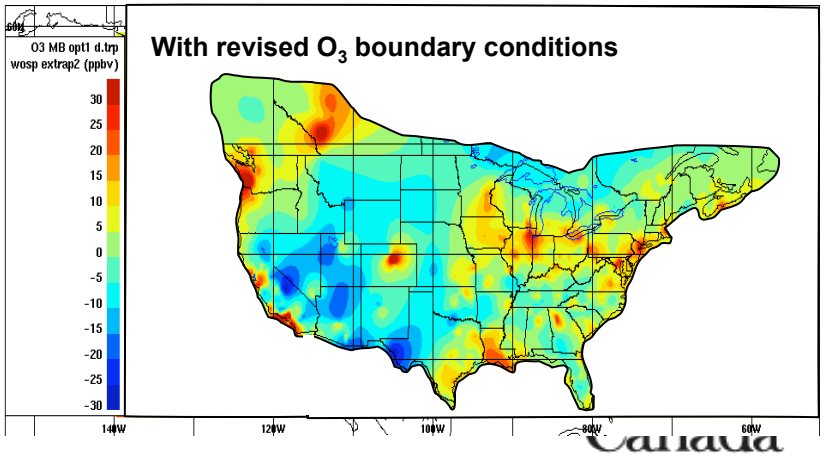
Original (middle) and revised (bottom) O_3 boundary conditions



Process analyses using measurement intensives

- BAQS-met 2007 intensive in Southern Ontario
- Compared O_3 surface & sonde observations to twelve 3-month simulations that used different approaches for specifying ozone top and boundary boundary conditions
- Large improvements in the column and at the surface can be achieved by adopting an optimum methodology while using O_3 climatological field as boundary conditions

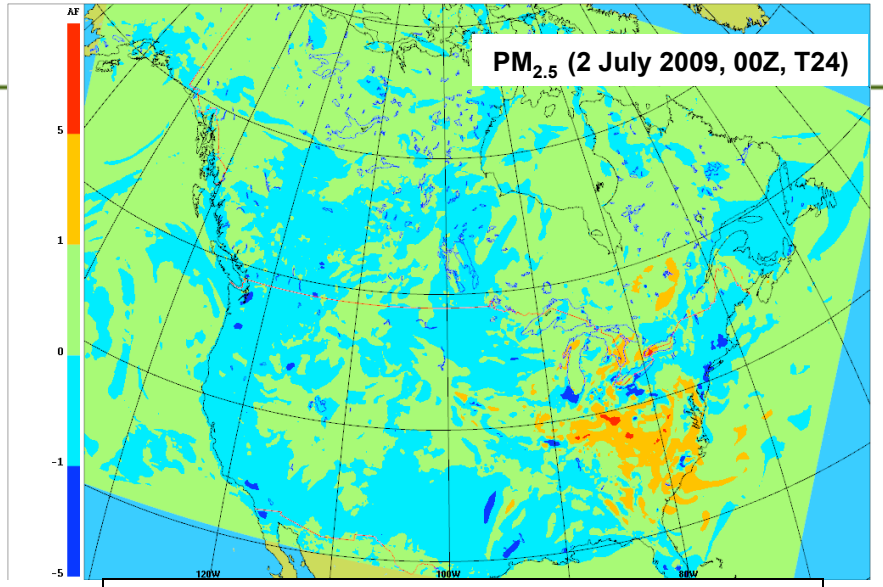




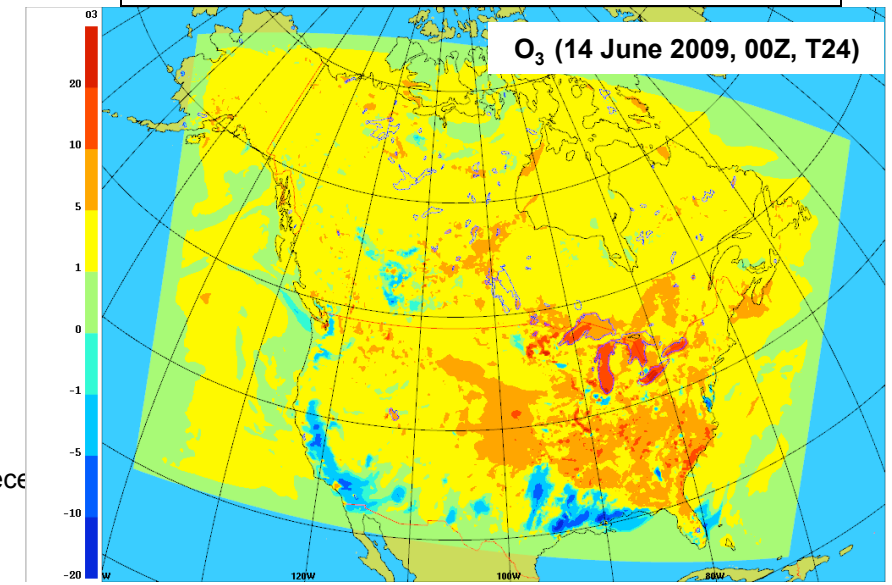
Research Area: PM forecast accuracy/ challenges

Sensitivity analyses to different representations

- Vertical diffusion scheme
  - Process splitting approach versus diffusion scheme with lower boundary conditions
  - Reduction by ~1-5 ug/m^3 in $PM_{2.5}$ surface field for eastern North America (very little changes in remainder of domain) – for a 24h test case
  - Reduction of surface O_3 levels by 5 to 20 ppb over water and by 1 to 10 ppb in the remainder of the domain (for a 24h test case)



Changes in surface field: Old - New



Active areas of research to strengthen forecast accuracy

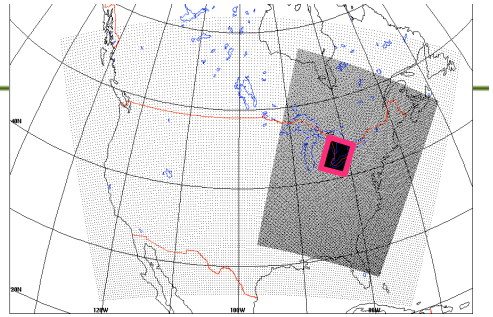
Current accuracy challenges:

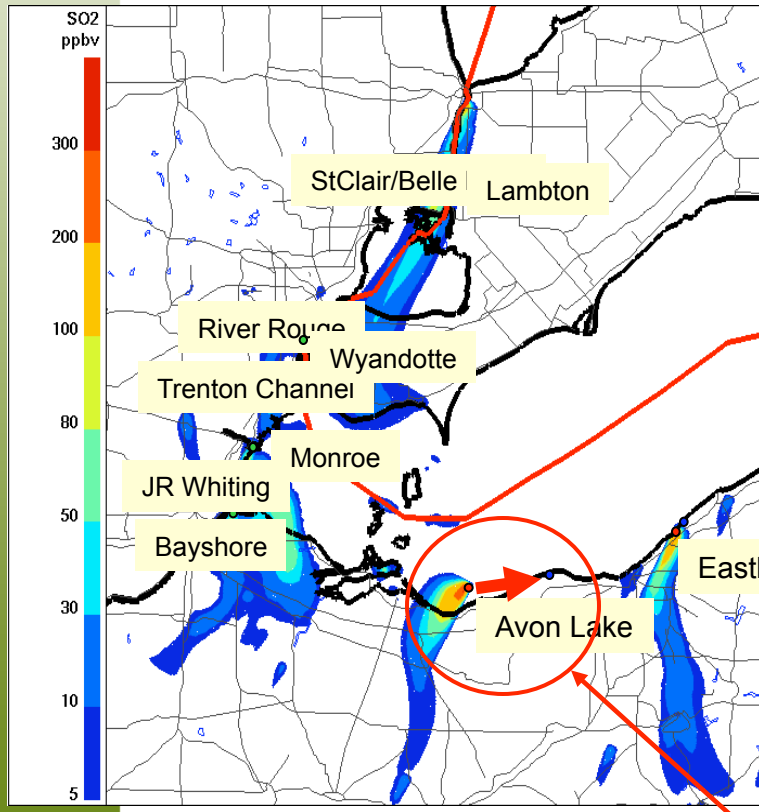
- PM forecasting
  - Good performance on directional change, magnitude an issue
    - GEM-MACH15 has a tendency to overestimate PM levels
    - Winter PM levels specific area of lower performance
- Still issues with over-forecasting of O_3

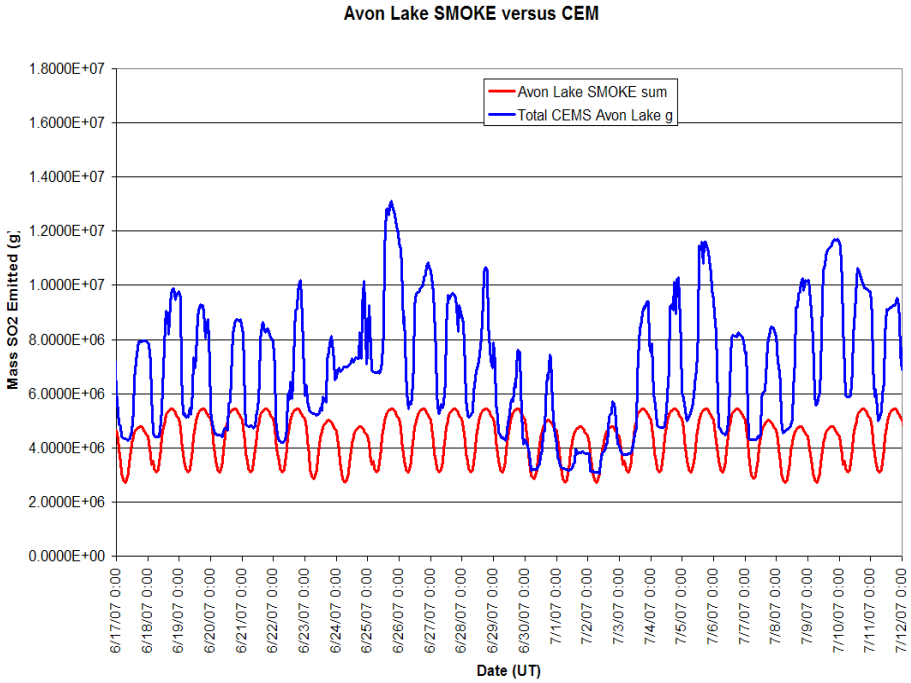
Are all primary sources represented ?

Research Area: Emission sources

- Working at high resolution in combination with detailed measurements to identify emission issues





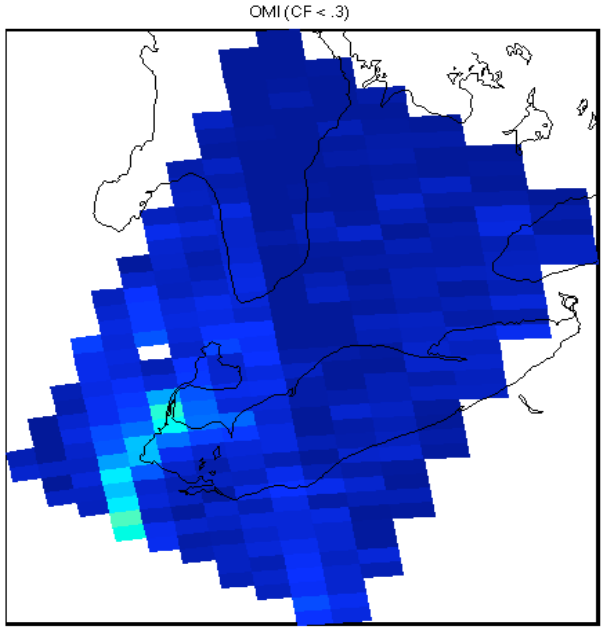


SMOKE derived (red) vs CEM (blue) SO2 emissions

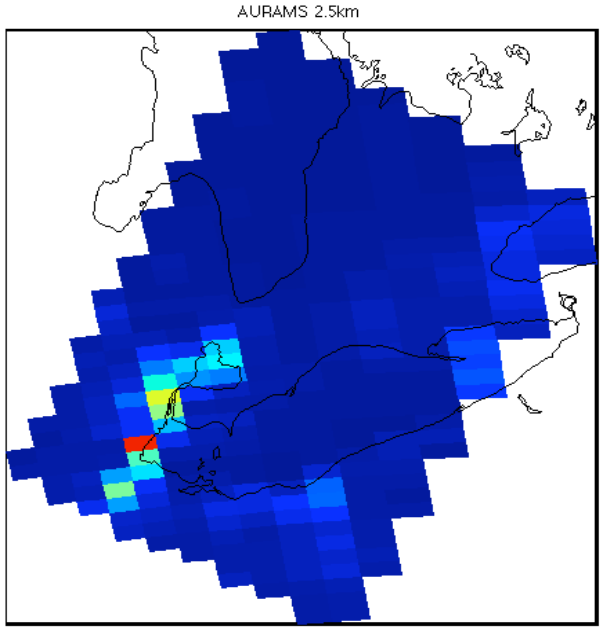
Location error ~33 km

Research Area: Emission sources

- Comparison of OMI satellite retrieval and high resolution AURAMS simulation



OMI



AURAMS 2.5km binned to OMI

Column NO_2 - 18:32Z (2:32 pm EDT) June 22nd, 2007

Preliminary Results (do not quote or cite)

Courtesy of: Colin Lee (U of T), Greg Evans (U of T), Randall Martin (Dalhousie), Paul Makar (EC/AQRD), Jeff Brook (EC/AQRD)

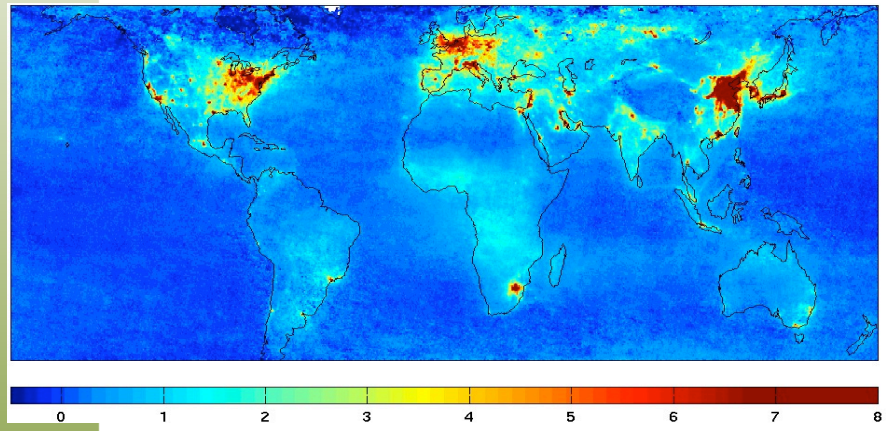
University of Toronto / Environment Canada collaboration to continue under the Canadian Aerosol Research Network.

Research Area: Emission sources

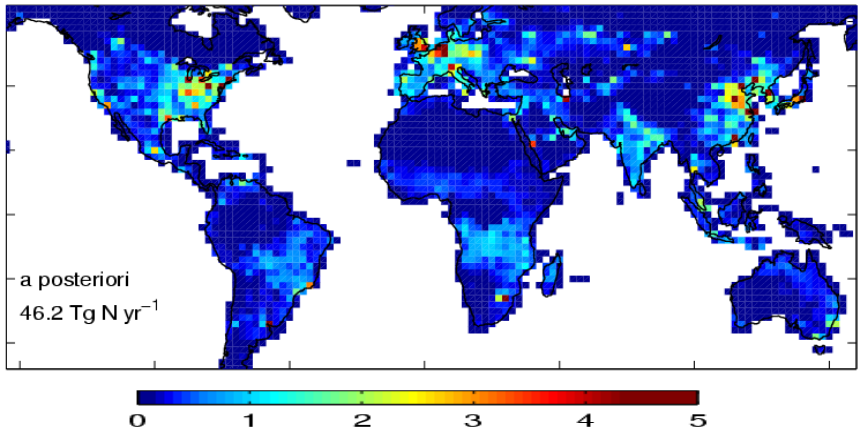
- **Using Satellite Observations of NO_2 to Contribute to Emission Inventory Development**

Inverse Modeling

Martin et al., 2006



SCIAMACHY Tropospheric NO_2 (10^{15} molec cm^{-2})

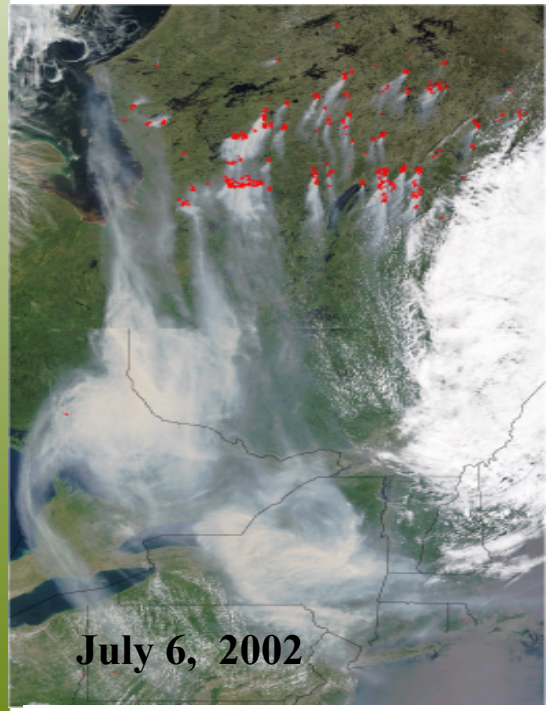


NO_x emissions (10^{11} atoms N cm^{-2} s^{-1})

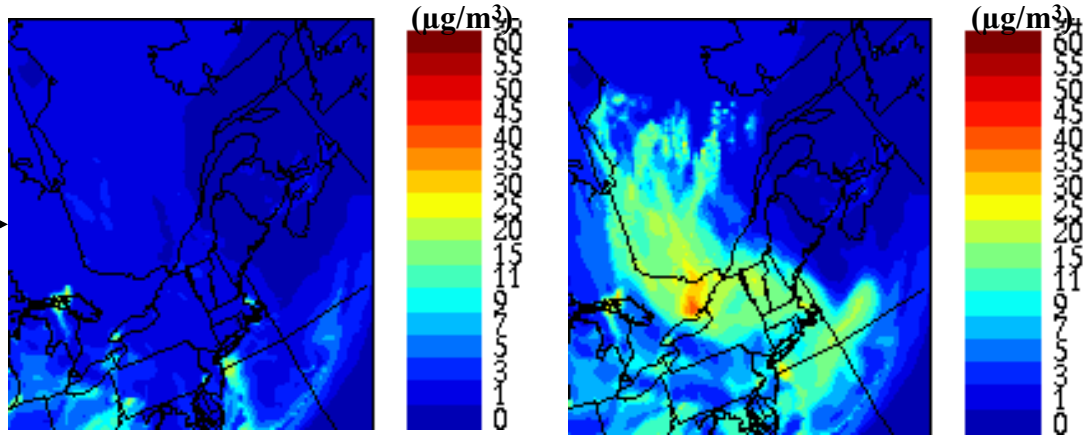
- **Initiative to be conducted in collaboration with Dalhousie to further this work at the regional/continental scale with Canadian focus**
  - integrate with bottom-up emission data
  - apply trends to inform emission updates towards monthly updates/adjustment of emission inventory

Research Area: Emission sources

- Inclusion of emissions from forest fires (wild and prescribed)
  - Intermittent but large summertime emitters of $PM_{2.5}$ and precursors that can be transported into populated areas
  - One of the largest air quality issues in Western Canada



Terra MODIS 1546-1553 UTC (NOAA)



CHRONOS control run 16Z July 6

CHRONOS with forest fire emissions

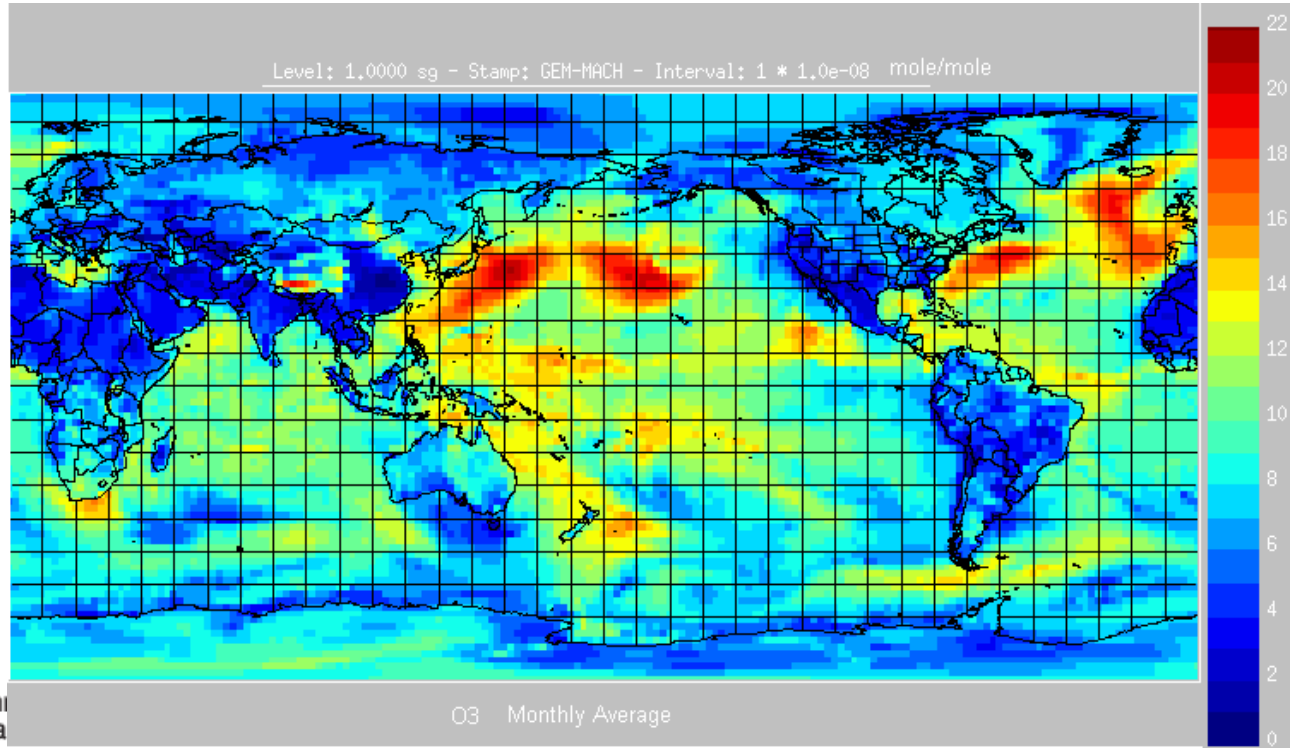
Example of air quality forecast model with and without inclusion of wild fire emissions

Canada

Research Area: Emission sources

Sources from outside the domain

- A global version of GEM-MACH is in development aiming at providing consistent and possibly (in the longer run) dynamic boundary conditions for the regional forecasts
- Representing the contributions from intercontinental transport of O_3 and $PM_{2.5}$



GEM-MACH Global O_3 distribution – January Mean

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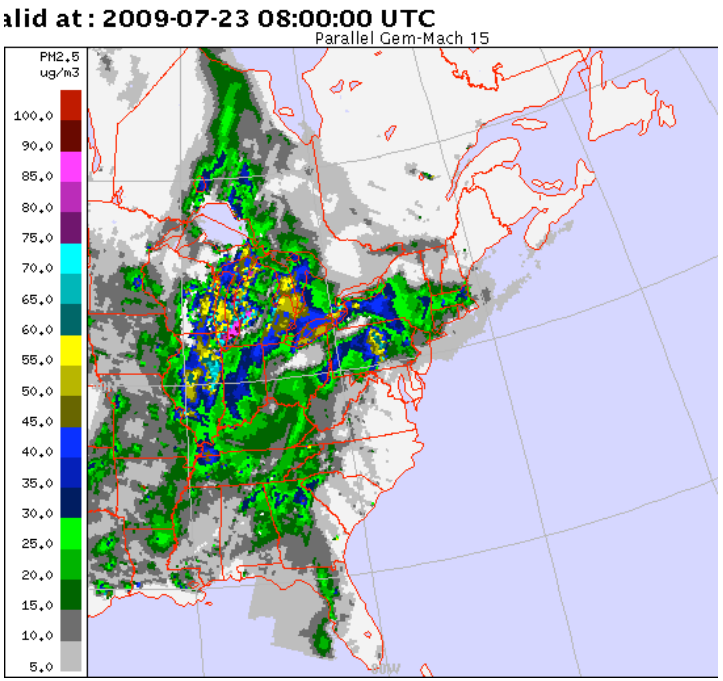
Active areas of research to strengthen forecast accuracy

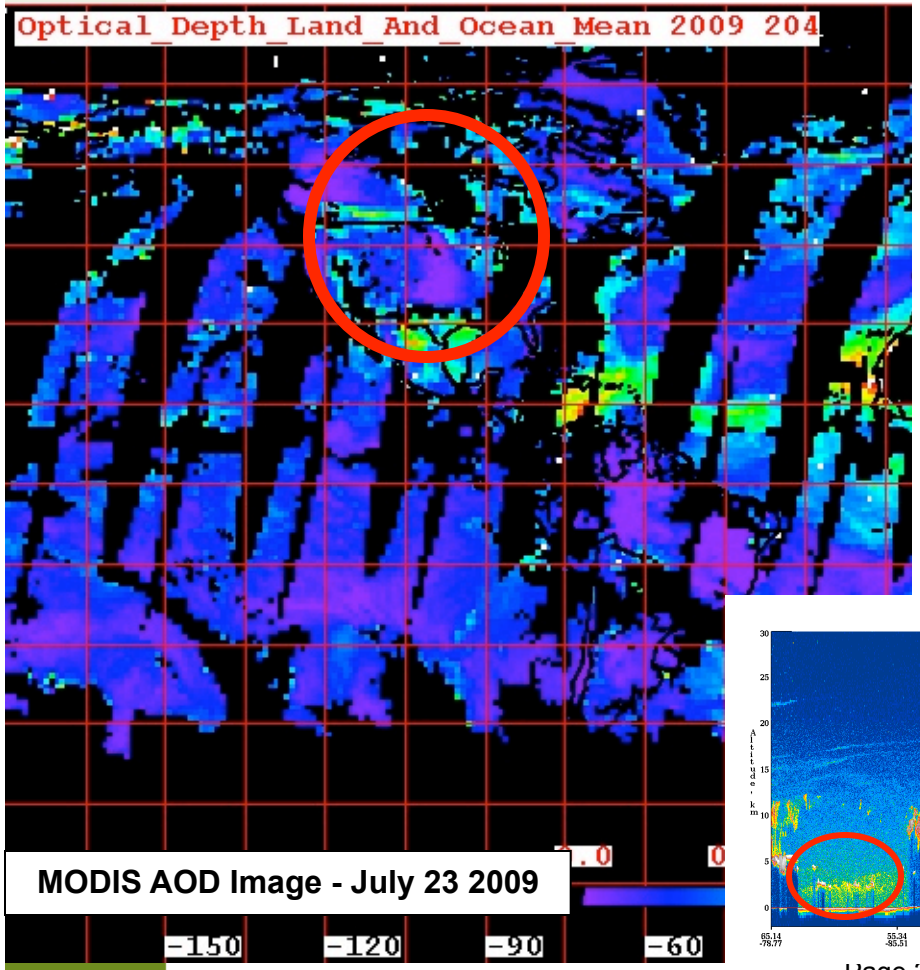
Program challenges:

- Expanding the AQHI program to rural and northern areas of Canada
  - How to assess performance in areas with limited observations?
  - Case study: Occurrences of high $PM_{2.5}$ levels in northern Québec and Ontario associated with cloud processing

GEM-MACH15 $PM_{2.5}$
July 23 2009

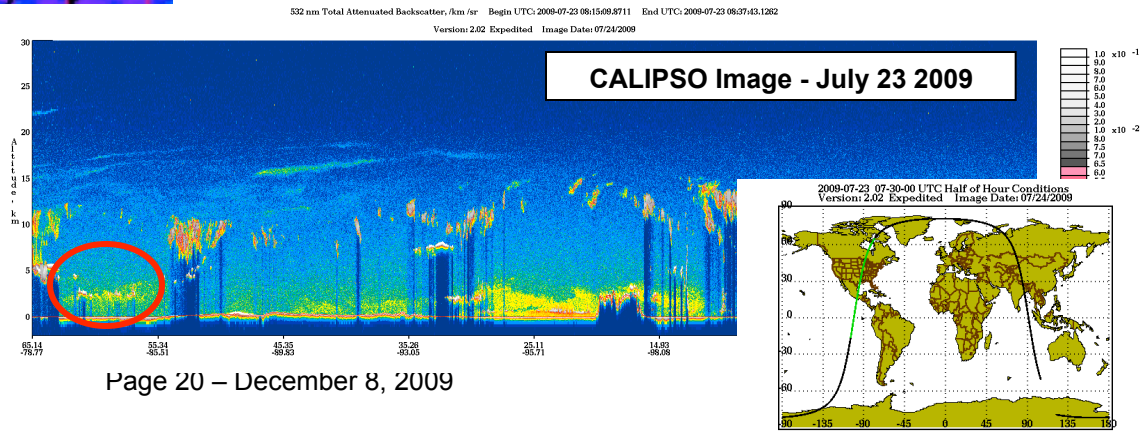


Research Area: Remote/rural areas



MODIS AOD Image - July 23 2009

- Events only detected with GEM-MACH15 and initially thought to be a model error
- Satellite information is supportive of the existence of these occurrences
- Initial model sensitivity analyses are linking events to aqueous phase chemistry and cloud processing
- Facing limitations with respect to the amount and type of data available and our ability to use them to further this analysis and the broader development of forecasting capability for remote areas



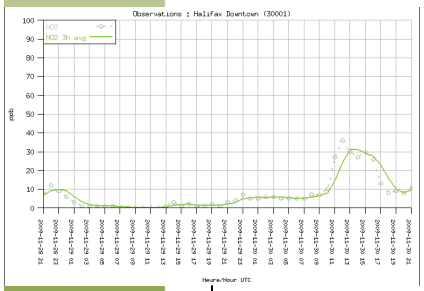
CALIPSO Image - July 23 2009

Active areas of research to strengthen forecast accuracy

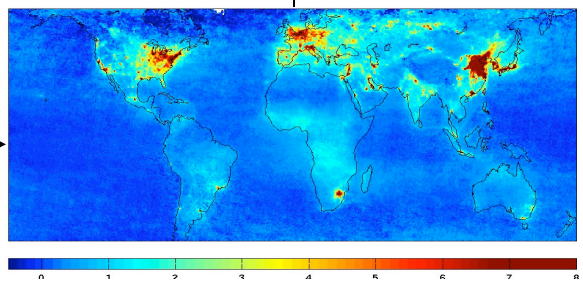
Program challenges:

AQHI = 10/10.4*100*[(exp(0.000871*NO_2)-1)+(exp(0.000537*O_3) -1)+(exp(0.000487*$PM_{2.5}$) -1)]

- AQHI is the only product worldwide with a strong focus (and high sensitivity) on NO_2 levels.
  - Collaborative work with Dalhousie to investigate use of satellite to improve NO_2 model forecast
  - Examining model ability with respect to NO_2, NO_x and NO_z through model simulations of test cases and comparison with true NO_2 analyser during mearsurement campaigns



Validation



SCIAMACHY Tropospheric NO_2 (10^{15} molec cm^{-2})

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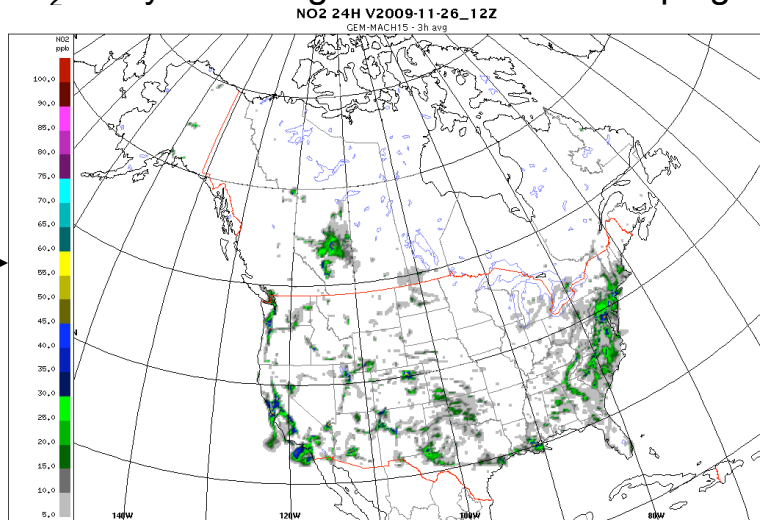
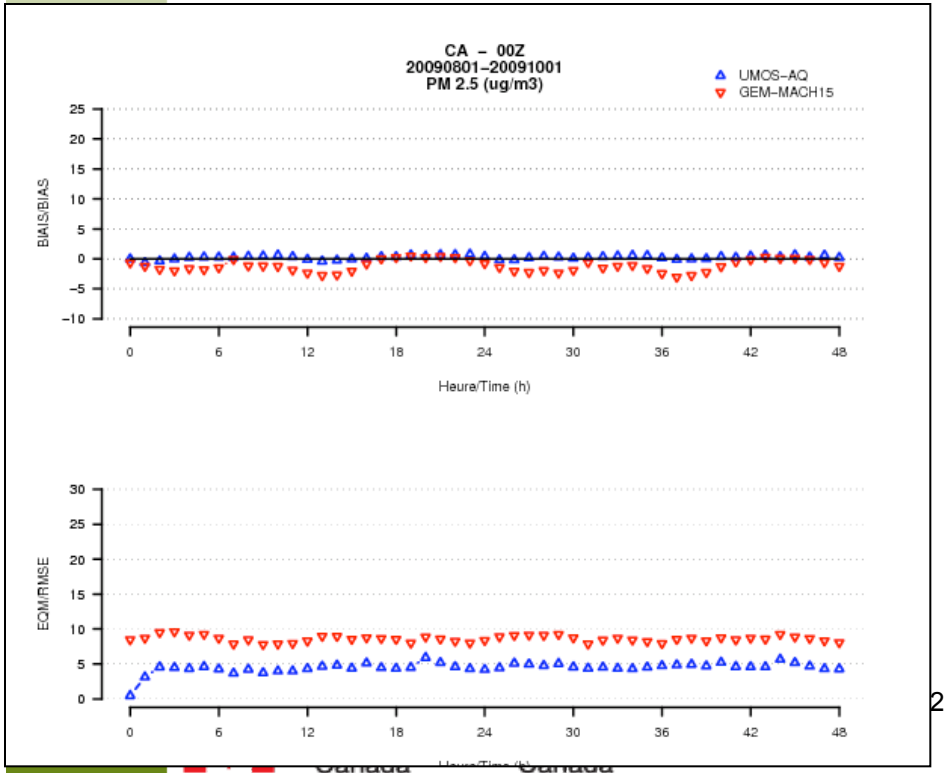


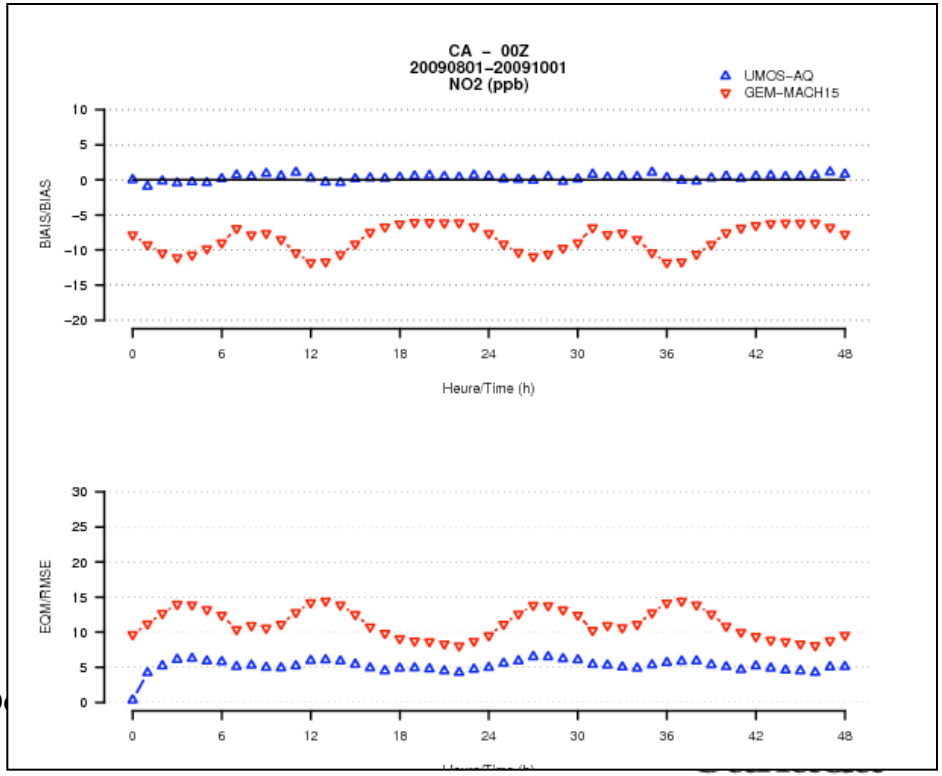
GEM-MACH15 NO_2 Surface field (ppb) – Nov 26, 2009 12Z

Active areas of research to strengthen forecast accuracy

Program challenges:

- Additional needs from forecaster's perspective
  - From 3D forecast to local point forecast: Model output Statistics
    - See Theme 4 presentation and poster



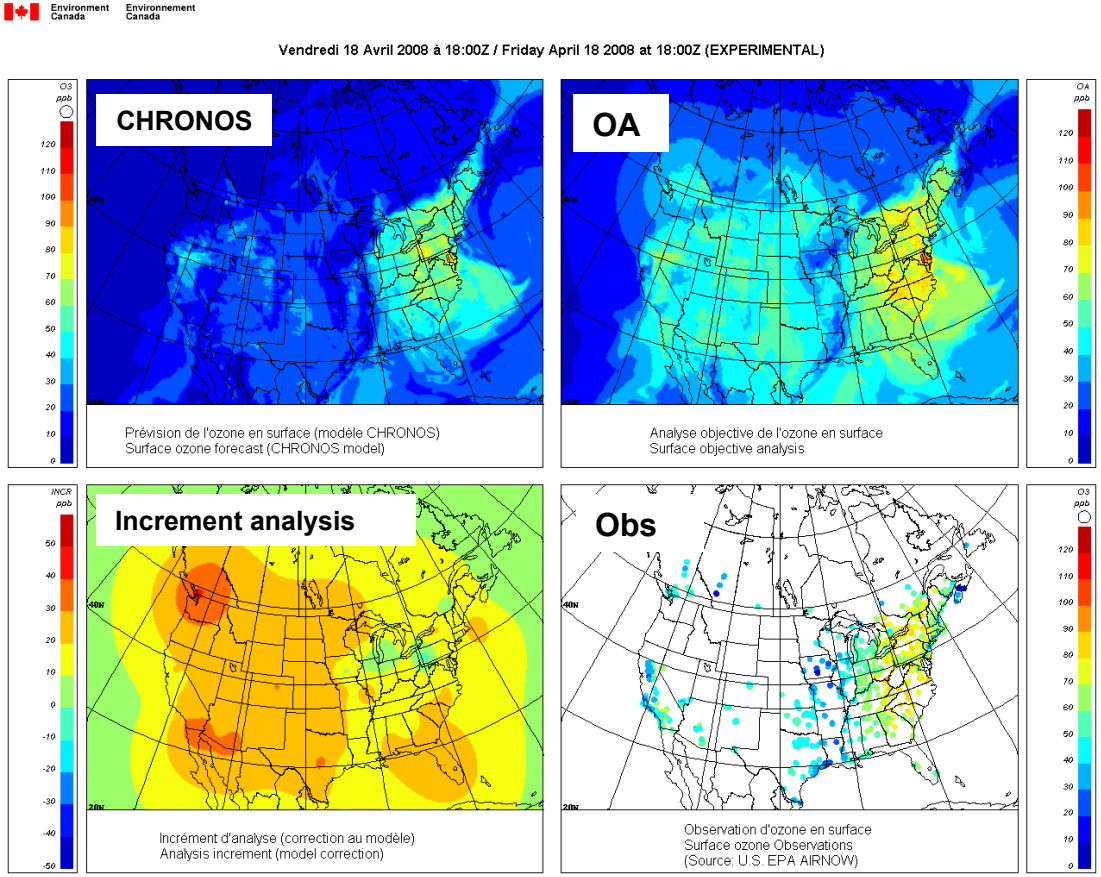


Active areas of research to strengthen forecast accuracy

Program challenges:

- Additional tool of interest from forecaster's perspective
  - Objective analysis and increment analyses (model correction)

- Ran in real-time since May 03
- Used surface data only
- Based on optimum interpolation analysis increments in **3D**
- Had ability to capture stratospheric intrusions as large analysis increments behind cold fronts
- Contributed to analysis of model performance and in need assessments for new measurement sites in remote areas



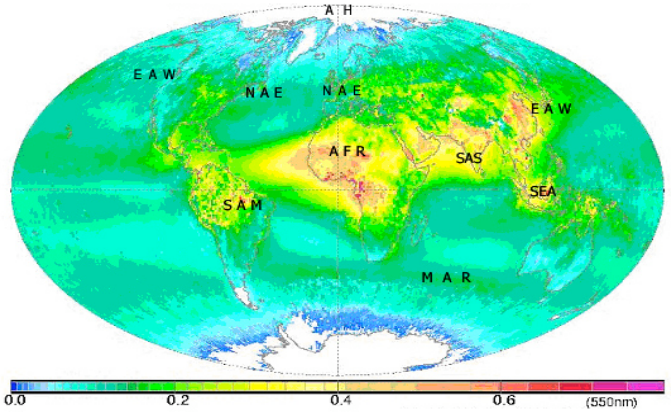
Research Area: Objective analysis

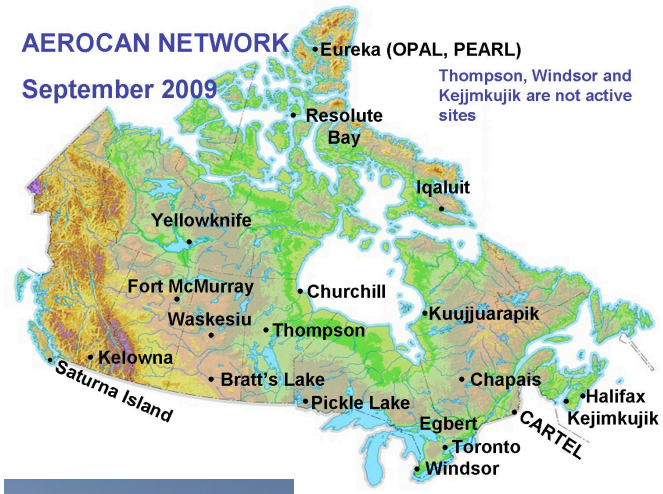
- Current status:
  - experimental objective analysis product was discontinued when GEM-MACH15 became operational
    - migration to GEM-MACH has to be sequential
- Effort to migrate capacity at planning stage:
  - Update will take advantage of knowledge acquire during initial development:
    - Benefit from much larger set of available surface data
    - Invest time on improving year round analysis and error covariances
      - issues with winter covariance errors in first version
  - Revisiting objective analyses capability for $PM_{2.5}$ and NO_2
    - Focus on understanding different sensitivity of OA to error covariances in comparison with O_3
- First steps to restarting effort on regional data assimilation
  - The OA model error covariances will form the basis for the perturbations in the EnsKS (Ensemble Kalman Smoother) assimilation

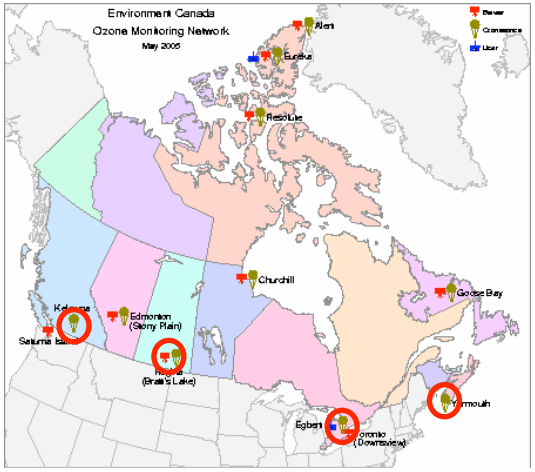
Research Area: Objective analysis and regional assimilation

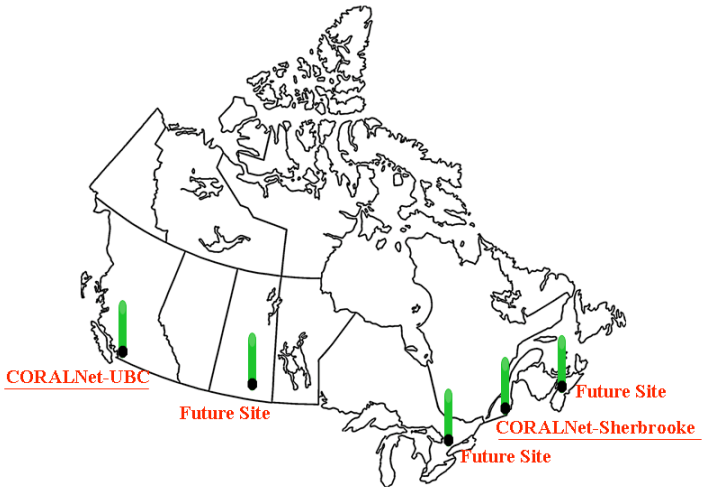
- Canadian analysis and assimilation efforts in support of air quality forecasting have focused on conventional surface network data (NAPS, CAPMoN, AIRNoW)
- It is envisioned to explore benefits that can be obtained from other sources of data

Satellite aerosol optical depth









Sunphotometer network

Environment Canada Environnement Canada

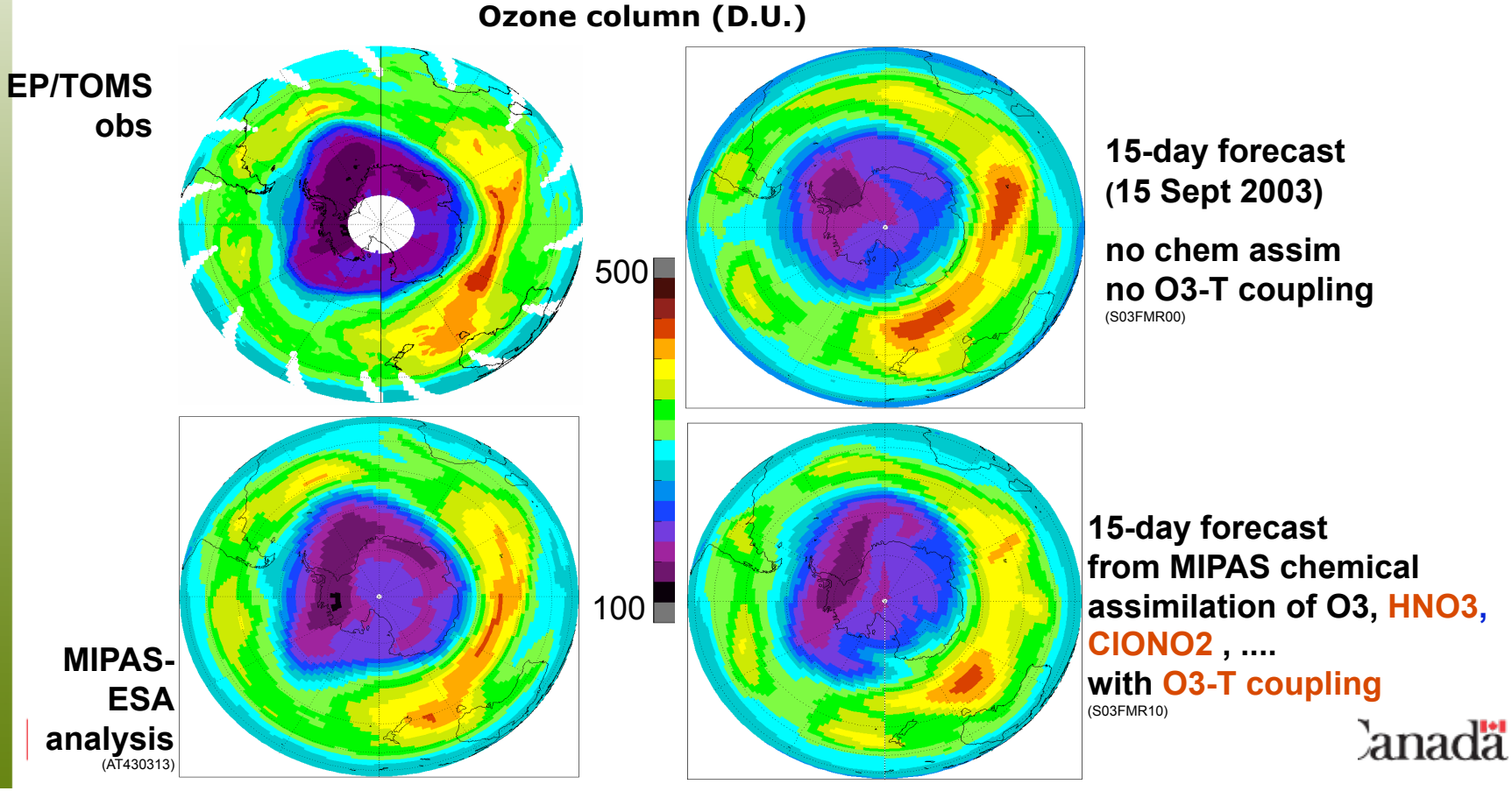
Ozone sonde network

CORALNet: Semi-autonomous Aerosol LIDAR Network - www.coralnet.ca

Canada

Research Area: Gaining experience in chemical data assimilation

- Significant effort from 2004-2008, to develop a stratospheric chemical data assimilation capability under contract for the European Space Agency
- Developed jointly with Belgium Institute for Space Aeronomy (BIRA)



Research Area: Gaining experience in chemical data assimilation

Satellite data used in support of stratospheric assimilation in GEM (ESA study)

- Limb sounding observations from ENVISAT in particular MIPAS and GOMOS, and MLS on EOS/Aura
- More recent efforts are focused on assimilating operational measurements on Metop/IASI and GOME2
- In preparation for operational missions such as NPP and Precursor Sentinel 5, plans are to assimilate the observations of OSIRIS and OMI

Research Area: Gaining experience in chemical data assimilation

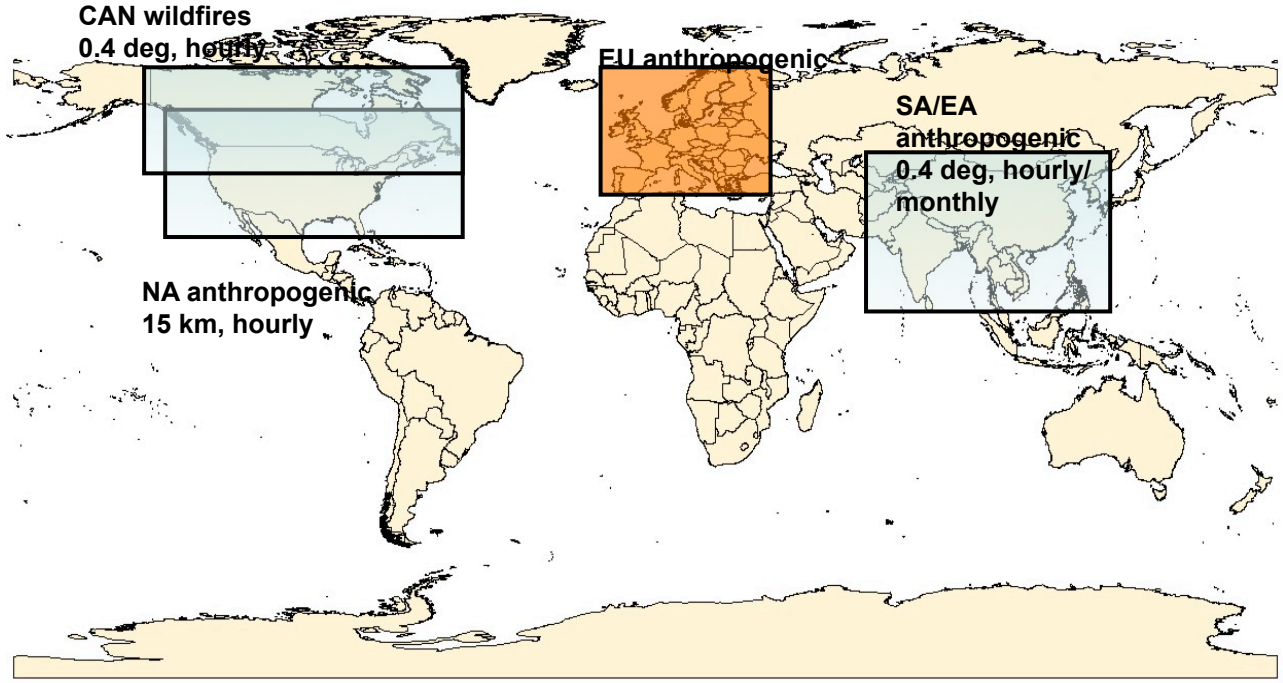
The BACCHUS project: continuing joint BIRA/Environment Canada project

- Further R&D to improve the stratospheric forecasting capability for Chemical Weather on global scales
  - primary goal of improving weather forecast
- Additional focus on AQ forecasting on continental scales
  - adapting and applying the assimilation methodology developed for the stratosphere
  - evaluating the potential of stratospheric/tropospheric assimilation (with tropospheric feedbacks)
- Characteristics of the Canadian chemical weather initiative
  - Looking at innovative approaches to complement existing chemical weather efforts (e.g. GEMS/MACC) from methodological perspective
  - Maximizing the use of chemical observations
    - Not limited to RT observations (e.g precursors species) and combinaison of surface, in situ, and remotely sensed observations

Research Area: Gaining experience in chemical data assimilation for AQFP

The BACCHUS project:

- Use the same model and emission information for both global and regional scales
  - e.g. Multi-scale approach allows regional chemical assimilation to feed the global model
- AQ modeling, assimilation and inverse methods to use an ensemble approach (e.g. EnsKF)



Canada

Future directions: Canadian satellites – Validation and assimilation activities

Continue chemical data assimilation efforts as new satellites are launched with relevant payloads

- **CASS** (Chemical Aerosol Sounding Satellite) joint CSA, NASA effort, with a SAGE III and ACE-FTS on board. Limb sounding instruments. Launch date 2014.

- **PCW** (Polar Communication and Weather) satellite. Two satellites in a Molynia orbit, overlooking the North Pole region in alternance and thus providing continuous ("geostationary" like) observations of aerosols and ozone in the core payload, with additional gases in a science payload that is yet to be determined.

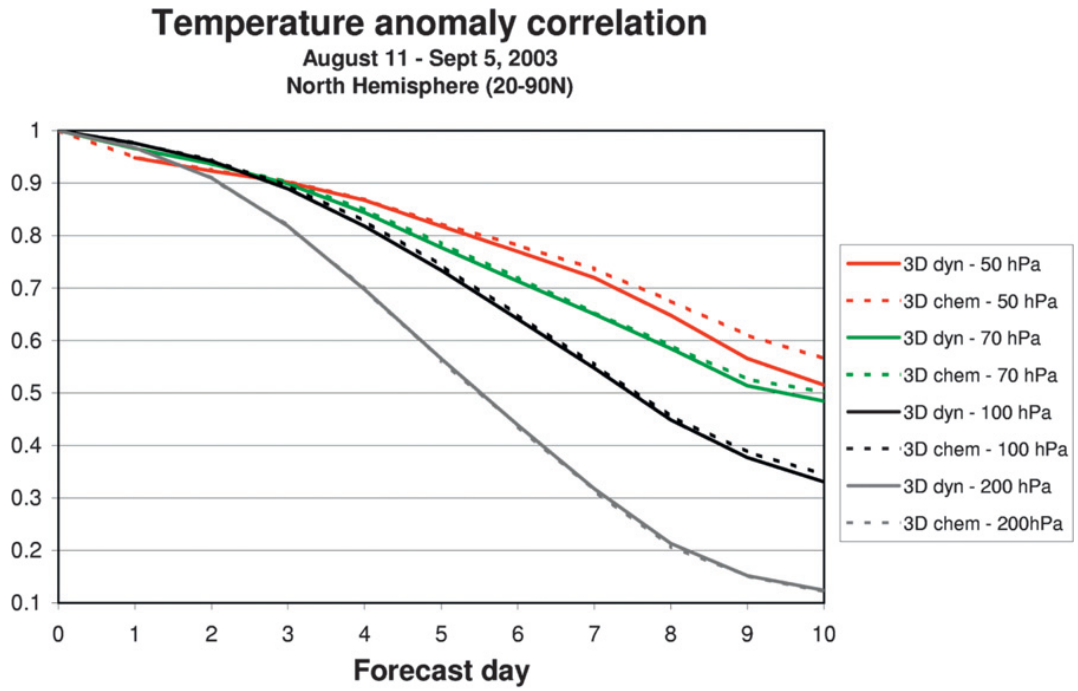
- **APPOC** (Atmospheric Processes Of Climate and its Changes) Mission: Six candidate missions, one of which to be selected

Future directions: two-way interactions

- With an on-line model, we are hoping to contribute to the building scientific knowledge on chemistry-aerosol-cloud-radiation feedbacks
  - Continuation of efforts from an assimilation perspective
  - Also from a process perspective (aerosol/cloud interactions)

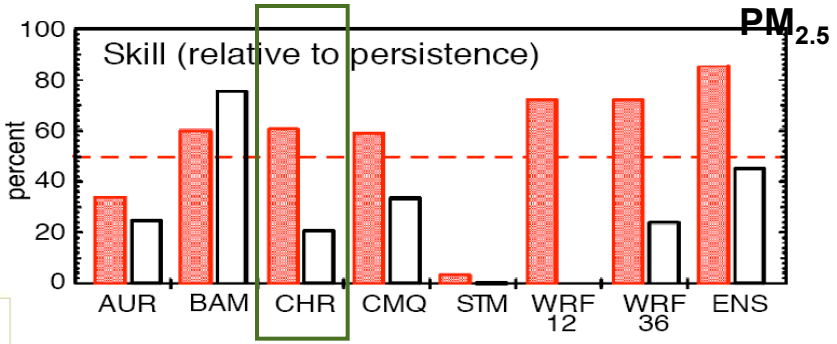
O_3 radiation impact on meteorology with coupled (two-way) chemistry-meteorology with assimilation system

(de Grandpre et al. 2009, MWR)

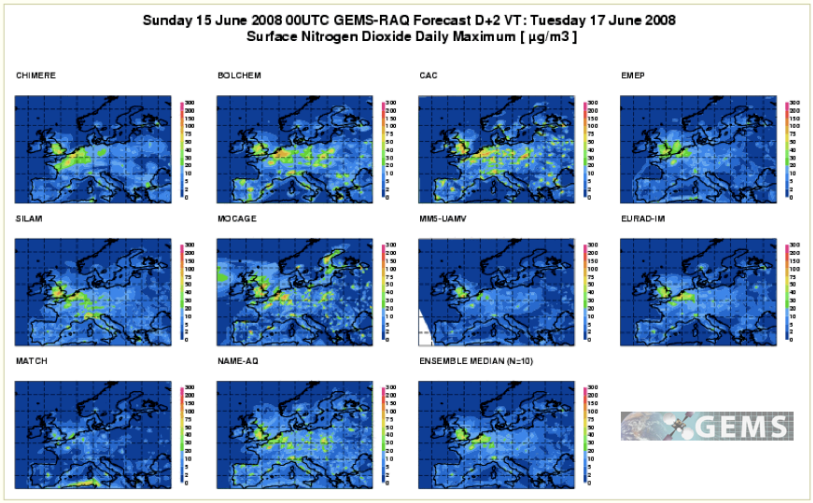


Future directions: ensembles

ICARTT 2004 and TEXAqS2006 air quality model ensemble
(McKeen et al., JGR, 2009 – doi: 10.1029/2008JD011697)



O_3



GEMS/MACC ensemble exercise

- 2010 NOAA/California field study/ model intercomparison & ensemble
  - Investigate feasibility of maintaining multi-model ensemble forecast effort beyond 2010 study (2010-2012)

Summary

- Making good progress in terms of AQ modelling for public forecasts
  - Can't underestimate the challenging road ahead to improve the accuracy (magnitude) of some forecasted entities, especially PM
- Have made baby steps to use chemical information of the atmosphere to improve weather forecast
  - Looking at continuing in this direction
- Just starting our efforts in using the full range of chemical data available to improve AQ modelling and forecasting
  - Need partnerships and multiple teams as there is much ground to cover
- Looking forward to the two days ahead to get an overview of the breadth of knowledge that the community has acquired so far and the strategic directions that are recommanded by the end of the meeting.