Impacts of Aerosol Direct/Indirect Effect Feedbacks and Forest Shading/Turbulence on Urban Air Quality Forecasts

Paul A. Makar, Ayodeji Akingunola, Craig Stroud, Junhua Zhang, Wanmin Gong, Michael D. Moran, Qiong Zheng

Modelling and Integration Section, Air Quality Research Division, ECCC

International Workshop on Air-Quality Forecasting Research, January 10-12, 2017

Outline

- Global Environmental Multiscale-Modelling Air-quality and CHemistry (GEM-MACH) model
  - Additions and modifications to the operational model
    - Feedbacks between AQ and weather
    - Forest canopies
- Domain and setup used for PanAm modelling
- Results:
  - The impact of feedbacks between AQ and Wx on high resolution mesoscale forecasts during PanAm.
  - The impact of forest canopy processes on AQ (10 km resolution only, so far)
- Preliminary Conclusions
- Next Steps

GEM-MACH: EC's AQ Model

- First described in Moran et al (2010) , and in multiple talks at IWAQFR2017
- GEM-MACH is an ***on-line*** chemical transport model
  - 2 bin aerosol size fraction representation
    - *Fast:* operational forecasts: less particle bins, less species to transport
    - Inorganic heterogeneous chemistry equilibrium done in "bulk mode"
    - Aqueous phase equilibrium done in bulk mode
    - Temporary rebinning to 12 bin distribution to improve particle microphysics performance
  - 12-bin aerosol size fraction representation
    - More realistic size distributions possible
    - Better performance for particle components (oil sands simulations)
    - Required, in order to accurately simulate feedbacks between aerosols and weather (the radiative and cloud properties of aerosols are very size dependent)
- Comparison of **v1.5.1** against 2006 and 2010 observations for North America and other peer models in *Atmospheric Environment* special issue on the Air Quality Model Evaluation International Initiative, Phase 2 (AQMEII-2); Makar et al, 2015 (a,b)).
- V2.0 of GEM-MACH now Canada's operational air-quality forecast model.

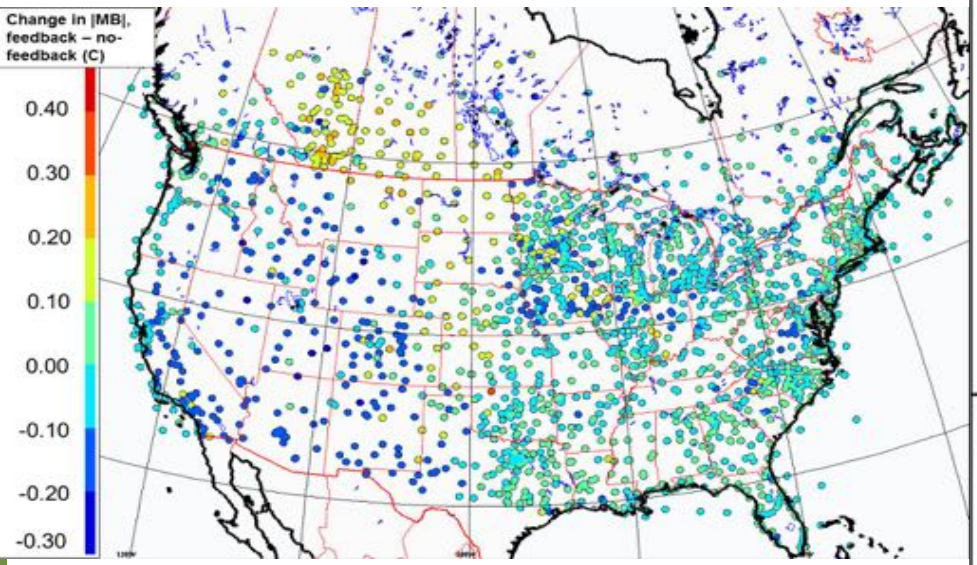
GEM-MACH: Feedbacks (1)

- Processes added to v1.5.1 (***and here, to v2***):
- Aerosol direct effect
  - Mie scattering approach
  - Homogeneous (internally mixed) core assumed
  - First time-step: Mie code generates a lookup table of aerosol optical properties based on aerosol size and composition.
  - At every time step, size-resolved optical properties are calculated and returned to the GEM radiative transfer code.
- Aerosol indirect effect
  - Modified Milbrandt-Yao Double Moment scheme
  - Chemistry ➔ Cloud formation:
    - Abdul-Razzak and Ghan parameterization : CCN(size, speciation)
  - Cloud formation ➔ Chemistry
    - Cloud droplet information from GEM microphysics are used to process gases and aerosols in the chemistry

GEM-MACH: Feedbacks (2)

Air Quality Model Evaluation International Initiative Phase 2 results, Makar et al, *Atm. Env.* 2015 (a,b)):
GEM-MACH v.1.5.1, 15km resolution.

Change in magnitude of annual surface temperature mean bias for GEM-MACH simulation (feedback |MB| - no-feedback |MB|), North American observation sites.



Feedbacks decrease the magnitude of the temperature mean bias, for the year 2010.

Comparison of summer hourly O_3 statistics: Feedbacks improve summer O_3 forecast

Variable	Statistic	Non-Feedback	Feedback
O_3 (Regional)	NP	187330	187287
	FA2 (%)	83.49	**83.72**
	FA5 (%)	96.75	***98.77***
	MB	4.21E+00	**3.81E+00**
	FB	1.20E-01	**1.09E-01**
	NMB (%)	12.78	**11.57**
	PCC	0.60	0.60
	ME	1.15E+01	**1.13E+01**
	NMSE	1.81E-01	**1.77E-01**
	NME (%)	34.96	**34.42**
O_3 (Urban + suburban)	NP	333840	334317
	FA2 (%)	79.26	**79.31**
	FA5 (%)	**95.06**	95.04
	MB	2.86E+00	***2.47E+00***
	FB	8.72E-02	***7.59E-02***
	NMB (%)	9.11	***7.88***
	PCC	0.63	0.63
	ME	1.16E+01	**1.15E+01**
	NMSE	2.12E-01	**2.10E-01**
	NME (%)	37.03	**36.65**

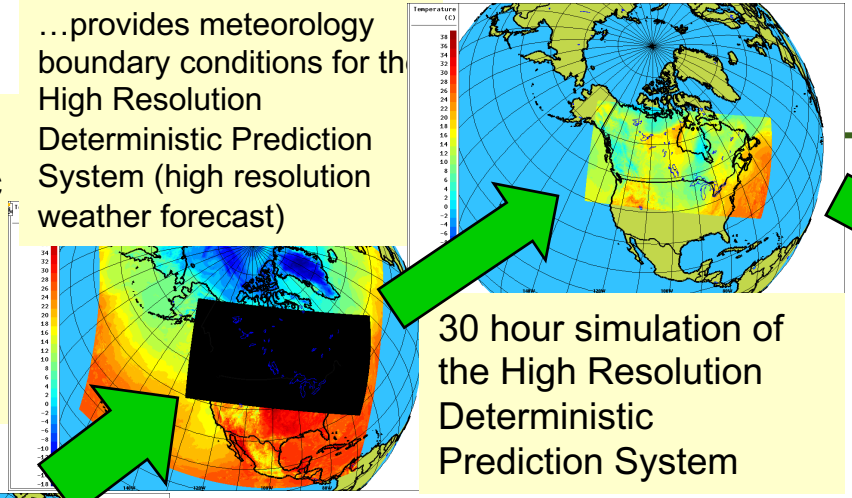
GEM-MACH: Feedbacks (3)

- Here: ***What about in Southern Ontario?***
- The question:
  - How much do AQ-weather feedbacks *matter*, in Southern Ontario?
  - Long version: To what extent can the aerosol direct and indirect effects influence the outcome of a short-term AQ and weather forecast, in the lower Great Lakes region?

GEM-MACH Description (c.f. talk by A. Akingunola)

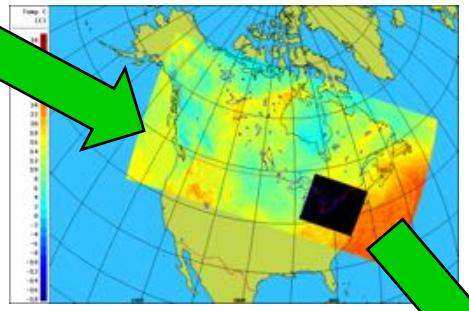
Regional Deterministic Prediction System (Weather Forecast)

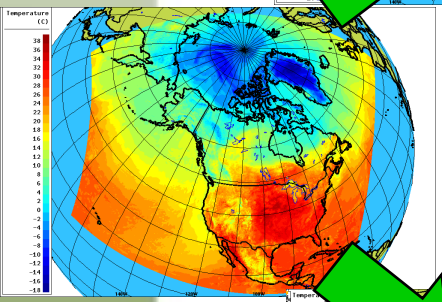
…provides meteorology boundary conditions for th… High Resolution Deterministic Prediction System (high resolution weather forecast)



30 hour simulation of the High Resolution Deterministic Prediction System

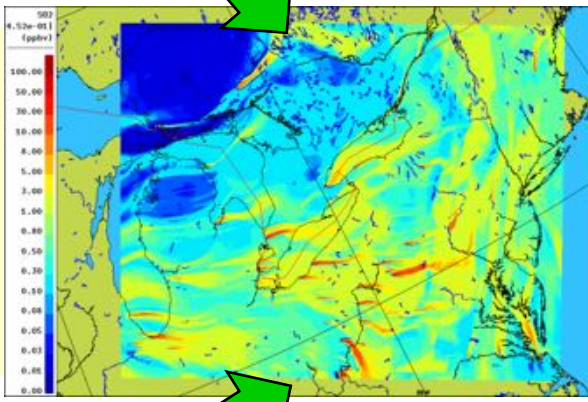
…provides meteorology boundary conditions for the high resolution GEM-MACH forecast

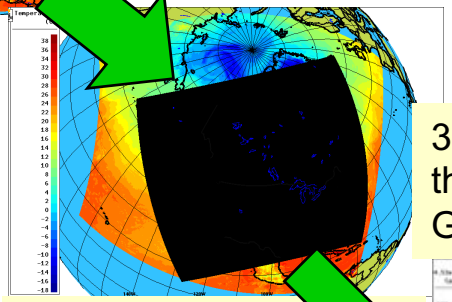




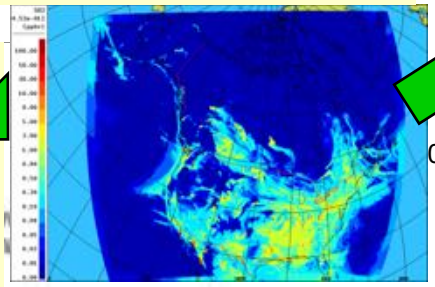
A cascade of model runs, repeated every day for the desired simulation.

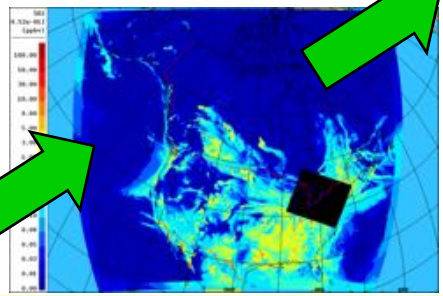
24 hour high resolution GEM-MACH forecast, with roll-over of last time step chemistry, for initial conditions of next day's chemistry





30 hour simulation of the North American GEM-MACH forecast





…provides meteorolog… boundary conditions Nor… American GEM-MACH forecast (MOZART climatologies for chemical boundary conditions)

…provides chemical boundary conditions for the high resolution GEM-MACH forecast, and updates the initial GEM-MACH meteorology every 24 hours.

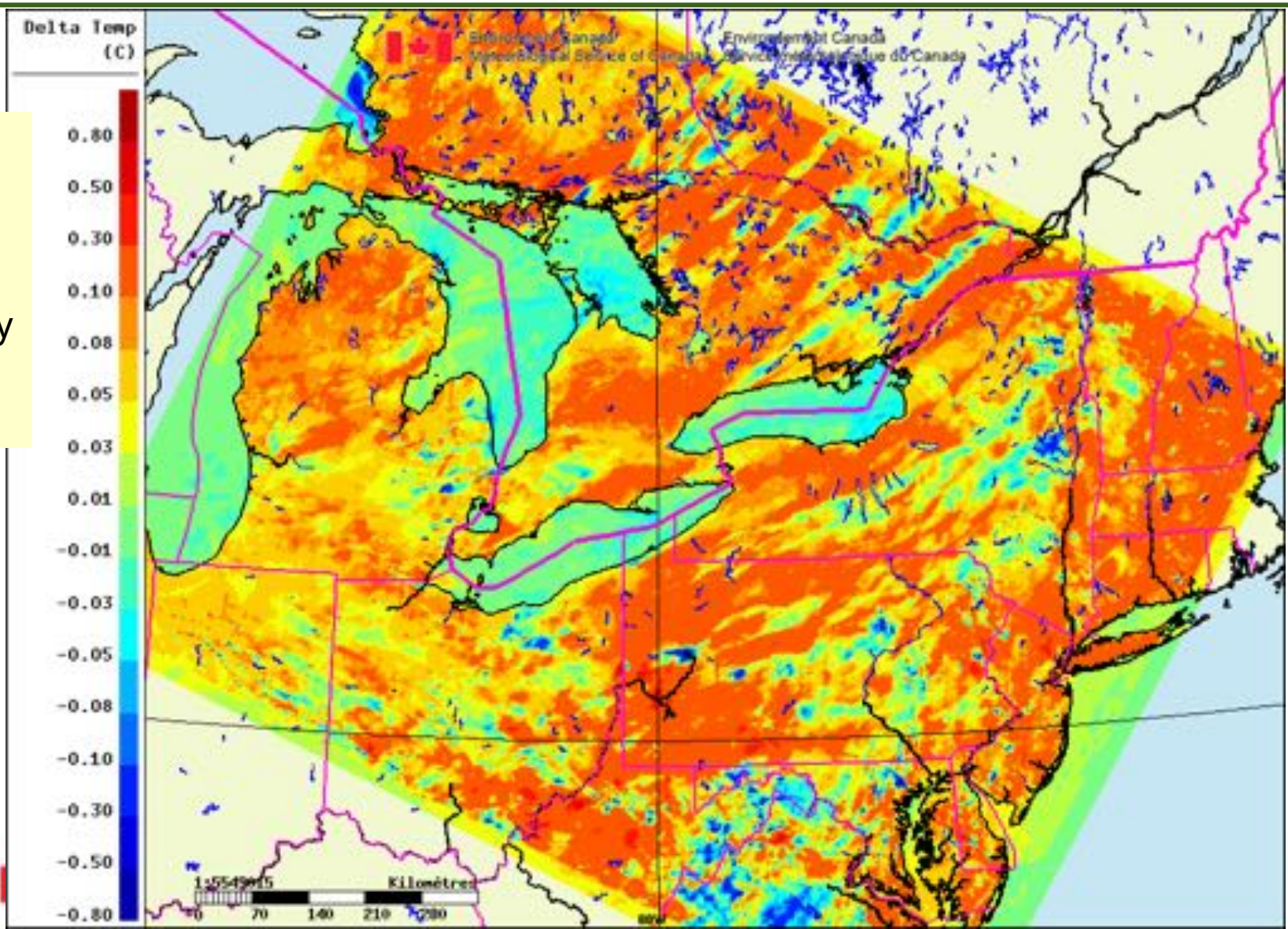
Feedback Simulations

- August 25th to 29th, focus on 27th to 29th**, 3 day averages**
  - Significant pollution event in Toronto
  - Lake breeze effects important
- Base Case:
  - Continental 10km GEM-MACH: no feedbacks
  - PanAm 2.5km GEM-MACH: no feedbacks
- Direct and Indirect Effect at high resolution:
  - Continental 10km GEM-MACH: direct effect
  - PanAM 2.5km GEM-MACH: direct and indirect effects
- ***All plots shown will be Scenario – Base Case***

Comparison of 3-day averages: *Entire 2.5km Pan Am Domain*

ΔTemperature {(feedback) – (no feedback)}

➔Increases in 3 day average temperature over land, by a few 10ths of a C.

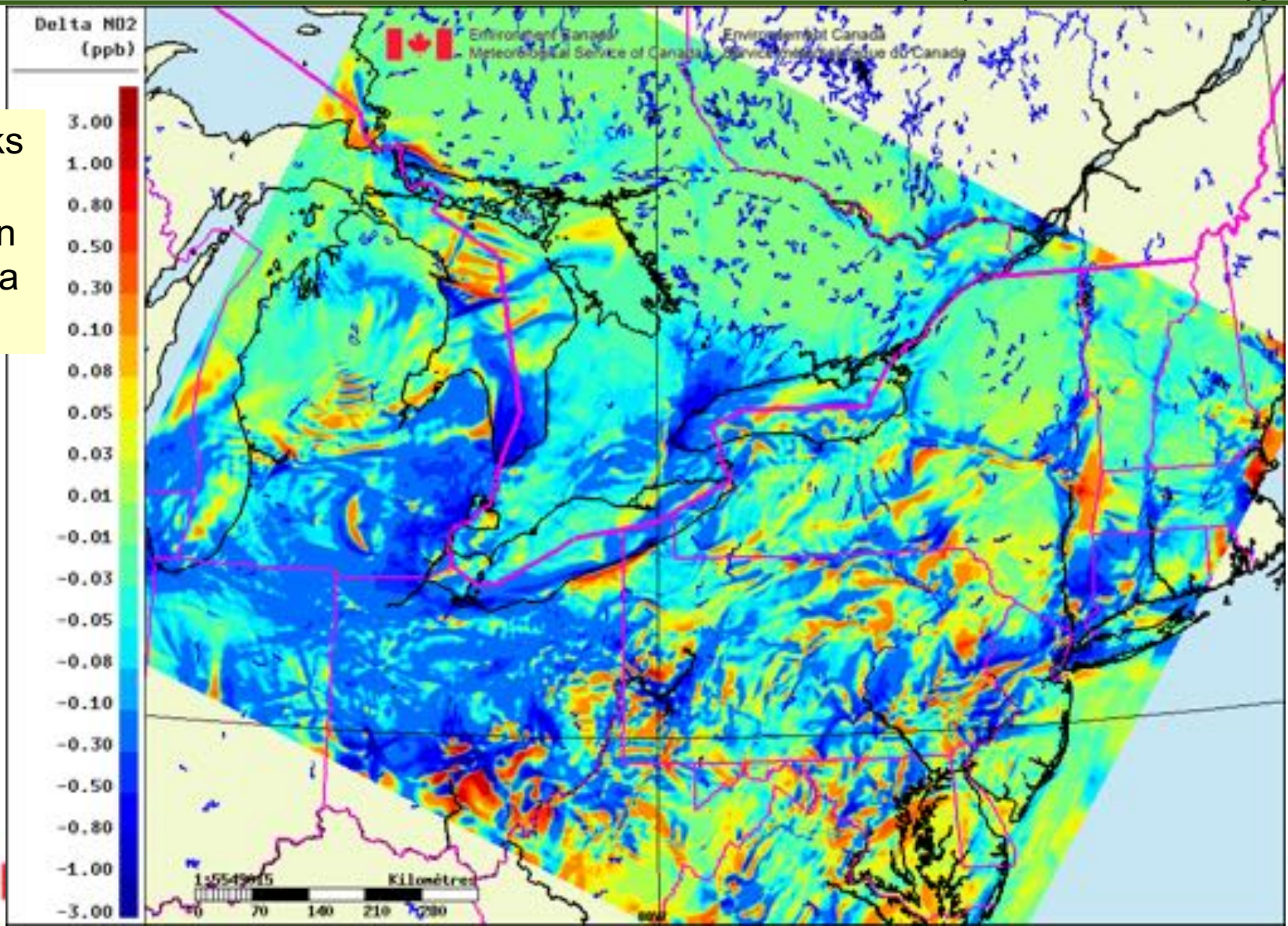


Comparison of 3-day averages: *Entire 2.5km Pan Am Domain*

ΔNO_2

{(feedback) – (no feedback)}

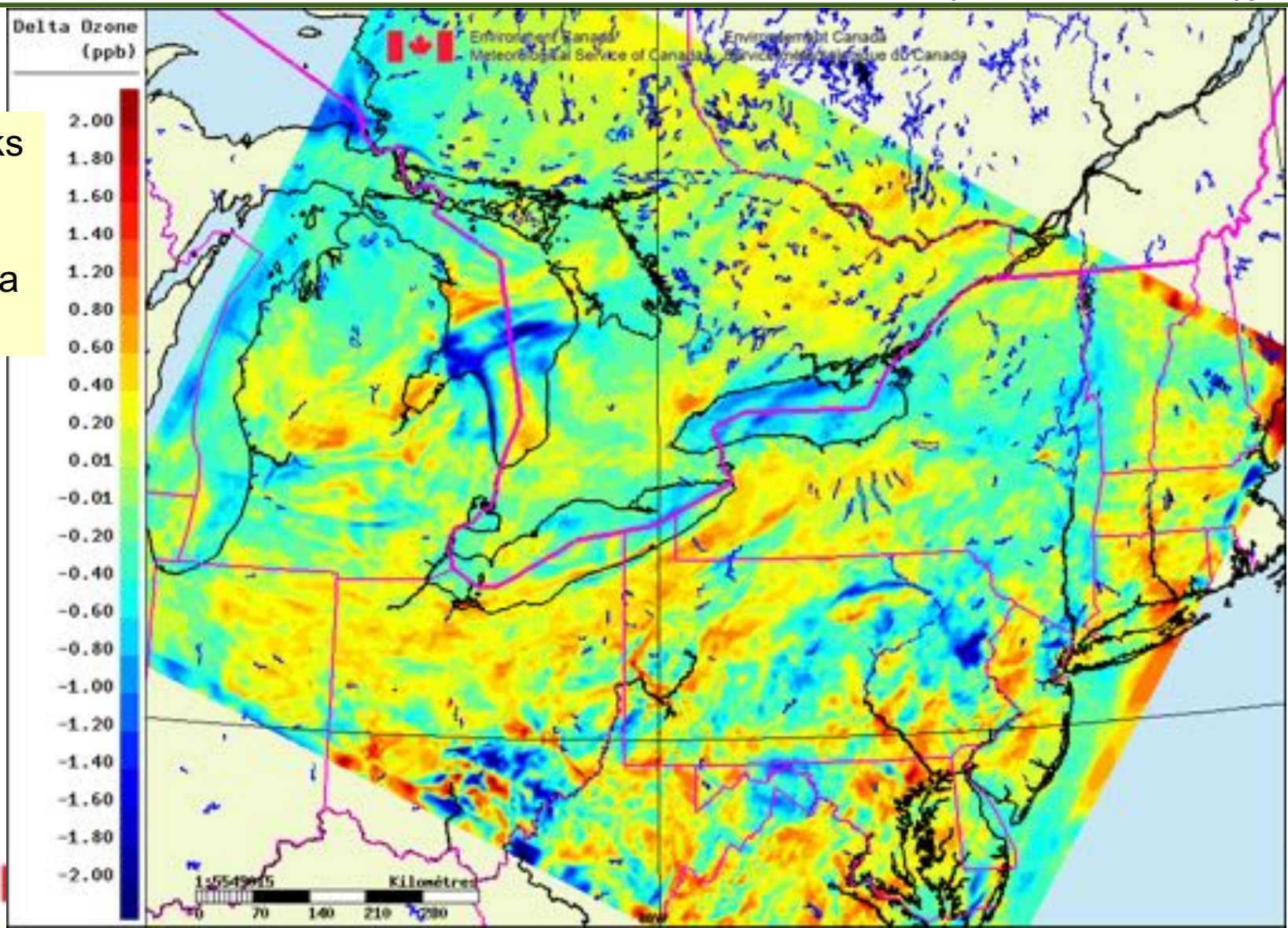
➔Feedbacks *decrease* NO_2 in urban areas up to a ppbv



Comparison of 3-day averages: *Entire 2.5km Pan Am Domain*

ΔO_3 {(feedback) – (no feedback)}

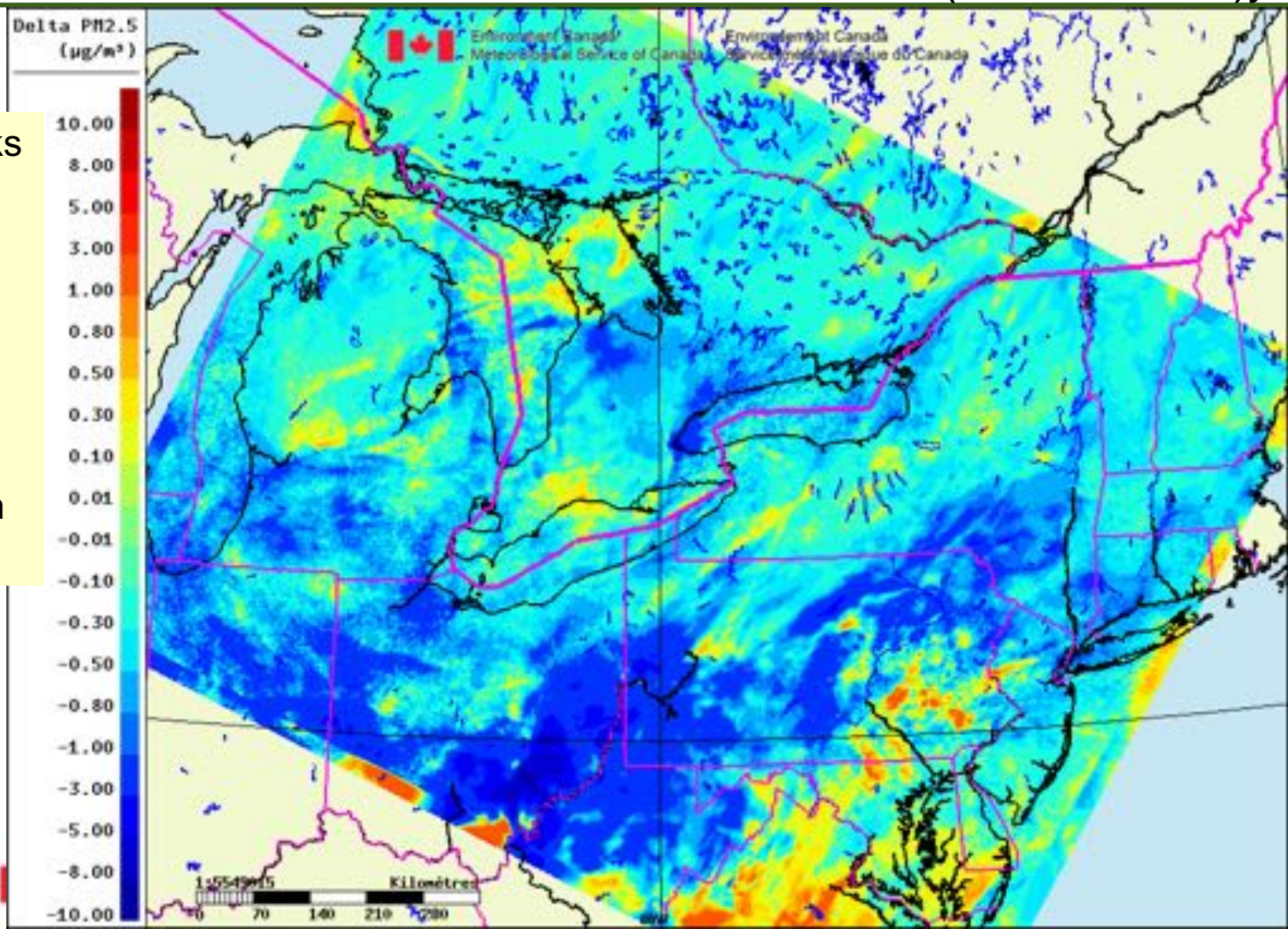
➔Feedbacks *increase* O_3 in urban areas up to a ~ 0.5 ppbv



Comparison of 3-day averages: *Entire 2.5km Pan Am Domain*

$\Delta PM_{2.5}$ {(feedback) – (no feedback)}

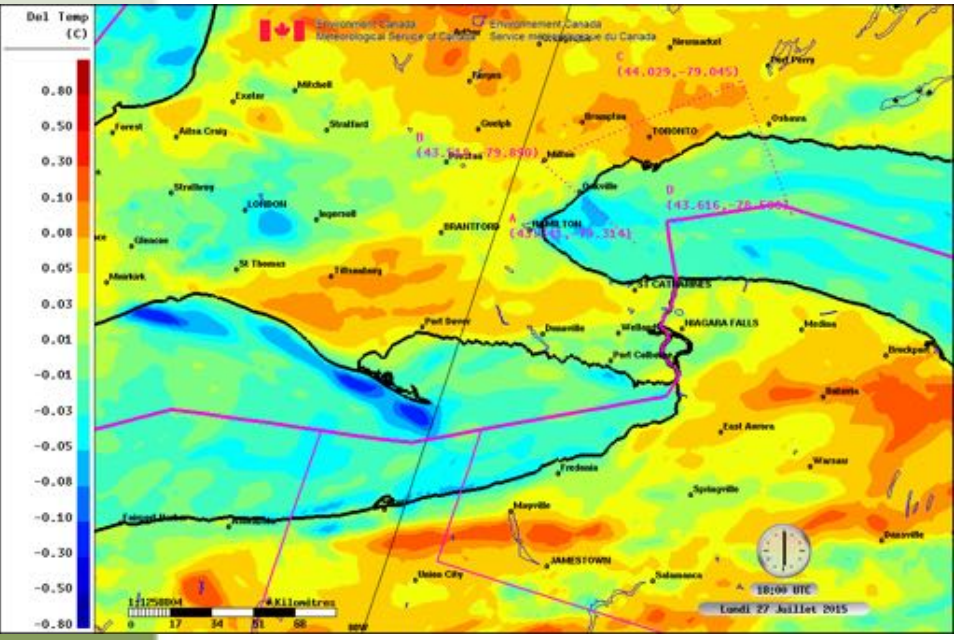
➔Feedbacks *decrease* $PM_{2.5}$ in urban areas by a ug/m3.
➔Regional decrease in $PM_{2.5}$ over Appalachian mountains.



Comparison of 3-day averages: *Entire 2.5km Lakes Erie, Ontario*

ΔTemperature {(feedback) – (no feedback)}

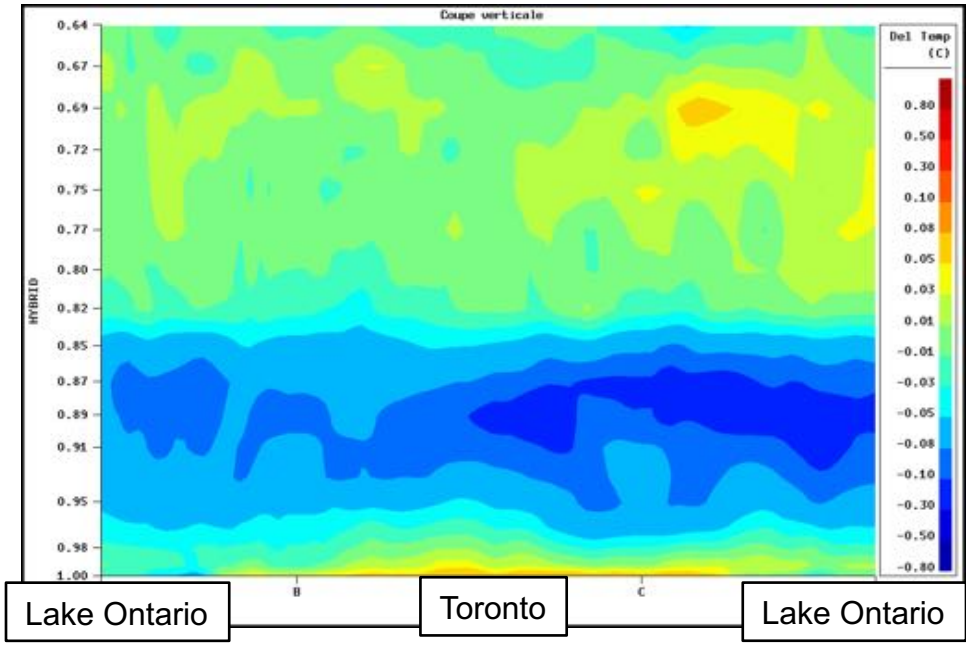
Surface



Surface temperatures increase

Cross-section

Lake Ontario →Toronto→ Lake Ontario



Gradient in temperature between surface and boundary layer increases.

The *temperature gradient* increase may be driving the residual circulation…

Comparison of 3-day averages: *Entire 2.5km Lakes Erie, Ontario*

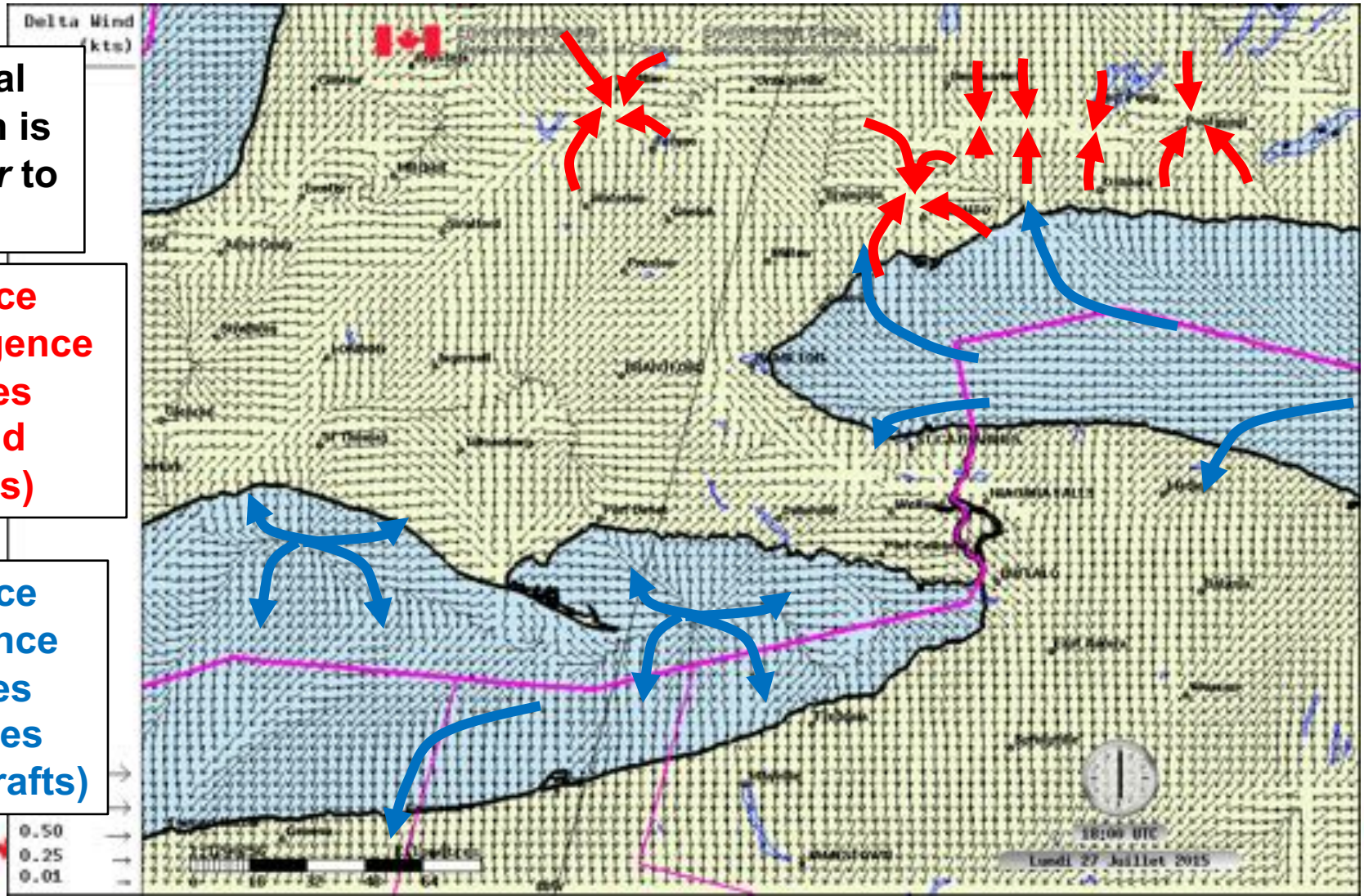
ΔWind {(feedback) – (no feedback)}

Surface

➔ **Residual circulation is from *water* to *land*.**

➔**Surface convergence increases over land (updrafts)**

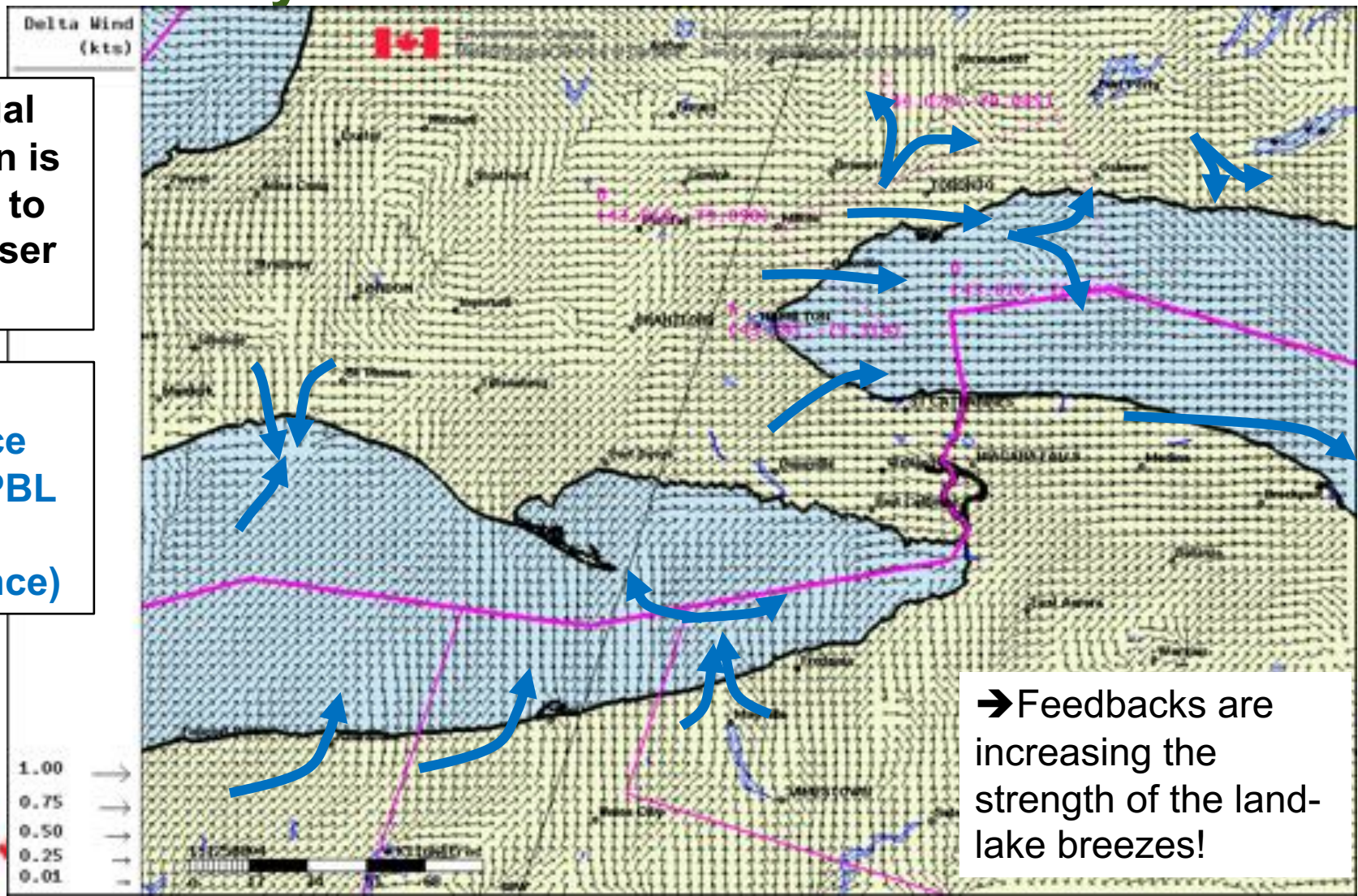
➔**Surface divergence increases over lakes (downdrafts)**



Comparison of 3-day averages: *Entire 2.5km Lakes Erie, Ontario*

ΔWind {(feedback) – (no feedback)}

Hybrid Level = 0.860



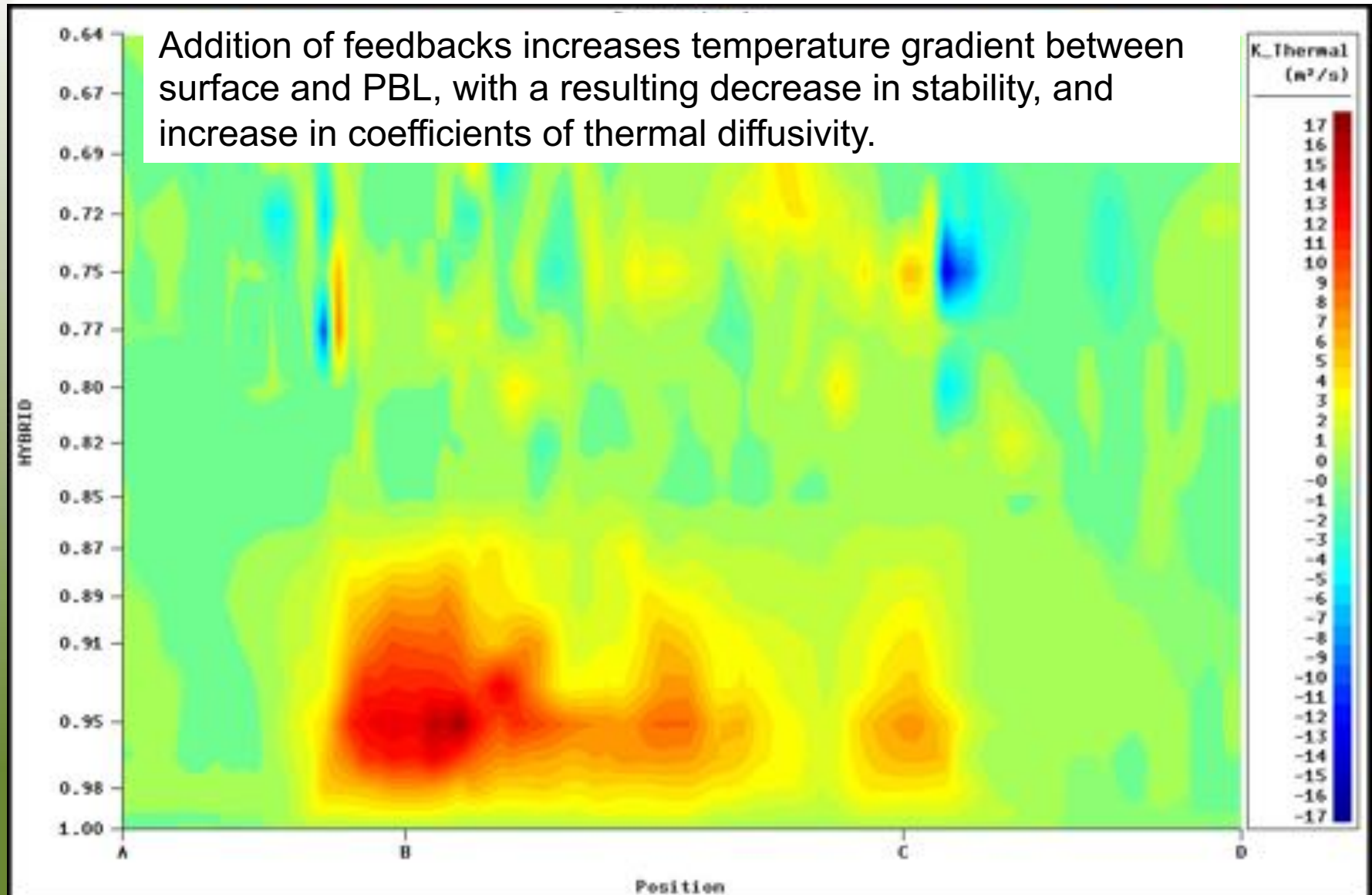
➔ **Residual circulation is from land to water, closer to PBL**

➔**Wind divergence close to PBL top (subsidence)**

➔Feedbacks are increasing the strength of the land-lake breezes!

Comparison of 3-day averages: *Toronto Cross-Section*

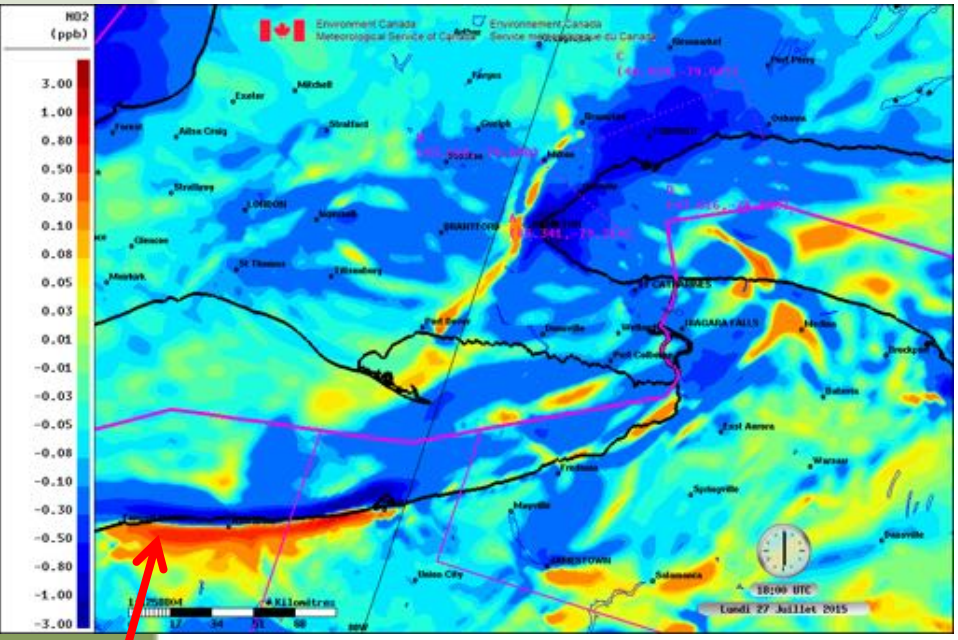
$\Delta K_{Thermal}$ {(feedback) – (no feedback)}



Comparison of 3-day averages: ΔNO_2 {(feedback) – (no feedback)}

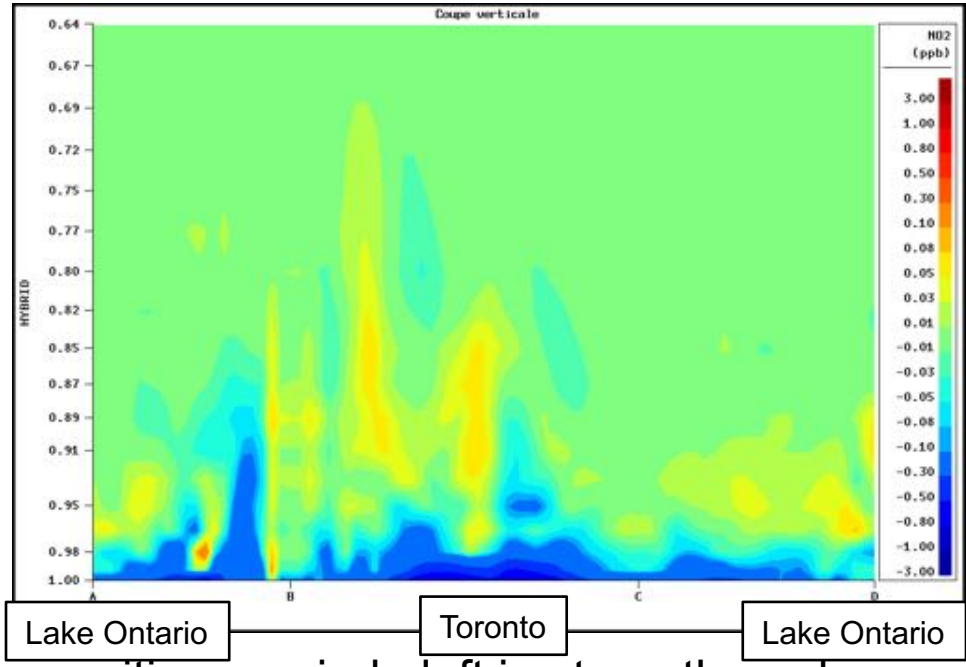
Entire 2.5km Lakes Erie, Ontario

Surface



Cross-section

Lake Ontario → Toronto → Lake Ontario



Lake Ontario — Toronto — Lake Ontario

➔Surface NO_2 concentrations drop over cities, carried aloft in strengthened circulation.

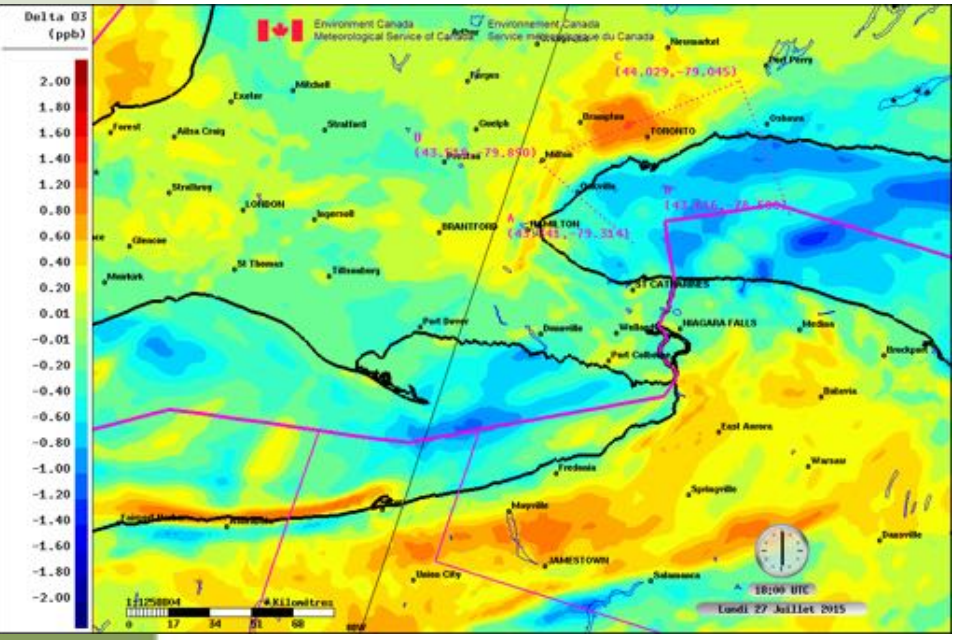
➔***Probably increased convection*** (stability has decreased; recall the temperature gradient increase)

Check out how moving the Lake Erie lake breeze front has changed surface NO_2!

Comparison of 3-day averages: *Entire 2.5km Lakes Erie, Ontario*

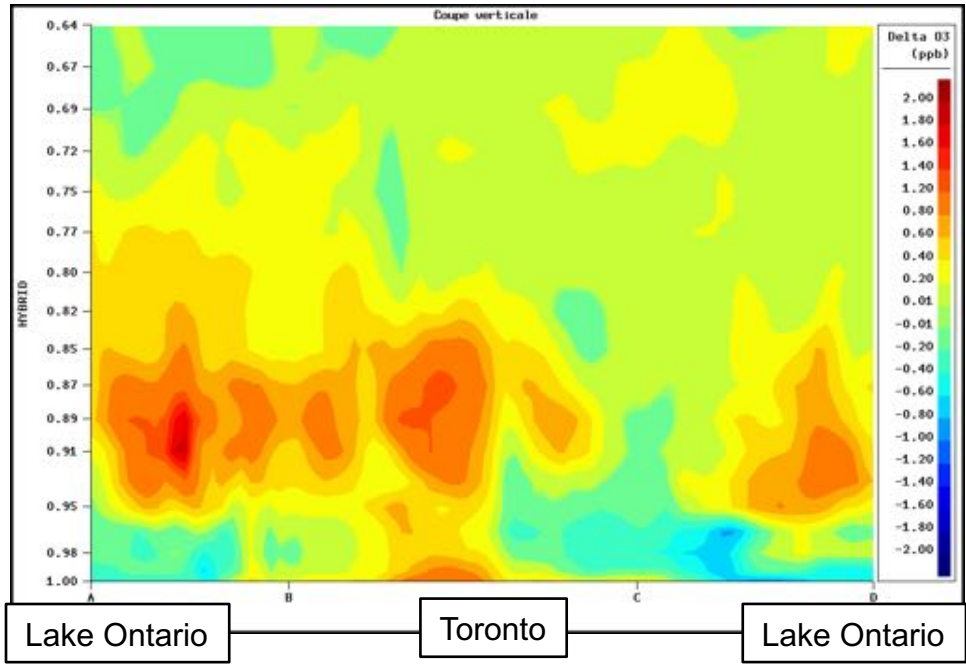
ΔO_3 {(feedback) – (no feedback)}

Surface



Cross-section

Lake Ontario →Toronto→ Lake Ontario



Lake Ontario — Toronto — Lake Ontario

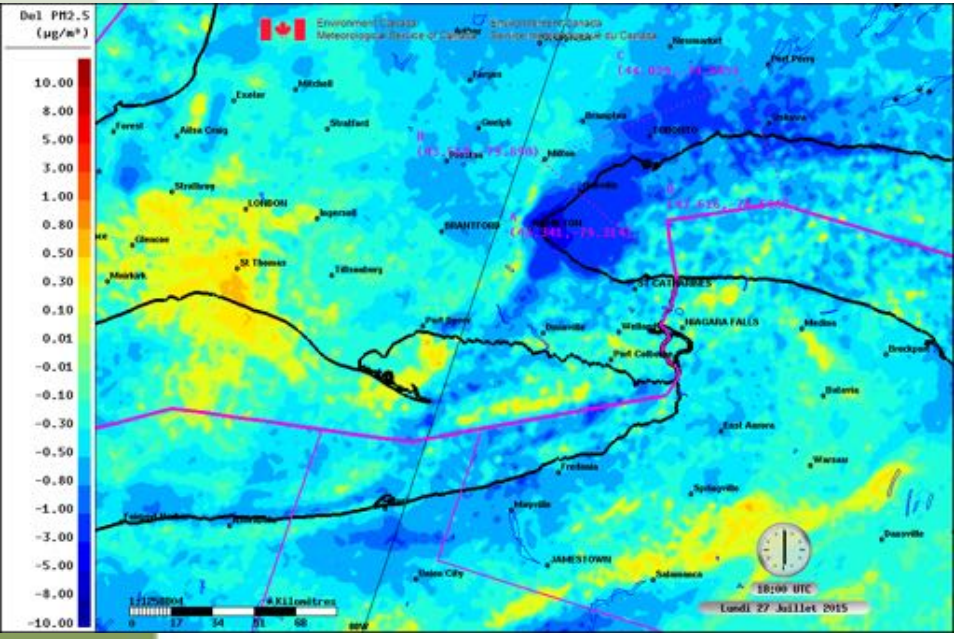
➔Surface O_3 has increased in Toronto by 0.5 to 0.8 ppbv***: less NOx titration***.

➔ O_3 just under the PBL has also increased: ***increased transport of O_3 precursors, and increased O_3 formation***.

Comparison of 3-day averages: *Entire 2.5km Lakes Erie, Ontario*

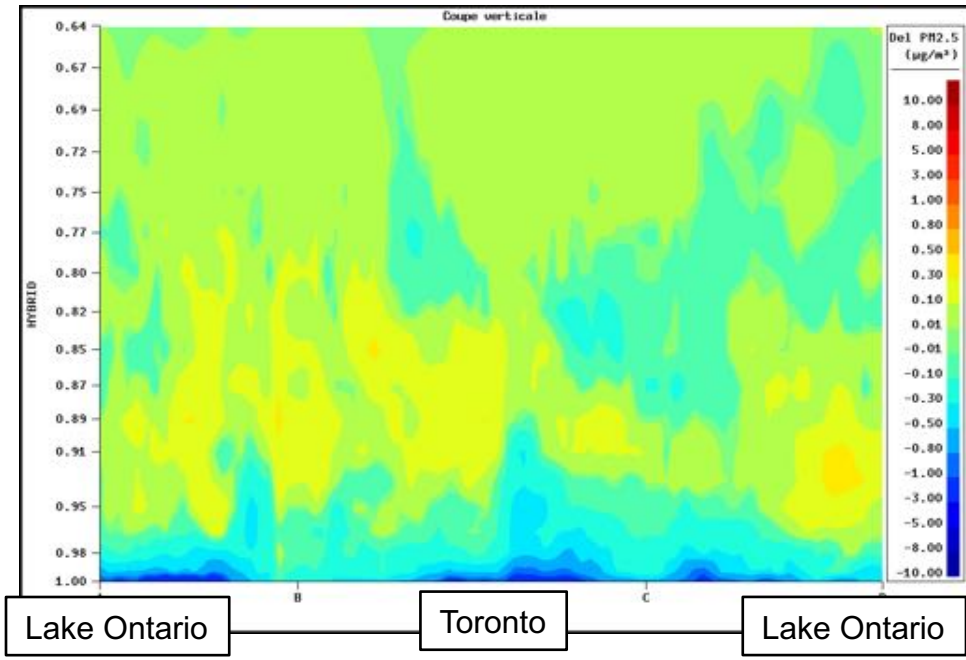
$\Delta PM_{2.5}$ {(feedback) – (no feedback)}

Surface



Cross-section

Lake Ontario →Toronto→ Lake Ontario



➔Surface $PM_{2.5}$ has decreased in Toronto by 1 ug/m^3 ***transport***.

➔Increases in $PM_{2.5}$ aloft: more secondary aerosol production from precursors, and transport of primary $PM_{2.5}$ (?)

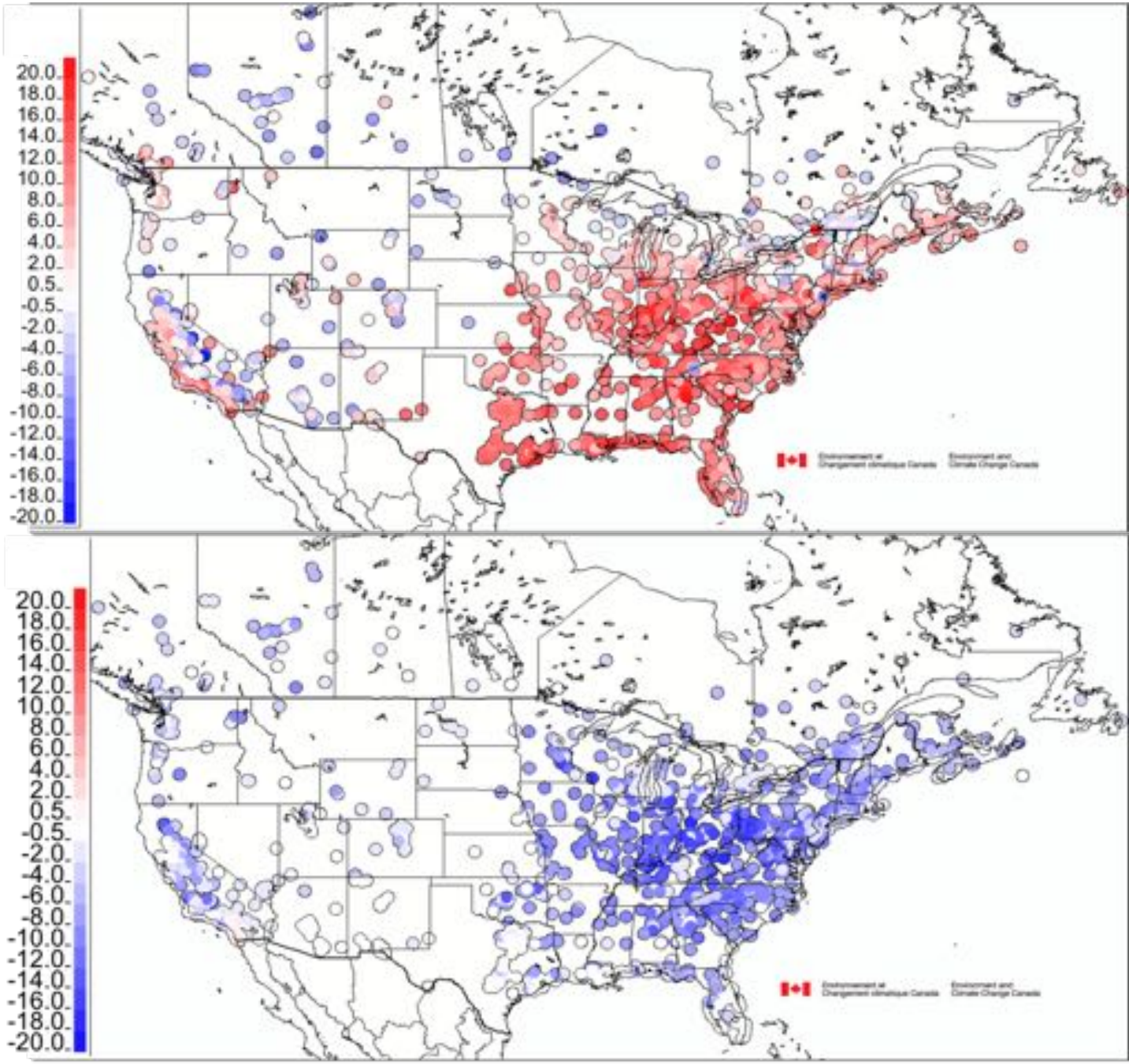
Forest Canopy parameterization

- Forests shade the atmosphere below the foliage
  - This reduces photolysis rates
- Forests have reduced turbulence below the foliage relative to the surrounding countryside
  - This reduces vertical transport of pollutants
- These two factors, combined, have a significant impact on tropospheric ozone formation
- Results from a one-month run of GEM-MACHv2, 10km resolution, operational domain follow (2.5km work still underway).
- Makar *et al, under review, Nature Communications*

Canopy effects on O_3

Operational model bias in hourly surface O_3, July 2010

Decrease in average model O_3 concentrations at observation sites, after canopy parameterization is added.

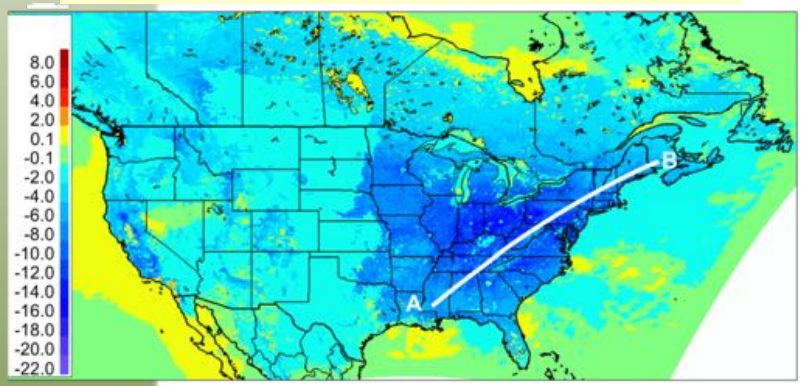


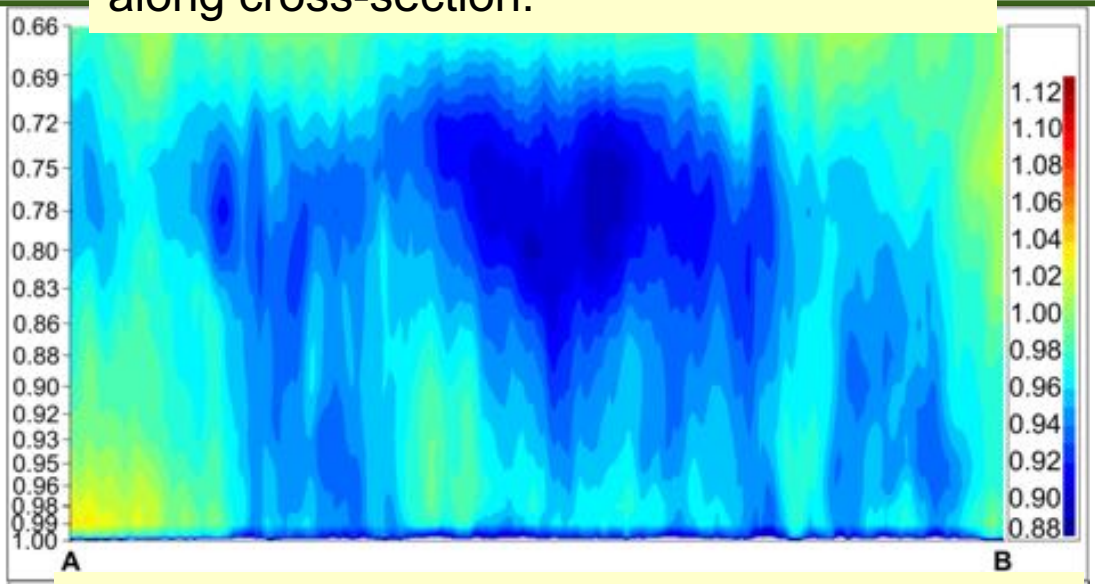
Environme
Climate Ch

Change in monthly average O_3 concentration across Eastern North America

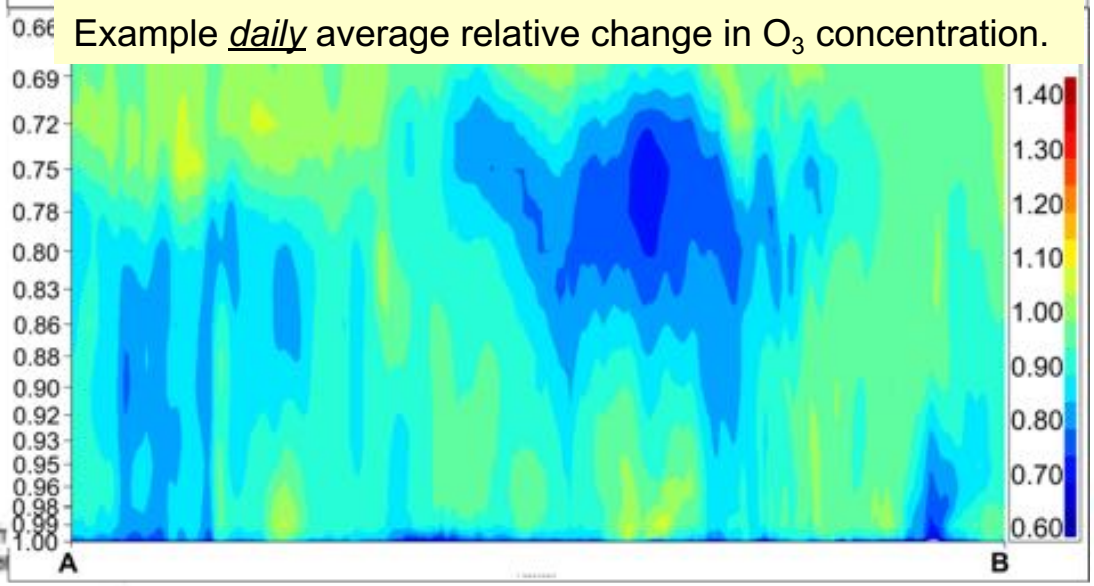
Relative change in *monthly* average O_3 along cross-section.

Change in monthly average surface O_3 (ppbv), and cross-section location.

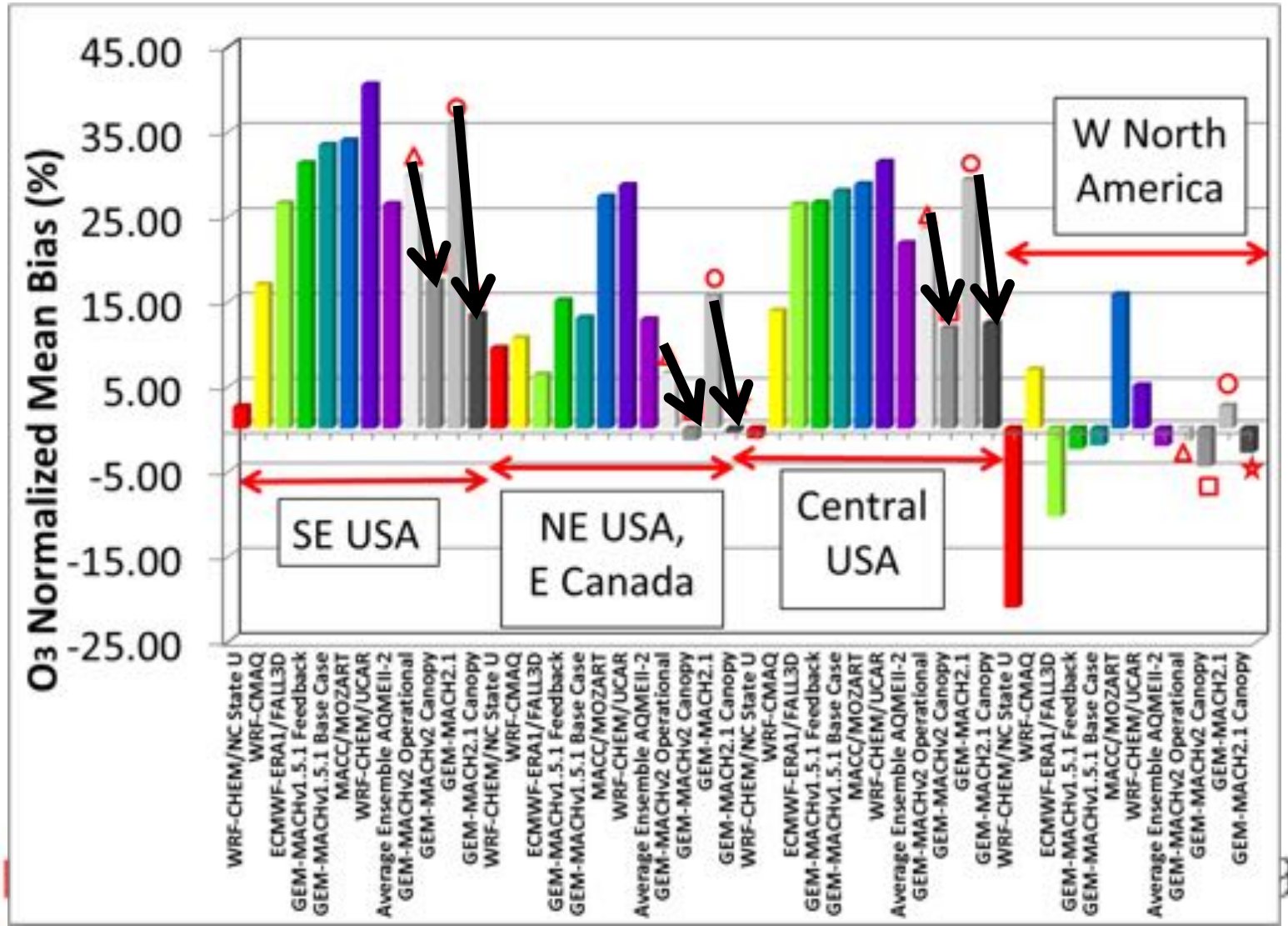




Example *daily* average relative change in O_3 concentration.



Canopy parameterization improves O_3 bias… sometimes by a LOT!



Canopy parameterization

- What does it do at high resolution?
- TBD! Working on porting the code to ECCC's new Cray supercomputer and the most recent version of GEM-MACH.

Summary and Next Steps

- Feedbacks at 2.5km resolution:
  - Increase the strength of the land-lake breeze circulation
  - Increase the temperature gradient in the lowest few km of the atmosphere (and decrease atmospheric stability)
  - Decrease surface $PM_{2.5}$ and NO_2
  - Increase $PM_{2.5}$ and NO_2 aloft
  - Increase surface O_3 and O_3 aloft
  - These results need to be *evaluated* using PanAm Games Legacy datasets (see workshop tomorrow).
- Forest canopy, 10km resolution:
  - Significant impact on average O_3 concentrations, reducing eastern North America bias to near zero.
  - How does this affect high resolution results? And interact with feedbacks?
  - TBD!
- Submit for publication… ☺

Thank-you for your interest!

Bonus slides

- The following slides are “hidden slides” and will be shown if they help answer questions from the audience.