Multi-scale greenhouse gas flux estimation systems in support of Canadian carbon cycle science and policy

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Why?

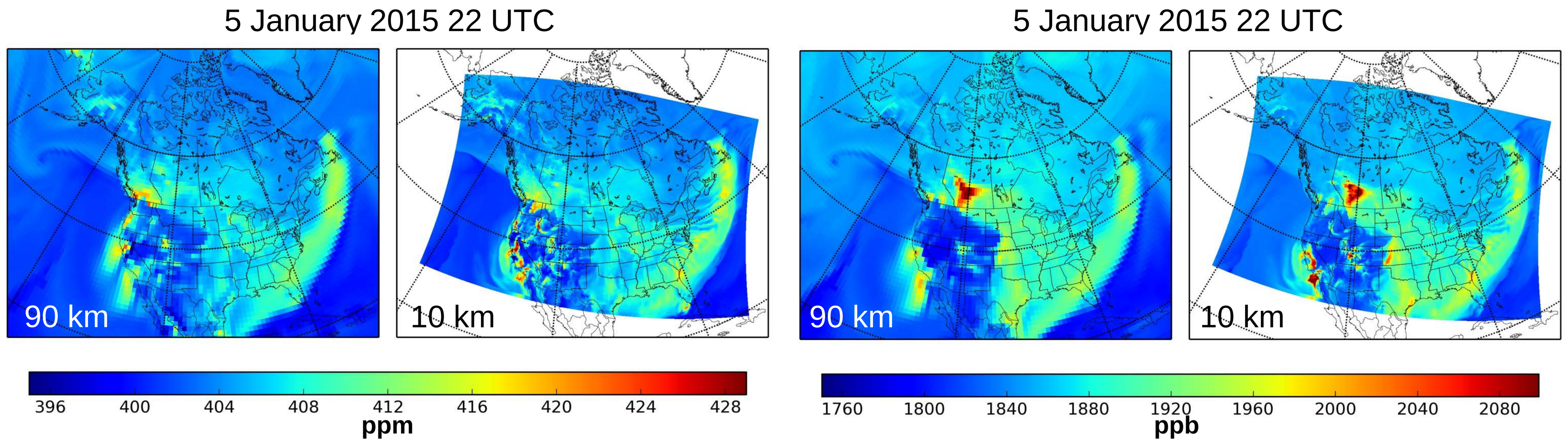
Environment and Climate Change Canada (ECCC) has a multiscale approach to the development of Greenhouse Gas (GHG) data assimilation systems. The goal is to estimate fluxes of CO_2 and CH_4 from national to urban scales using atmospheric and geophysical observations in order to address carbon cycle science and policy needs such as

- The quantification of natural sources and sinks of CO_2 in boreal regions
- The monitoring of GHG emissions over a potentially thawing permafrost
- The ability to detect the impact of potential mitigation efforts on CO_2 and CH_4 emissions with the aim to provide timely information to stakeholders
- Contribution to national and international research collaborations (WMO-DAOS, WMO-IG³IS, Canadian Space Agency, U of Toronto)

The Regional Scale

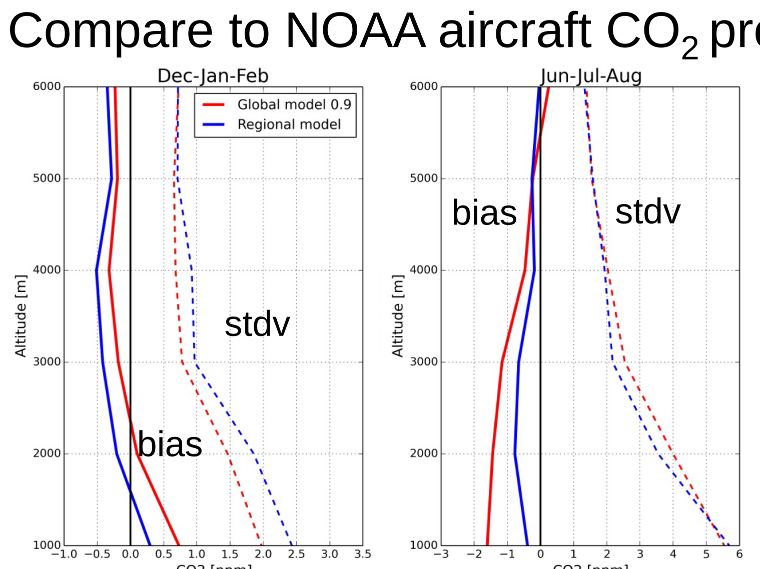
CO_2 near surface — 5 January 2015 22 UTC

CH_4 near surface — 5 January 2015 22 UTC



The global model provides lateral GHG boundary conditions for the regional model. The regional model uses meteorological analyses from the operational Regional Deterministic Prediction system every 24 h.

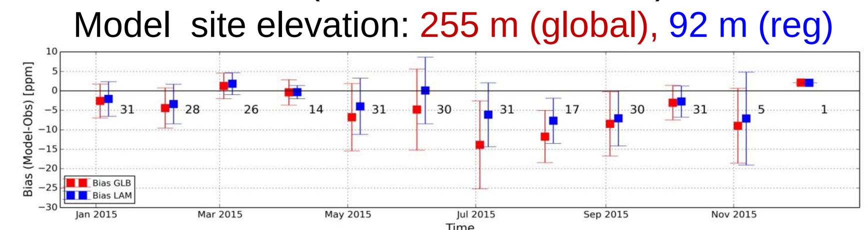
Compare to NOAA aircraft CO_2 profiles



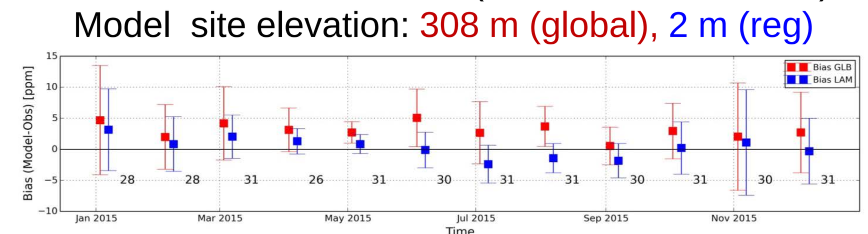
Sites used: Briggsdale, Colorado; Capa May, New Jersey, Dahlen, North Dakota, Estevan Point, BC; East Trout Lake, SK, Homer, Illinois, Park Falls, Wisconsin; Worcester, Massachusetts; Poker Flat, Alaska; Charleston, South Carolina; Southern Great Plains, Oklahoma; Sinton, Texas; Trinidad Head, California, West Branch, Iowa

Monthly bias of afternoon (12-16 LST) mean CO_2

Toronto Island (41.4°N,79.4°W, 87 m)
Model site elevation: 255 m (global), 92 m (reg)



Walnut Grove, California (38.3°N,121.5°W, 0 m)
Model site elevation: 308 m (global), 2 m (reg)



Walnut Grove tower intake height used: 483 m

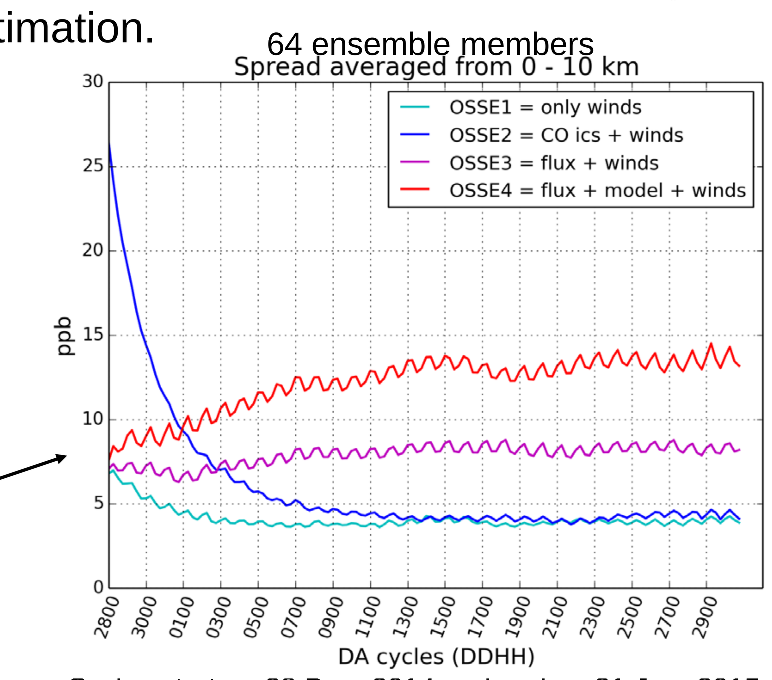
- **Current research**: (a) Evaluating benefit of regional model over global model with same coarse resolution fluxes, (b) Understanding relative role of initial and boundary conditions in controlling regional GHG distributions. (Kim et al., 2019a,b In Prep.)
- **Next steps**: Develop assimilation system using Lagrangian approach and/or nested ensemble Kalman Filter to get flux estimates over Canada on regional scales

The Global Scale

- The ECCC Carbon Assimilation System (EC-CAS) uses modeling and assimilation tools used for operational weather prediction: The Global Environmental Multiscale (GEM) model (Girard et al., 2014) and the Ensemble Kalman Filter (EnKF) (Houtekamer et al., 2014).
- Adaptation of GEM for GHG simulation involved implementation of mass conservation, tracer variable definitions as mixing ratios with respect to dry air, addition of tracer transport through deep convection and tuning of boundary layer scheme (Polavarapu et al., 2016)
- Currently, 3 species are simulated: CO_2, CH_4 and CO. A simplified climate-chemistry is used for CH_4 and CO with monthly OH climatology from Spivakovsky et al. (2000).
- The assimilation system extends the EnKF for GHG state and flux estimation. Currently, the EnKF is being tested and tuned for CO state estimation.

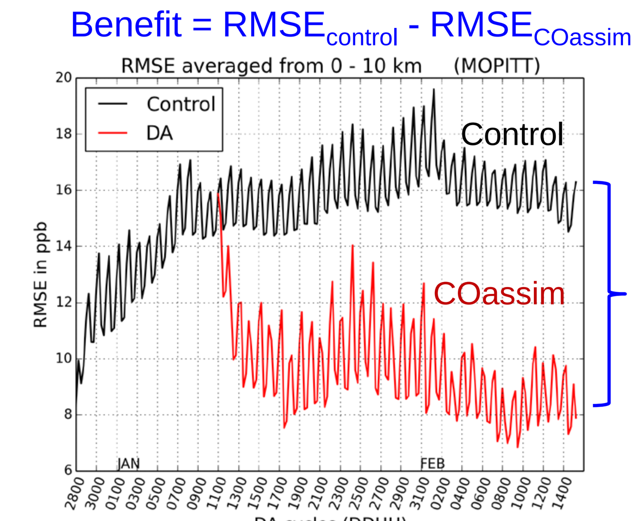
Relative contributions to CO forecast uncertainty

The EnKF works well when the ensemble spread reflects the true forecast error. With only uncertainty in meteorological analyses (cyan curve), CO forecast spread saturates at 4 ppb. Adding CO initial condition uncertainty (blue curve) makes little difference. However, allowing for uncertainty in surface fluxes (pink curve) doubles the spread to 8 ppb. Allowing for model errors (due to convection, PBL modeling, etc.), flux errors and meteorological analysis errors produces the greatest ensemble spread of 13-14 ppb (red curve).



Cycles start on 28 Dec. 2014 and end on 31 Jan. 2015
No CO observations are assimilated in these cycles.

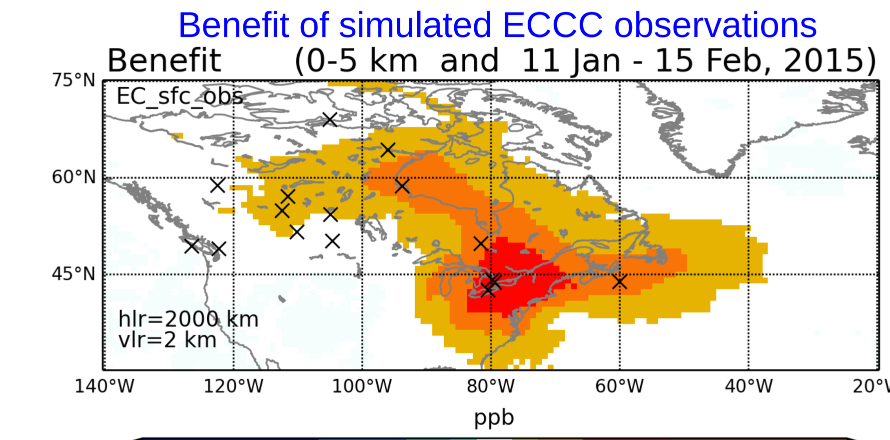
Benefit = $RMSE_{control}$ - $RMSE_{COassim}$



The benefit of assimilating CO observations in EnKF compared to control cycle (which uses only met obs)

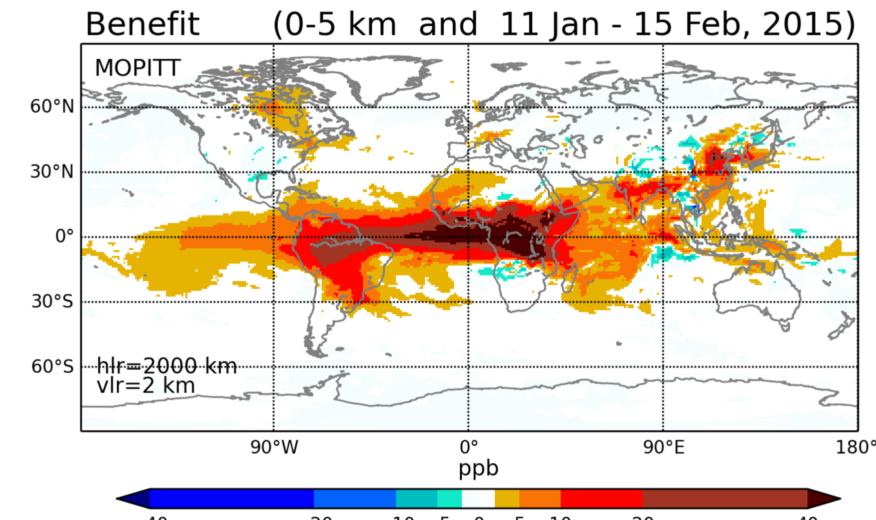
- Identical twin experiment, 64 ensemble members
- Obs error = 10%, no correlations
- Prior covariance localization radii = (2000, 2) km
- Flux error correlation = 2000 km

Benefit of simulated ECCC observations



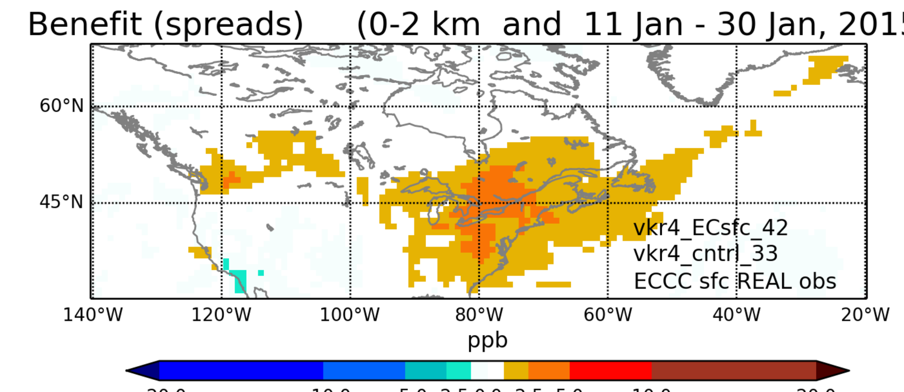
The reduction in RMSE obtained by assimilating hourly in situ observations from 17 sites in ECCC's network

Benefit of simulated MOPITT observations



The reduction in RMSE from assimilating MOPITT profiles using averaging kernels thinned to 0.9°

EnKF with real ECCC observations

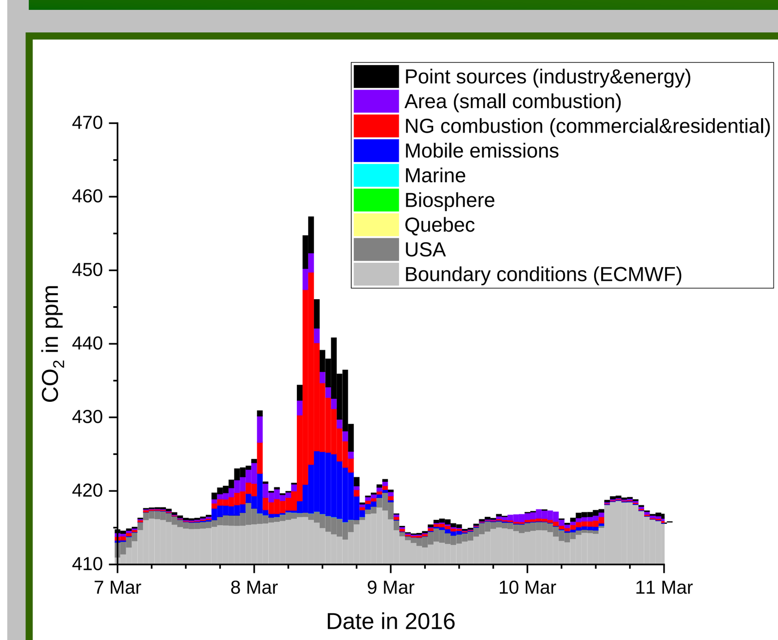


Reduction in forecast spread from a *first attempt* at assimilating real obs: 11 sites in ECCC's network. Tuning of EnKF parameters still needs to be done.

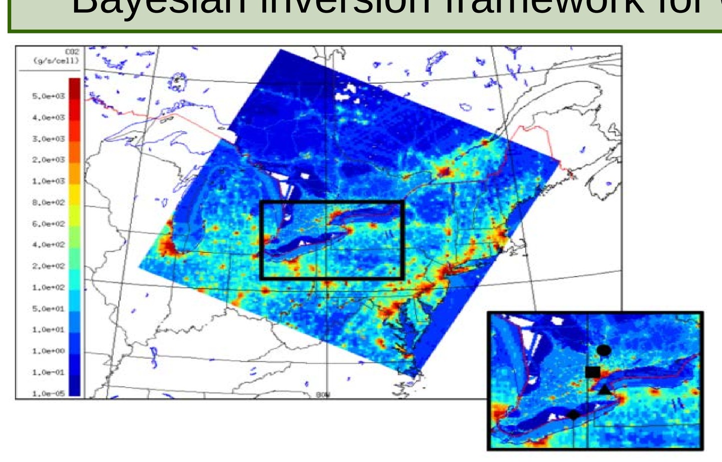
- **Current research**: (a) Tune EnKF parameters for real CO obs, (b) document EC-CAS state estimation for CO using OSSEs and synthetic data networks (Khade et al., In Prep.)
- **Next steps**: (a) Test ability to retrieve CO fluxes, (b) Extend EnKF for CO_2 state and flux estimation, (c) Extend EnKF for CH_4 state and flux estimation.

The Urban Scale

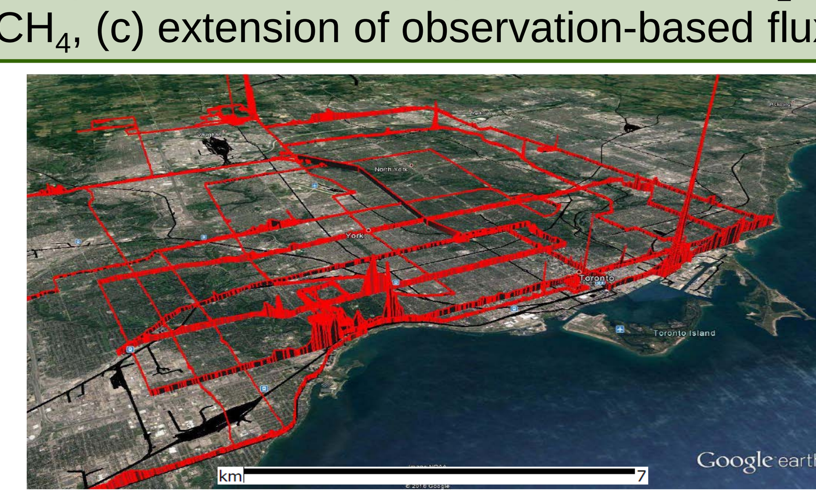
- **Current research**: (a) Completion of inverse modelling framework over GTHA for CO_2 and CH_4, (b) Modelling and additional measurements of carbon isotopes and co-emitted species for source apportionment, (c) integration of data from novel measurement systems (total column GHG and lower-cost sensors) and mobile platforms.
- **Next steps**: (a) Perform a sector-specific inversion experiment for CO_2 (base year 2016), (b) establishing a Bayesian inversion framework for CH_4, (c) extension of observation-based flux estimates for CH_4 until 2018.



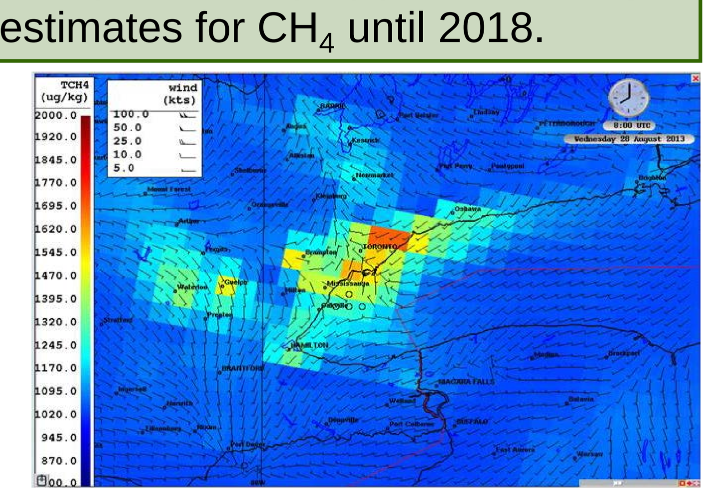
Forward simulation of CO_2 concentration at Toronto monitoring site (20m a.g.l.), by source category, using GEM-MACH at 2.5x2.5 km². Dominant influence from natural gas combustion for domestic heating and traffic sources within the urban area. Boundary conditions will be provided by our regional scale model in future.



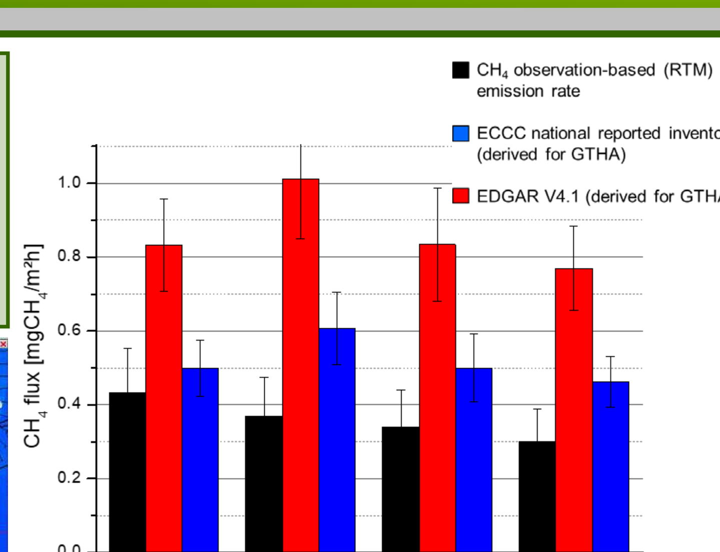
Novel CO_2 emission inventory in Southern Ontario used as prior in forward and inverse modelling. Symbols denote locations of the four existing continuous atmospheric monitoring stations (TOR, EGB, HLN, TKP).



Mobile surveys of (fugitive) CH_4 sources in the Greater Toronto Area to identify subgrid variability of CH_4 concentrations/sources as well as future application of gaussian plume and CFD modelling to quantify site-scale emissions.



Forward simulation of total CH_4 in Southern Ontario using GEM-MACH at 10x10km² (recently updated to 2.5x2.5km² and now including 12 source categories from 15 source regions)



Estimated CH_4 emissions in Southern Ontario derived from two inventories and one top-down method (**R**adon **T**racer **M**ethod). Top-down suggest lower emissions than reported, long-term trend (beyond 2009) also suggests a further decrease until 2018.

References

Girard, C. et al. (2014) Mon. Weather Rev., doi:10.1175/MWR-D-13-00255.1
Houtekameter et al. (2014) Mon. Weather Rev., doi:10.1175/MWR-D-13-0000138.1
Polavarapu et al. (2016) Atmos. Chem. Phys., doi:10.5194/acp-16-12005-2016
Spivakovsky et al. (2000) J. Geophys. Res., doi:10.1029/1999JD901006

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