2026 Annual Joint Meeting COCCON – IRWG – TCCON
June 22-26 2026, Göteborg, Sweden

Urban OP-FTIR atmospheric composition measurements and the planetary boundary layer

Petra Duff[1], Orfeo Colebatch[1], Elisabeth Galarneau[2], Mark Gordon[3], Sylvie Leroyer[4], Audrey Lauer[4], Zen Mariani[5], Samir Singh[3], Craig Stroud[6], Kimberly Strong[1]

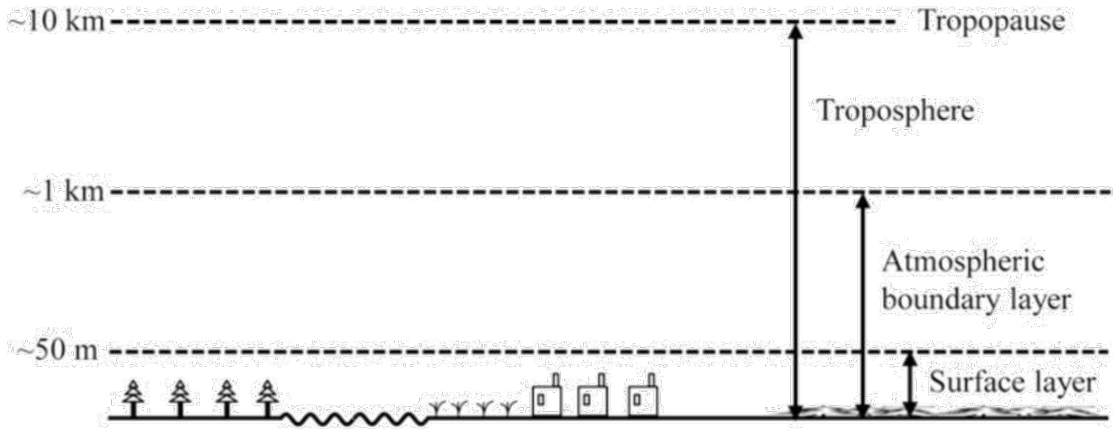
[1]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[2]*Earth Science Research and Integration, Environment and Climate Change Canada, Toronto, Ontario, Canada*
[3]*Dept. of Earth & Space Science & Engineering, York University, Toronto, Ontario, Canada*
[4]*Terrestrial Environment Numerical Prediction Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada*
[5]*Earth Observation and Research Section, Environment and Climate Change Canada, Toronto, Ontario, Canada*
[6]*Modelling and Integration Research Section , Environment and Climate Change Canada, Toronto, Ontario, Canada*

Outline

- Planetary boundary layer height analysis and the SOLID Mesonet
- University of Toronto Open-Path FTIR system and SWAPIT
- Preliminary results and next steps

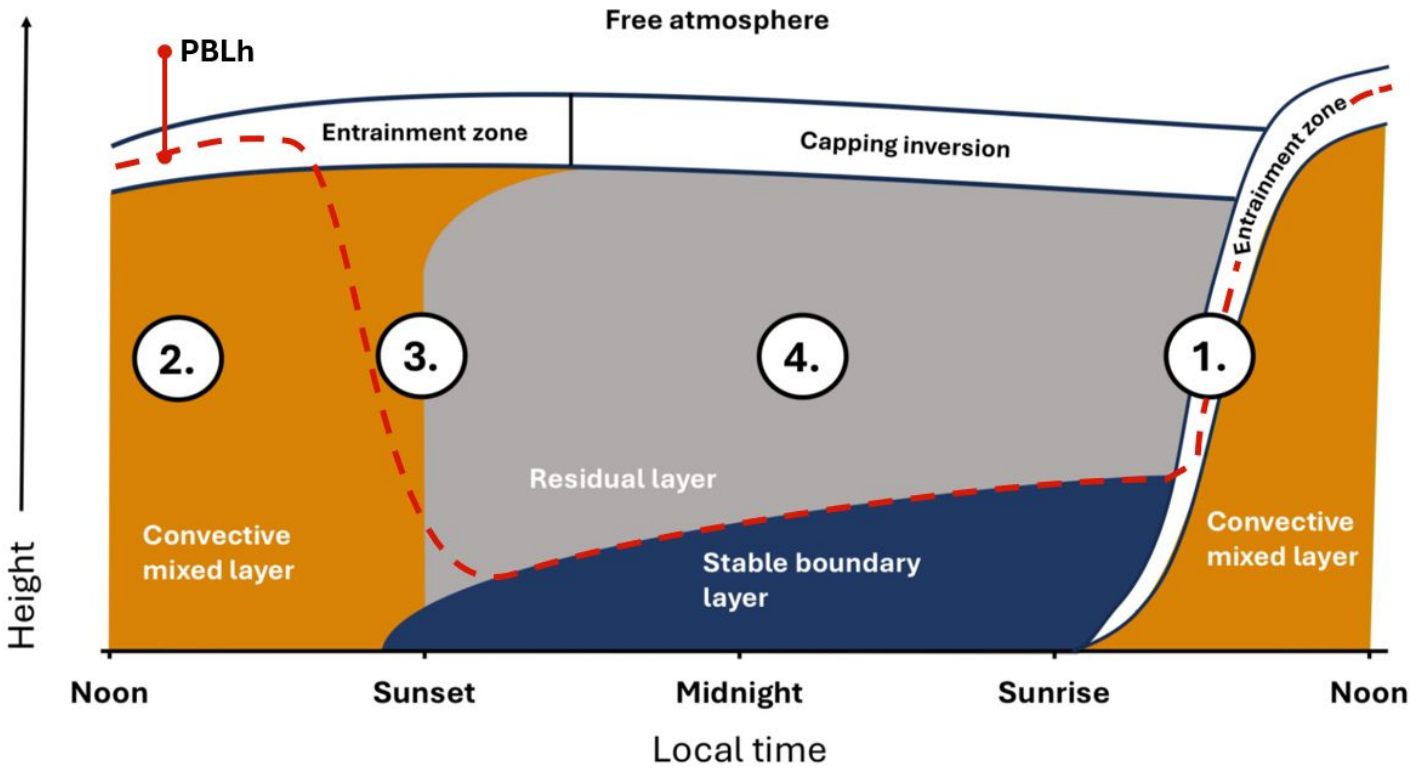
Background: Planetary Boundary Layer Height

- The planetary boundary layer (PBL): many possible definitions; interface layer between the Earth's surface and the free atmosphere
  - Definition used here: layer in which turbulence responds to surface forcings in short timescales [1]
- Characterized by turbulent air motion, well-mixed constituents, strong diurnal variations
- PBL height (PBLh) is an important parameter in many modeling and measurement applications



Division of the lower atmosphere. From Lee, 2023.

Diurnal PBL evolution



Typical diurnal variation of the PBL.

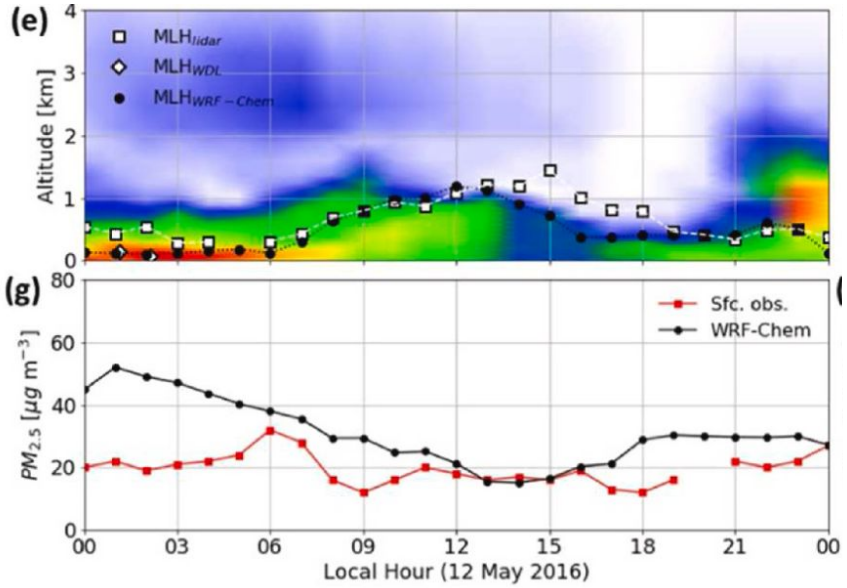
Can be described by 4 periods:

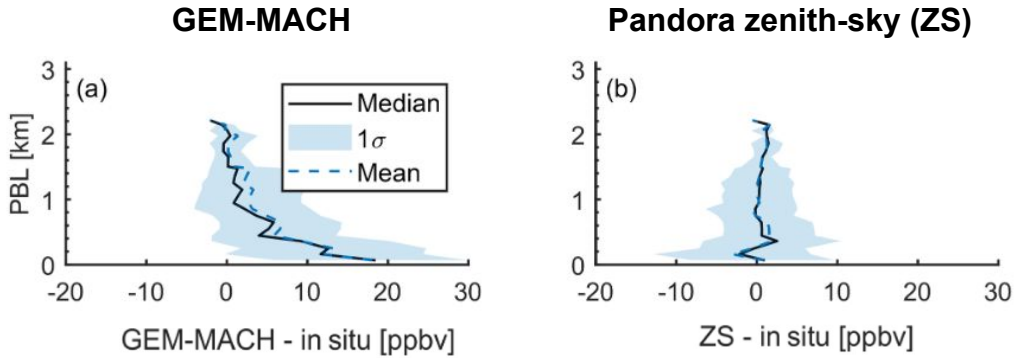
1. *Sunrise*: turbulent entrainment deepens PBL
2. *Daytime*: convective PBL, consistent PBLh
3. *Sunset*: convection collapses, residual layer aloft
4. *Nighttime*: stable PBL, slowly growing PBLh

Motivation

- Models may poorly estimate atmospheric constituents because of poor PBLh estimates (e.g. GEM-MACH [2], WRF-Chem [3])
- Accurate PBLh estimates are needed for column-to-surface mole fraction conversions [4]
- Understanding PBLh trends informs trends in atmospheric constituents [5]

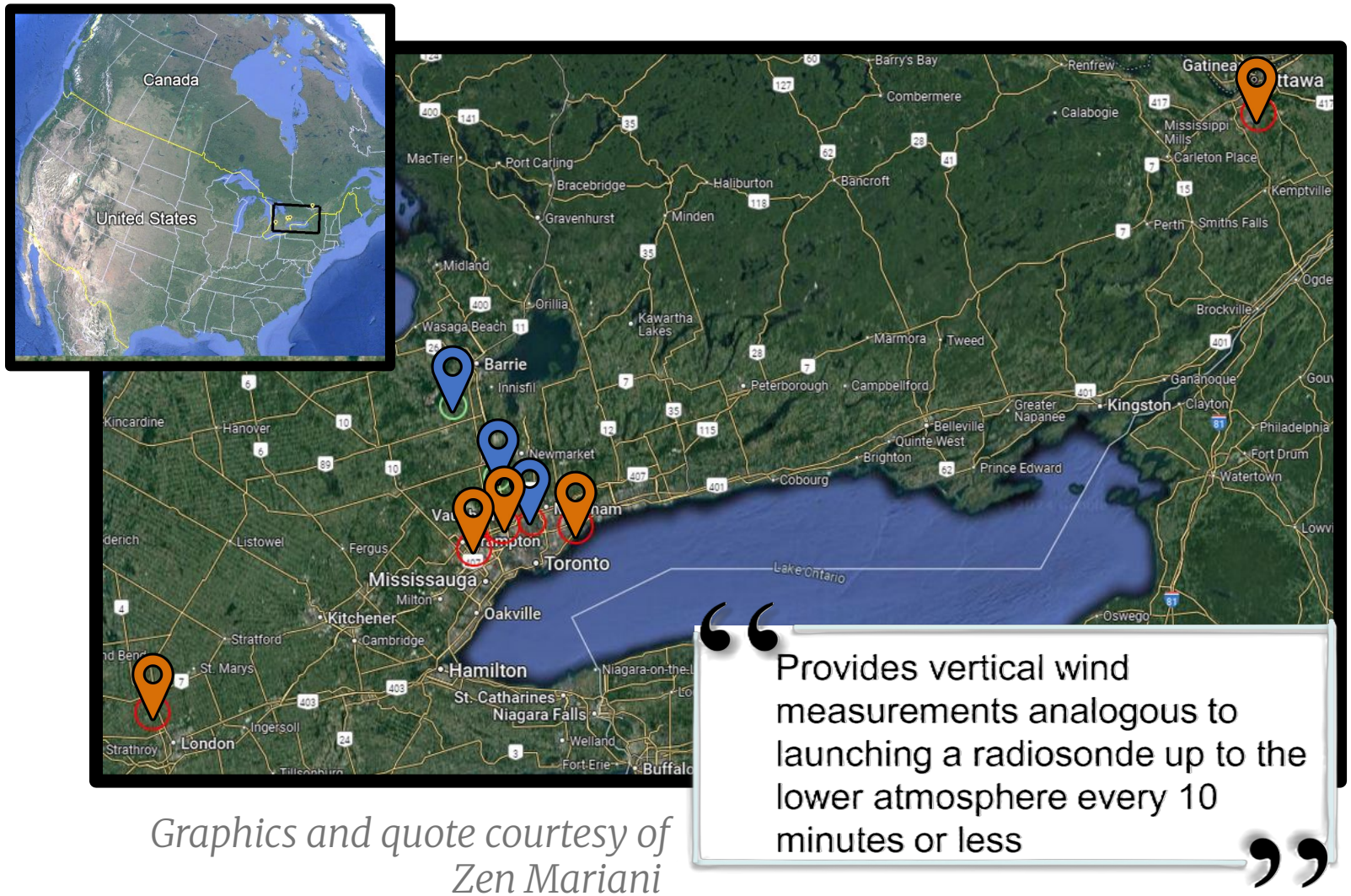
Comparing PBLh and PM2.5 from WRF-Chem and observations shows PM2.5 overestimation with PBLh underestimation (from Park, 2022).





Comparing PBLh and surface NO_2 from GEM-MACH and Pandora zenith-sky measurements to in-situ shows PBLh-dependent bias (from Zhao, 2019).

SOuthern Ontario LIDar (SOLID) Mesonet



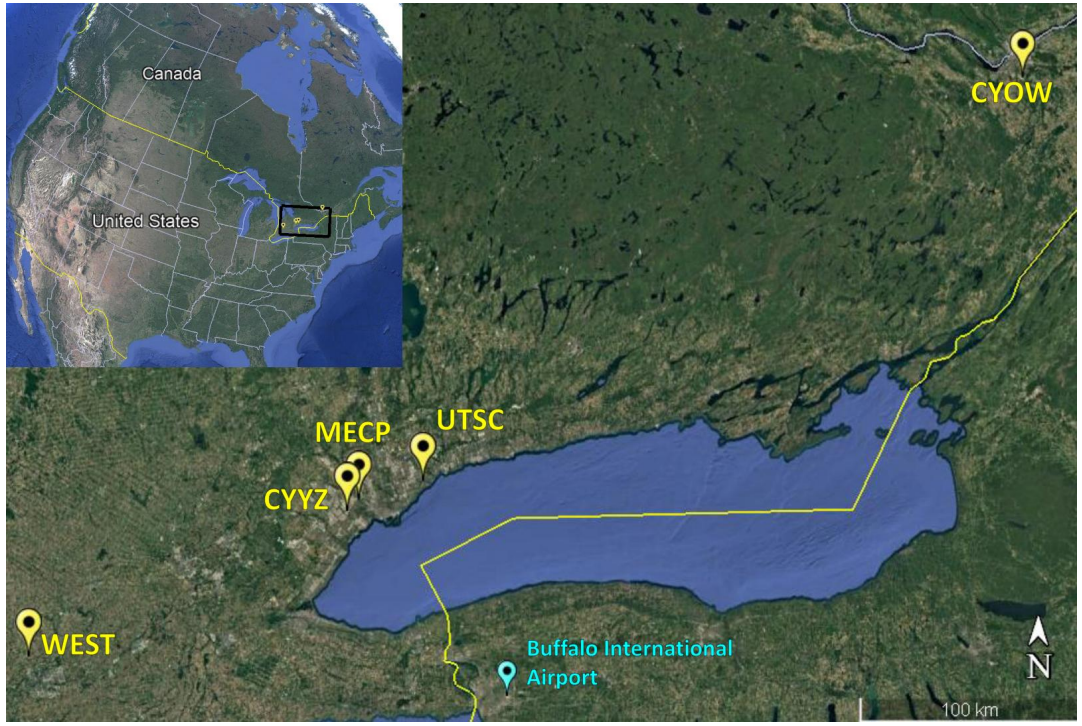
Graphics and quote courtesy of Zen Mariani

Mixed-design network of Doppler lidar (DL) sites around Toronto:

- 5 Halo STREAMline XR+ instruments
- 3 Leosphere 100S Windcube instruments

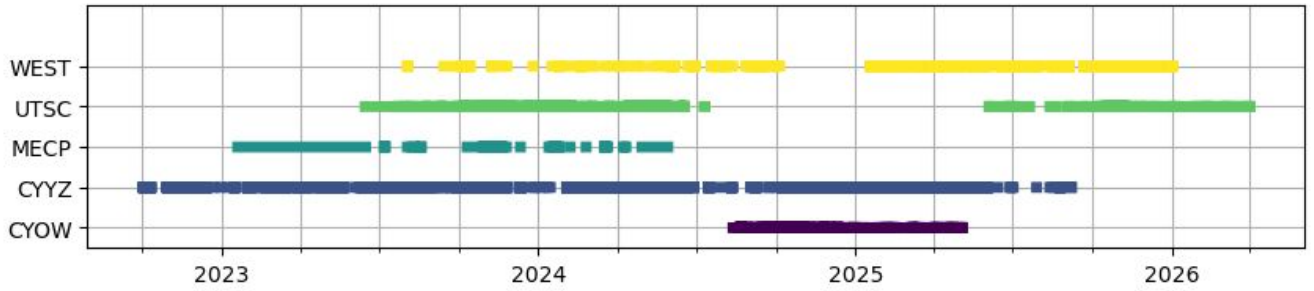
Only Halo data are used in this study due to data availability. The first instrument (CYYZ) was deployed in Nov. 2022. Wind and backscatter profiles are available in real-time at **http://hiwr.ca/mesonet.php** [6].

SOuthern Ontario LIDar (SOLID) Mesonet



Map of SOLID sites used in this study, with the Buffalo International Airport used for radiosonde comparison included (Google Earth).

Site	Lat (°)	Lon (°)	Altitude (m a.s.l.)	Altitude (m AGL)	Deployment date	Region type
CYOW	45.3273	-75.6637	112	0	September 7, 2024	Airport hangars
CYYZ	43.6660	-79.6062	163	1	Nov. 15 2022	Airport runways
MECP	43.7109	-79.5422	141	10	November 6, 2023	Urban, highways
UTSC	43.7835	-79.1880	152	21	October 20, 2023	Urban
WEST	43.0753	-81.3373	280	2	October 17, 2023	Farmland



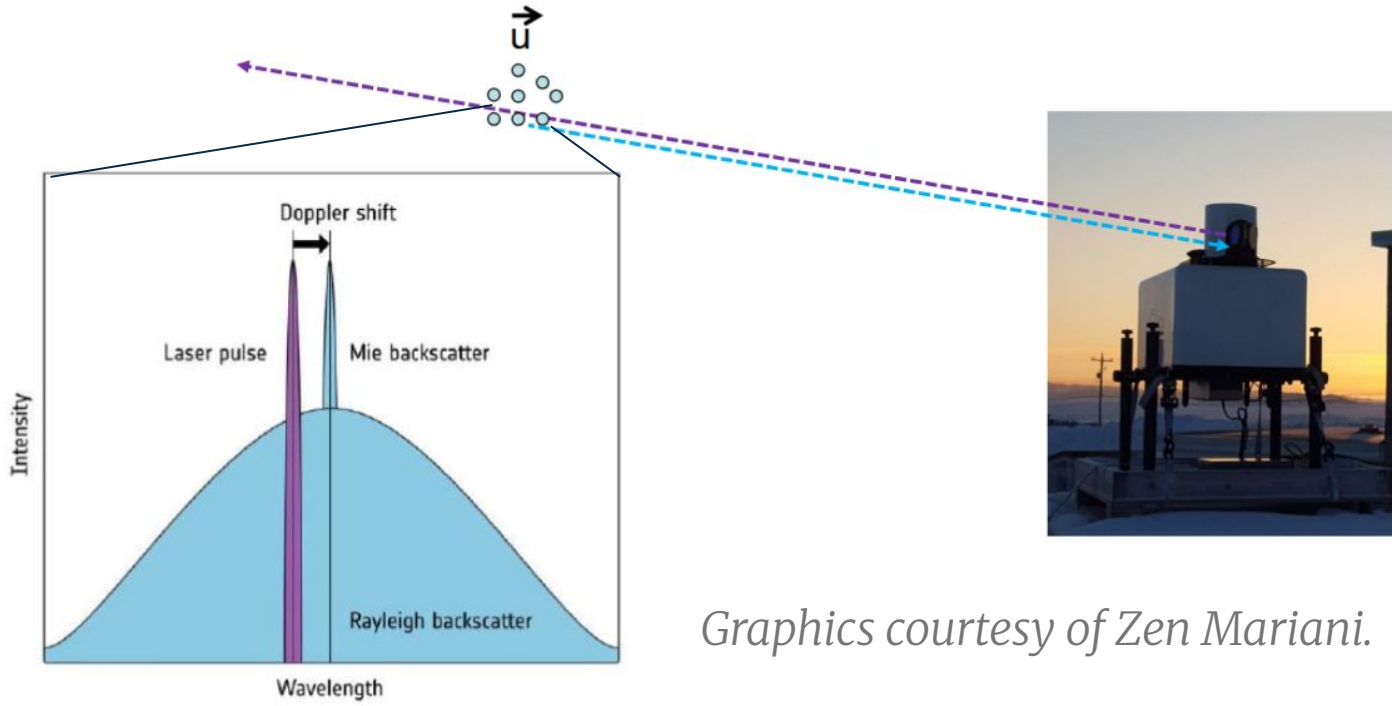
Data availability for each site.

Doppler lidar

- Autonomous, ground-based scanning lidar
- Measures the line-of-sight wind speed (towards/away from lidar) and aerosol backscatter
- Measured velocity is highly accurate (< + 0.3 m/s), can be deployed in environments and conditions where radiosondes cannot
- 24/7 operation during all weather

Geophysical Variable	Vertical Resolution	Temporal Resolution	Maximum Vertical Range*
Wind Profile (u, v)	3 m	10* min (*customizable)	2 – 4* km
Vertical Velocity (w)	3 m	2 sec	2 – 4* km

*Depends on atmospheric conditions (aerosols, PBLh)



Graphics courtesy of Zen Mariani.

PBLh estimation



Backscatter coefficient (β)

Vertical wind speed (w)

σ_β^2

$h_{DL,\beta}$

σ_w^2 , by threshold

$h_{DL,wt}$

σ_w^2, by gradient

$h_{DL,wg}$

Mechanism: Height of max σ_β^2 to find entrainment zone [7].
Advantage: Location-agnostic.
Disadvantage: Not valid in stable conditions.

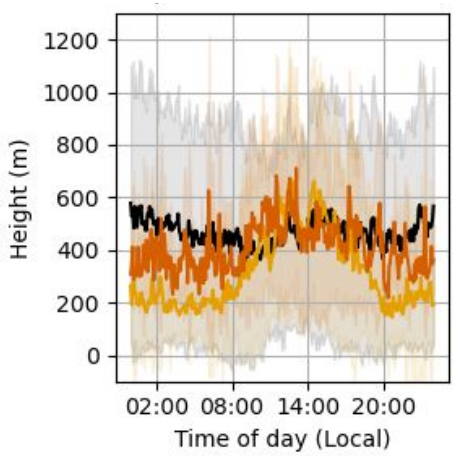
Mechanism: Height of σ_w^2 sinking below a threshold (0.04 m^2/s^2) [8,9].
Advantage: Less sensitive to noise at high altitudes.
Disadvantages: Threshold can be location-dependent.

Mechanism: Height of min $\nabla\sigma_w^2$ is minimized (most negative).
Advantage: Location-agnostic.
Disadvantages: Noise creates sharp gradients.

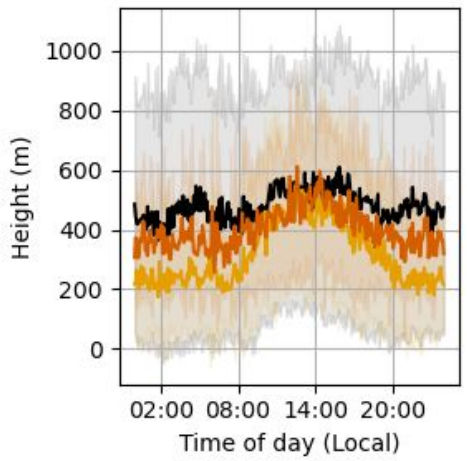
* σ_β^2 = variance in aerosol backscatter
σ_w^2 = variance in vertical wind speed
$\nabla\sigma_w^2$ = gradient in vertical wind speed variance

Diurnal variation

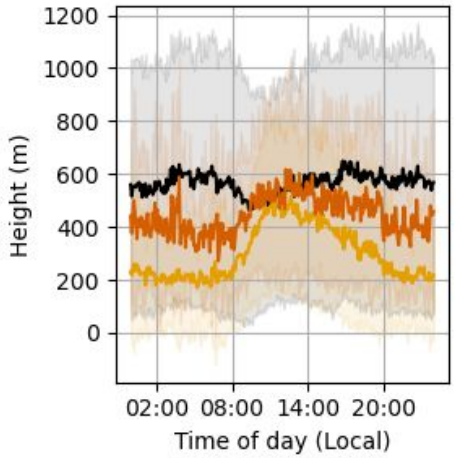
CYOW



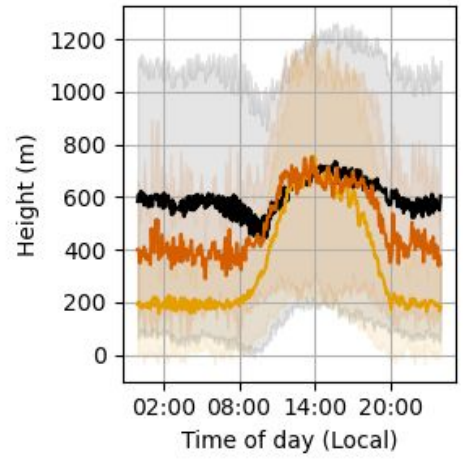
MECP



UTSC

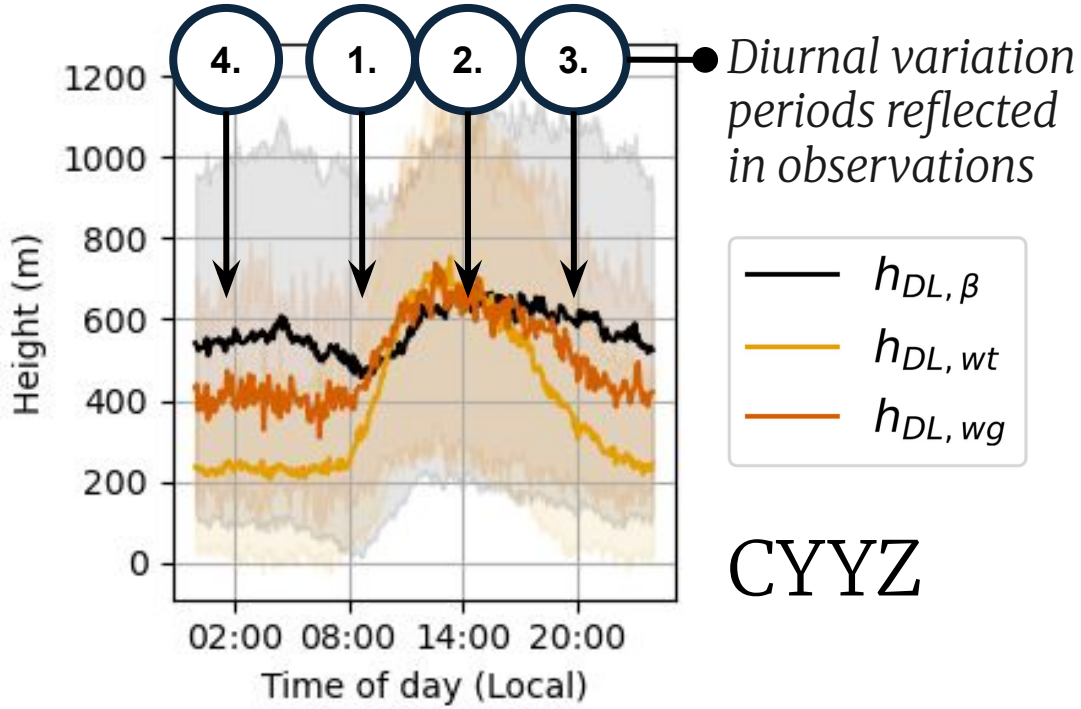


WEST



Mean diurnal variation in each PBLh estimate across available data period for each site (shaded to ±1σ).

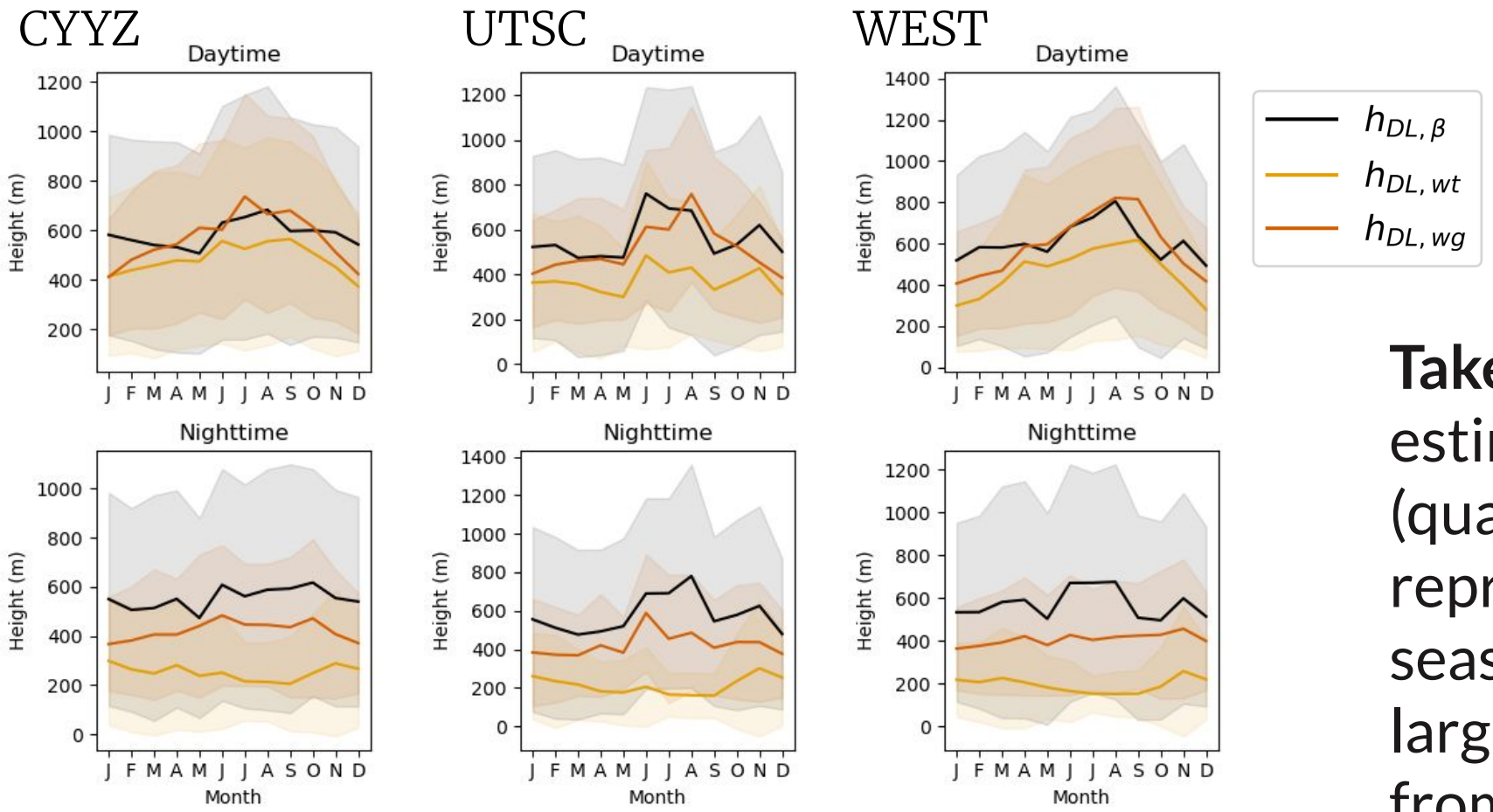
Takeaways: DL-based estimates can (qualitatively) reproduce expected diurnal variation; best performance from $h_{DL,wt}$.



Diurnal variation periods reflected in observations

CYYZ

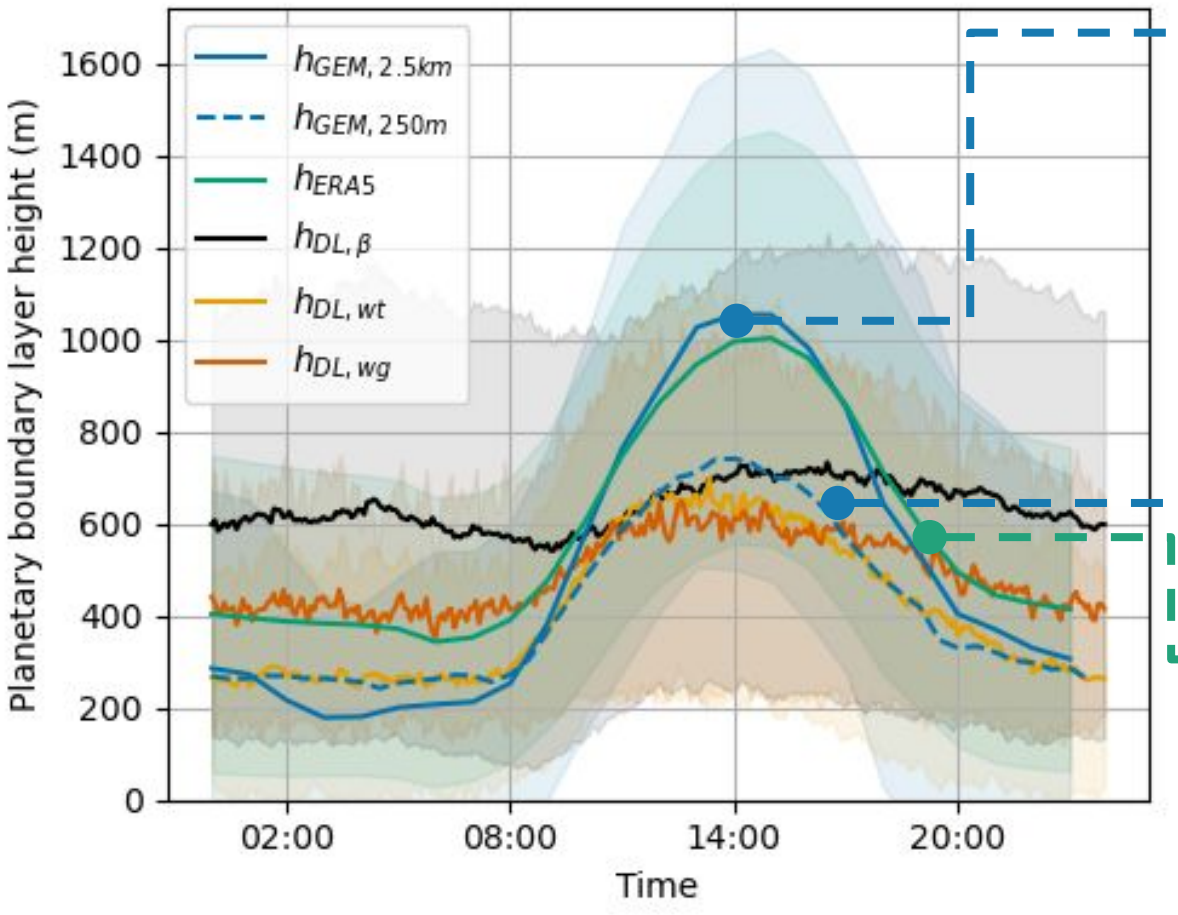
Seasonal variation



Mean monthly variation in each PBLh estimate across available data period for each site with data availability over one year (shaded to ±1σ). .

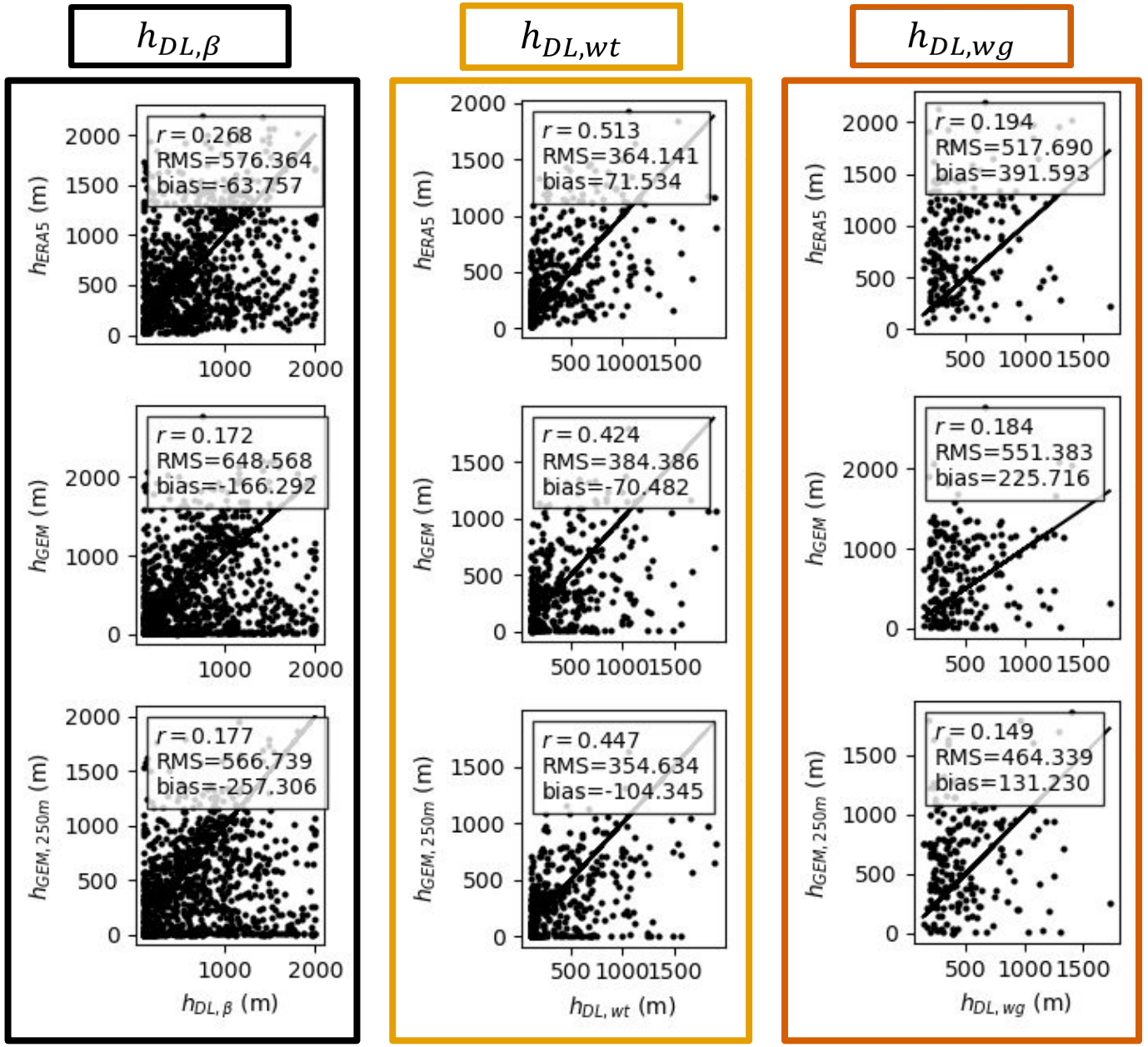
Takeaways: DL-based estimates can (qualitatively) reproduce expected seasonal variation; largest amplitude from $h_{DL,wg}$.

Intercomparison with model and reanalysis



Mean diurnal variation in each PBLh estimate across available data period for CYYZ over Jan - Mar 2024 (shaded to ±1σ).

- **Global Environmental Multi-scale (GEM) model:** Environment and Climate Change Canada's operational weather forecast model (2.5km resolution) [10].
  - Ensemble estimate conditional on atmospheric stability, uses surface parameters + buoyancy profile
- **250m resolution GEM:** Better at resolving urban environments [11]
- **European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5):** 31 km resolution [12]
  - Bulk Richardson number threshold method

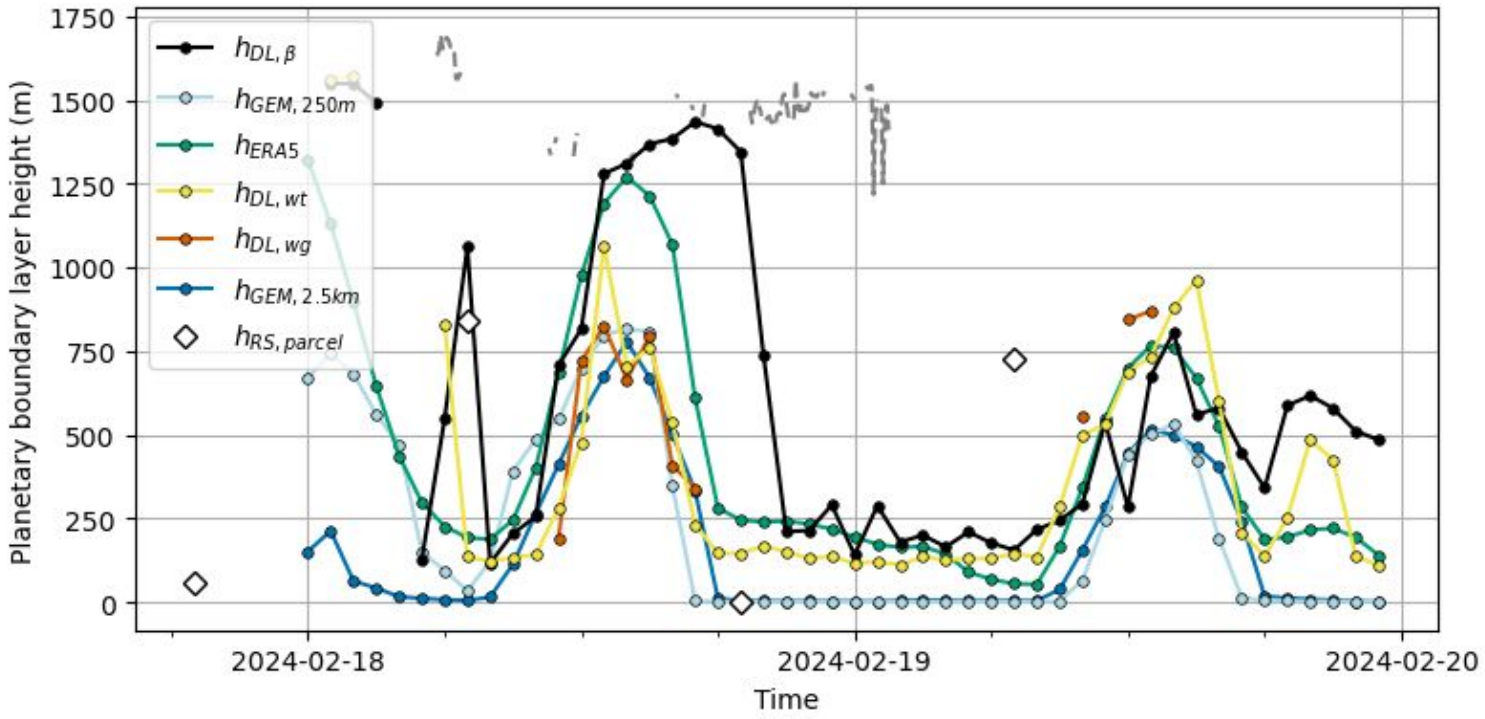


Takeaways:

- h_{GEM} and h_{ERA5} show greatest agreement with $h_{DL,wt}$
- Comparison statistics are typical of literature

Comparison to radiosondes

Radiosonde estimates (parcel method) taken from observations at the Buffalo International Airport (NOAA); case study days chosen based on manually inspecting weather maps for homogenous conditions between Buffalo and Toronto.



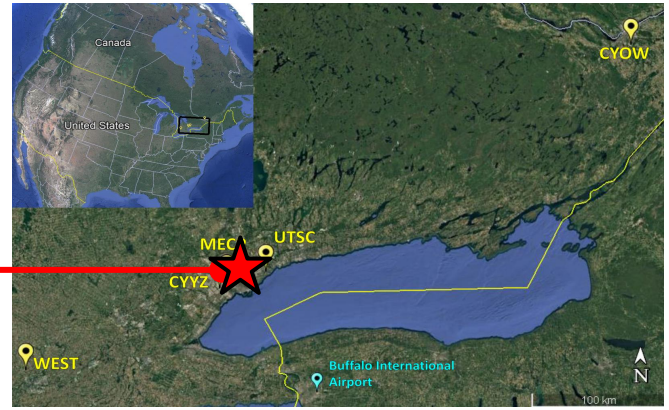
Comparing PBLh estimates for Feb. 18–20.

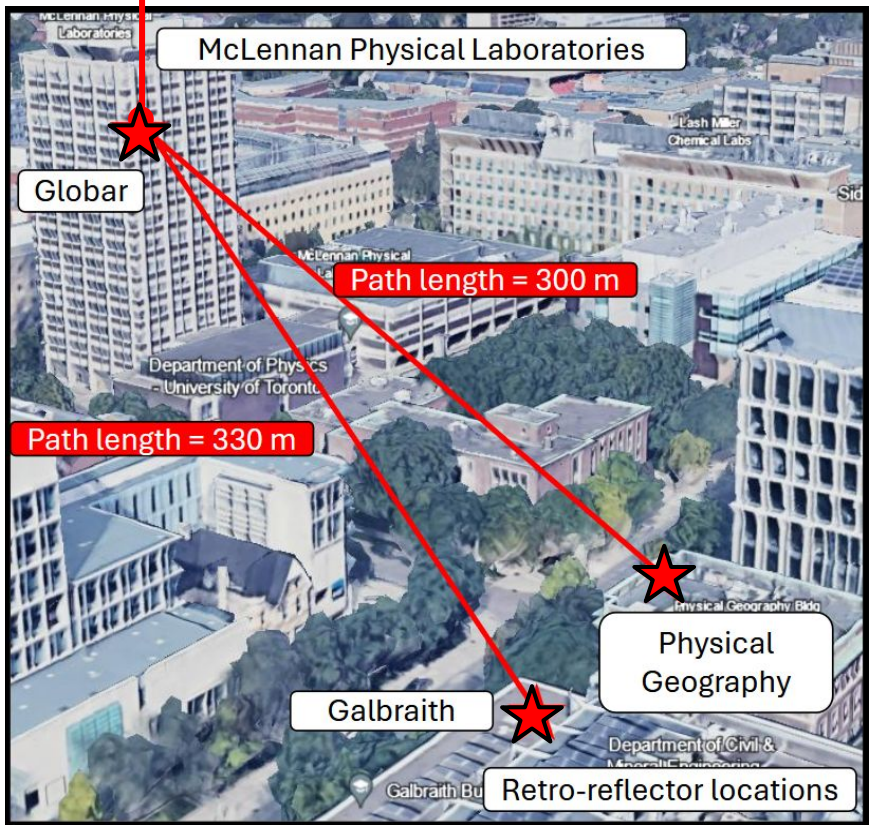
Takeaways:

- Good (qualitative) agreement with radiosonde
- $h_{DL,wg}$ suffers from data gaps, $h_{DL,\beta}$ from noise surrounding cloudy conditions
- Low nighttime h_{GEM}, high daytime h_{ERA5}.

University of Toronto Open-Path Fourier Transform Infrared (OP-FTIR) spectrometer

- Located at UofT in downtown Toronto
  - Approx. 3.5 km north of Lake Ontario.
- Spectrometer and telescope: McLennan Physical Laboratories (MP) building (~45 m above ground level, or AGL)
- Retro-reflector: Physical Geography (PG) building roof (~30 m AGL), two-way pathlength of ~300 m
  - Before summer 2021: Galbraith building (~20 m AGL), two-way pathlength of ~330 m
- Co-located with weather stations (MP, PG), barometer (MP)

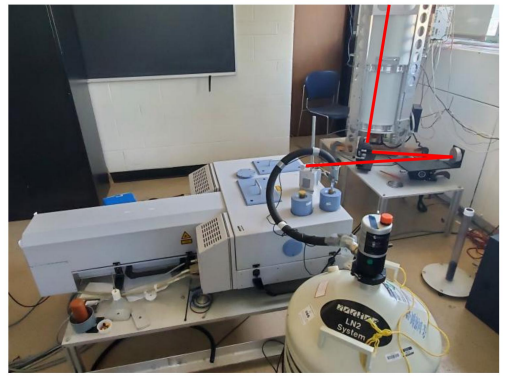




CO
CO_2
N_2O

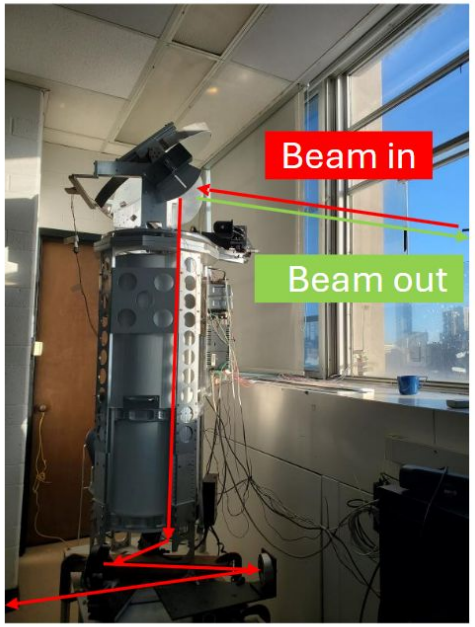
University of Toronto Open-Path Fourier Transform Infrared (OP-FTIR) spectrometer

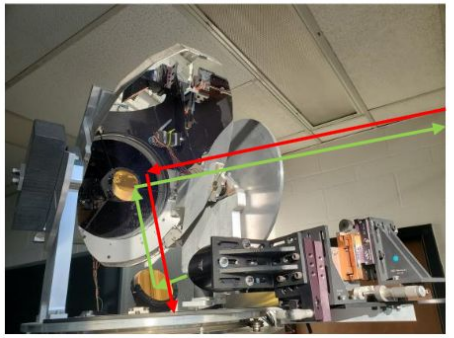
- Bruker IFS 125M spectrometer
- CaF_2 beam-splitter (14000-1850 cm^{-1}) and an InSb detector (9600-1850 cm^{-1})
- Measurements recorded at 0.4 cm^{-1} resolution over 1900-6000 cm^{-1}
- Internal globar source producing IR beam
- Telescope with a gold-coated steerable mirror to direct the IR beam towards the retro-reflector and array of off-axis parabolic (OAP) mirrors to collimate the beam on its way out and back into the instrument
- Gold-coated corner cube array retro-reflector
- Retrievals done using Multiple Atmospheric Layer Transmission (MALT5) model [6]



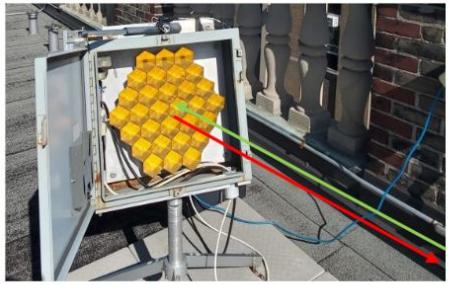
The Bruker 125M spectrometer.

The telescope.





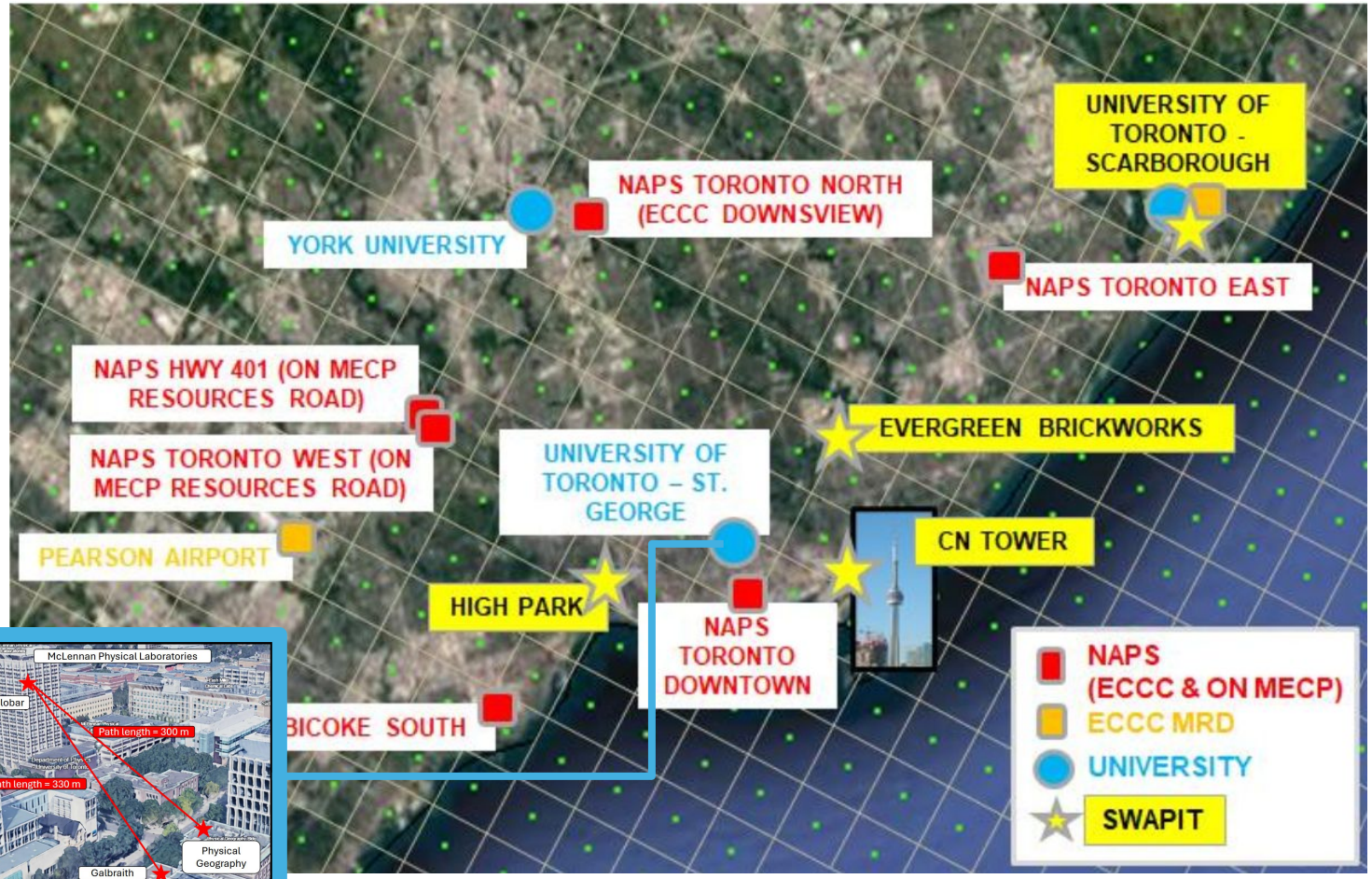
The primary, steerable mirror.



The retro-reflector.

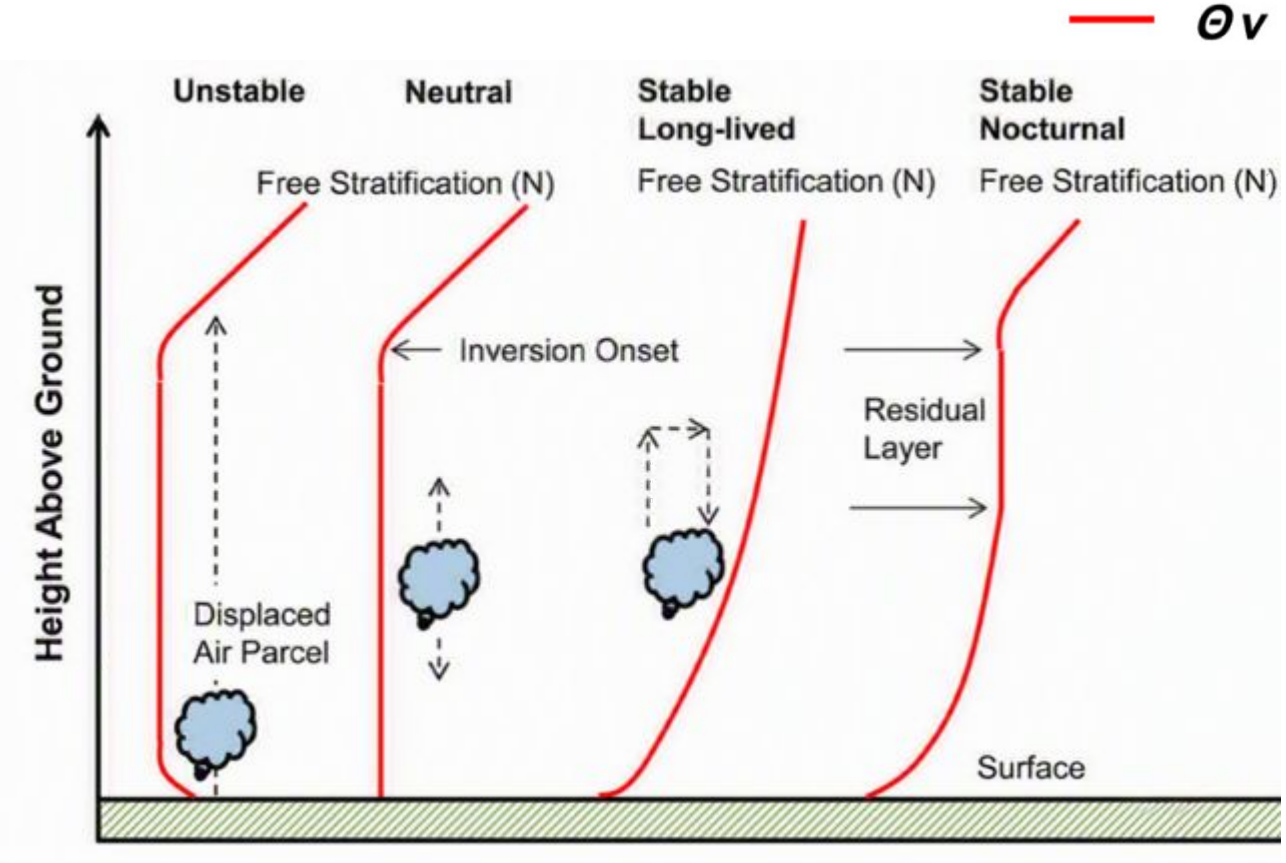
Study of Winter Air Pollution in Toronto (SWAPIT)

- Intensive ECCC measurement campaign in Toronto from January 25 - March 7 2024 [13]
- Focused on characterizing urban air pollutant mixtures in under-investigated winter conditions
- UofT OP-FTIR data included; provides complementary long-term dataset for PBLh analysis



Time period: Stability

- SWAPIT focuses on wintertime conditions characterized by stable PBL conditions
- Stable PBLh is tricky to find
  - Profiles often lack sharp gradients characteristic of convective conditions
  - PBL often not turbulent at all
- Disparities in aerosol distribution and turbulent PBL, introducing uncertainty in surface pollutant estimation

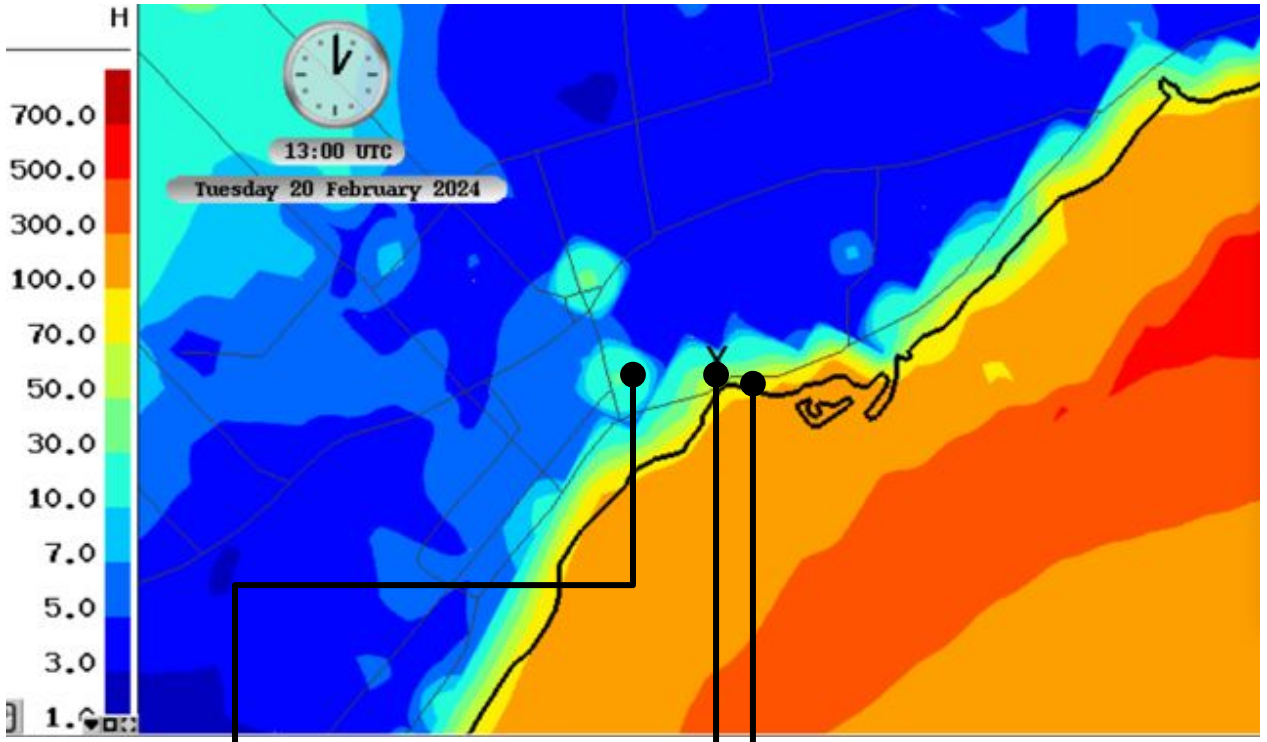


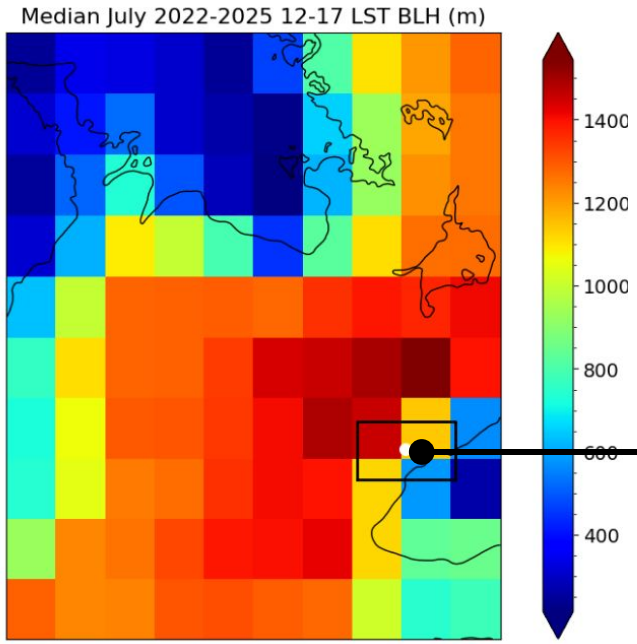
Atmospheric boundary layer schematic showing stable, neutral, and unstable conditions (θ_v: Virtual Potential Temperature) (from Aliabadi et al., 2016)

Location: Lake and urban heat island effects

- SOLID and SWAPIT sites are affected by moderating lake effect
  - Warming (higher PBLh) in winter and cooling (lower PBLh) in summer
- Summer also gives urban heat island effect
- Potentially complex PBLh-pollutant dynamics

GEM PBLh, winter (figure from Stroud, et al. 2026).





CYYZ (SOLID)

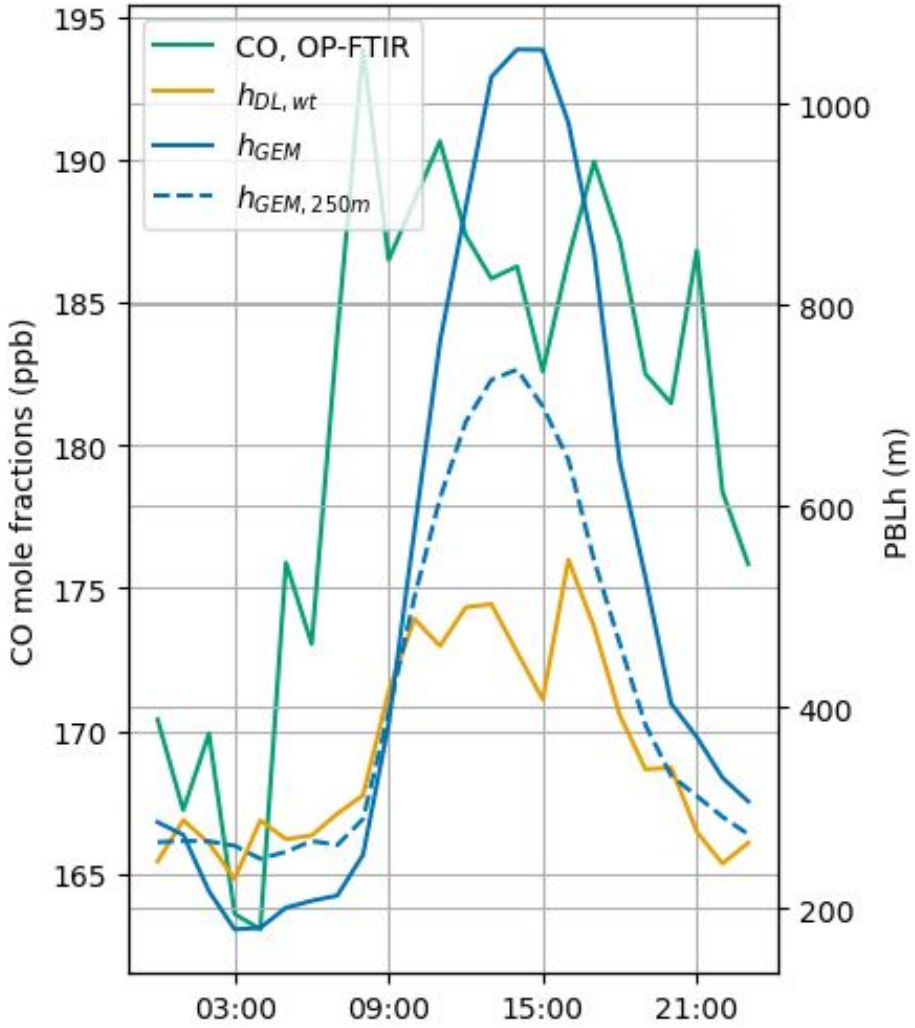
High Park (SWAPIT)

OP-FTIR (UofT)

ERA5 PBLh, summer

Investigating CO variability

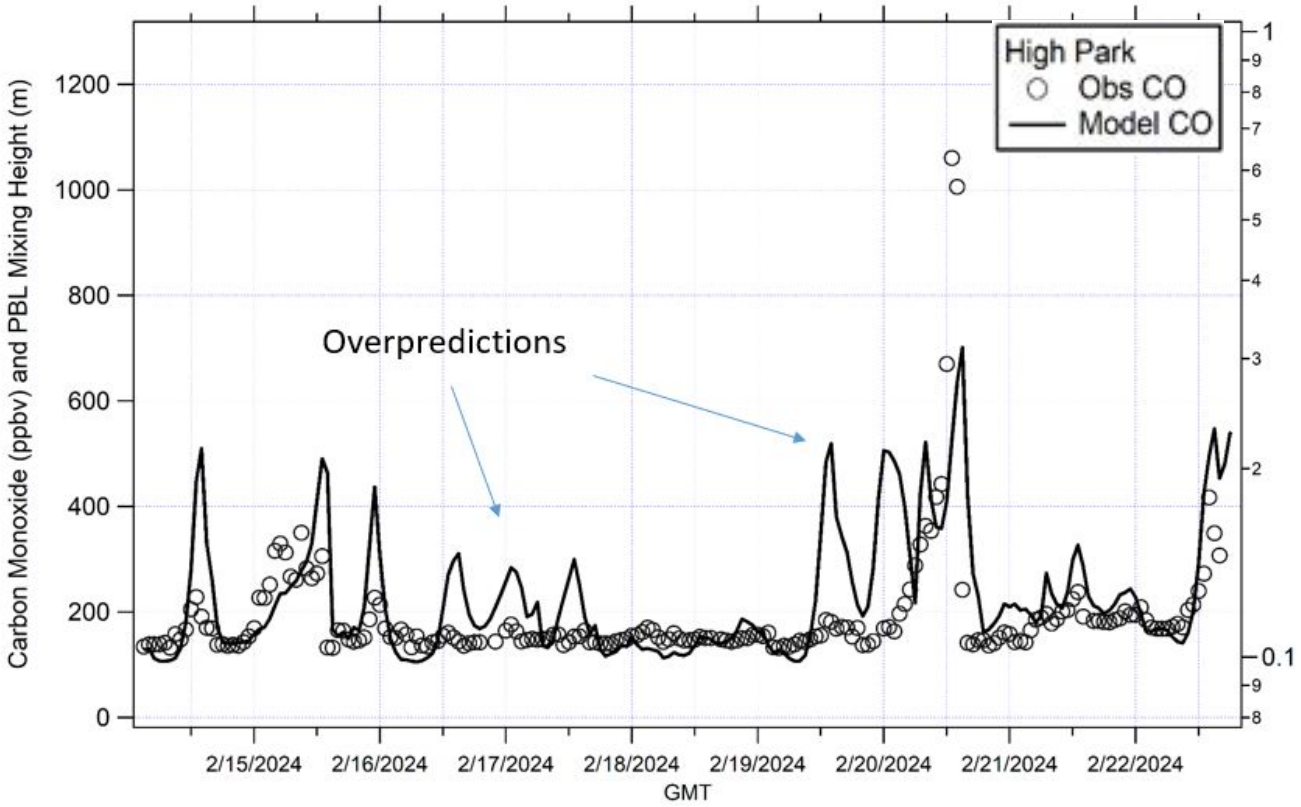
- There are CO emission sources in the PBL and few uptake processes; theoretically surface observations are affected strongly by PBLh
- So far no statistically significant correlation between OP-FTIR CO observations and PBLh from Doppler lidar or models found
- Further understanding of PBLh impact from complementary datasets needed to draw conclusions

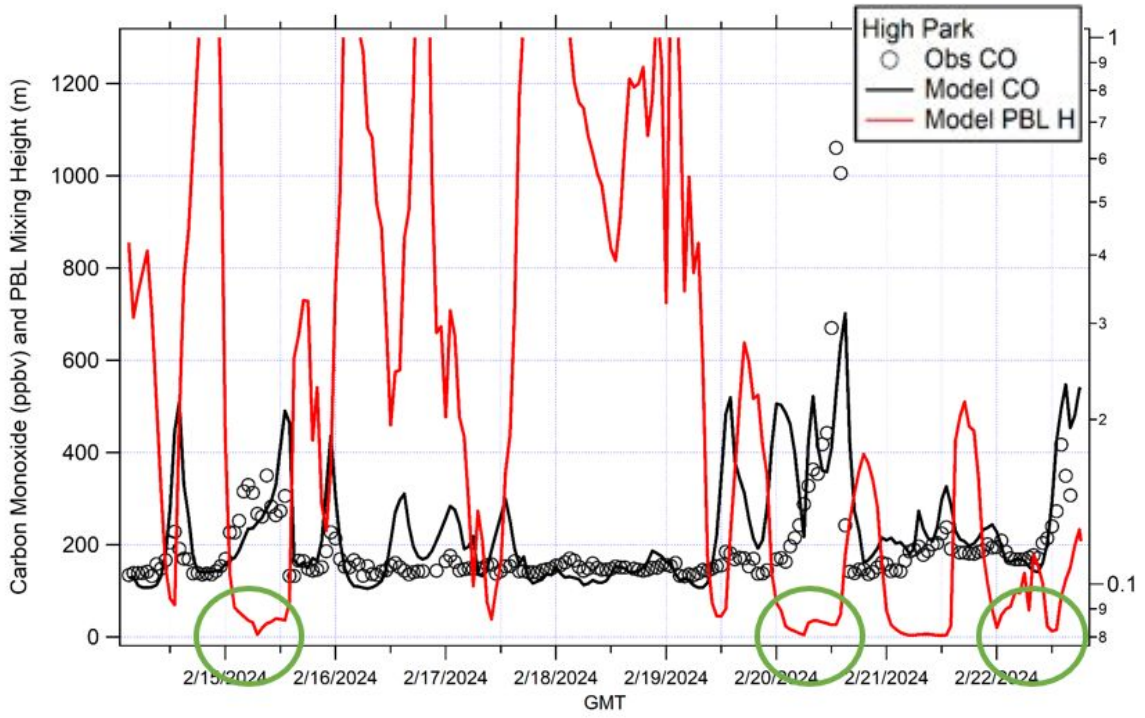


Mean diurnal variation of OP-FTIR CO and PBLh from Doppler lidar, GEM, and 250m GEM over Jan-Mar 2024.

Evaluating models: first steps

*PBLh evaluated at CYYZ, CO measured at High Park

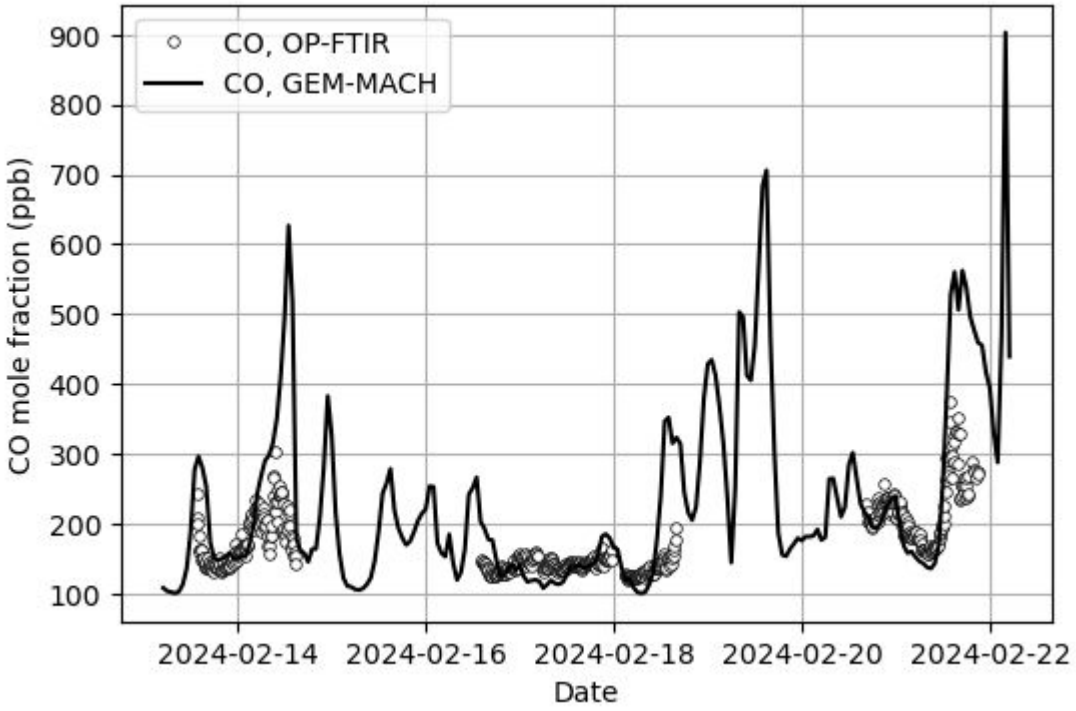


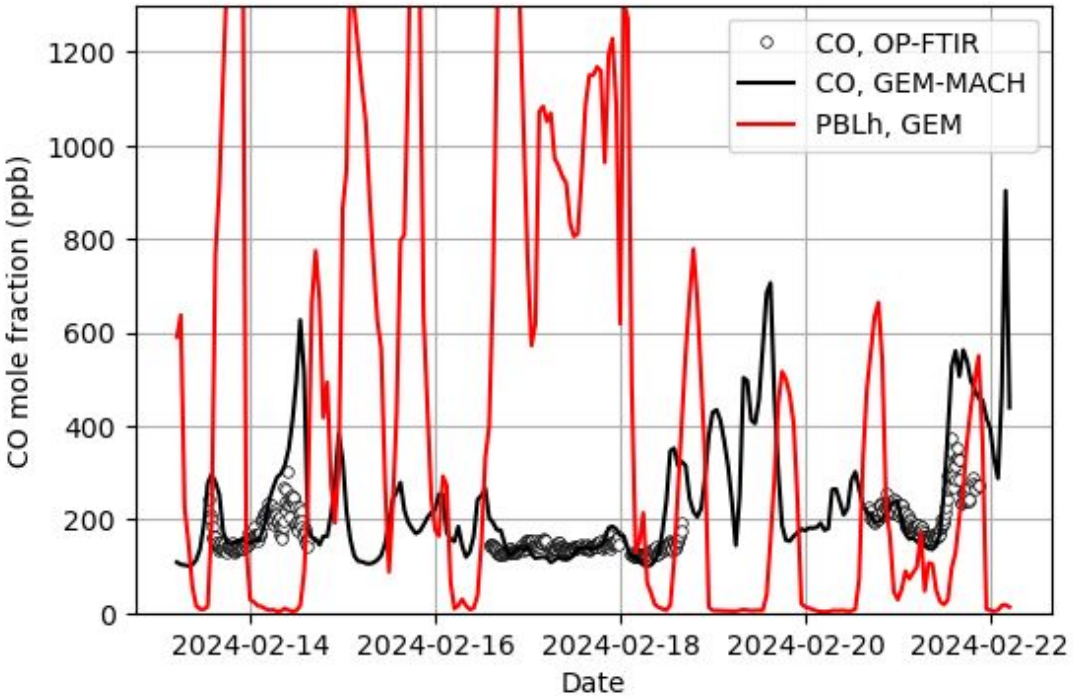


From Stroud *et al.* (2026): GEM Modeling Air quality and Chemistry extension (GEM-MACH) model can over-predict CO - possible link to mixing

Evaluating models: first steps

*PBLh evaluated at CYYZ, CO measured at UofT



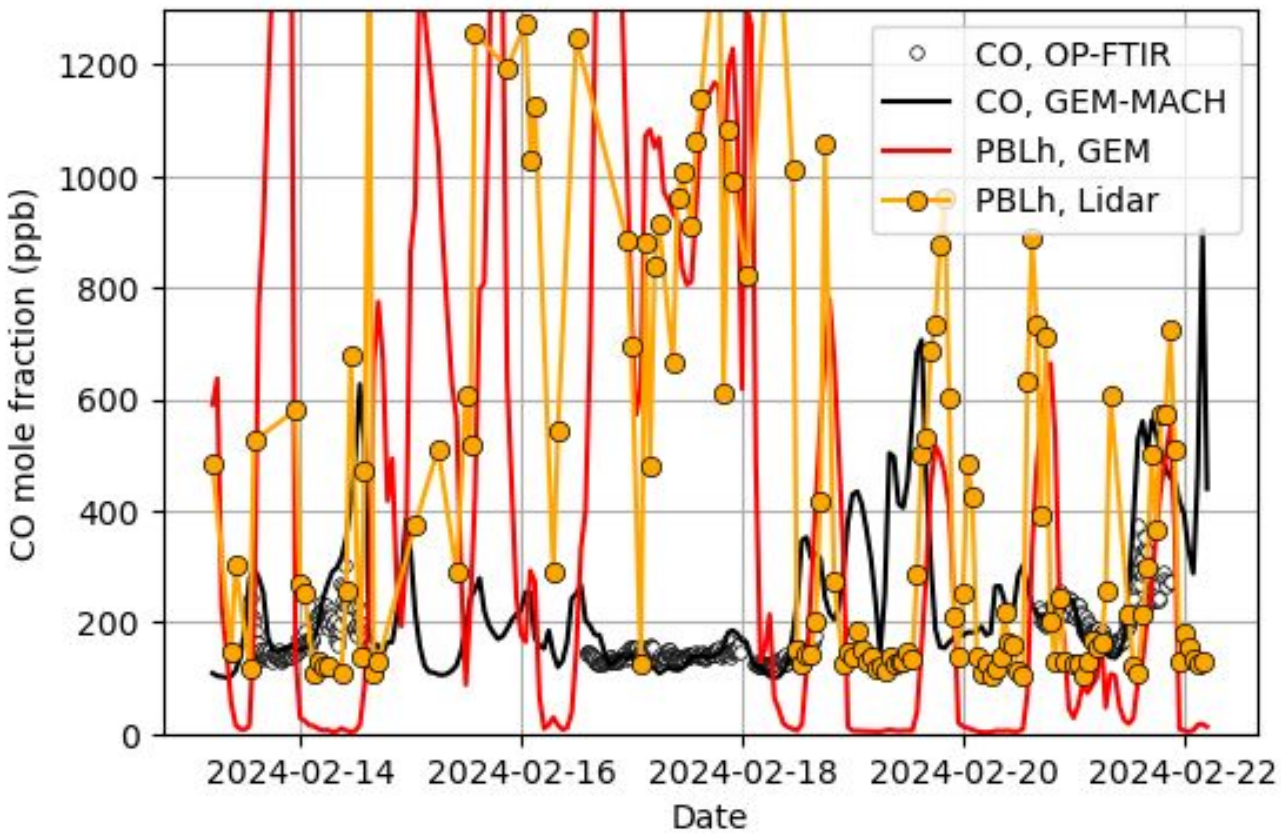


Similar analysis completed for UofT OP-FTIR system and GEM-MACH (some small differences between GEM-MACH output versions from last slide; data gaps in OP-FTIR CO due to rainy conditions).

Evaluating models: first steps

- Possible link to PBLh estimation errors
- Further analysis with more atmospheric pollutants needed to draw conclusions

*PBLh evaluated at CYYZ, CO measured at UofT



Summary and next steps

- We are able to produce reliable, long-term, high-temporal-resolution PBLh estimates in Southern Ontario.
- UofT OP-FTIR provides long-term, 24h surface trace gas observations that can be used to investigate PBLh impacts on variability and evaluate models
- SWAPIT campaign observations provide a large dataset of multiple PBL pollutants in interesting atmospheric conditions
- Future work:
  - Identify PBLh-related variability by investigating multiple PBL pollutants in OP-FTIR and SWAPIT data
  - Evaluate GEM-MACH surface pollutant estimates and investigate any inaccuracies in PBLh estimation
  - Take advantage of simultaneous DL wind speed and aerosol backscatter measurements to characterize residual layer and stable nocturnal PBL relationship

Thank you!

Questions?

Acknowledgements: We thank Environment and Climate Change Canada and the Natural Sciences and Engineering Research Council of Canada for their support, and Robert Crawford for his work with SOLID Mesonet Data.

[1] Stull (2012). *An introduction to boundary layer meteorology*, Vol. 13. Springer Science & Business Media.

[2] Moran, *et al.* (2026). Geosci. Model Dev. 19(10), 4205-4270.

[3] Park, *et al.* (2022). Atmos. Poll. Res. 13, 101310.

[4] Zhao, *et al.* (2019). Atmos. Chem. Phys. 19, 10619–10642.

[5] McKeen, et al. (2007). J. Geophys. Res.: Atmos., 112(D10).

[6] Mariani, *et al.* (2026). J. Atmos. Oceanic Technol. Accepted.

[7] Emeis, et al. (2008). Meteorol. Z. 17, 621.

[8] Tucker, *et al.* (2009). J. Atmos. Ocean Tech. 26, 673–688.

[9] Schween, et al. (2014). Atmos. Meas. Tech. 7, 3685–3704 .

[10] Cˆot´e, *et al.* (1998). Mon. Weath. Rev. 126, 1373–1395.

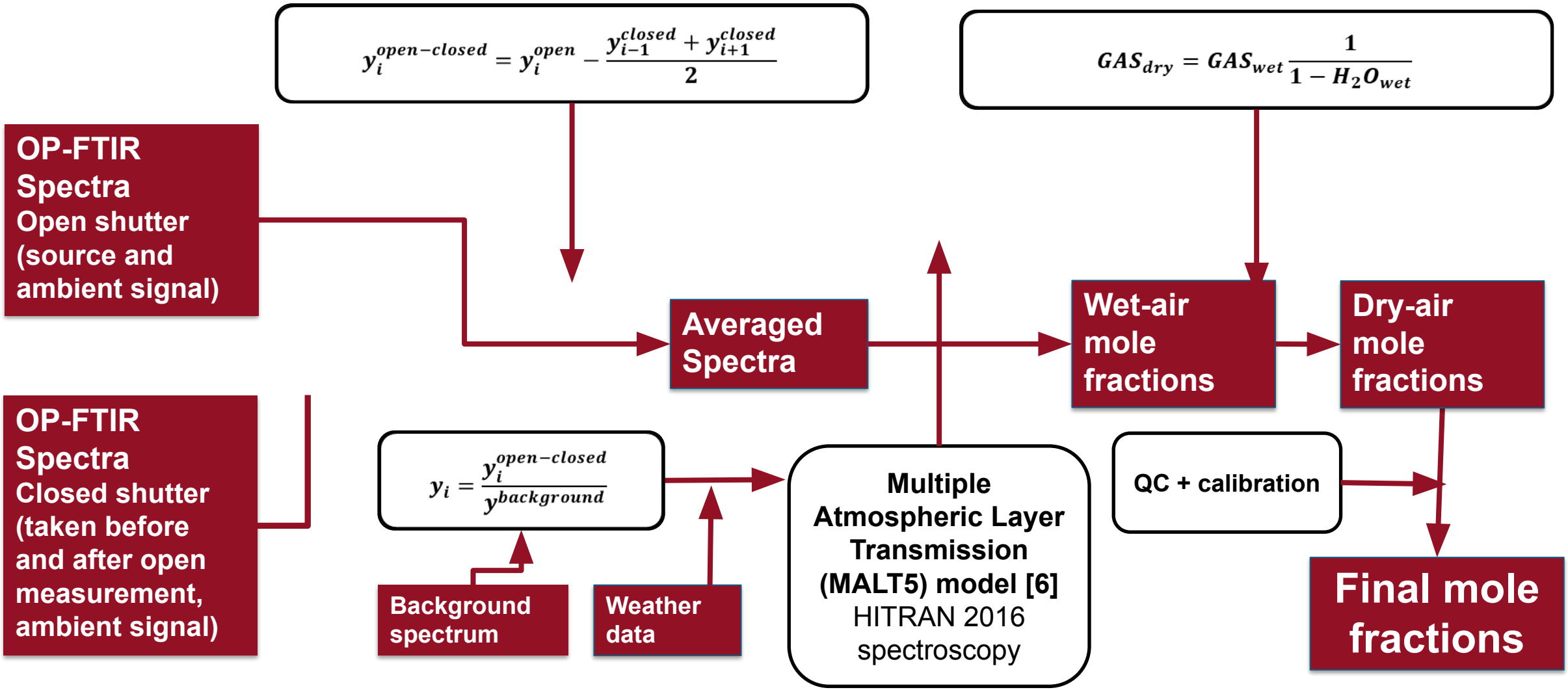
[11] Leroyer, *et al.* (2022). Atmos. 14, 1030.

[12] Hersbach, *et al.* (2020). Q. J. Roy. Met Soc. 146, 1999–2049.

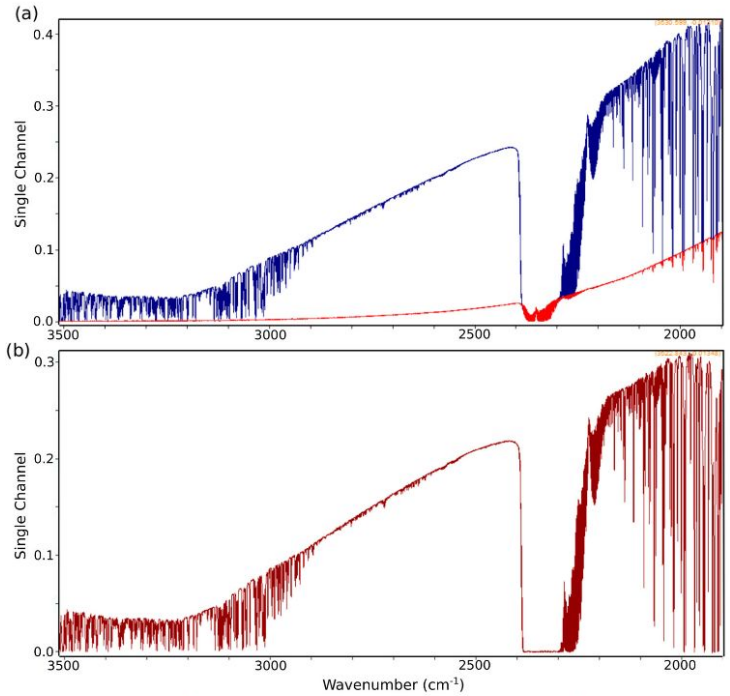
[13] Galarneau, et al. (2024) Study of Winter Air Pollution in Toronto (SWAPIT): Science Plan.

[14] Lee (2018). *Fundamentals of boundary-layer meteorology*(Vol. 256). Springer International Publishing.

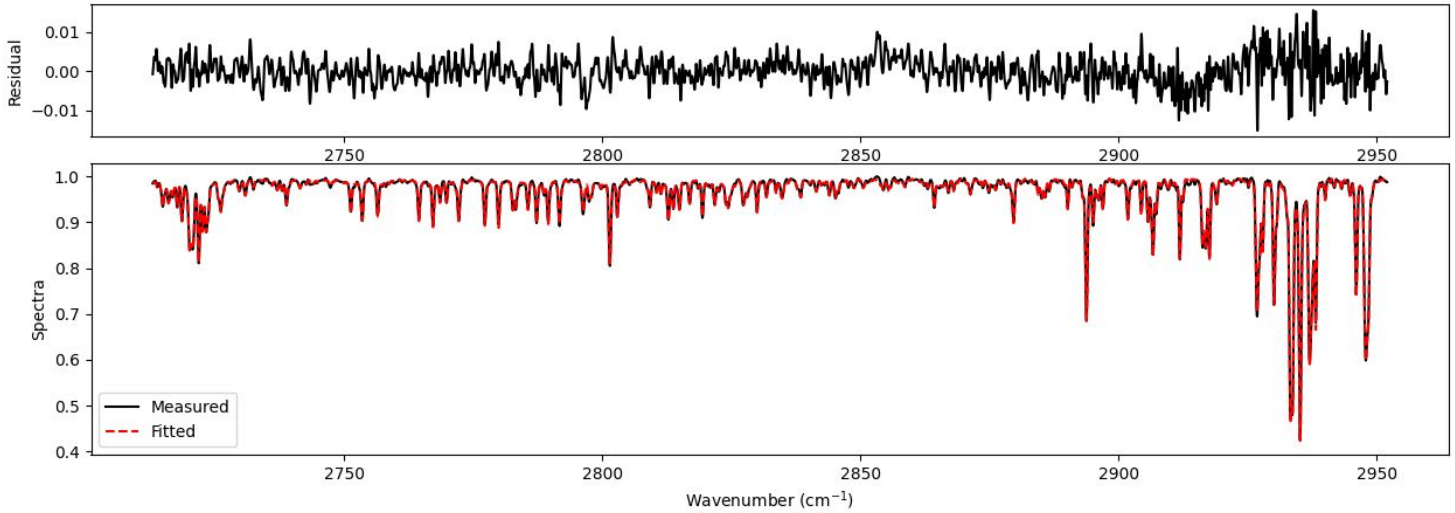
OP-FTIR Workflow



OP-FTIR Workflow



An example of (a) open shutter spectra (blue) and closed (red), and (b) with the closed spectrum subtracted [5].



A MALT5 spectral fit over the 2713–2952 cm^{-1} range used to retrieve H_2O and HDO.