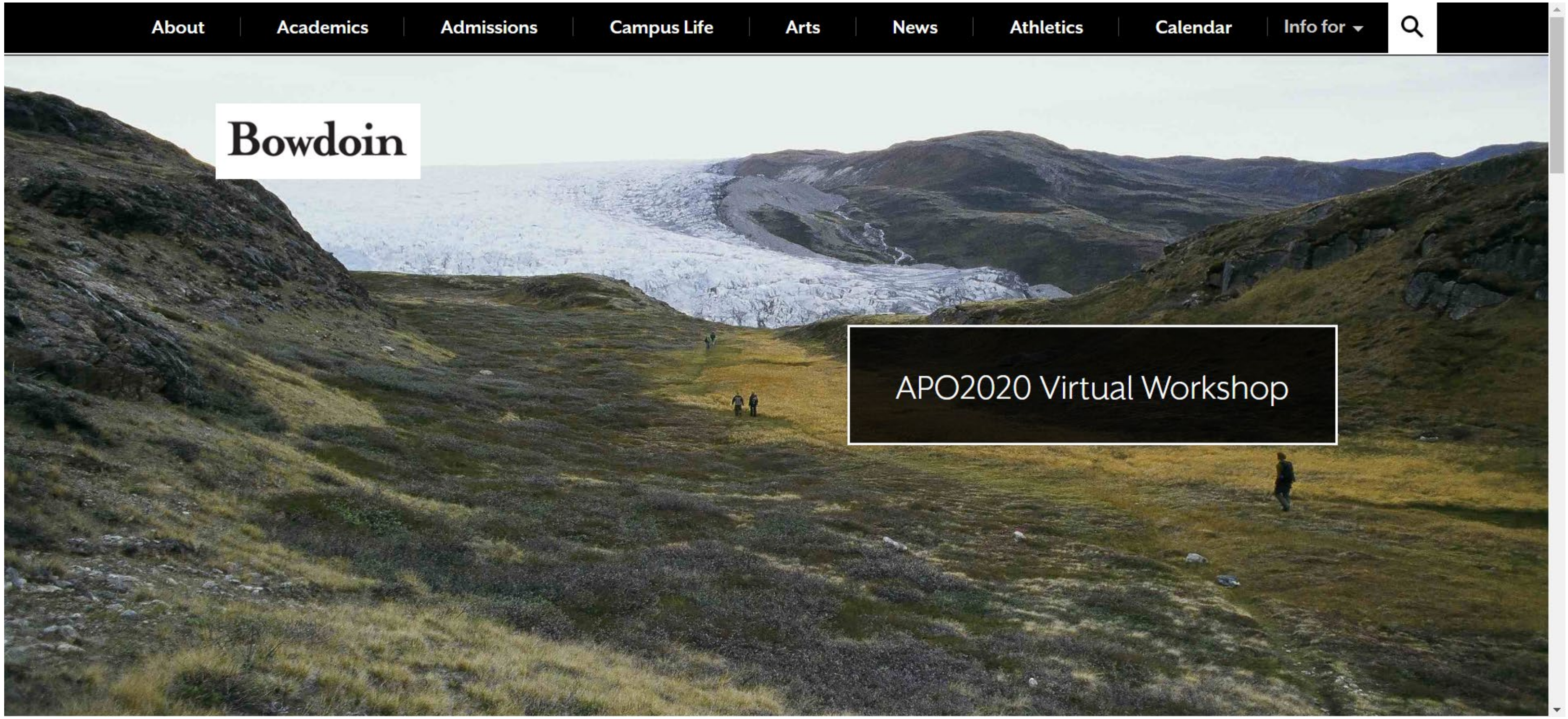
The APO Forward Model Intercomparison Experiment

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Britton Stephens, Matt Long, Frederic Chevallier, Yuming Jin, Ralph Keeling, Ingrid Luijkx, Shamil Maksyutov, Eric Morgan, Yosuke Niwa, Prabir Patra, Christian Rödenbeck, Jesse Vance

NSF

Third Atmospheric Potential Oxygen Workshop – 2020 (virtual)

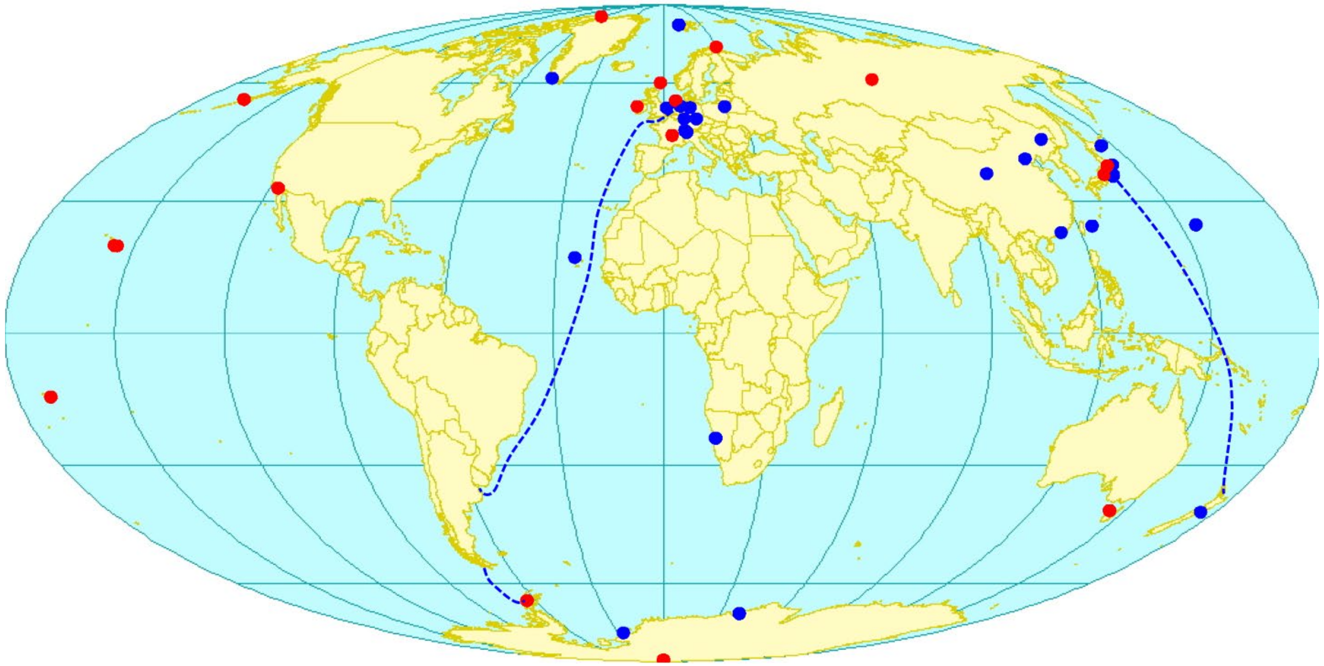


Collaborative goals:

1. Working toward reconciling scales to support analysis using merged data sets
2. **Engaging with atmospheric transport modeling community for APO simulations**

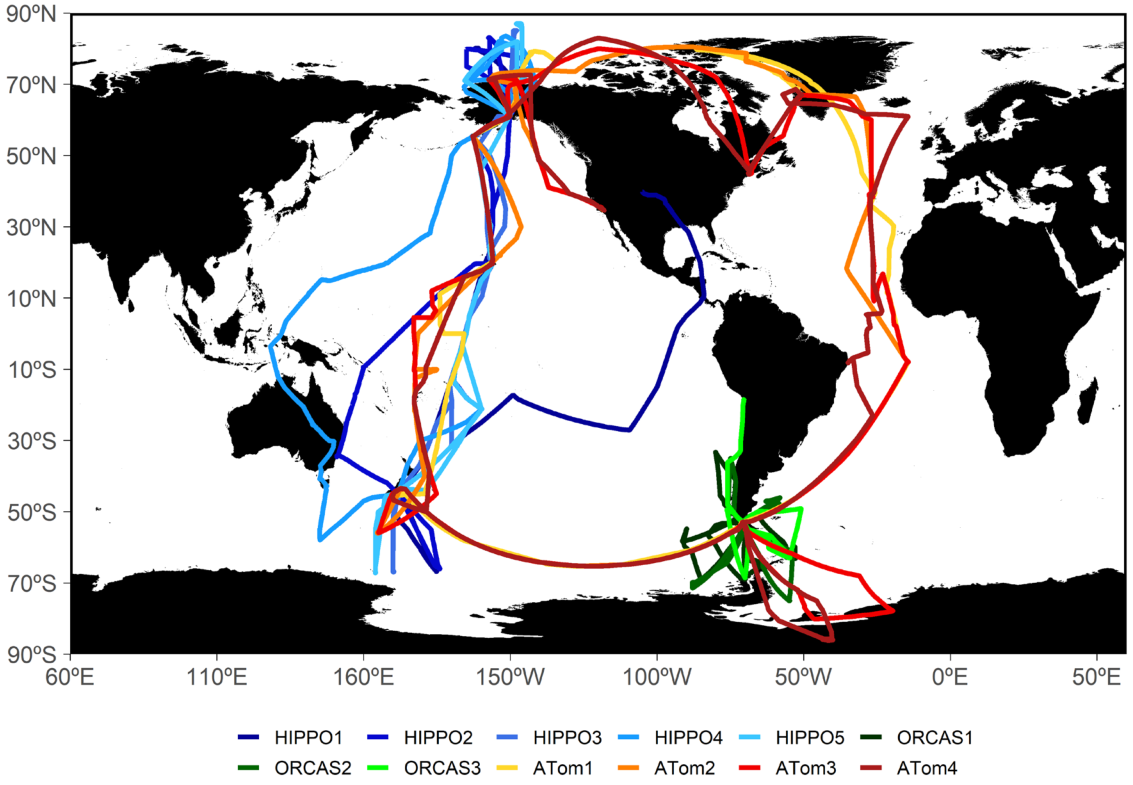
Motivation 1: Interpretation of atmospheric O_2 measurements

Station and Shipboard Observations



Courtesy Andrew Manning

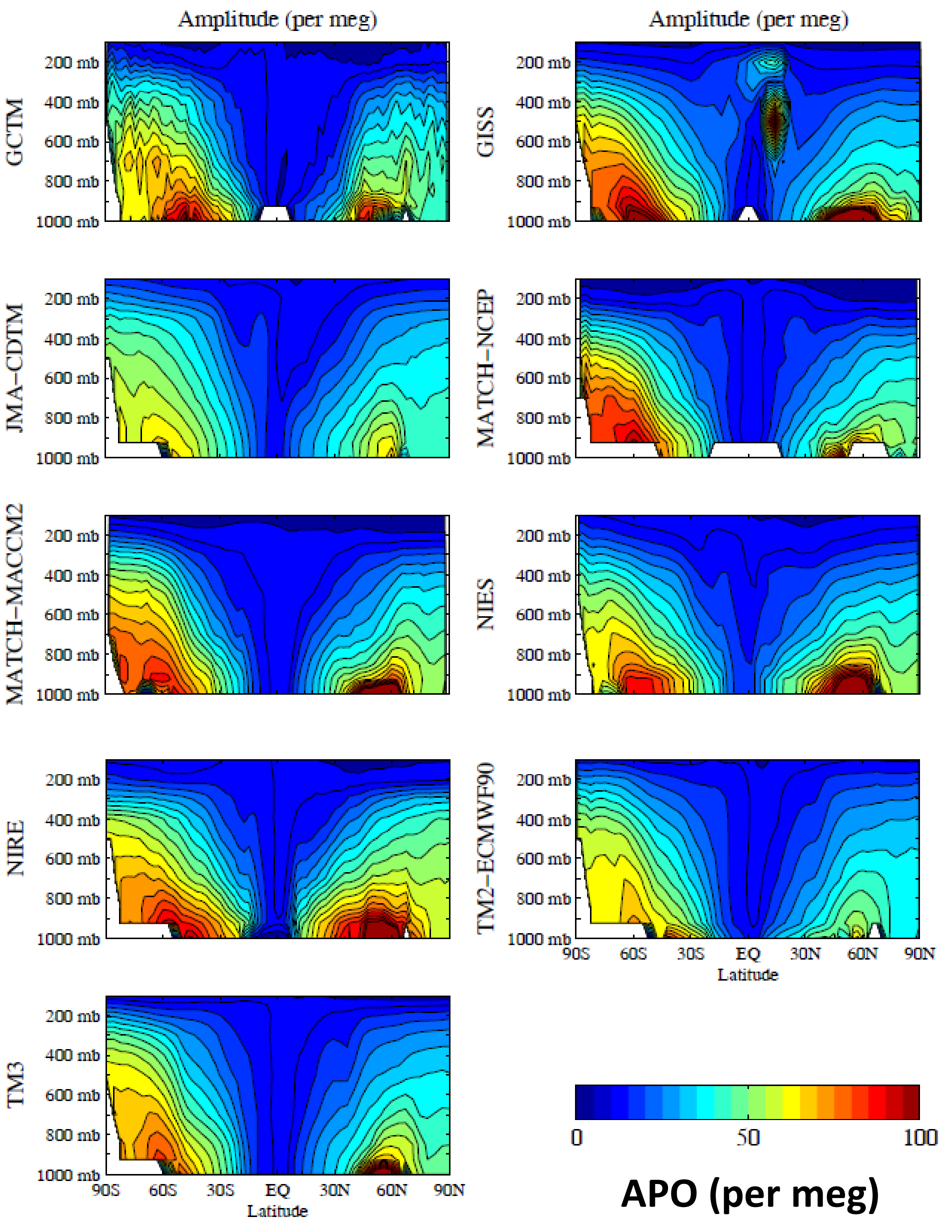
HIPPO, ORCAS, and ATom Airborne Campaigns

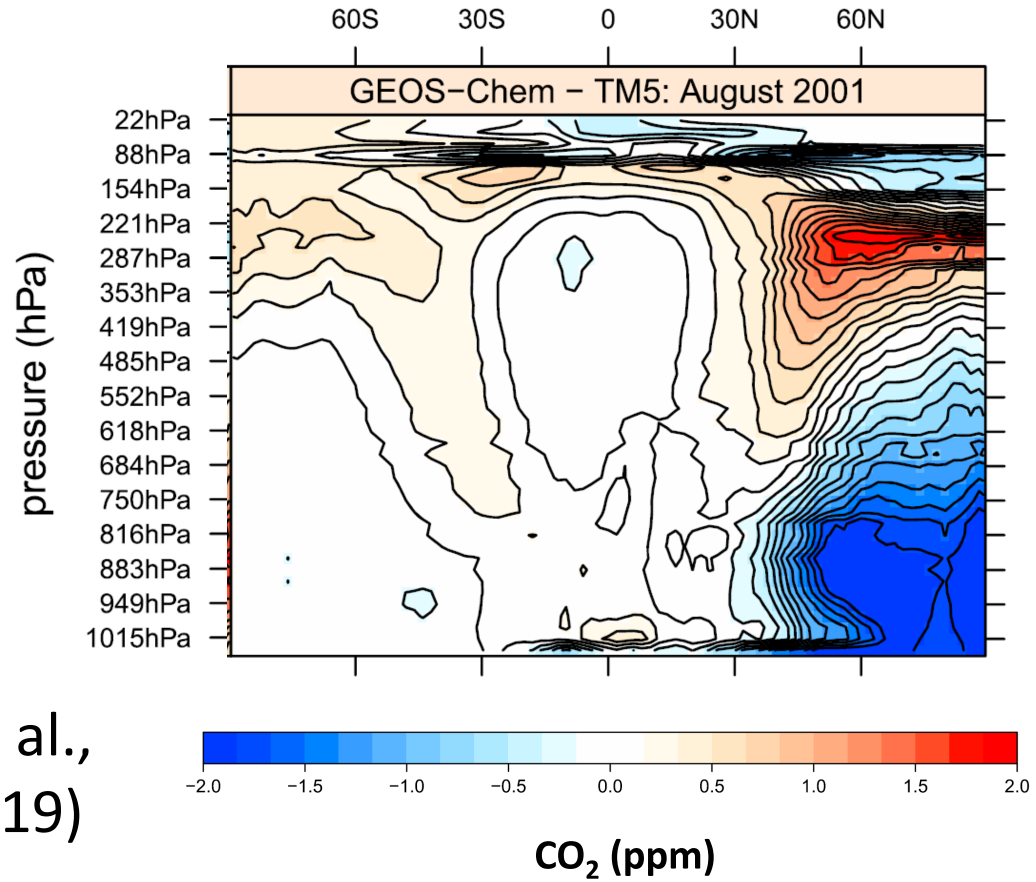


Details on all records can be found here:
https://docs.google.com/document/d/1mBcd9GG_ZcE3eiDIHYq5yA16D5Seq6dx
(prepared by Karina Adcock and Penelope Pickers)

From Jin et al., PNAS, submitted.

Motivation 2: Evaluation of atmospheric transport models





Schuh et al., (GBC, 2019)

TransCom O_2 Experiment (Tegan Blaine, SIO Dissertation, 2005)

Contributing models

Abbreviation	Model System Name	Grid (lat x lon x lev)	Transport Model	Meteorology	Run start, valid period	Leads	References
CAM-SD	Community Atmospheric Model w/ MERRA-2 nudging	0.9x1.25x56	CAM	MERRA-2	Run start: Jan 1986 Valid period: 1989-2019	Matt Long and Jesse Vance	
CAMS_LMDZ	Copernicus Atmosphere Monitoring Service	1.875 x 3.75 x 39	LMDZ6A	ECMWF		Frederic Chevallier	Chevallier et al. (2010, 2005); Chevallier (2013)
CTE_TM5	CarbonTracker Europe	1 x 1 x 25	TM5	ECMWF		Ingrid Luijkx and Wouter Peters	van der Laan-Luijkx et al. (2017)
Jena_TM3	Jena CarboScope	4 x 5 x 19	TM3	NCEP		Christian Roedenbeck	Rodenbeck et al. (Rödenbeck et al., 2003); Rödenbeck (2005)
MIROC4-ACTM	MIROC4-ACTM	2.8 x 2.8 x 67	MIROC4-ACTM	JRA-55		Prabir Patra	Patra et al. (2018); Saeki and Patra (2017); Chandra et al., in review (2021)
NICAM-TM (glevel-5)	NICAM-based Transport Model	~223 km	NICAM-TM_gl5	JRA-55	Run start: Jan1986 Valid period: 1989-2020	Yosuke Niwa	Niwa et al. (2011, 2017)
NICAM-TM (glevel-6)	NICAM-based Transport Model	~112 km	NICAM-TM_gl6	JRA-55	Run start: Jan1986 Valid period: 1989-2020	Yosuke Niwa	Niwa et al. (2011, 2017)
NIES	NTFVAR	3.75 x 3.75 x 42 / 1 x 1 x 40	NIES-TM/ FLEXPART	ERA-5/JRA-55	Jan. 1, 2000 Jan. 1, 2003 - Dec. 31, 200X	Shamil Maksyutov	Belikov et al. (2011), (Maksyutov et al., 2021)

Provided input fluxes (10 fields)

Jena APO inversion (version apo99X_v2021) posterior fluxes (Rödenbeck et al., 2008)

- Seasonal air-sea APO flux only

CESM Forced Ocean–Sea-Ice (FOSI) simulation (Yeager et al., 2022)

- Air-sea O_2, CO_2, and N_2 fluxes

Bottom-up air-sea flux estimates

- O_2 : Seasonal component from dissolved O_2 climatology of Garcia and Keeling (2001), scaled by 0.82 according to Naegler et al. (2006). Annual mean component from ocean inversion of Resplandy et al. (2016) using transport from MITgcm-ECCO
- CO_2 : pCO_2-based product of Landschützer et al. (2016) v.2021
- N_2 : Estimated using ERA5 heat fluxes and sea-surface temperatures, and sea-surface salinity from the World Ocean Atlas, v.2018

Fossil fuel fluxes

- OCO-2 v10 MIP fossil-fuel fluxes (fossil CO_2 fluxes only)
- GCP-GridFED fossil-fuel fluxes, v. 2021.3 (fossil CO_2 emission and O_2 uptake tracers)

Required Output for 2009-2018

Concentrations matching:

1. Primary aircraft campaigns
   - HIPPO, ORCAS, and ATom
2. Scripps O_2 Program stations
   - 10 station records
3. ARSV Laurence M. Gould
4. AIST/JMA aircraft samples

Optional Output

- T, P, and Q
- All ObsPack files
- Additional Fixed Sites
- Additional Shipboard Records
- 3D fields
- Earlier records

Experiment protocol with fluxes and more details available here:
https://docs.google.com/document/d/1xcFHXuTbaldQTHUUnNz7aVItHhR6HWexPlW8JaKUFuc

Contribution details

Abbreviation	Required ObsPack	Optional Full ObsPack	Optional Additional Ship	Optional Additional Fixed	Optional 3D	Optional T, P, Q	Other
CAM-SD	X				X	X	Winds, BL height, land CO2
CAMS_LMDZ	X						
CTE_TM5	X	X		X	X	X	Hz winds; BL height; CTE components
Jena_TM3	X	X					
MIROC4-ACTM	X		X				Additional selected ObsPack records, inversion CO2
NICAM-TM (glevel-5)	X	X	X	X	X	X	2D surface fields
NICAM-TM (glevel-6)	X	X	X	X	X	X	2D surface fields
NIES	X		X	X			

Initial processing

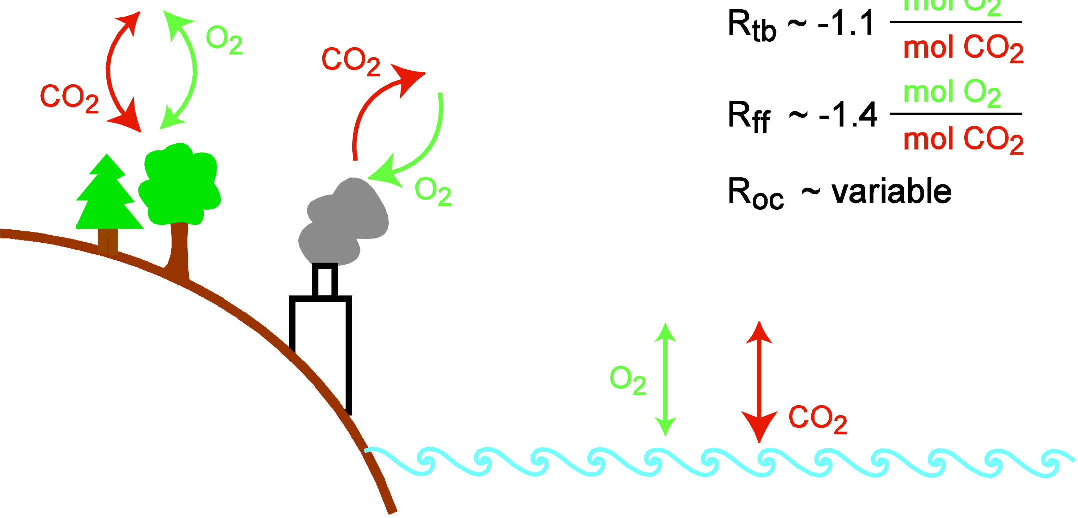
1. Calculation of derived APO tracers (in addition to apo_jena):
    - apo_diss from Garcia and Keeling (2001) O_2, Landschützer et al. (2016) CO_2, and ERA N_2 air-sea fluxes
    - apo_cesm from CESM O_2, CO_2, and N_2 air-sea fluxes
    - apo_gridfed from GridFed O_2 and CO_2 fossil fluxes
    - apo_oco2mip CO_2 fossil fluxes and a global O_2:CO_2 ratio of -1.38
2. All required output reprocessed into ObsPack format with common variable names
3. All reprocessed and original output on a Globus endpoint with public access planned

    (contact Britt Stephens if interested in collaborating sooner than public release)

Planned and potential analyses

1. Extrapolation of aircraft observations to hemispheric-scale SNO (Stephens and Jin)
2. Evaluation of diabatic mixing in transport models (Jin)
3. Evaluation of ocean and fossil contributions to O_2:CO_2 ratios observed at terrestrial forest sites (Stephens and Battle)
4. Evaluation and correction of aircraft-based estimates of Southern Ocean CO_2 exchange (Jin and Vance)
5. Evaluation and correction of aircraft-based estimates of Southern Ocean O_2 exchange (Stephens and Jin)
6. Evaluation and improvement of flux products (TBD)
7. Evaluation of ocean contributions to APOff (TBD)

Atmospheric O_2 and CO_2 Exchange

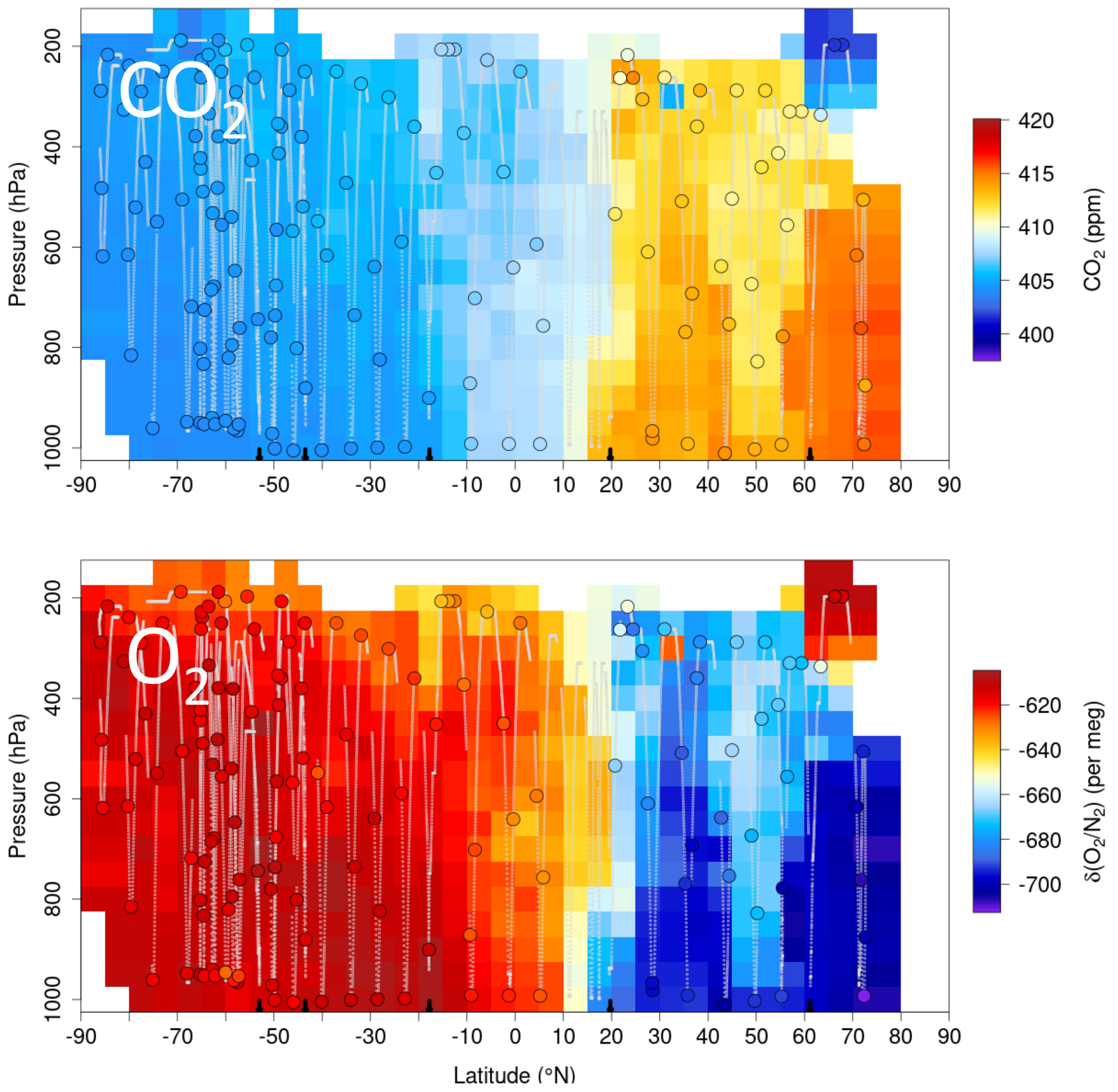


$R_{tb} \sim -1.1 \frac{\text{mol } O_2}{\text{mol } CO_2}$

$R_{ff} \sim -1.4 \frac{\text{mol } O_2}{\text{mol } CO_2}$

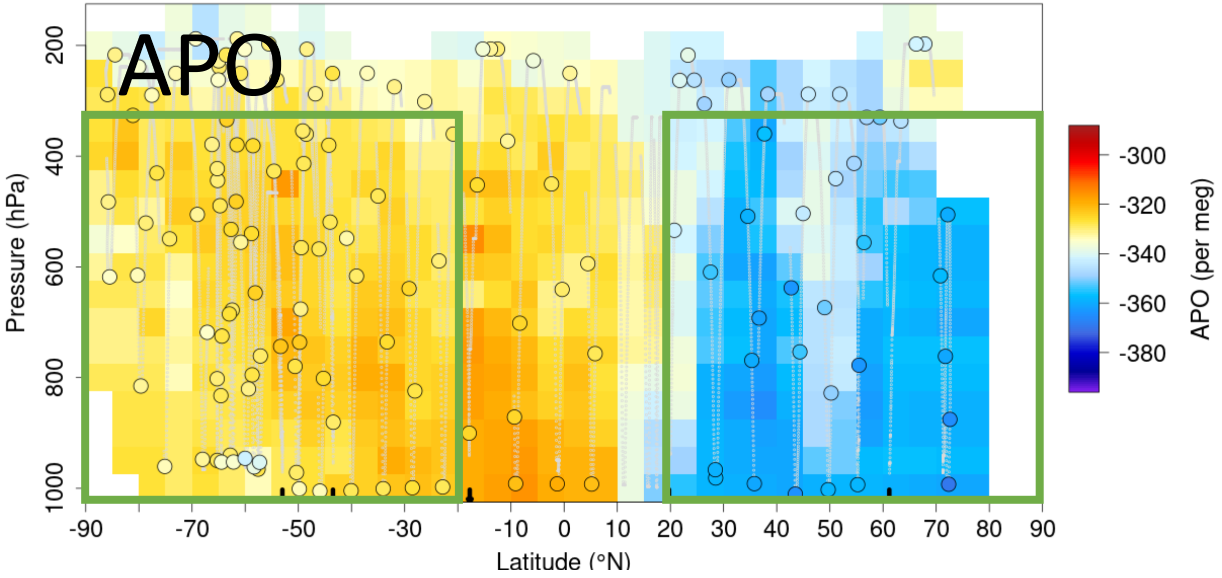
R_{oc} ~ variable

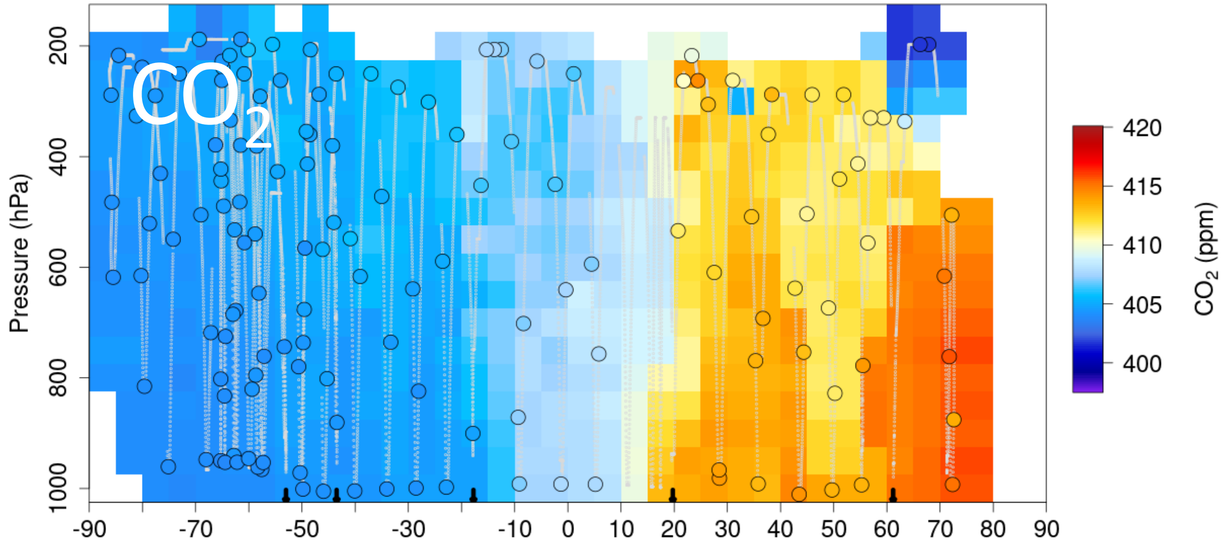
ATom-4 Southbound (27 Apr – 9 May, 2018)

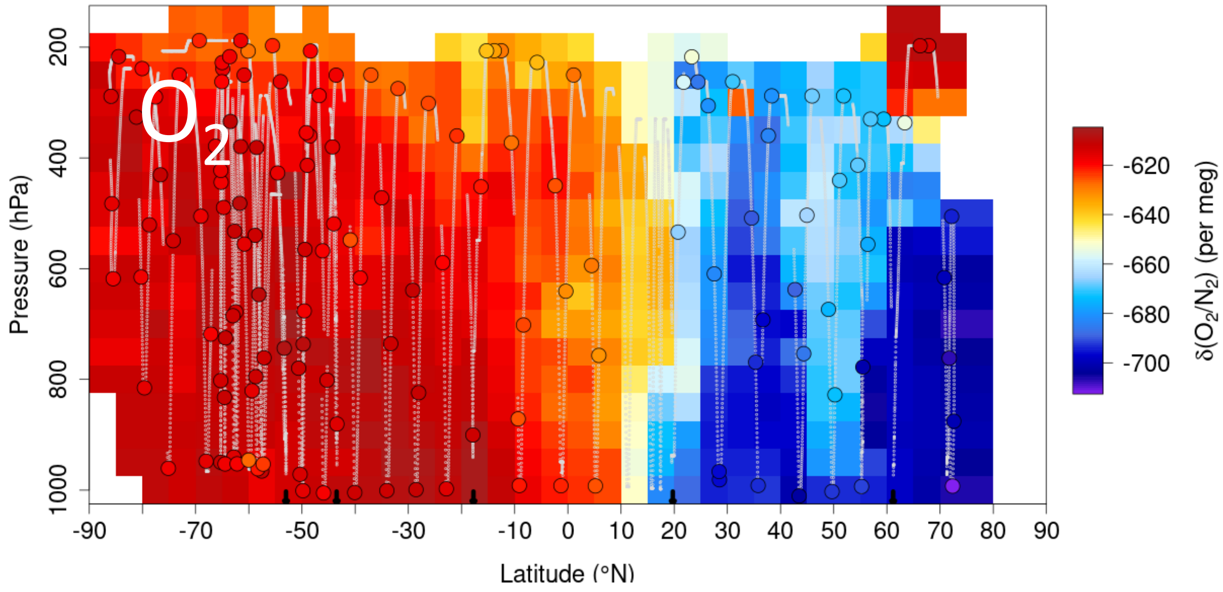


Stephens et al., AMT, 2021

ATom-4 Southbound (27 Apr – 9 May, 2018)

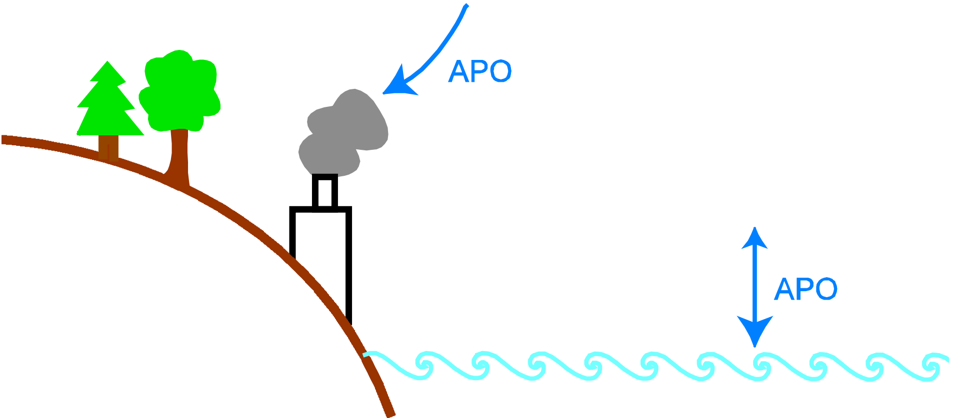




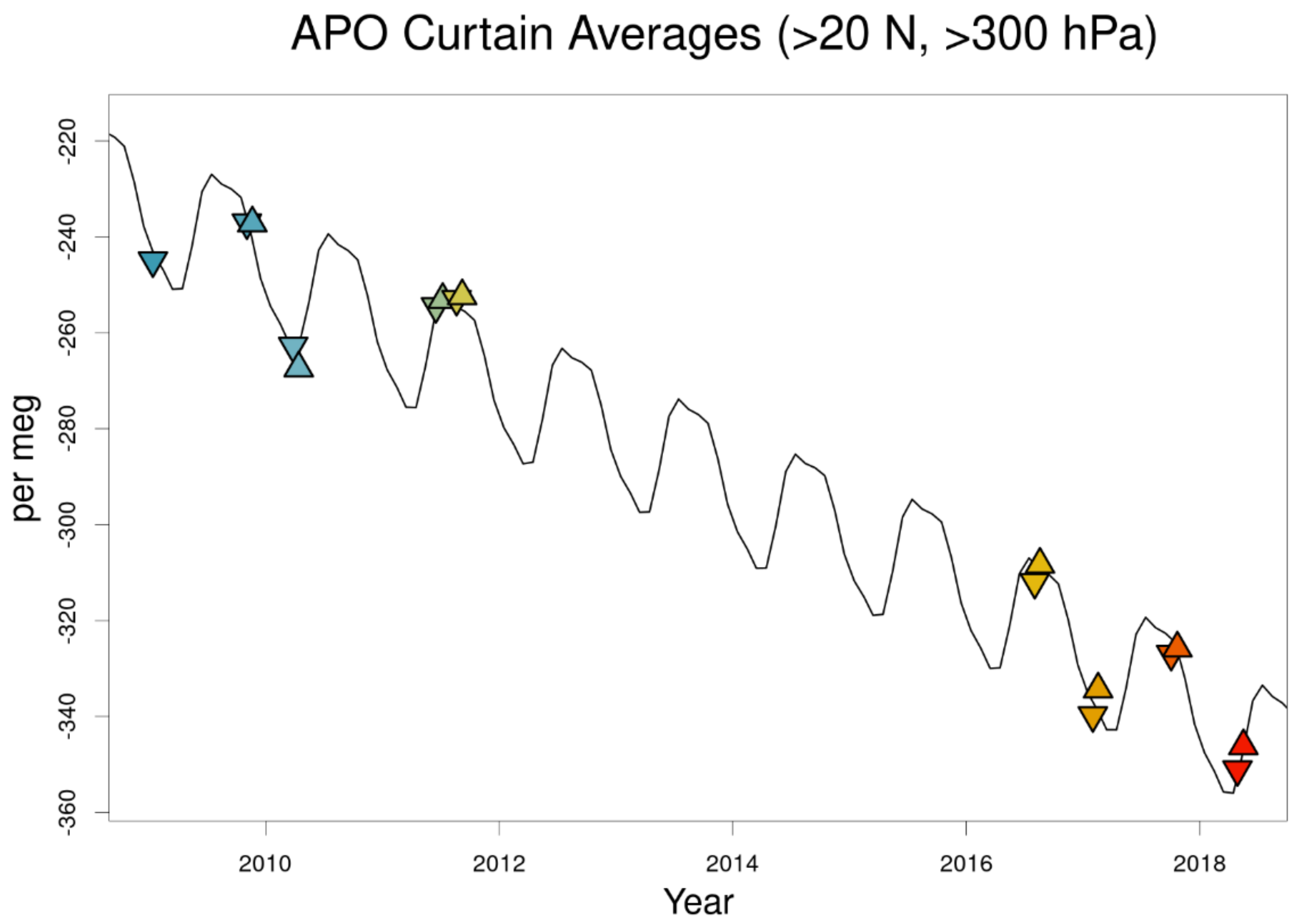


Atmospheric Potential Oxygen

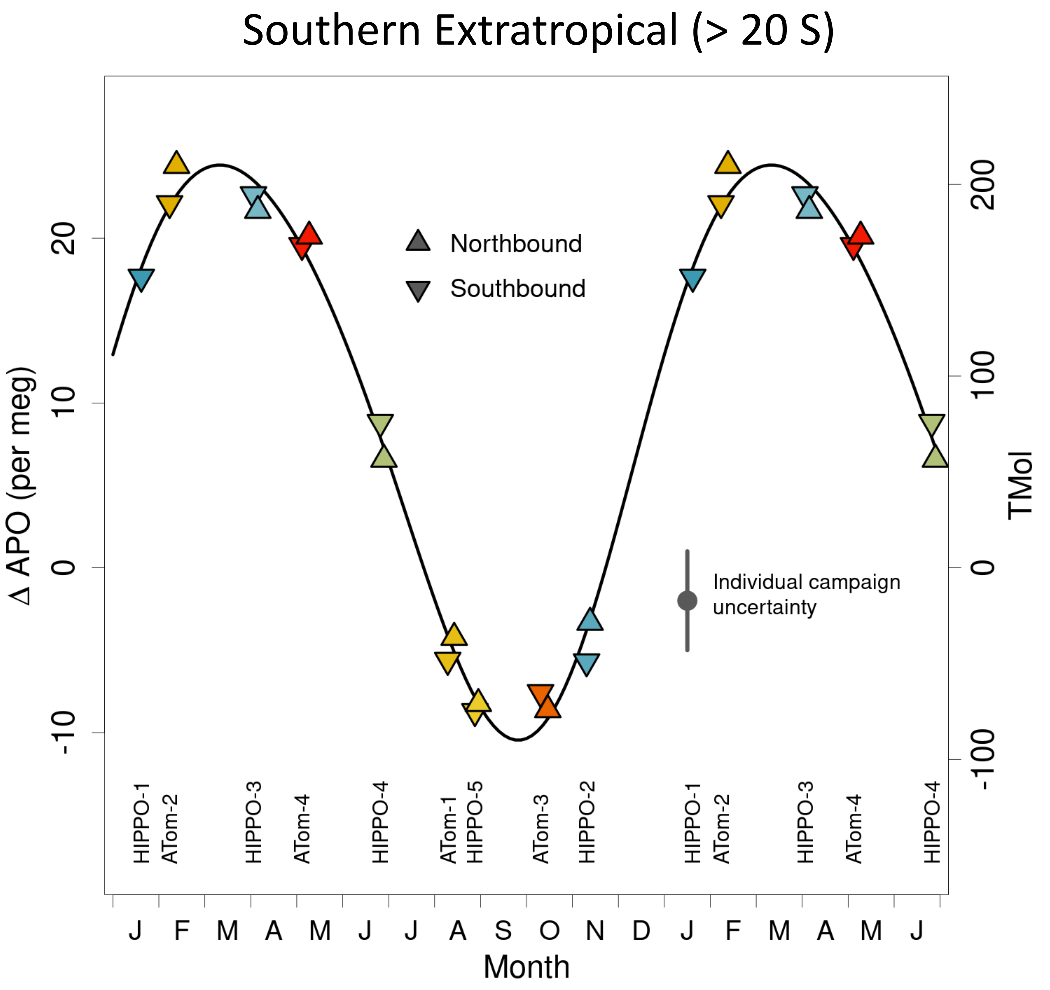
$$APO = O_2 + 1.1*CO_2$$

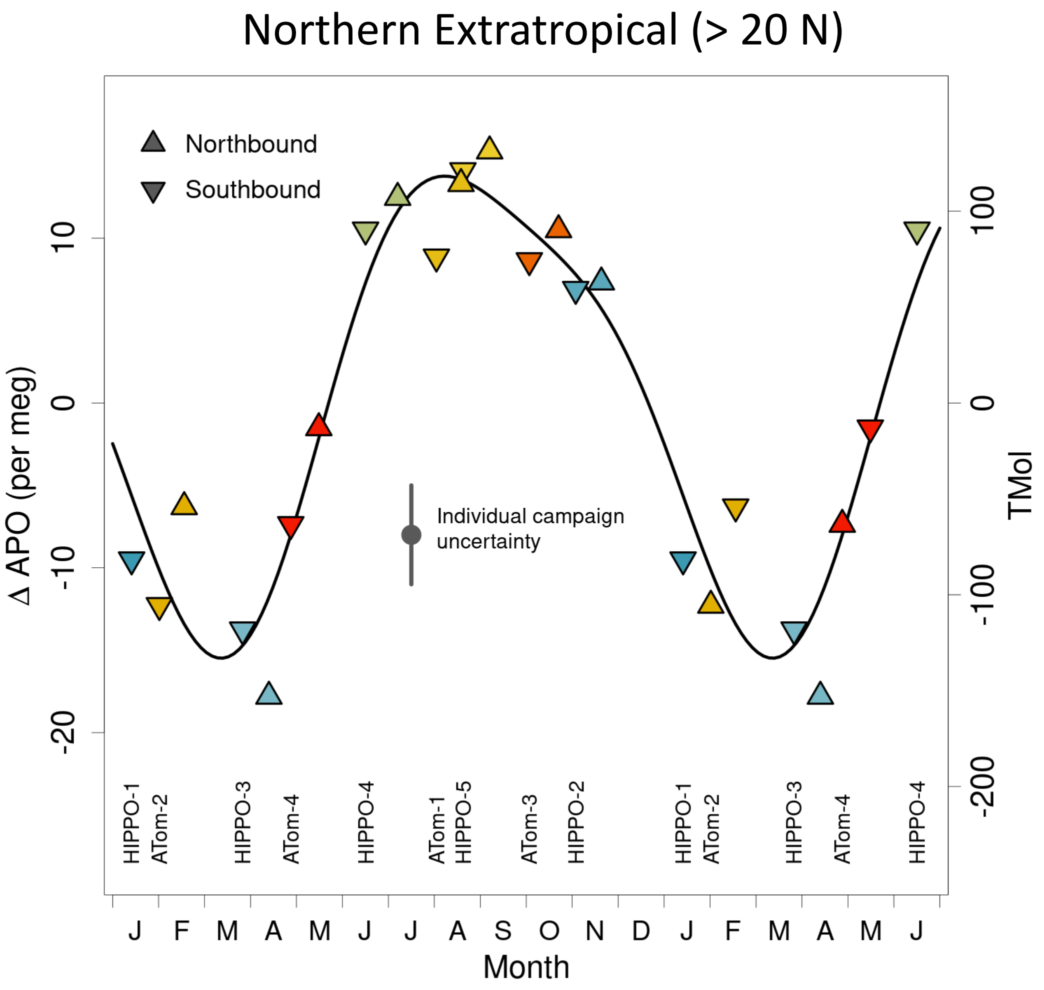


Stephens et al., AMT, 2021


APO Curtain Averages (>20 N, >300 hPa)
per meg
-220
-240
-260
-280
-300
-320
-340
-360
2010
2012
2014
2016
2018
Year

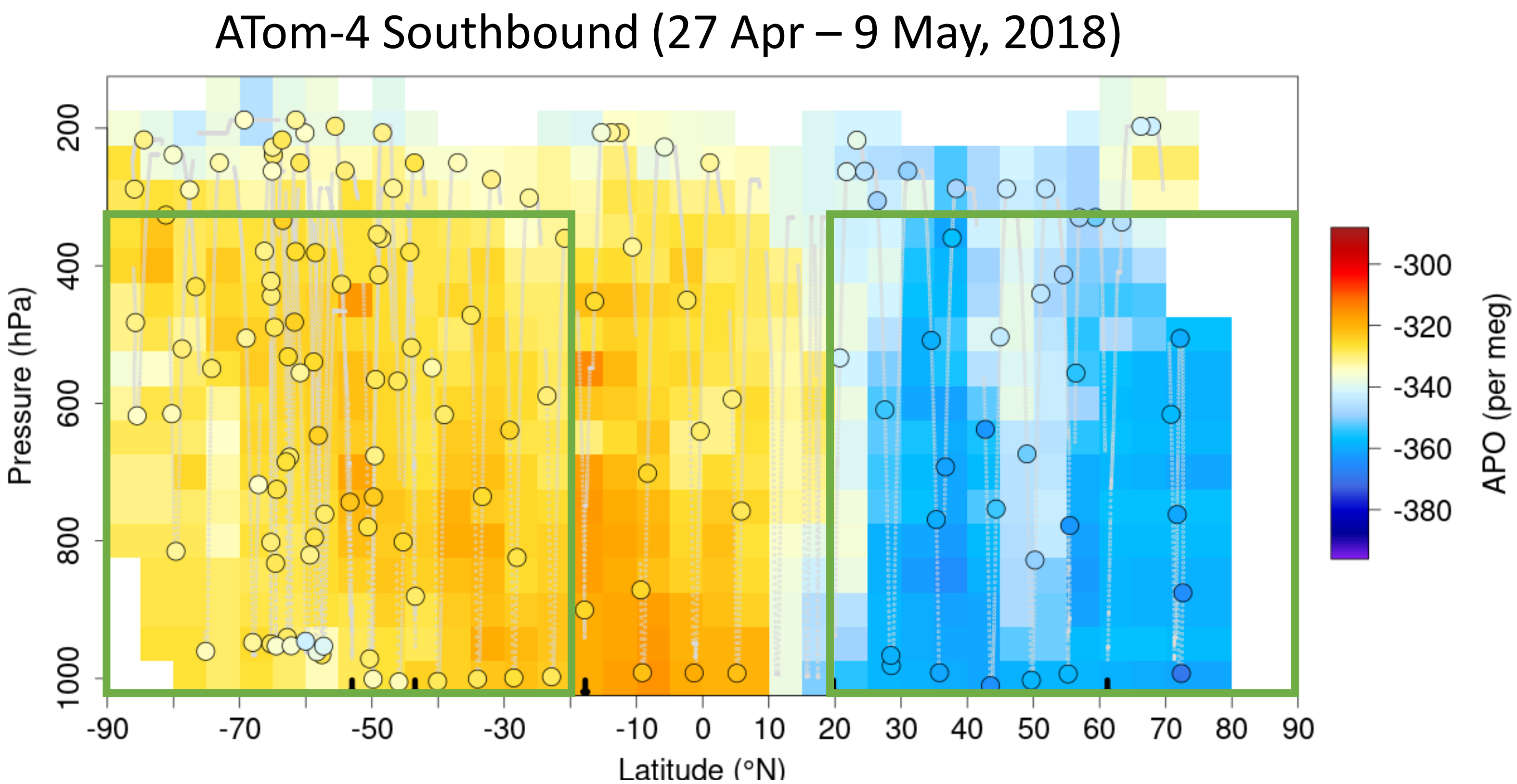
Tropospheric average APO concentration





- Poleward of 20 degrees, > 300 hPa, N_2O stratosphere filter, pressure and cos(lat) weighted

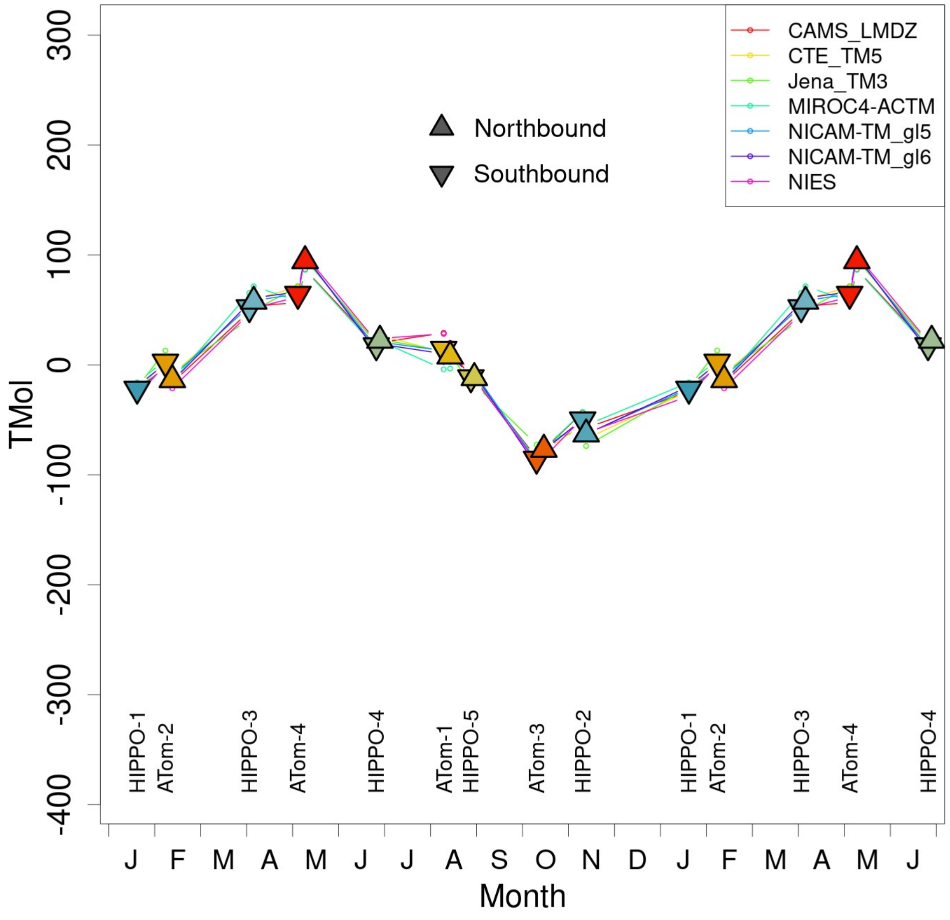
Single-box inversions for Southern and Northern Extratropics



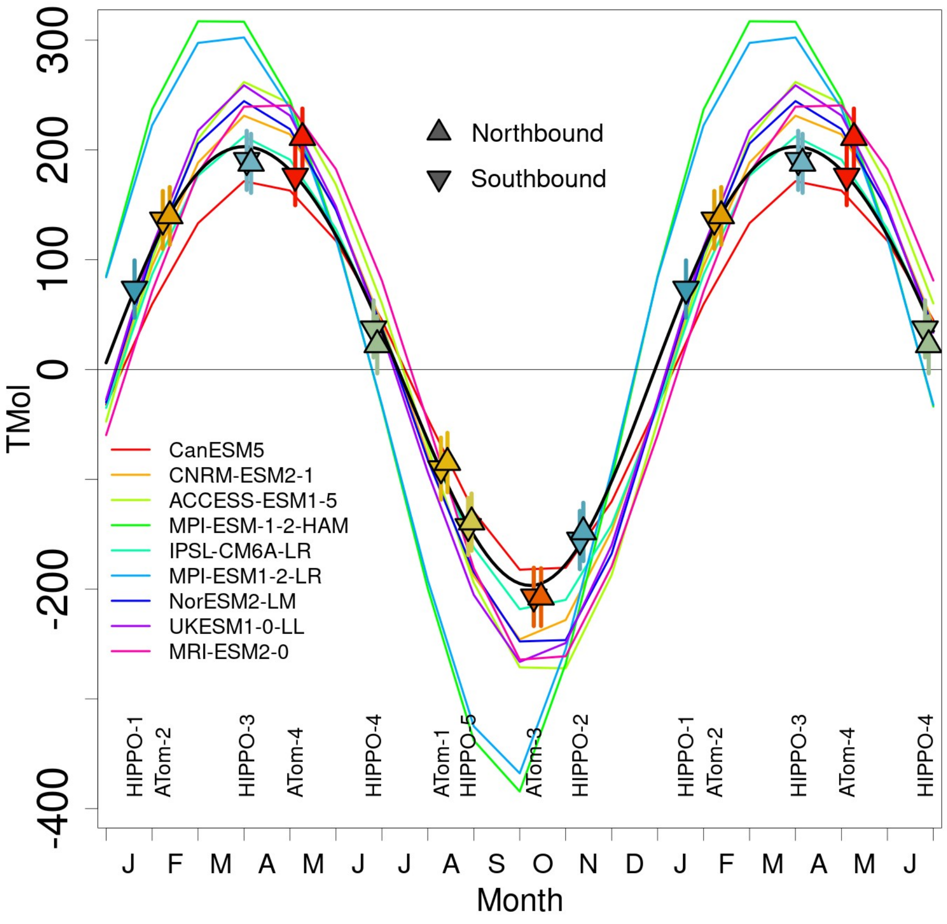
- APO Forward Experiment simulations used to correct for spatial sampling bias and mixing out of the box
- Corrections derived from the difference between box average APO concentration and integrated APO flux

HIPPO and ATom southern extratropical APO curtain averages

Southern Extratropical Spatial / Mixing Correction

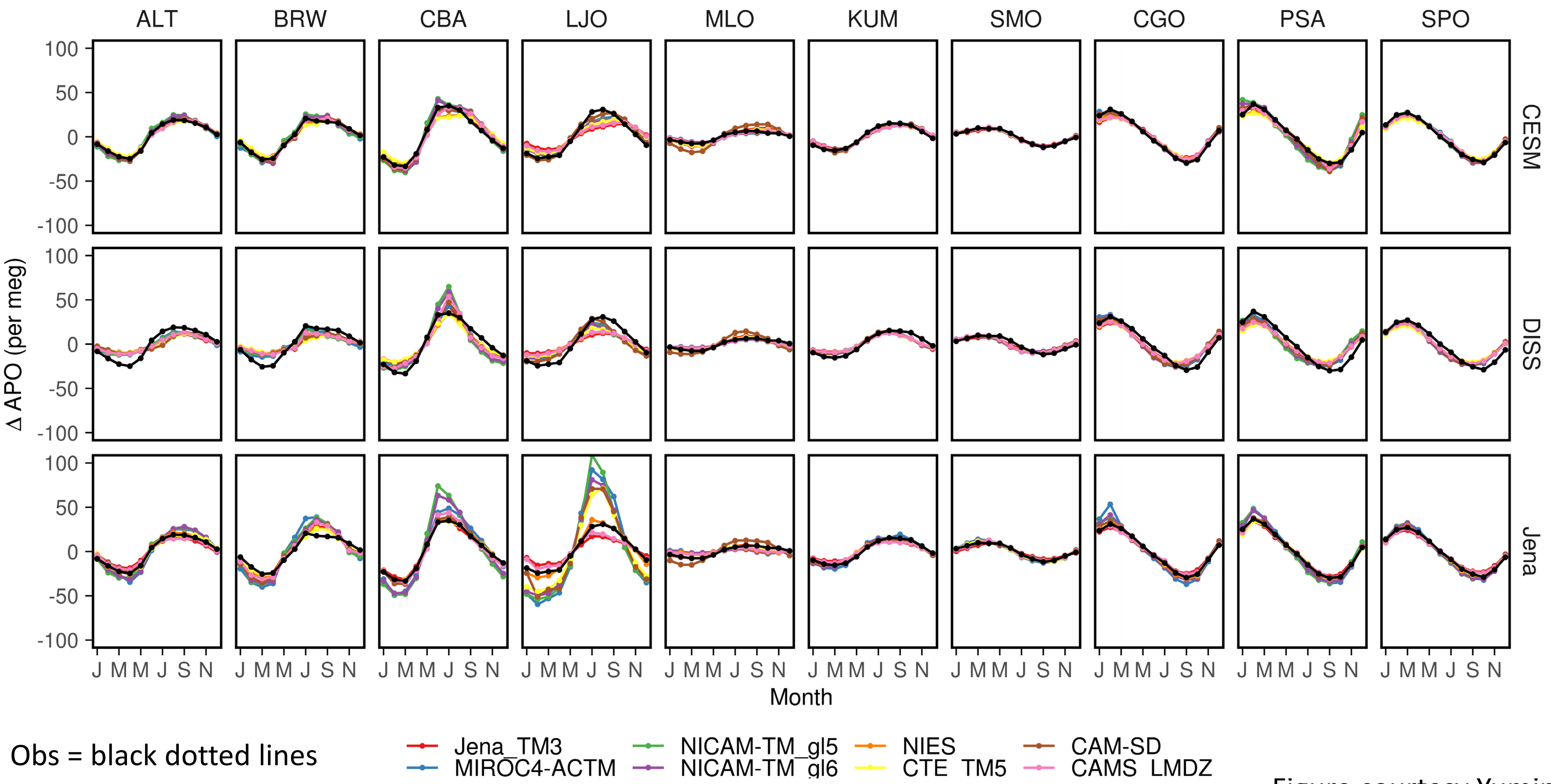


Cumulative 90S-20S APO Flux and CMIP6



(see a more advanced approach in Yuming Jin's talk this afternoon)

Station APO seasonal cycle comparison

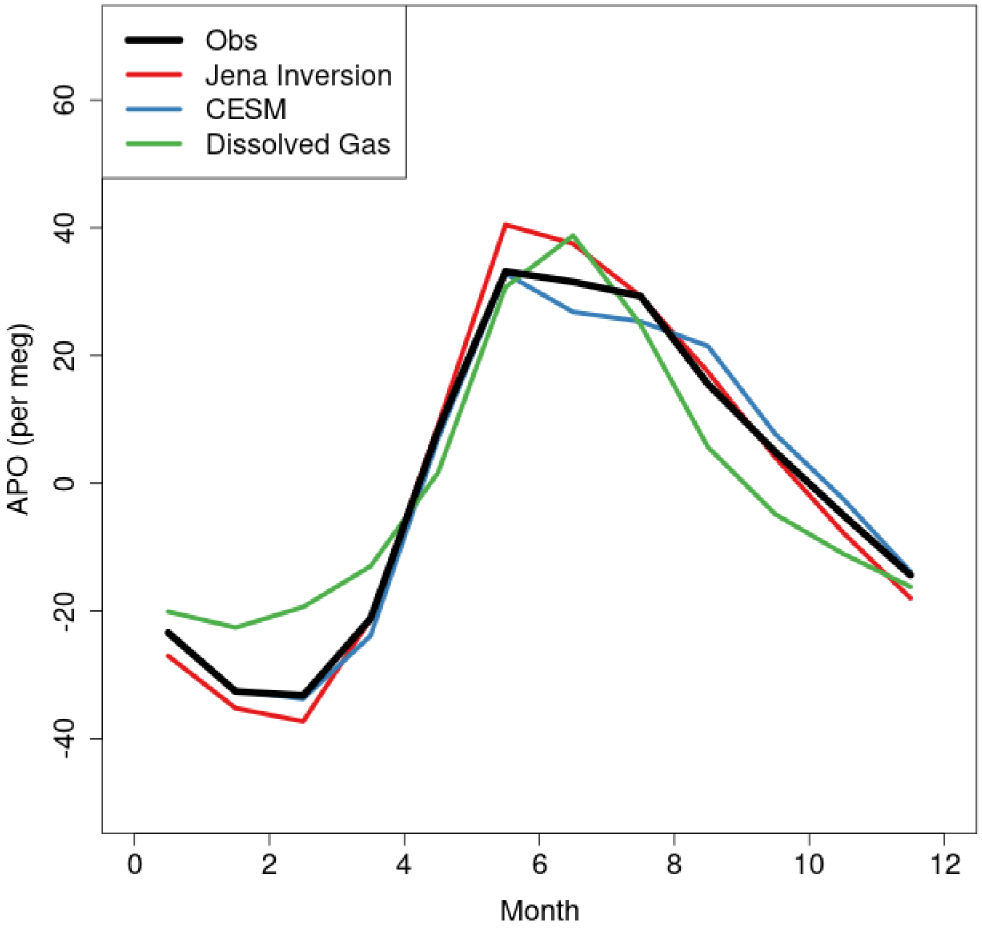


Obs = black dotted lines

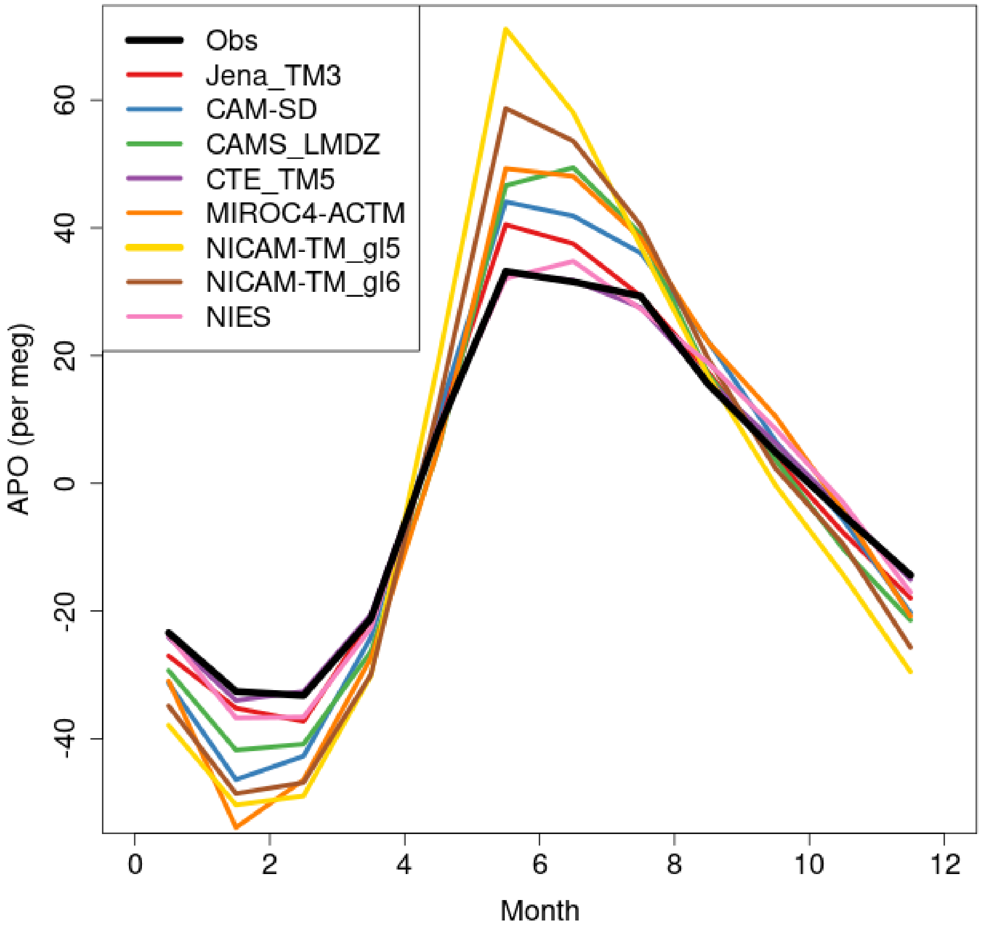
Figure courtesy Yuming Jin

APO Seasonal Cycles at Cold Bay, Alaska

TM3-Jena Transport of Various APO Tracers

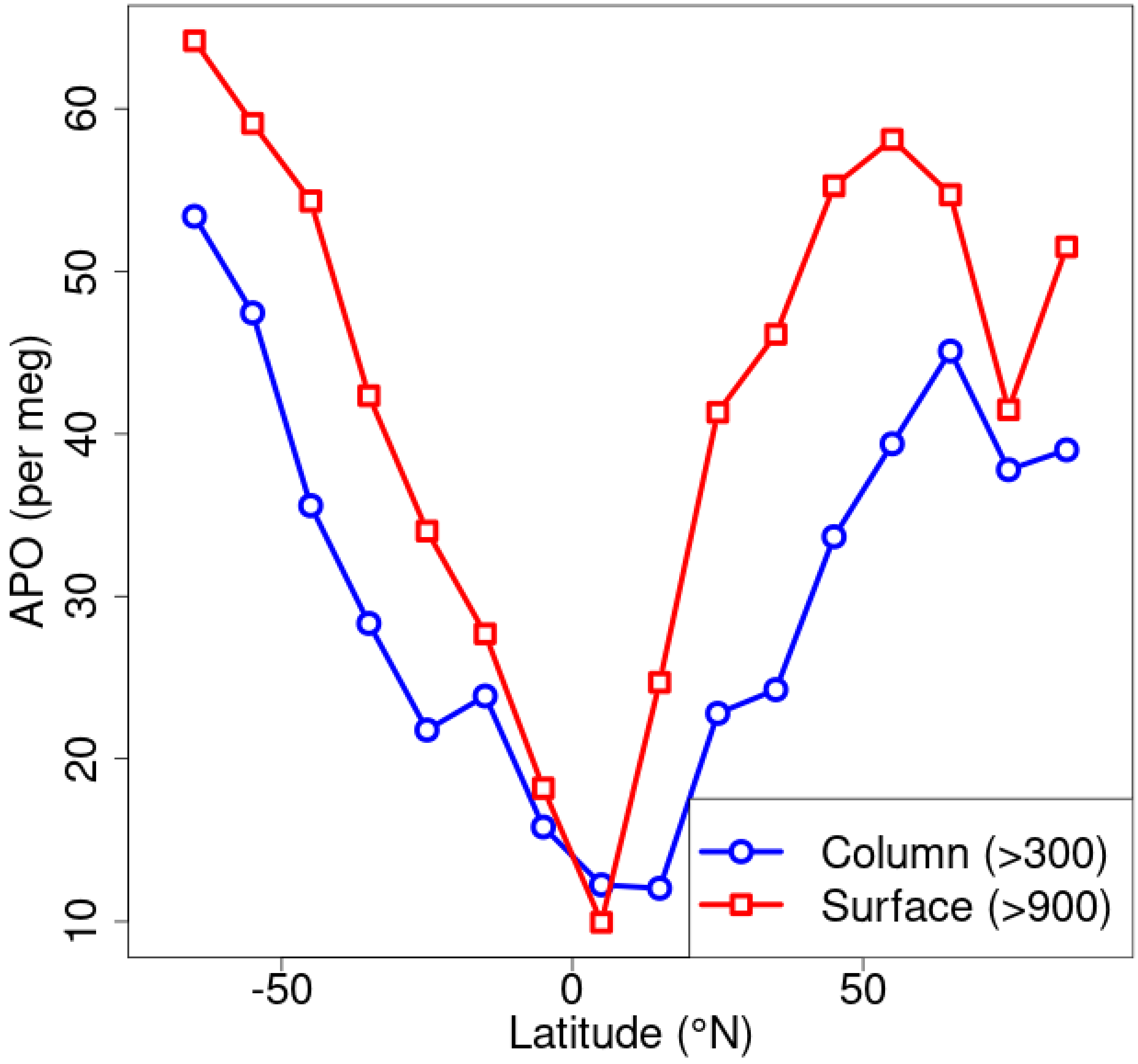


Various Model Transport of Jena Inversion Fluxes



Trend for each record removed, 2002-2019 means.

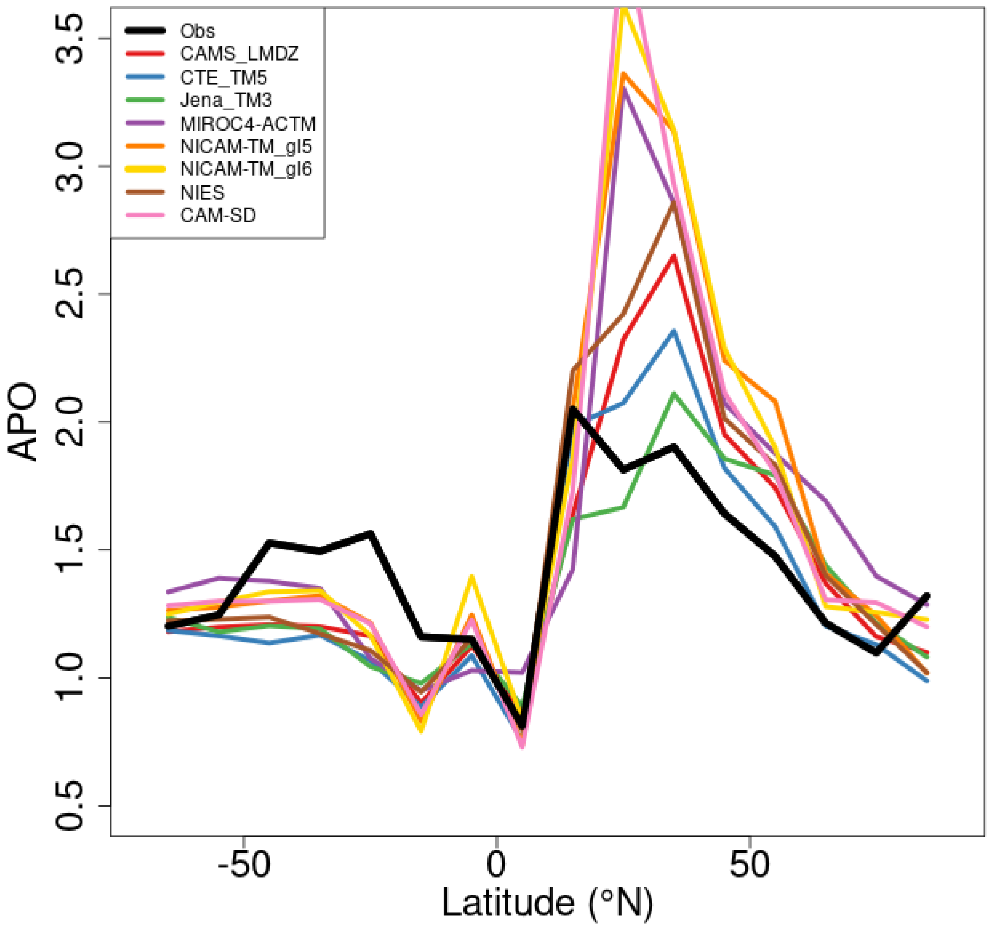
Observed Column Mean and Near-surface Seasonal APO Amplitudes



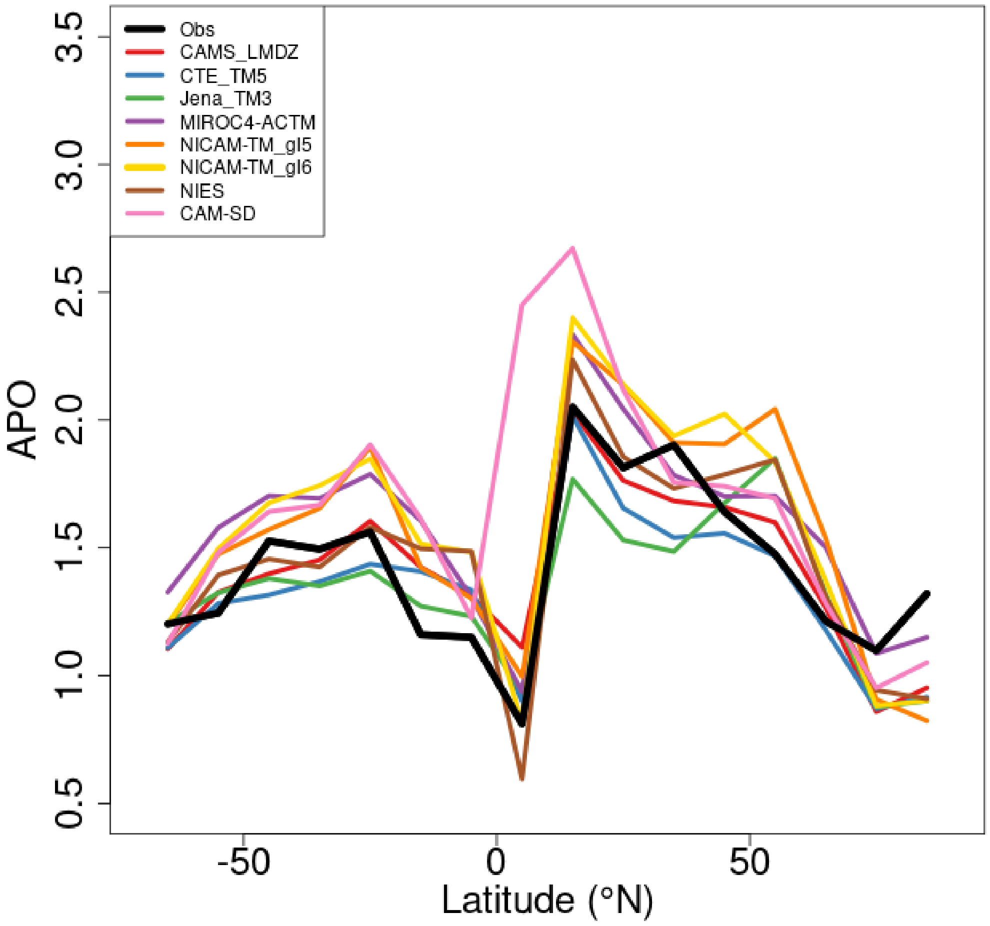
Seasonal APO Amplitude Ratio

Surface (> 900 hPa) : Column (1000 – 300 hPa)

Jena APO Inversion Fluxes

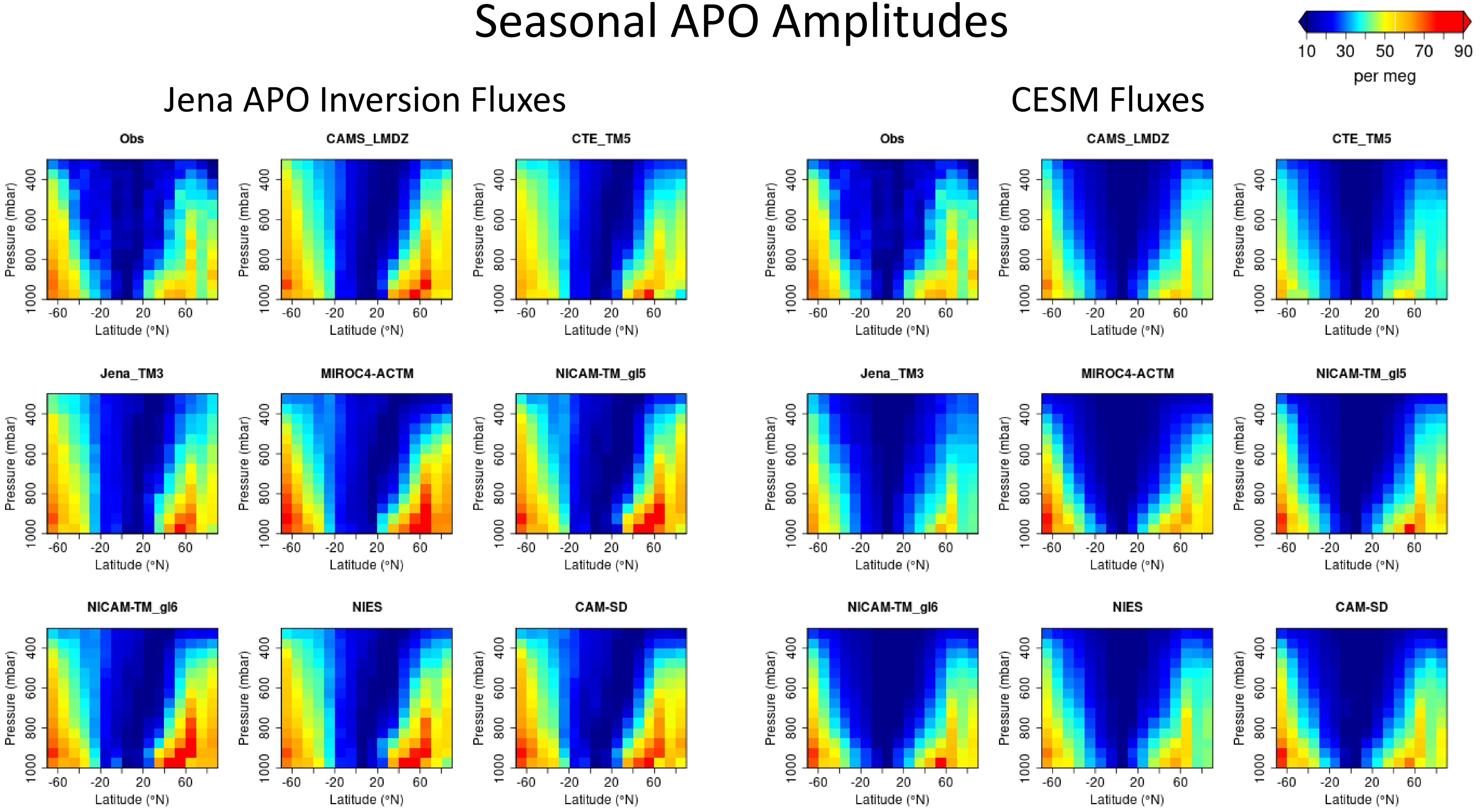


Dissolved Gas Fluxes

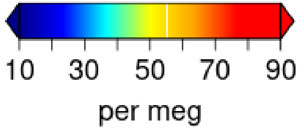


Surface APO amplitude reflects differences in speed of seasonal changes in fluxes more than in vertical mixing

Seasonal APO Amplitudes

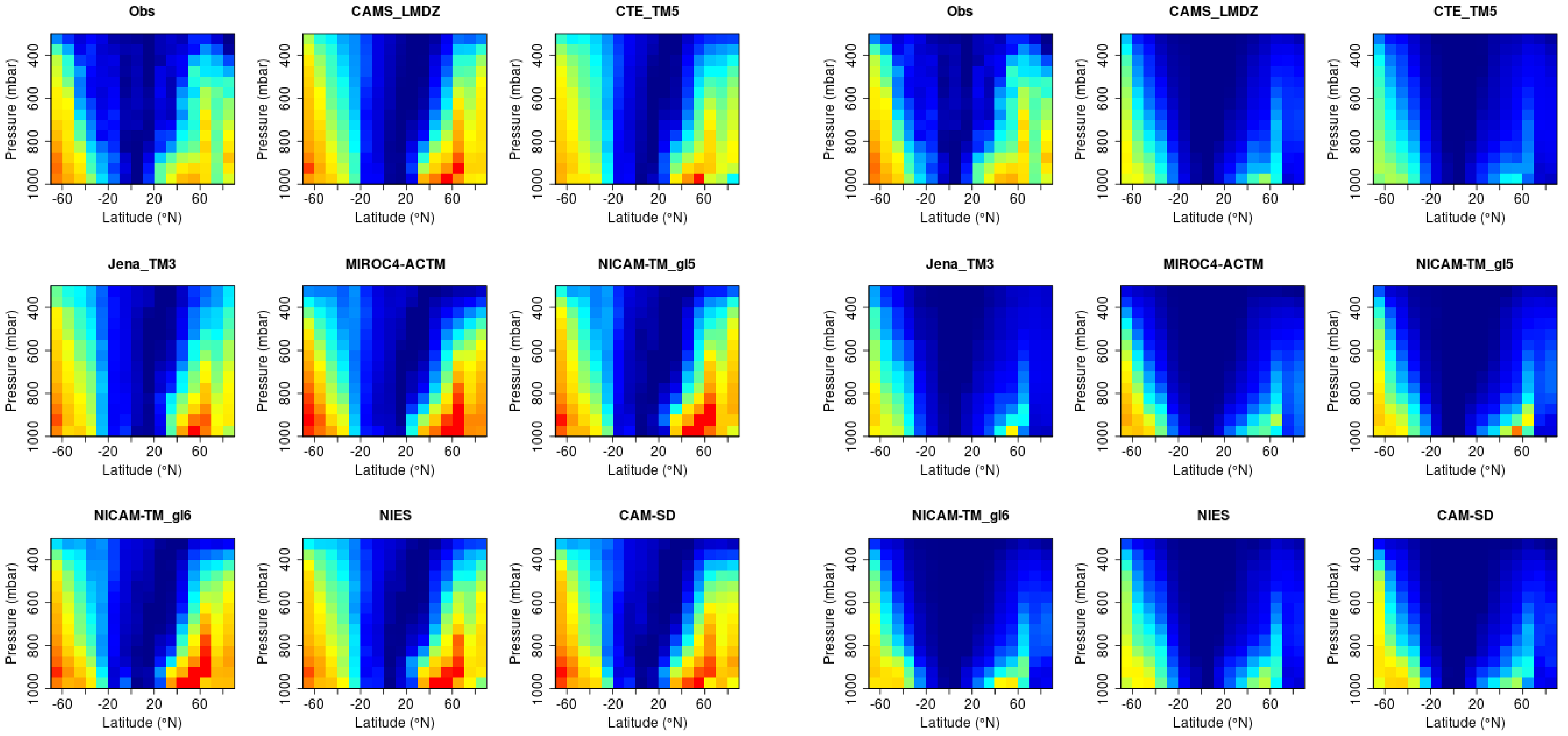


Seasonal APO Amplitudes



Jena APO Inversion Fluxes

Dissolved Gas Fluxes



Annual average APO

CESM = apo_cesm + apo_oco2mip

DISS = apo_diss + apo_oco2mip

Jena = apo_jena + apo_oco2mip

1. Detrended observation or model data using linear trend at CGO of the corresponding model (or observation).
2. Binned data into pressure-latitude bins.
3. Fit a 2-harmonic with offset to each bin. The annual average APO is calculated as the offset.

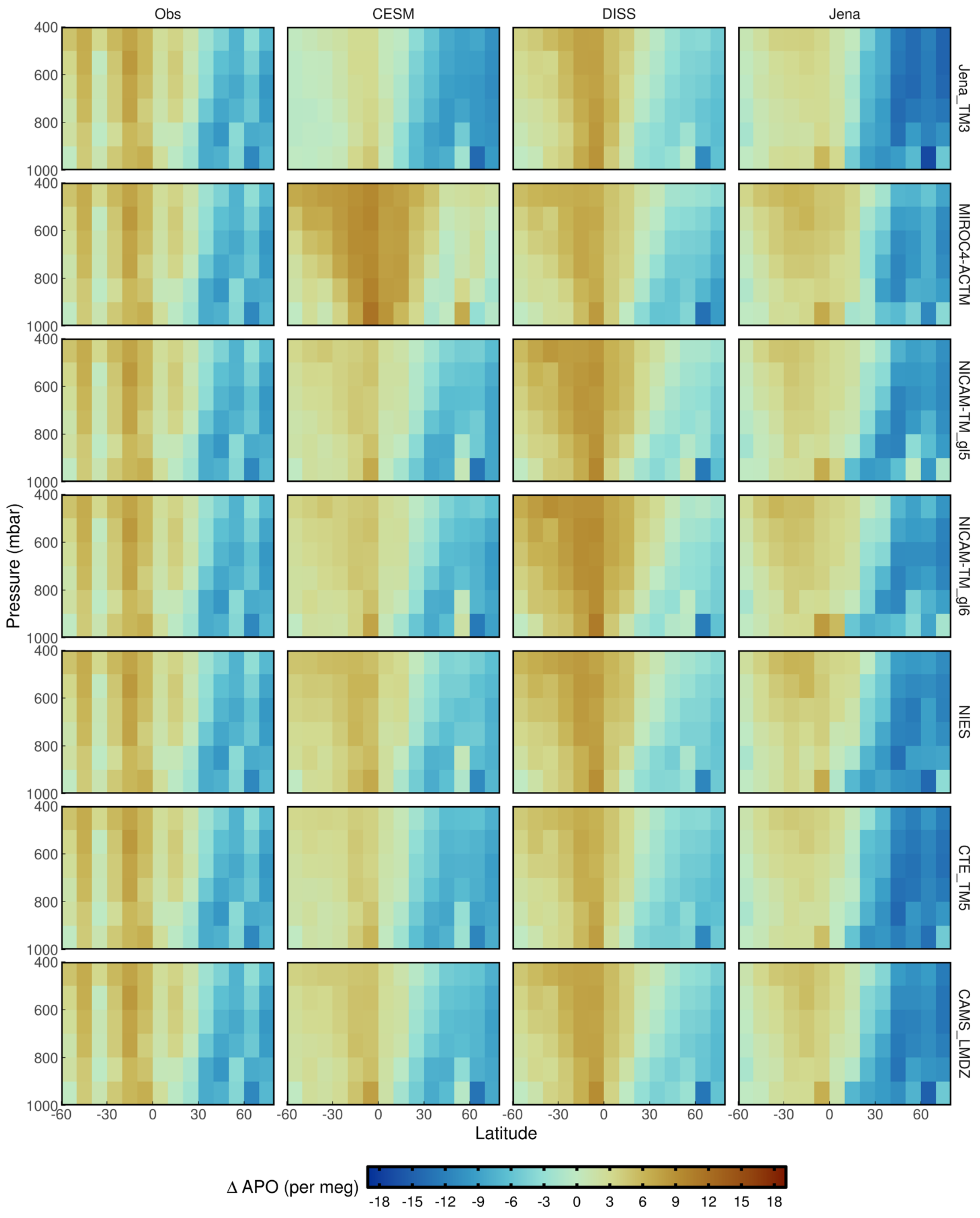
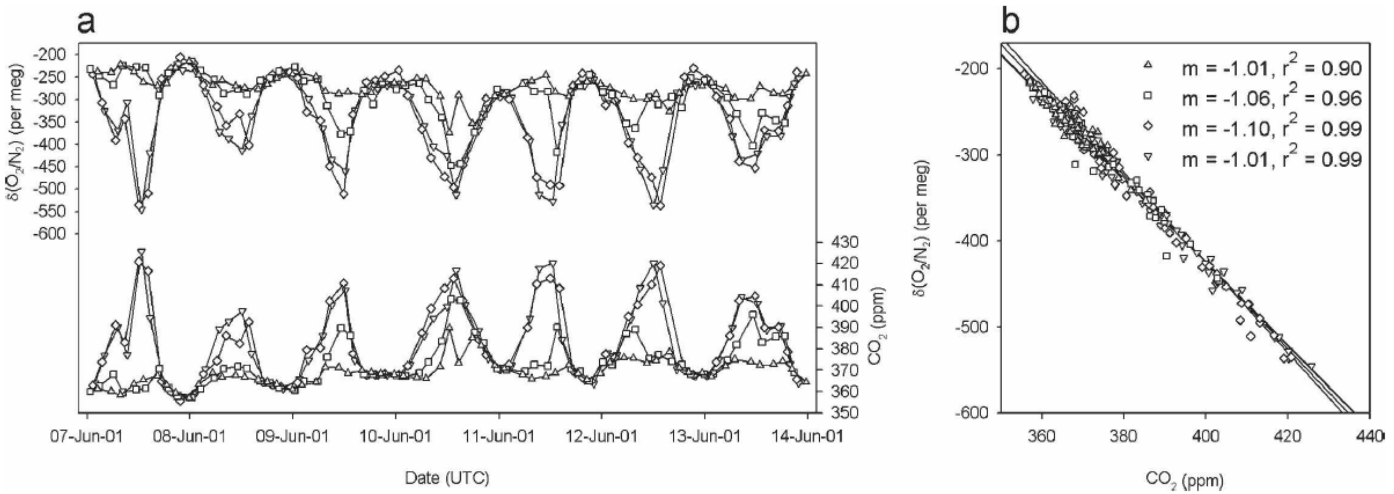


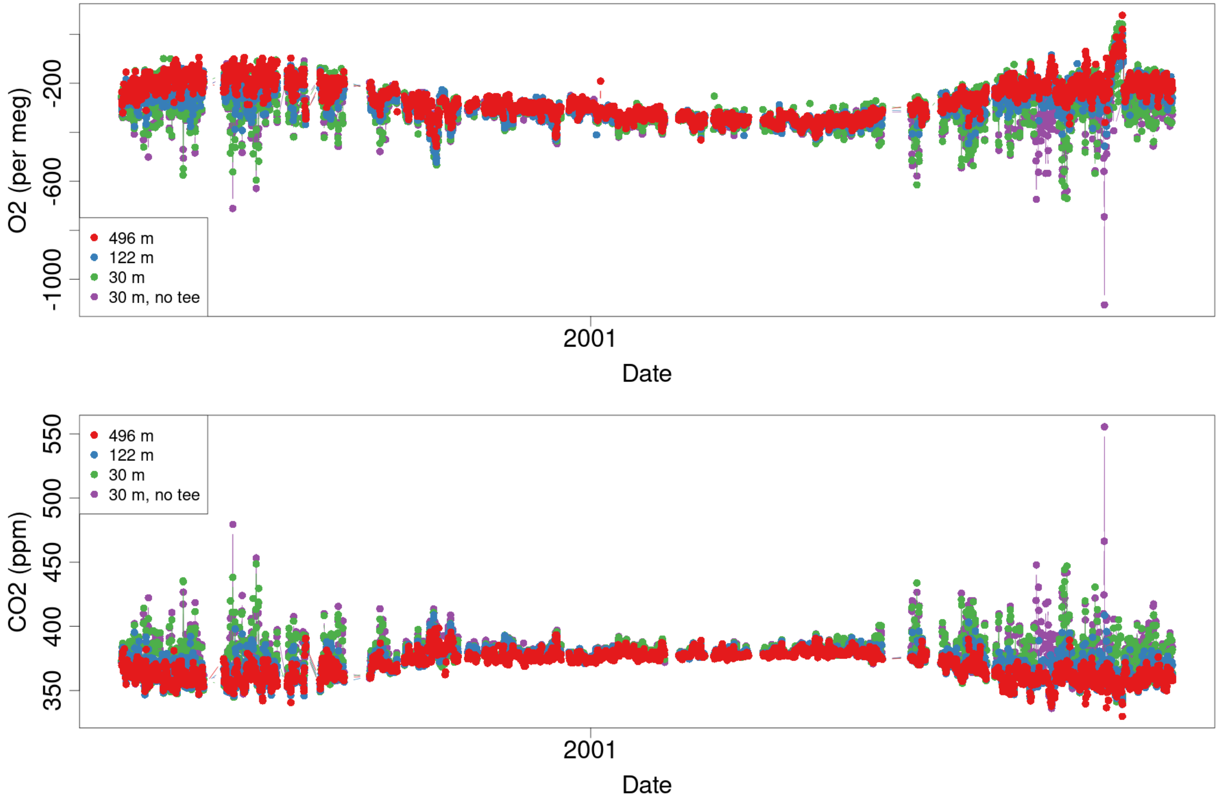
Figure courtesy Yuming Jin

Ecosystem O_2:CO_2 Ratios

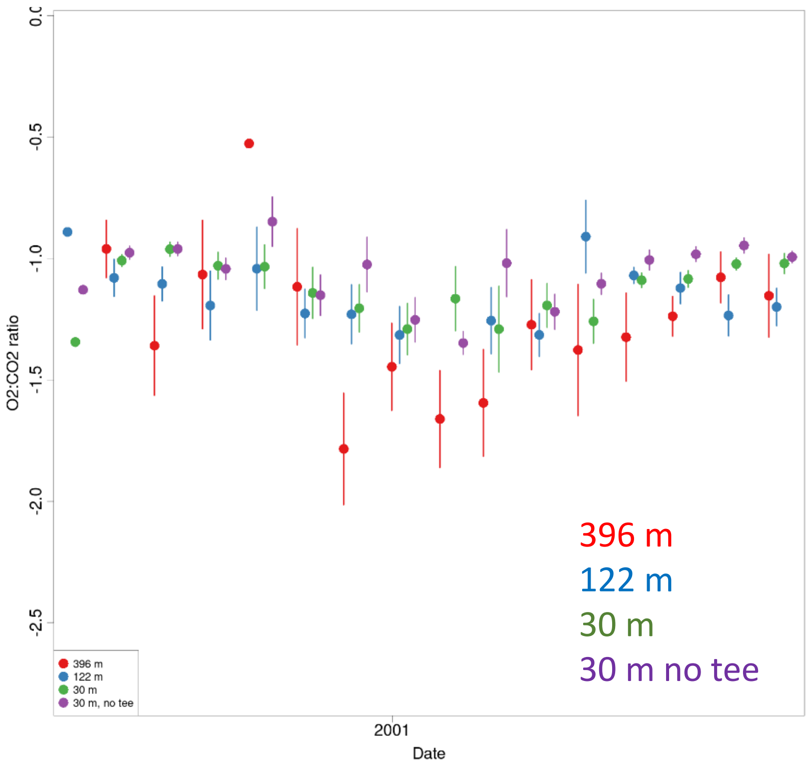


Stephens et al., JTech, 2007

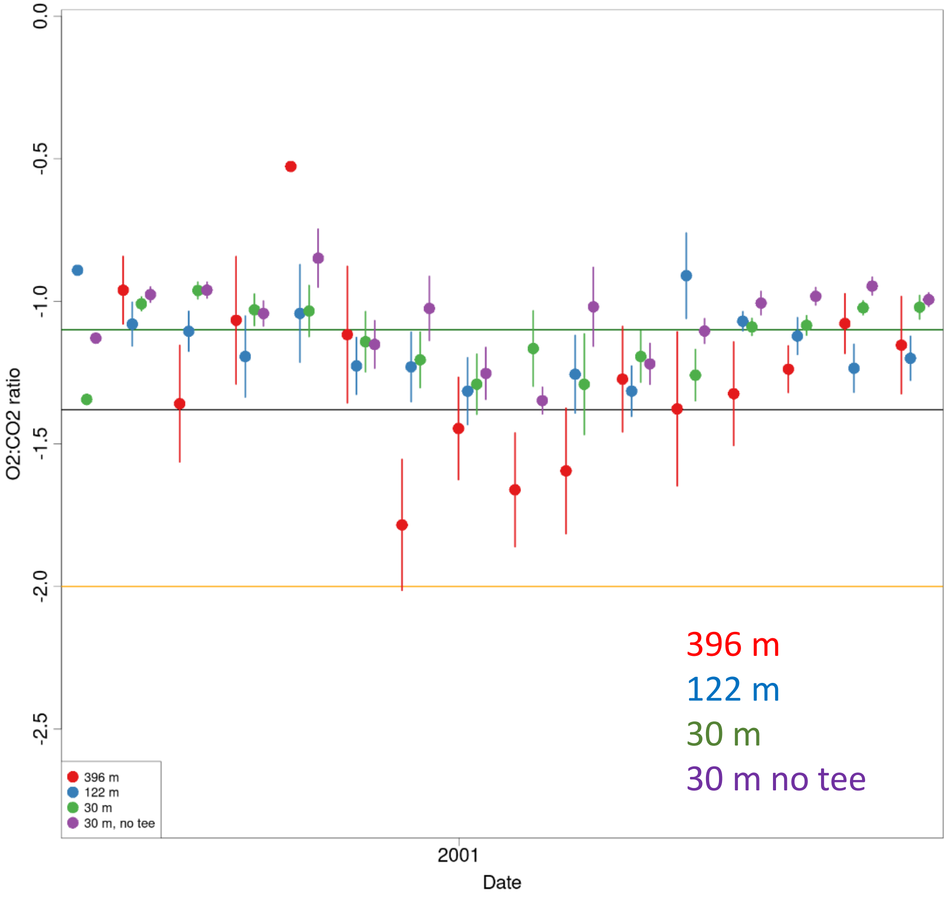
WLEF O_2 and CO_2 (2000-2001)



WLEF Nighttime Buildup Ratios



WLEF Nighttime Buildup Ratios



Harvard Forest Day and Night Ratios

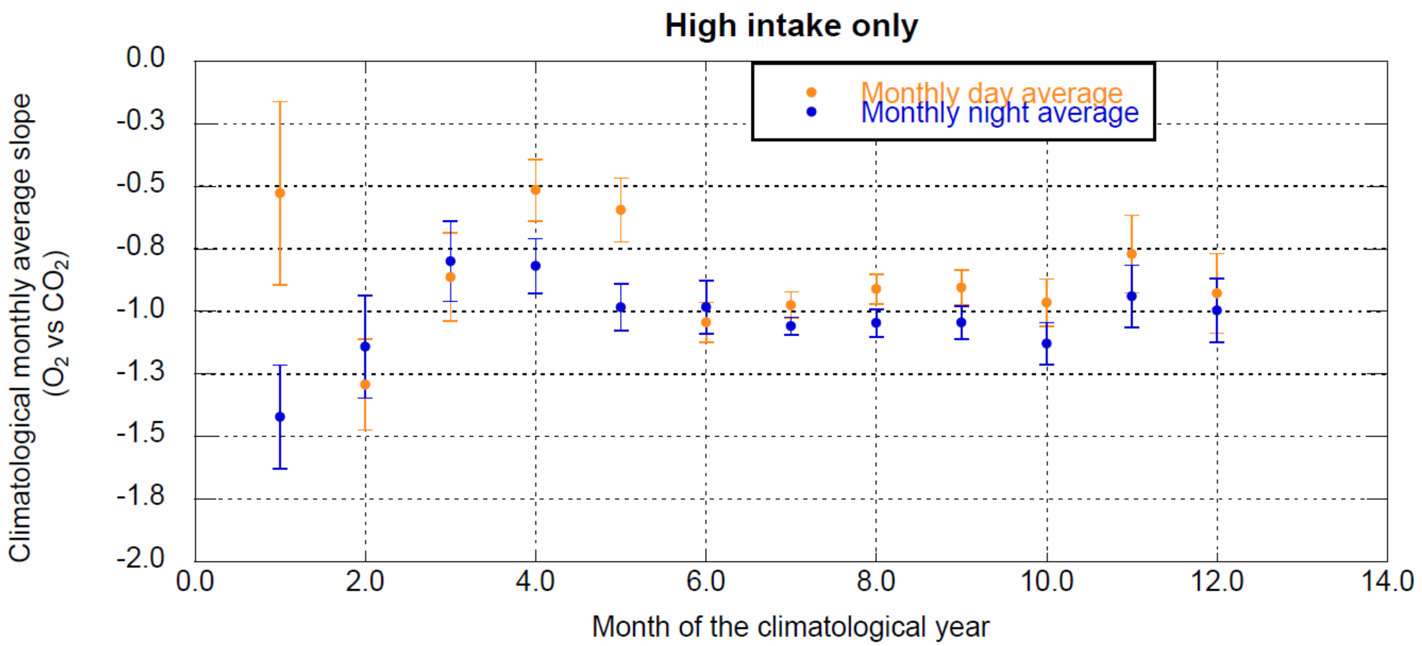
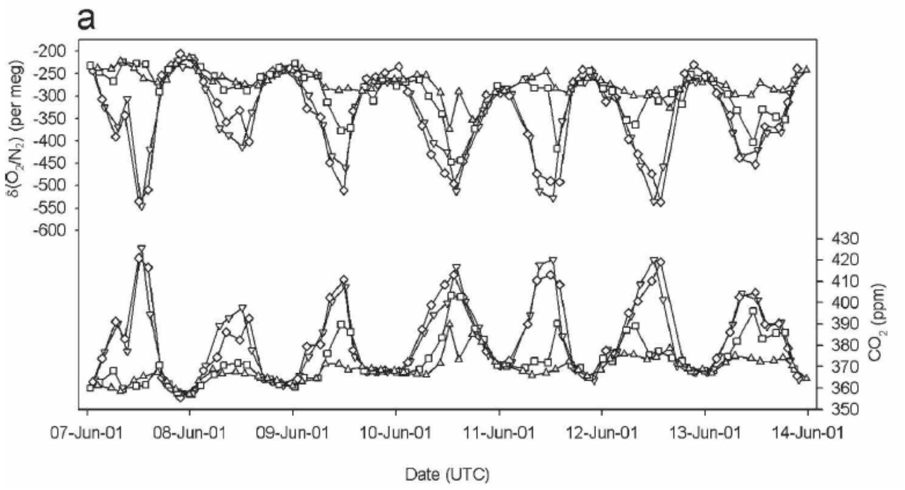


Figure courtesy Mark Battle

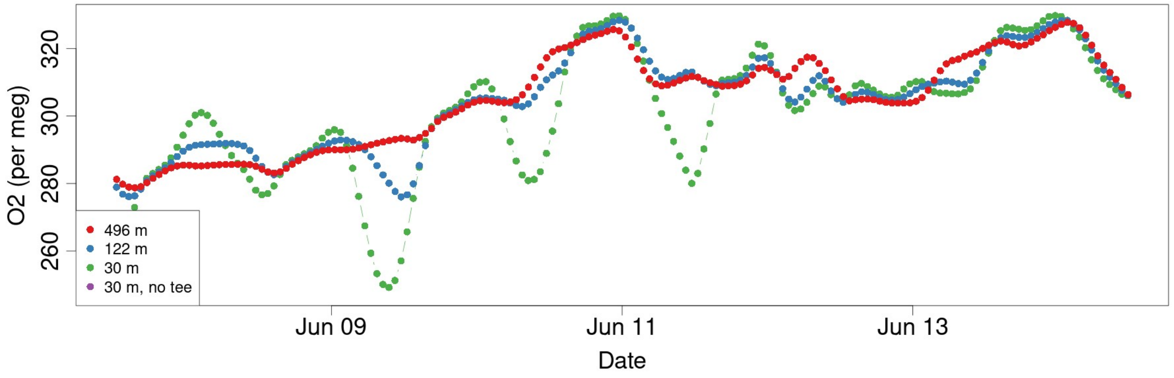
Modeled WLEF O_2 and CO_2

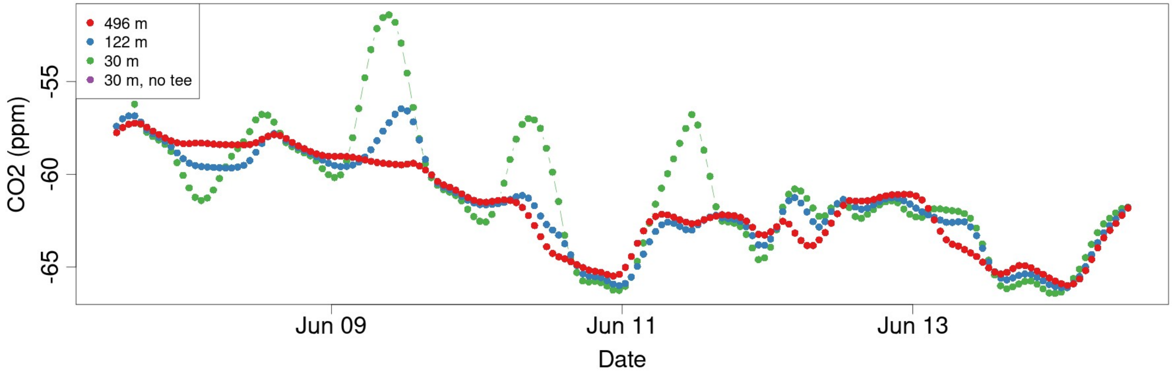
CT with 34 levels has much larger diurnal cycles than CTE with 25



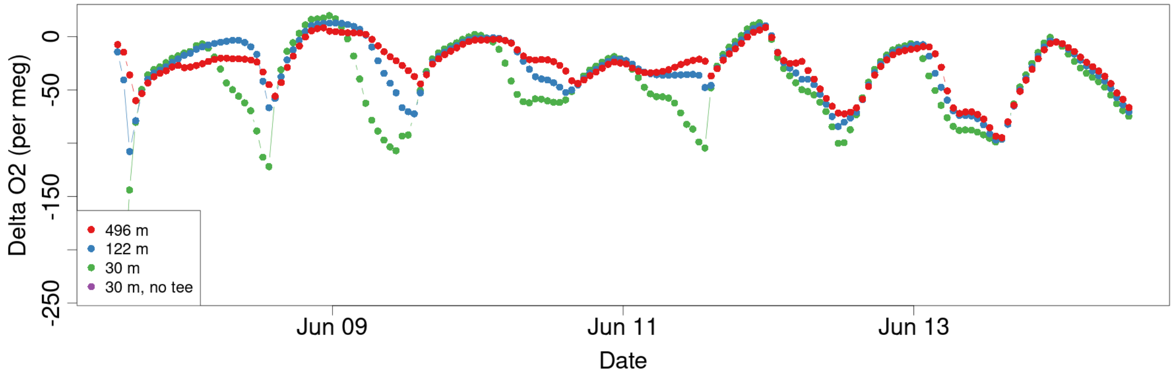
Stephens et al., JTech, 2007

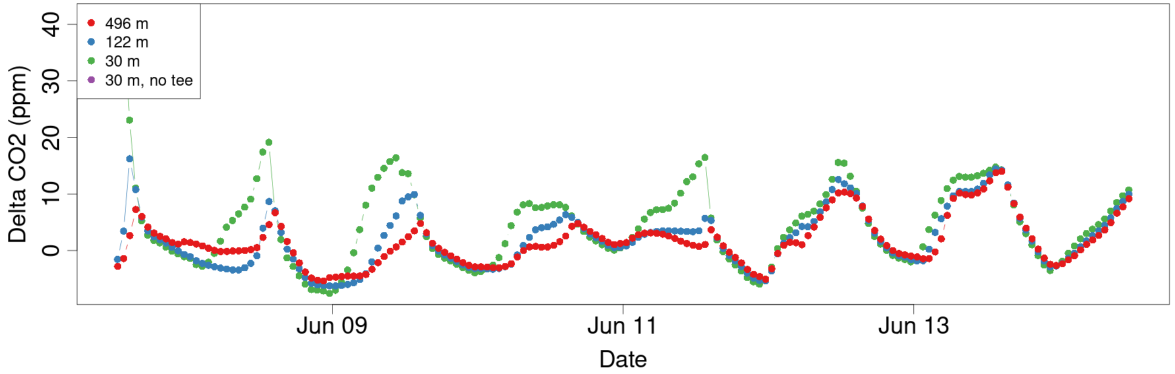
CTE_TM5 (Total)





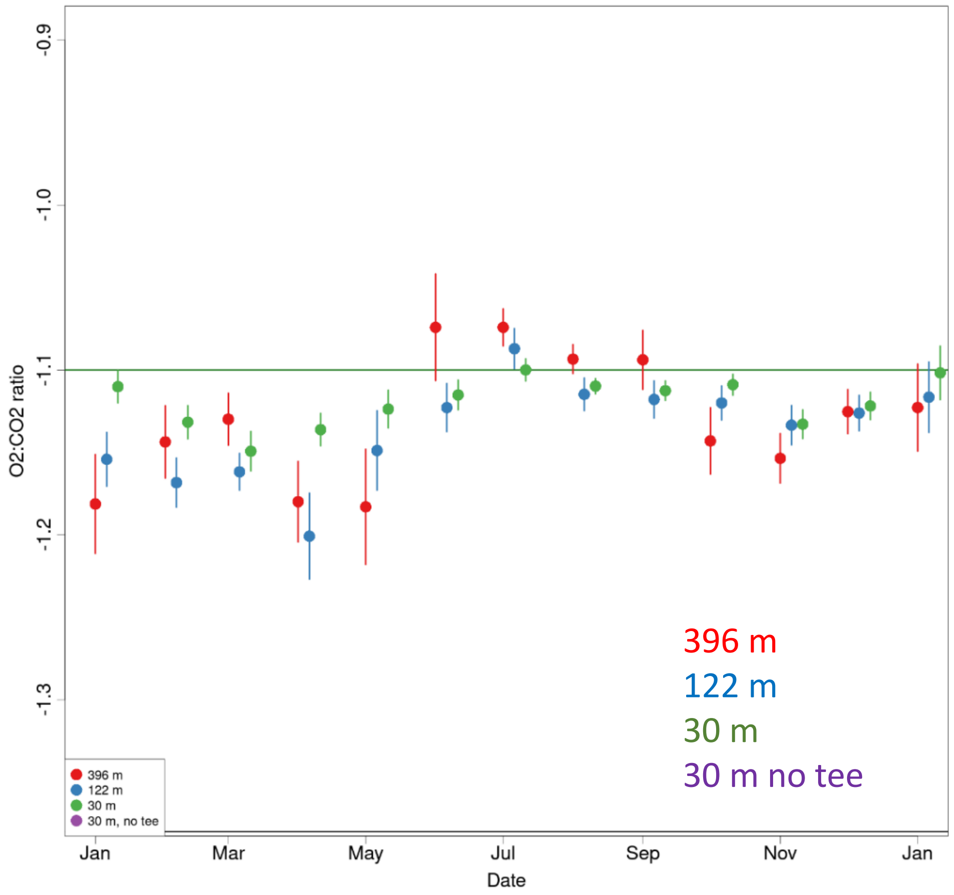
CTE_TM5 (Ocean, FF) + CT2022 (Land)



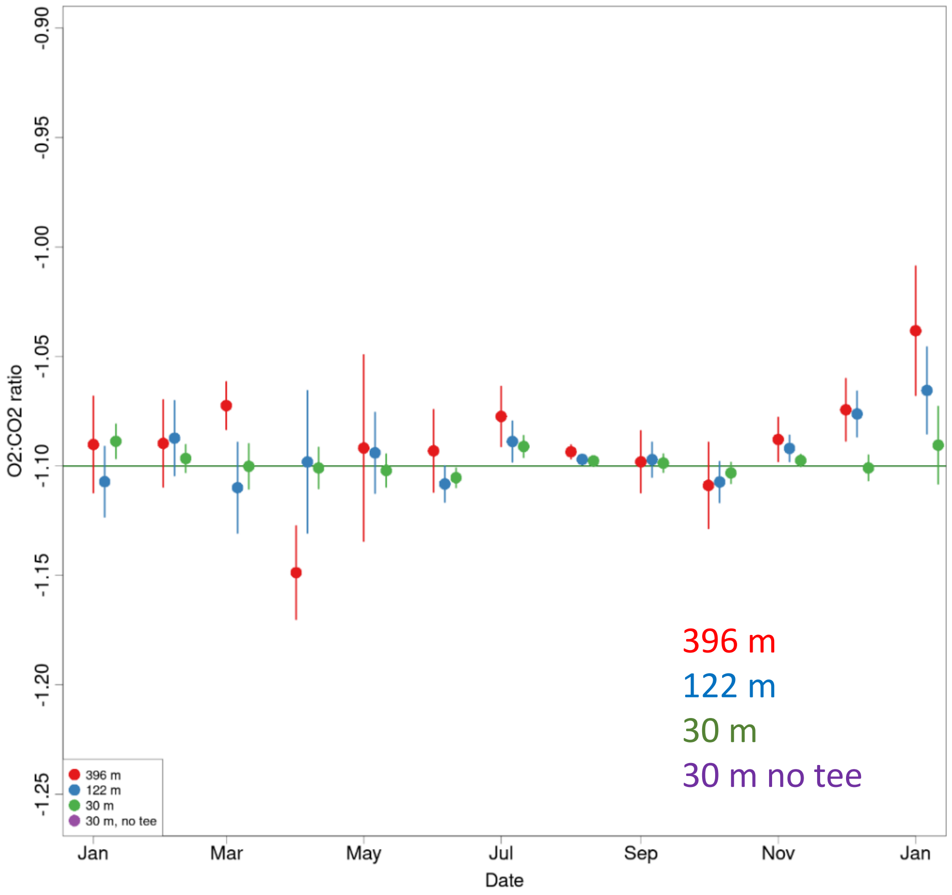


Modeled WLEF O_2 and CO_2

CTE_TM5 (Total)



CTE_TM5 (Land + Ocean)

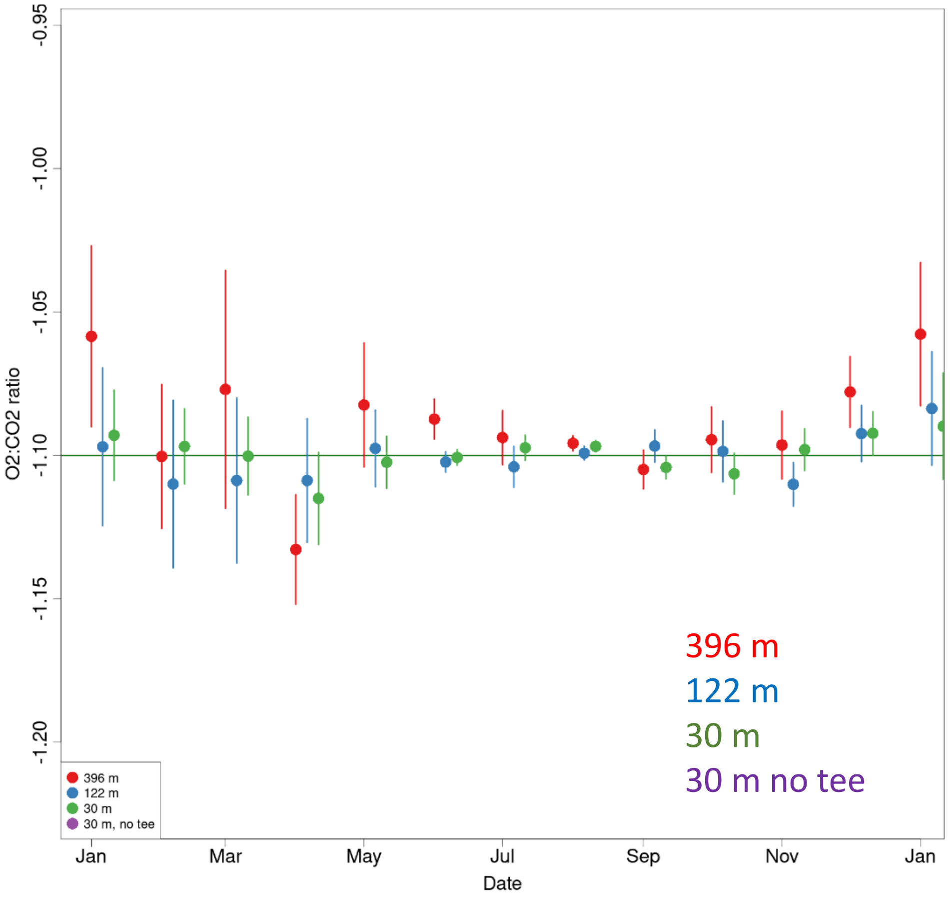


Fossil fuel signals cause winter ratios to diverge from -1.1 but not by as much as observed.

Modeled WLEF O_2 and CO_2

CTE_TM5 (Ocean, FF) + CT2022 (Land)

CTE_TM5 (Ocean) + CT2022 (Land)



Similar result with CT2022 Land.

Conclusions and Future Work

1) The APO Forward Model Intercomparison Experiment is ongoing and currently includes 8 submissions from 7 international groups

2) Initial applications include interpretation and extrapolation of atmospheric O_2 observations and evaluation of model transport

3) Potential future augmentations include:

- Additional contributions (e.g. a GEOS model, LPDM)
- Additional perturbed fossil sources (Patra)
- Common specified land fluxes
- APO run as components and total
- 3D output from more models
- Fluxes optimized to match curtain averages
- More APO inversions? Other ideas?