

Atmospheric Potential Oxygen forward Model Intercomparison Project (APO-MIP) - Experiment Protocol

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Overview

Goals: This effort aims to generate a suite of forward atmospheric transport model simulations of APO and its components (O_2 , CO_2 , and N_2), using different models and source fields, to support quantification of hemispheric-scale seasonal air-sea APO fluxes from airborne campaign observations. These APO flux estimates in turn will be used to constrain Earth system model representations of hemispheric marine productivity. The transport simulations are also intended for use in evaluating seasonal variations and long-term trends in $O_2:CO_2$ ratios over the Southern Ocean using shipboard and station measurements. These simulations may also be useful in other studies, including evaluation of the transport models themselves, and community efforts following the previous APO workshop (<https://gollum.uea.ac.uk/apo-2020.shtml>), and leading up to and following the upcoming O2 Workshop (<https://www.bowdoin.edu/physics/news-events/atmo2-workshop/index.html>).

Simulation time period: The earliest APO station record begins in 1989. Fluxes are provided over a single common time period, starting in Jan. 1986 and ending in Dec. 2020. However, fluxes for two tracers (`apo_jena` and `co2_oco2mip`) are only available from 1999 or 2000, respectively, and are set to zero in the provided files prior to then. We suggest transport runs for as long as practical given available wind fields, and we request a minimum spin up of three years. To span the HIPPO (2009-2011), ORCAS (2016), and ATom (2016-2018) campaigns, we request a minimum simulation period of Jan. 1, 2006 - Dec. 31, 2018, using Jan. 1, 2006 - Dec. 31., 2008 for spin-up. Those able to start prior to 1999 in the case of `apo_jena`, or 2000 in the case of `co2_oco2mip`, can either choose to use the provided zero fluxes for the earlier years, or conduct separate transport simulations with different start times. Analyses of these tracers will only use the valid period starting three years after their fluxes start.

Background initialization and concentration units: Precision considerations preclude simulating the true background concentrations for O_2 or N_2 . Rather, these species should be modeled as trace deviations against an arbitrary background with submitted concentrations in ppm dry air mole fraction (as for CO_2). These concentrations will later be converted at NCAR to deviations in units of per meg according to Eq. 5 in Stephens et al. (Stephens et al., 1998). Background concentrations for all species should be initialized as 400.0 ppm everywhere. Only in the case of linear transport and a model that allows negative concentrations, background concentrations may instead be initialized as 0.0 ppm everywhere.

Required output

Simulated concentrations sampled to match the GLOBALVIEWplus (GV+) v7.0 ObsPack (https://gml.noaa.gov/ccgg/obspack/release_notes.html#obspack_co2_1_GLOBALVIEWplus) files listed below, which correspond to a subset of existing Scripps, NCAR, and AIST/JMA APO observations. Please submit concentrations for the valid period only, not including spin up. Note, the HIPPO, ATOm, and Gould ObsPack files correspond to CO₂ observations by different laboratories, but the sample times are similar to the NCAR APO measurements. The preferred output format is that of the existing ObsPack netCDF files with variables added for model output, though other formats can be handled if necessary (e.g., CAMS and CarboScope plain text output for which custom ingest code has already been developed).

Primary aircraft campaigns:

co2_hip_aircraft-insitu_59_allvalid.nc
co2_orc_aircraft-insitu_3_allvalid-merge10.nc
co2_tom_aircraft-insitu_1_allvalid.nc

Scripps O₂ Program stations:

co2_alt_surface-flask_4_representative.nc
co2_brw_surface-flask_4_representative.nc
co2_cba_surface-flask_4_representative.nc
co2_cgo_surface-flask_4_representative.nc
co2_kum_surface-flask_4_representative.nc
co2_ljo_surface-flask_4_representative.nc
co2_mlo_surface-flask_4_representative.nc
co2_psa_surface-flask_4_representative.nc
co2_smo_surface-flask_4_representative.nc
co2_spo_surface-flask_4_representative.nc

ARSV Laurence M. Gould:

co2_gould_shipboard-insitu_1_allvalid.nc

AIST/JMA aircraft samples:

co2_aoa_aircraft-flask_19_allvalid.nc

Encouraged output

The following output would be very useful, but recognizing it may present challenges for some, it is not required for participation.

T, P, and Q: If possible, we also request model temperature, pressure, and humidity (absolute, specific, or relative) corresponding to the measurements. These will be useful in evaluating model transport, and in calculating concentration gradients over pressure, potential temperature, or equivalent potential temperature (Jin et al., 2021; e.g., Long et al., 2021) using modeled rather than observed values.

All ObsPack files: If convenient routines exist, we also request output for all files in the GV+ v7.0 ObsPack. Some of these also correspond to existing APO records and even records with no matching APO observations could potentially be useful for future network design.

Additional Fixed Sites: The number of sites with past or ongoing APO measurements beyond those listed above is now quite extensive, however these records exist in many different formats and are not all in publicly available repositories. For these records, rather than providing specific sampling times, we have prepared a list of latitude, longitude, and altitude coordinates, and we request hourly (or daily) time series output at these locations from those who are able. The location file is here:

[Fixed_sites.csv](#)

Additional details on these records, including institutions and references can be found [here](#) (thanks to Karina Adcock and Penelope Pickers at UEA).

Note that longitudes are positive 0-180 E or negative 0-180 W and we use the altitude / elevation / intake_height definitions from ObsPack, namely:

```
altitude = sample_altitude_in_meters_above_sea_level
site_elevation = surface_elevation_in_meters_above_sea_level:
intake_height = sample_intake_height_in_meters_above_ground_level
altitude = site_elevation + intake_height
```

Our preferred output format would be a single netcdf file containing output for all sites and tracers, but other formats (e.g. flat text, separated by tracer or site) are acceptable.

Additional Shipboard Records: We also request model output corresponding to the NIES VOS, AIST R/V MIRAI, and UEA Cap San Lorenzo (Hamburg Süd) sampling programs. We have prepared three csv files containing UTC date and time, latitude, and longitude:

[NIES_loc.csv](#) [MIRAI_loc.csv](#) [HAM_loc.csv](#)

Thanks to Andy Jacobson, these sample locations are also available in ObsPack format:

[apo_NIES-VOS-misc_shipboard_unknown_20_unknown.nc](#)

[apo_AIST-Mirai-misc_shipboard_unknown_62_unknown.nc](#)

[apo_Cap-San-Lorenzo-misc_shipboard_unknown_13_unknown.nc](#)

Please assume an inlet height of 30 m (ASL) for these records, though the actual intake heights vary from 25-40 m. Our preferred output format would be netcdf files for each record containing output for all tracers, but other (e.g. flat text) formats are acceptable.

3D fields: If temporary storage allows, we also request daily mean 3D gridded concentration fields. These would provide valuable information in the context of assessing the zonal and temporal representativeness of the aircraft and station measurements. We can transfer and store data at NCAR. Globus (globus.org) is the preferred transfer method if available, but FTP or other mechanisms are acceptable.

Provided input flux fields

Forward runs are requested for ten distinct tracers (with suggested output variable naming):

- 1) One posterior Jena APO inversion field (apo_jena)
- 2) CESM O₂, CO₂, and N₂ fields (o2_cesm, co2_cesm, n2_cesm)
- 3) Bottom-up O₂, CO₂, and N₂ fields (o2_gk01r16, co2_somffn, n2_era)

- 4) One OCO-2 v10 MIP fossil fuel CO₂ field (co2_oco2mip)
- 5) GCP-GridFED fossil fuel CO₂ emission and O₂ uptake fields (co2_gridfed, o2_gridfed)

Download location:

- 1) https://app.globus.org/file-manager?origin_id=ad10d685-f279-4923-8109-0f4dd1745f42&origin_path=%2F [to be replaced by APO-MIP data repository]

Global daily total fluxes

To facilitate checking of output, we are providing daily global flux time series here:

[apo-forward-flux-products-daily-totals.csv](#)

For each tracer, the simulated time derivative in global atmospheric abundance should match these values.

Parameters common to all fields:

- 1) File format: netCDF 64-bit offset
- 2) Resolution: 1° latitude x 1° longitude x daily
- 3) Units: mol / m² / sec
- 4) Time period: Jan. 1, 1986 – Dec. 31, 2020

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

- 1) Tracers: air-sea APO flux (O₂ and N₂ components only)
- 2) Original files from <http://www.bgc-jena.mpg.de/CarboScope/?ID=apo>.
- 3) Original time period: 1999 – 2020. *Prior to Jan. 1999, this field contains zeros for flux.*
- 4) Original resolution: 2° latitude x 2.5° longitude x daily
- 5) Filename: SFAPO_OCN.carboscope.apo99X_v2021.1x1.19860101-20201231.nc
- 6) Suggested output variable name: 'apo_jena'

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

- 1) Tracers: air-sea O₂, CO₂, and N₂ fluxes
- 2) JRA-55 forced ocean-ice integration of CESM2.2
- 3) Original time period: 1958 – 2020
- 4) Original resolution: Nominal 1° latitude x 1° longitude grid with North Pole displaced to Greenland. Daily CO₂ and O₂ flux output. Monthly heat flux data used for N₂ flux computation.
- 5) Filenames:
 - a) SFO2_OCN.cesm_fosi_smye.1x1.19860101-20201231.nc
 - b) SFCO2_OCN.cesm_fosi_smye.1x1.19860101-20201231.nc
 - c) SFN2_OCN.cesm_fosi_smye.1x1.19860101-20201231.nc
- 6) Suggested output variable names: 'o2_cesm', 'co2_cesm', 'n2_cesm'

Bottom-up air-sea flux estimates:

- 1) Tracers: air-sea O₂, CO₂, and N₂ fluxes
- 2) O₂

- a) Seasonal component from dissolved O₂ measurement based climatology of Garcia and Keeling (2001), scaled by 0.82 according to Naegler et al. (2006).
 - b) Annual mean component from ocean inversion of Resplandy et al. (2016) using transport from MITgcm-ECCO
 - c) Original time periods: Monthly / annual climatologies, which we repeat 1986 – 2020
 - d) Original resolutions: Garcia and Keeling = 1.125° latitude x 1.125° longitude x monthly, Resplandy = 21 regions x annual
 - e) Filename: SFO2_OCN.gk2001_R2016.1x1.repeat_monclim.19860101-20201231.nc
 - f) Suggested output variable name: 'o2_gk01r16'
- 3) CO₂
- a) pCO₂-based product of Landschützer et al. (2016) v.2021
 - b) Accessed from: https://www.ncei.noaa.gov/access/ocean-carbon-data-system/oceans/SPCO2_1982_present_ETH_SOM_FFN.html
 - c) Original time period: 1982 – 2020
 - d) Original resolution: 1° latitude x 1° longitude x monthly
 - e) Filename: SFCO2_OCN.MPI-SOM-FFN.1x1.19860101-20201231.nc
 - f) Suggested output variable name: 'co2_somffn'
- 4) N₂
- a) Estimated using ERA5 heat fluxes and sea-surface temperatures accessed from:
 - b) <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview>
 - c) Also using sea-surface salinity from the World Ocean Atlas, v.2018 accessed from: <https://www.ncei.noaa.gov/data/oceans/woa/WOA18/DATA/salinity/netcdf/decav/1.00>
 - d) Using Eq. 2 from Keeling and Shertz (1992) 1992 ($F = -dC/dT * Q/C_p$) and N₂ solubility coefficients of Hamme and Emerson (2004).
 - e) Scaled by 1/1.3 according to Jin et al. (2007)
 - f) Original time periods: ERA5 = 1979 – 2021, WOA 1981 – 2010 climatology repeated 1986 – 2020
 - g) Original resolutions: ERA5 = 0.25° latitude x 0.25° longitude x monthly, WOA = 1° latitude x 1° longitude x monthly
 - h) Filename: SFN2_OCN.era5_shf.1x1.19860101-20201231.nc
 - i) Suggested output variable name: 'n2_era'

Fossil fuel fluxes:

- 1) OCO-2 v10 MIP fossil-fuel fluxes
 - a) Tracers: fossil CO₂ fluxes only
 - b) For 2000-2019, based on monthly fluxes from: https://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2020.html disaggregated to hourly

- c) For 2020, based on 2019 fluxes scaled using <https://www.nature.com/articles/s41597-020-00708-7>
 - d) As prepared by Sourish Basu and Ray Nassar for the OCO-2 v10 MIP
 - e) Accessed from: <https://doi.org/10.5281/zenodo.4776925>
 - f) Submitted CO₂ concentrations will be scaled at NCAR by a global average oxidative ratio of -1.4 to produce estimates of O₂ consumption.
 - g) Original time period: Jan. 2000 – Mar. 2021. *Prior to Jan. 2000, this field contains zeros for flux.*
 - h) Original resolution: 1° latitude x 1° longitude x hourly
 - i) Filename: SFCO2_FF.OCO2-MIP.v2020.1.1x1.19860101-20201231.nc
 - j) Suggested output variable name: 'co2_oco2mip'
- 2) GCP-GridFED fossil-fuel fluxes (version 2021.3)
- a) Tracers: fossil CO₂ emission and O₂ uptake tracers
 - b) Based on Jones et al. (2021) but with oxidative ratio fix and other updates.
 - c) Accessed from: <https://doi.org/10.5281/zenodo.5956612>
 - d) Original time period: 1959 – 2020
 - e) Original resolution: 0.1° latitude × 0.1° longitude x monthly
 - f) Filenames:
 - i) SFCO2_FF.GCP-GridFED.v2021.3.1x1.19860101-20201231.nc
 - ii) SFO2_FF.GCP-GridFED.v2021.3.1x1.19860101-20201231.nc
 - g) Suggested output variable names: 'co2_gridfed', 'o2_gridfed'

Table 1. Participating 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	1986, 1989-2019	Matt Long	(Danabasoglu et al., 2020) (2020)
CAMS_LMDZ	Copernicus Atmosphere Monitoring Service	1.875 x 3.75 x 39	LMDZ6A	ECMWF	1986, 1991-2020	Frederic Chevallier	Chevallier et al. (2005, 2010); Chevallier (2013)
CTE_TM5	CarbonTracker Europe	1 x 1 x 25	TM5	ECMWF	2000, 2003-2020	Ingrid Lujkx and Wouter Peters	van der Laan-Luijkx et al. (2017)
Jena_TM3	Jena CarboScope	4 x 5 x 19	TM3	NCEP	1986, 1989-2020	Christian Roedenbeck	Rödenbeck et al. (2003); Rödenbeck (2005)
MIROC4-ACTM	MIROC4-ACTM	2.8 x 2.8 x 67	MIROC4-ACTM	JRA-55	1986, 1991-2020	Prabir Patra	Patra et al. (2018); Saeki and Patra (2017); Chandra et al., (2022)
NICAM-TM (glevel-5)	NICAM-based Transport Model	~223 km	NICAM-TM_gl5	JRA-55	1986, 1989-2020	Yosuke Niwa	Niwa et al. (2011, 2017)
NICAM-TM (glevel-6)	NICAM-based Transport Model	~112 km	NICAM-TM_gl6	JRA-55	1986, 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	2000, 2003-2020	Shamil Maksyutov	Belikov et al. (2011), (Maksyutov et al., 2021)

Table 2. Output received

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
CAMS_LMDZ	X						
CTE_TM5	X	X		X	X	X	Hz winds; BL height; CTE components
Jena_TM3	X	X			X		
MIROC4-ACTM	X	partial					Additional selected ObsPack records, ACTM inversion result
NICAM-TM (glevel-5)	X	X	X	X	X	X	P, T, Q, 2D surface fields
NICAM-TM (glevel-6)	X	X	X	X	X	X	P, T, Q, 2D surface fields
NIES	X		X	X			

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