High Performance Aircraft for Global Scale Oceanography

[Image: Alec Chin]

Britton Stephens
NCAR Earth Observing Laboratory

with thanks to Matt Long (NCAR); Ralph Keeling, Eric Morgan, Jonathan Bent (SIO); Kathryn McKain, Colm Sweeney (NOAA/CU); Eric Kort (U Mich); the HIPPO, ORCAS, and ATom Science Teams; and collaborating modeling groups

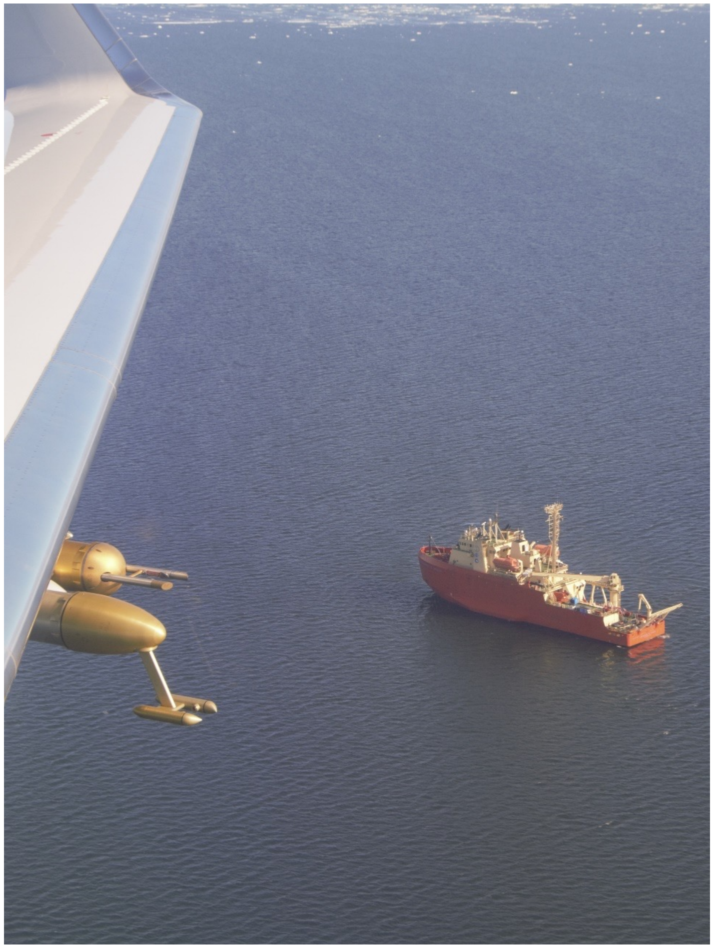
NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH NSF NASA

Outline

- Global aircraft campaigns: HIPPO (GV 2009-2011), ORCAS (GV 2016), and ATom (DC-8 2016-2018)
- Improved estimates of Southern Ocean air-sea CO_2 exchange
- Hemispheric-scale estimates of marine productivity

Key points

- Aircraft can capture atmospheric signals that are representative of large-scale ocean processes and largely independent of transport uncertainty
- High-performance[1] aircraft are uniquely suited to address grand challenge problems in ocean and climate science at global scale



[Image: Jonathan Bent]

[1]defined here as > 5000 lb payload, > 5000 nm range, > 8 hrs endurance

NCAR Airborne Oxygen Instrument (AO2)

$\delta(O_2/N_2)$
CO_2

Stephens et al., AMT, 2021

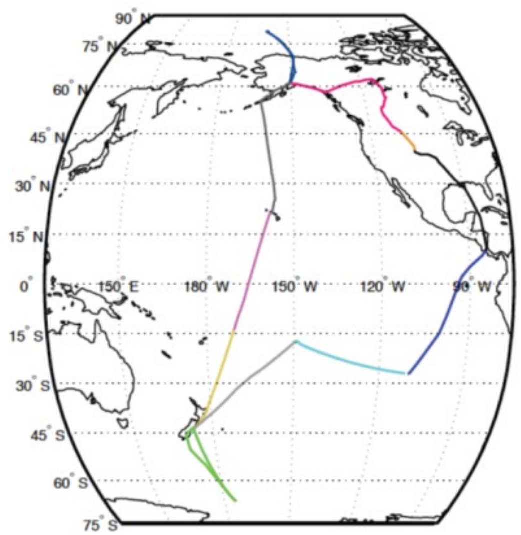
NCAR/Scripps Medusa Flask Sampler

$\delta(O_2/N_2)$
CO_2
$\delta(Ar/N_2)$
$\delta^{13}C$ of CO_2
$\delta^{18}O$ of CO_2
$\Delta^{14}C$ of CO_2

HIPPO HIAPER Pole-to-Pole Observations

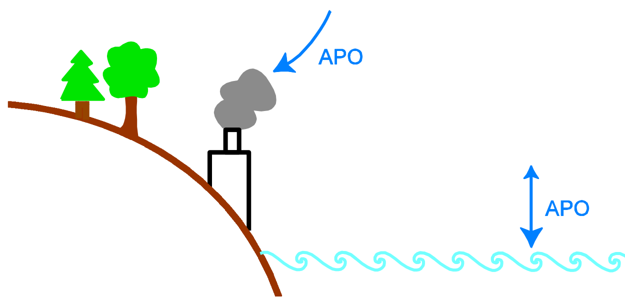
2009-2011

- PIs: Harvard, NCAR, Scripps, NOAA
- Global and seasonal survey of CO_2, O_2, CH_4, CO, N_2O, H_2, SF_6, COS, CFCs, HCFCs, O_3, H_2O, CO_2 isotopes, Ar, black carbon, and hydrocarbons (over 90 species).
- NSF / NCAR Gulfstream V
- Five 3-week campaigns over 3 years, across Pacific continuously profiling between 87 N and 67 S
- https://www.eol.ucar.edu/field_projects/hippo



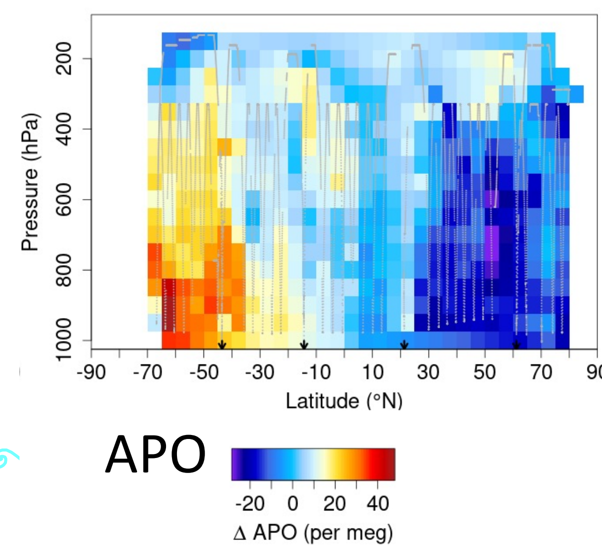
Atmospheric Potential Oxygen
aka "oceanic oxygen"

$APO = O_2 + 1.1*CO_2$



Stephens et al., GBC, 1998

HIPPO1 January 2009

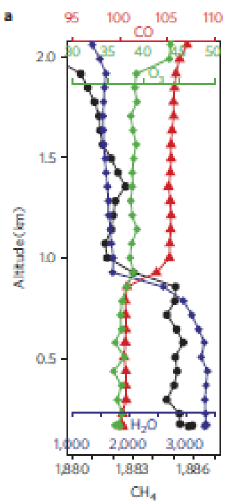


HIPPO oceanography examples

LETTERS
PUBLISHED ONLINE: 22 APRIL 2012 | DOI: 10.1038/NGEO1452
nature geoscience

Atmospheric observations of Arctic Ocean methane emissions up to 82° north

E. A. Kort[1,2]*, S. C. Wofsy[1], B. C. Daube[1], M. Diao[3], J. W. Elkins[4], R. S. Gao[4], E. J. Hintsa[4,5], D. F. Hurst[4,5], R. Jimenez[6], F. L. Moore[4,5], J. R. Spackman[4,7] and M. A. Zondlo[3]

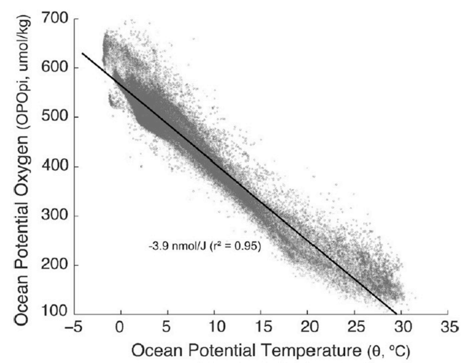


Kort et al., Nat. Geo., 2014

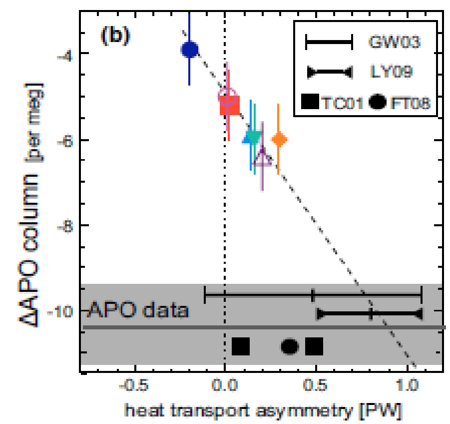
Clim Dyn
DOI 10.1007/s00382-016-3029-3

Constraints on oceanic meridional heat transport from combined measurements of oxygen and carbon

L. Resplandy[1] · R. F. Keeling[1] · B. B. Stephens[2] · J. D. Bent[2] · A. Jacobson[3] · C. Rödenbeck[4] · S. Khatiwala[5]



Observed north-south gradient in “oceanic O_2” signal



Resplandy et al., Clim. Dyn., 2016

2009-2011

HIAPER Pole-to-Pole Observations

- PIs: Harvard, NCAR, Scripps, NOAA
- Global and seasonal survey of CO_2, O_2, CH_4, CO, N_2O, H_2, SF_6, COS, CFCs, HCFCs, O_3, H_2O, CO_2 isotopes, Ar, black carbon, and hydrocarbons (over 90 species).
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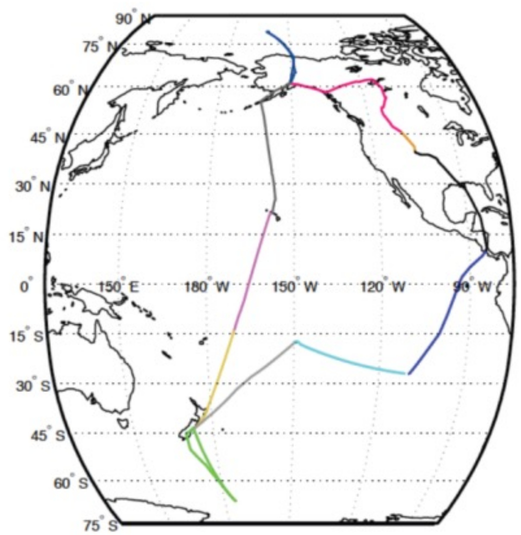
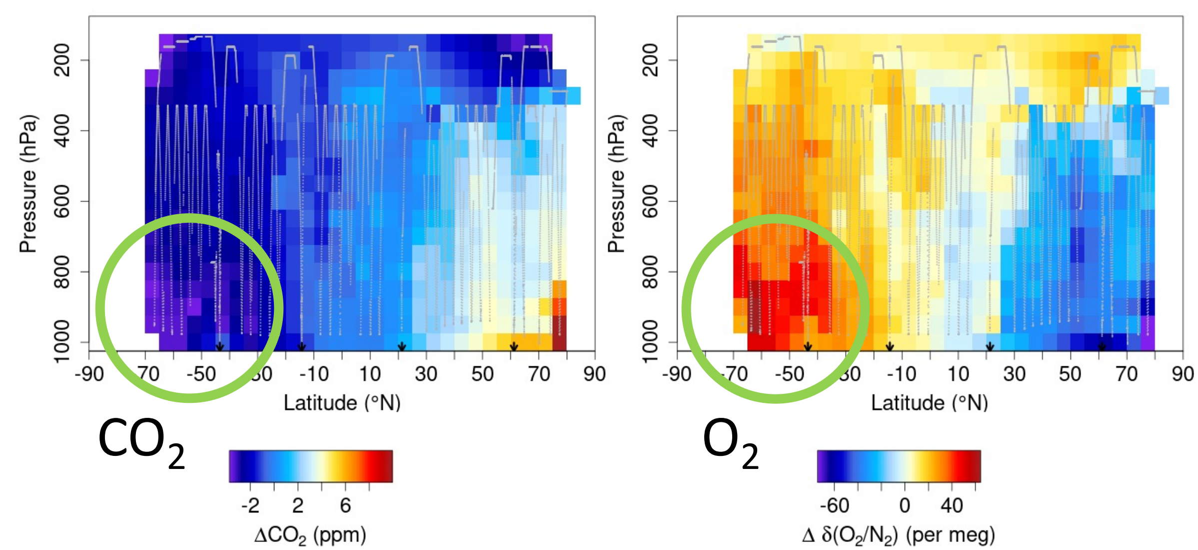
HIPPO1 January 2009

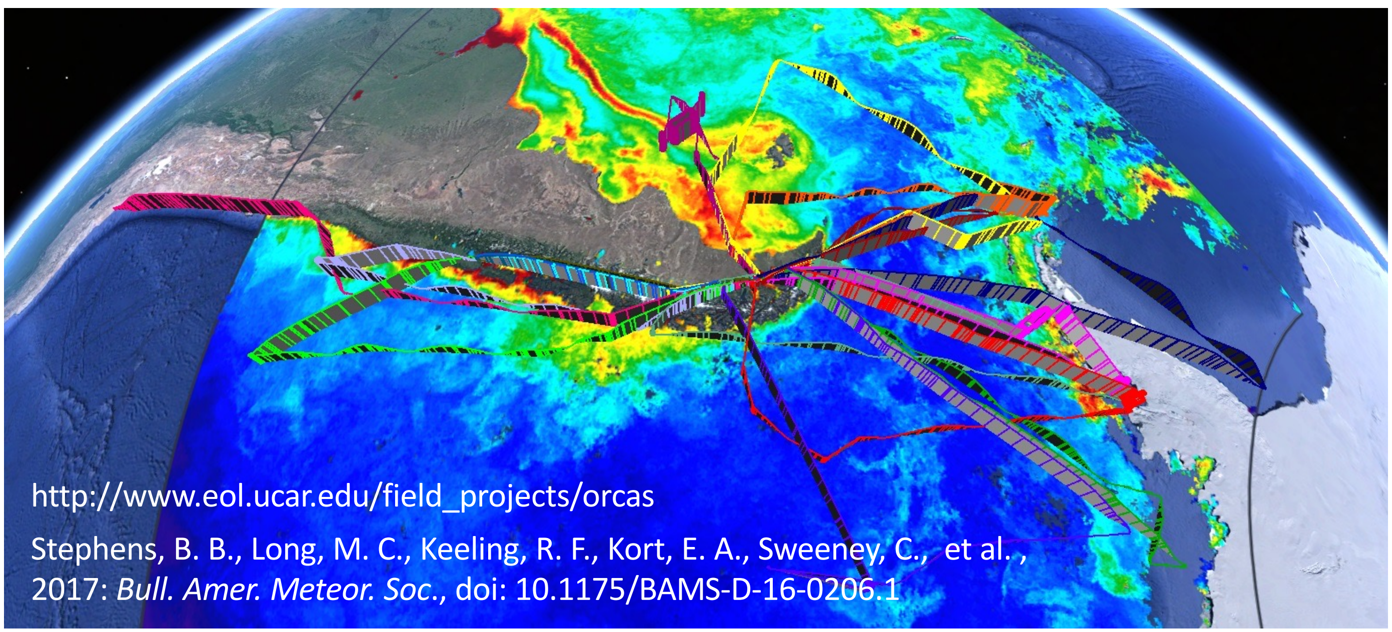




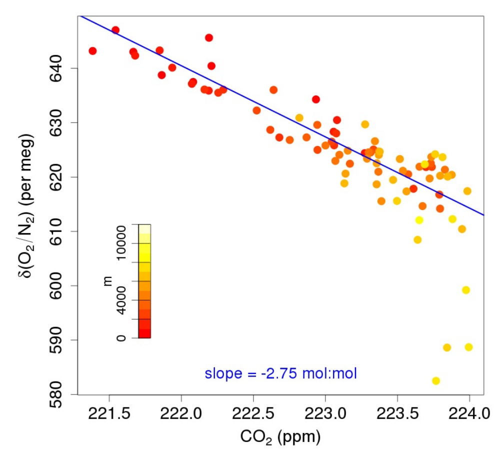
ORCAS

2016 O_2/N_2 Ratio and CO_2 Airborne Southern Ocean Study

- PIs: NCAR, Scripps, CU/NOAA, U. Michigan, U. Miami, JPL
- Intensive survey of biogeochemical tracers over the Southern Ocean adjacent to Drake Passage
- NSF / NCAR Gulfstream V
- Six-week campaign 15 January to 29 February, 2016
- Regional boundary-layer sampling and large-scale profiling transects



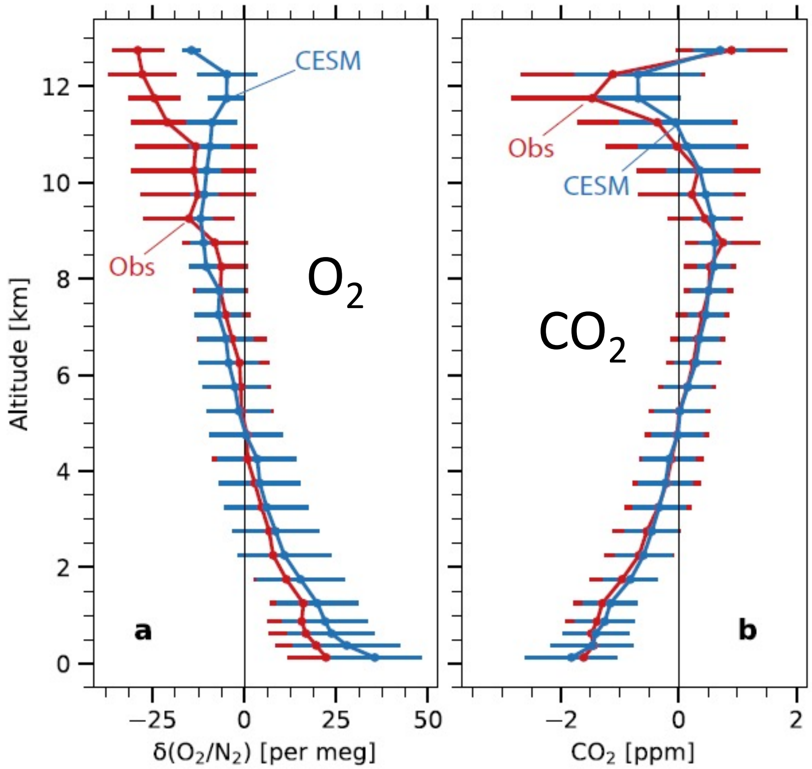
Whole campaign O_2:CO_2 relationship



Early ORCAS Results

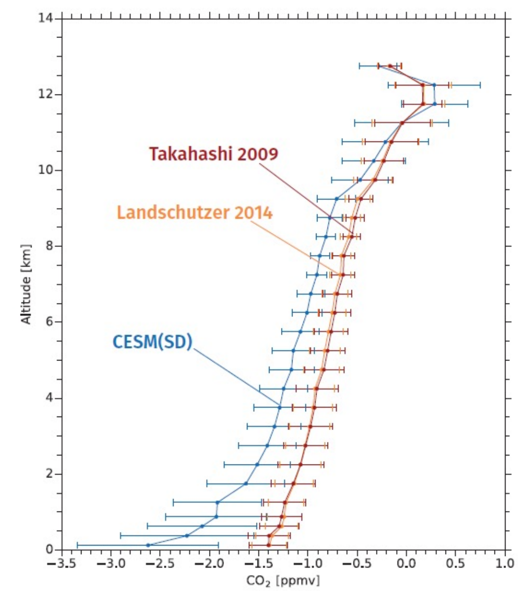
- Negative O_2:CO_2 correlations revealed the dominance of biological drivers on summertime CO_2 fluxes
- O_2 and CO_2 gradients suggest CESM overestimates summertime O_2 outgassing
- CO_2 gradients and O_2:CO_2 ratio suggest climatologies underestimate summertime CO_2 ingassing

CESM(SD) Compared to Observations



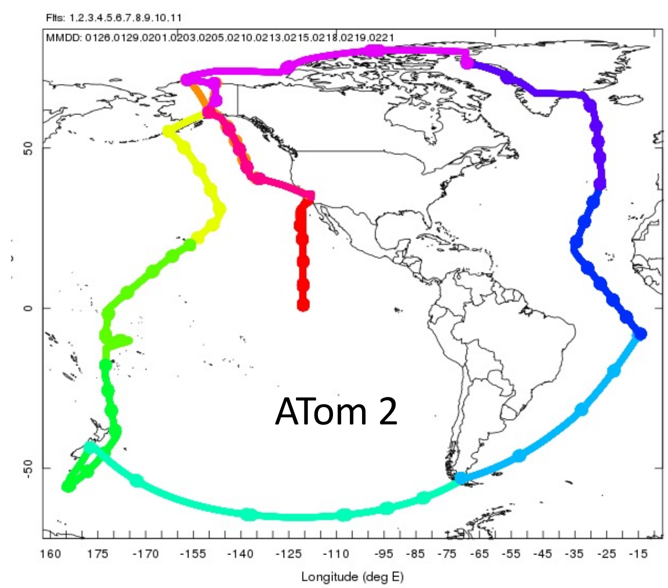
Stephens et al., BAMS, 2017
Morgan et al., JGR, 2019

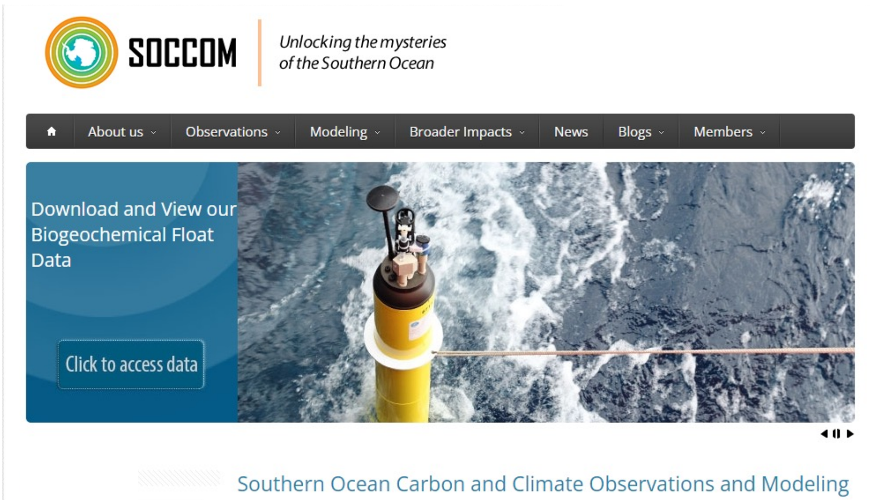
CESM(SD) compared to pCO_2-based products

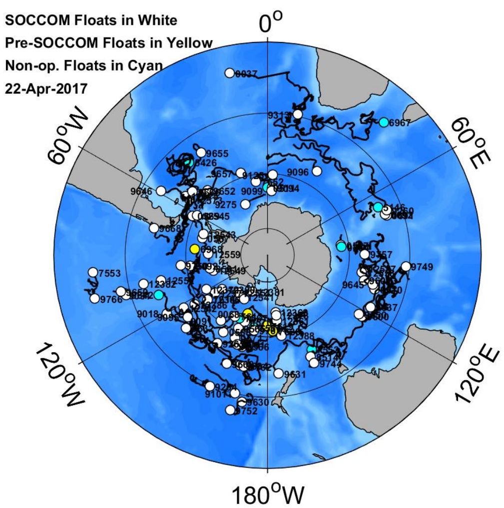


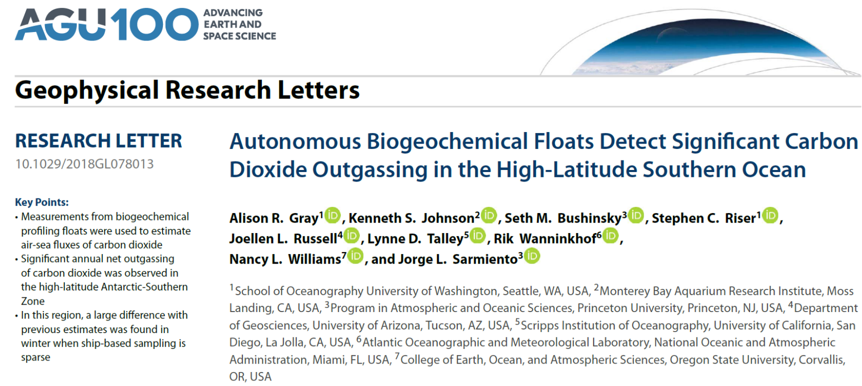
2016-2018

- PIs: Harvard, UC Irvine, NOAA, NASA
- Global and seasonal survey of > 300 chemical and aerosol species, with a focus on CH_4 and O_3 reactivity
- NCAR/Scripps carbon cycle component funded by NSF
- NASA DC-8
- Four 4-week campaigns over 3 years, transecting both the Pacific and Atlantic between 87 N and 67 S
- Continuous profiling between surface and 12 km








AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

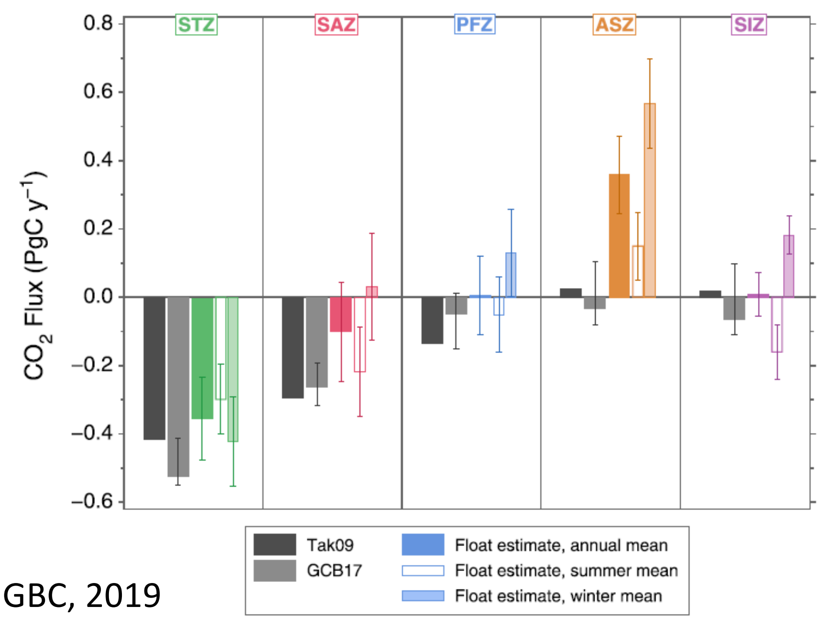
RESEARCH LETTER
10.1029/2018GL078013

Key Points:
- Measurements from biogeochemical profiling floats were used to estimate air-sea fluxes of carbon dioxide
- Significant annual net outgassing of carbon dioxide was observed in the high-latitude Antarctic-Southern Zone
- In this region, a large difference with previous estimates was found in winter when ship-based sampling is sparse

Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean

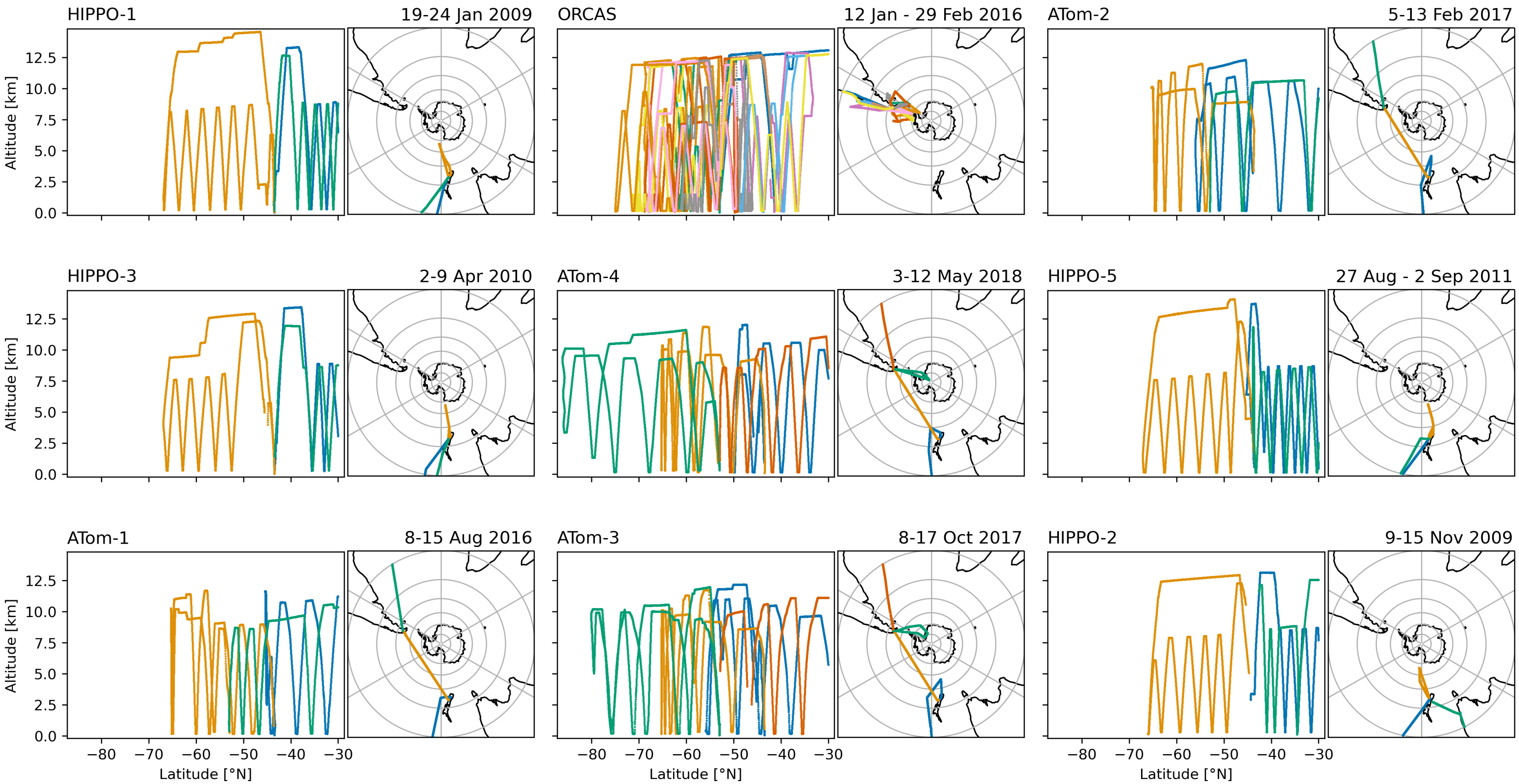
Alison R. Gray[1], Kenneth S. Johnson[2], Seth M. Bushinsky[3], Stephen C. Riser[1], Joellen L. Russell[4], Lynne D. Talley[5], Rik Wanninkhof[6], Nancy L. Williams[7], and Jorge L. Sarmiento[3]

[1]School of Oceanography University of Washington, Seattle, WA, USA, [2]Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA, [3]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, [4]Department of Geosciences, University of Arizona, Tucson, AZ, USA, [5]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA, [6]Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, USA, [7]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA



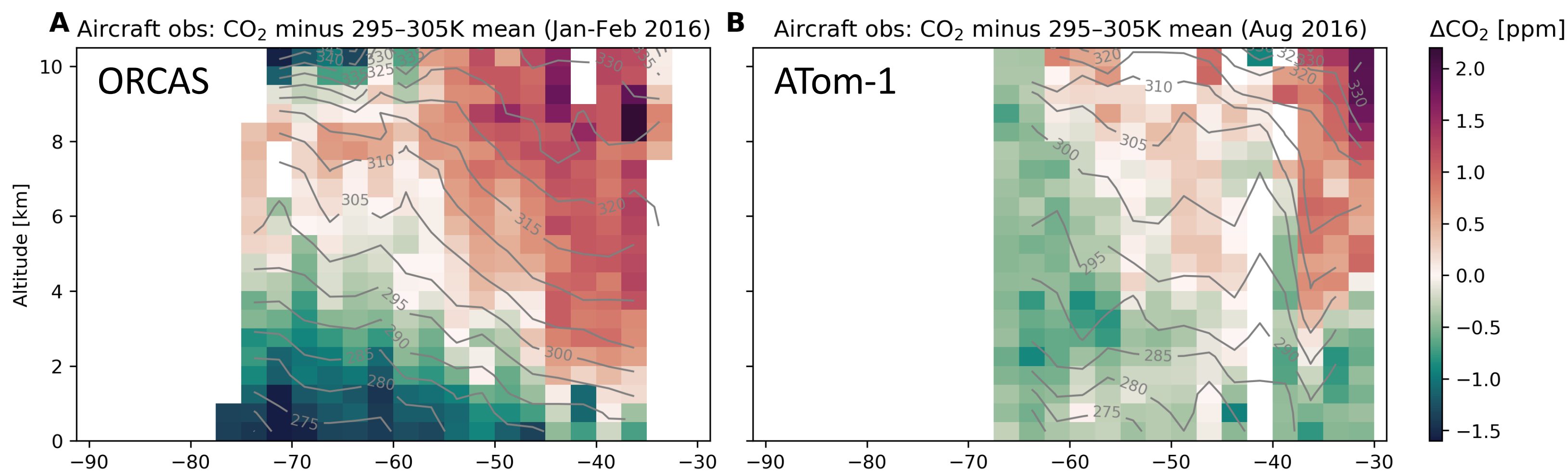
Gray et al., GBC, 2019

A decade of aircraft observations over the Southern Ocean



Long et al., Science, 2021

Observed patterns in atmospheric CO_2 over the Southern Ocean



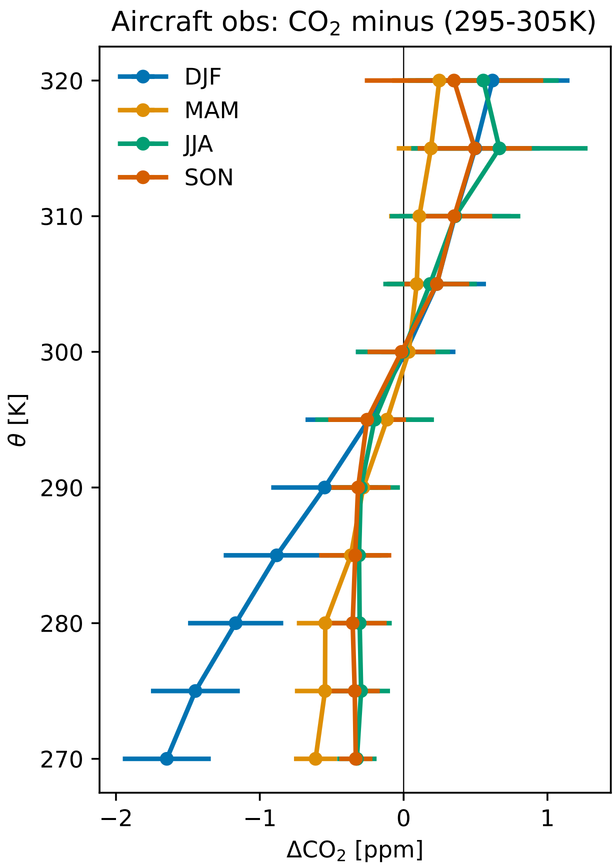
- "Vertical" Gradient metric

$$\Delta_\theta CO_2 = \langle CO_2 \rangle_{\theta<280K} - \langle CO_2 \rangle_{295K<\theta<305K}$$

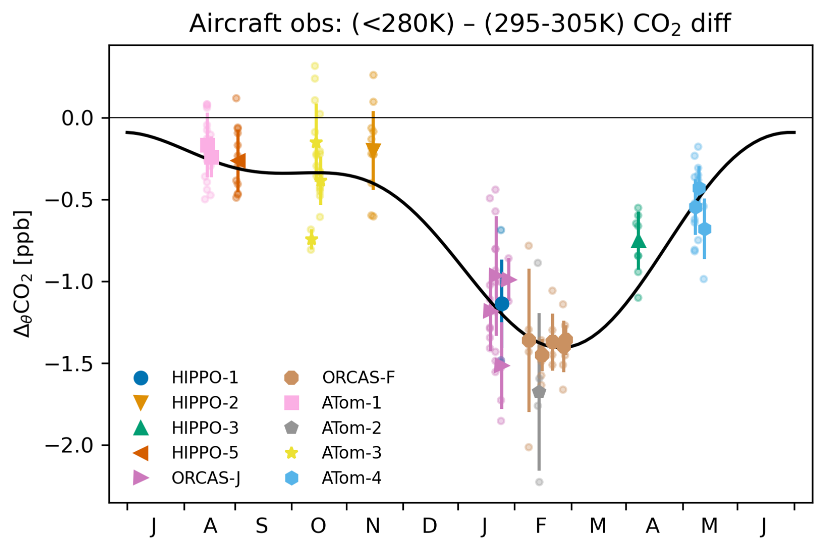
where $\langle\cdot\rangle$ is the median value of CO_2 in the specified θ (potential temperature) range.

Long et al., Science, 2021

Seasonal evolution of gradients in $\Delta_\theta CO_2$



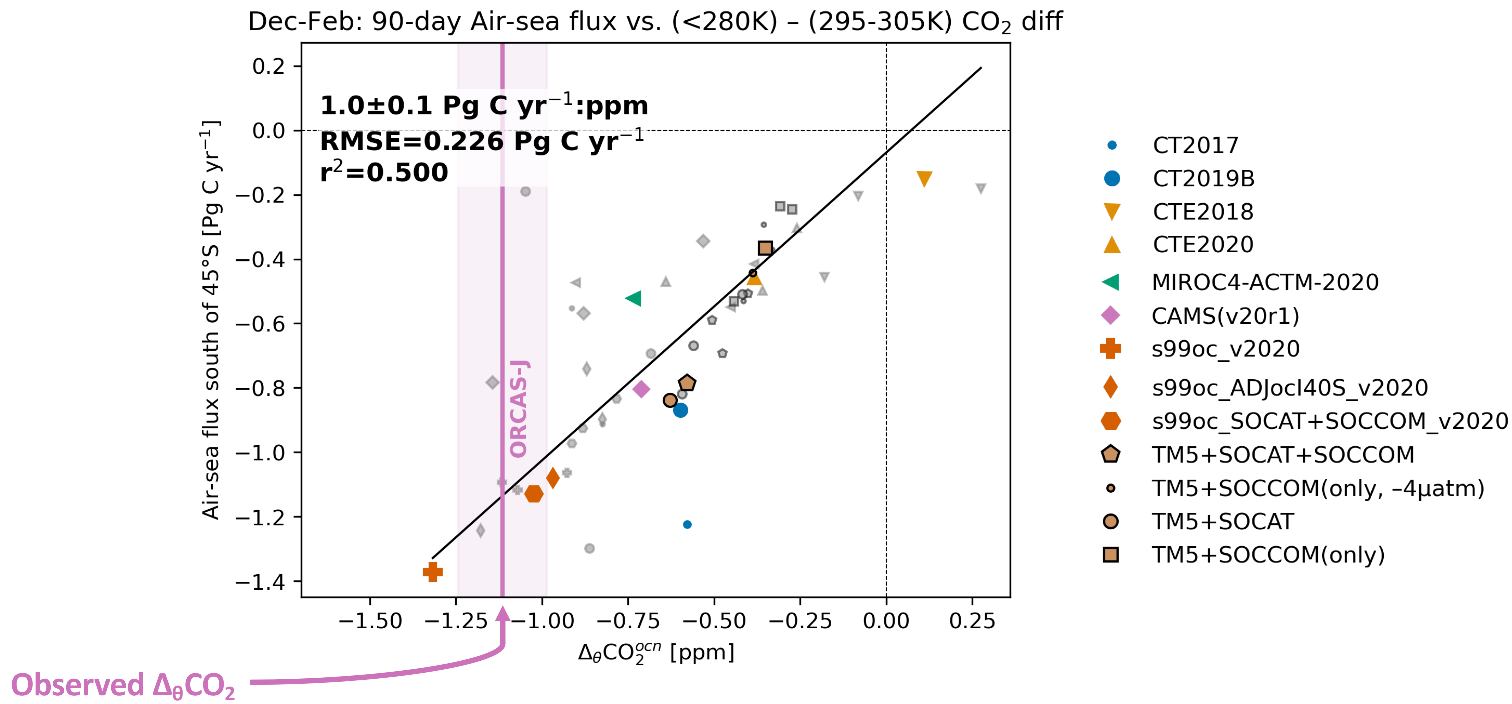
$\Delta_\theta CO_2$ from all HIPPO, ORCAS, and ATom



Long et al., Science, 2021

Emergent constraints on Southern Ocean air-sea CO_2 flux

Models sampled like observations: 90-day mean flux (>45°S) versus $\Delta_\theta CO_2$



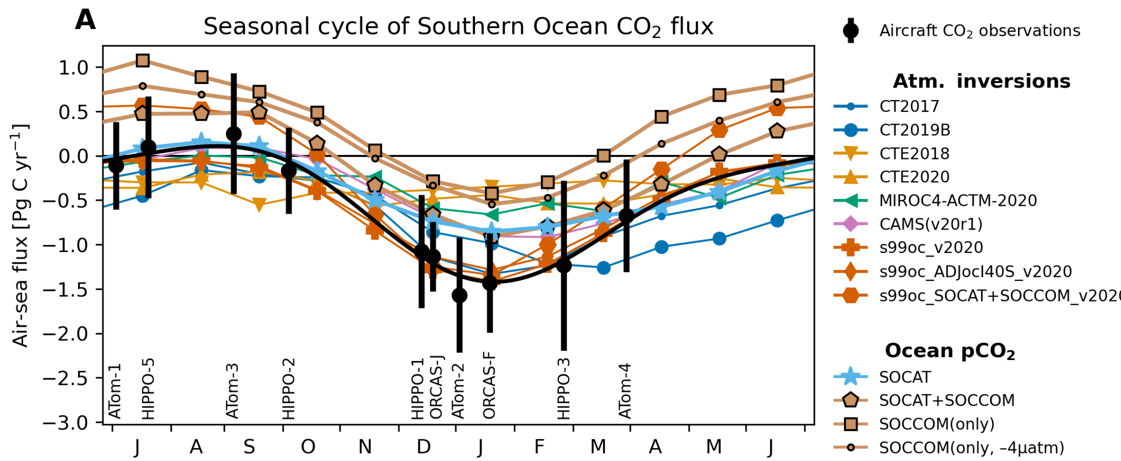
Long et al., Science, 2021

CARBON CYCLE

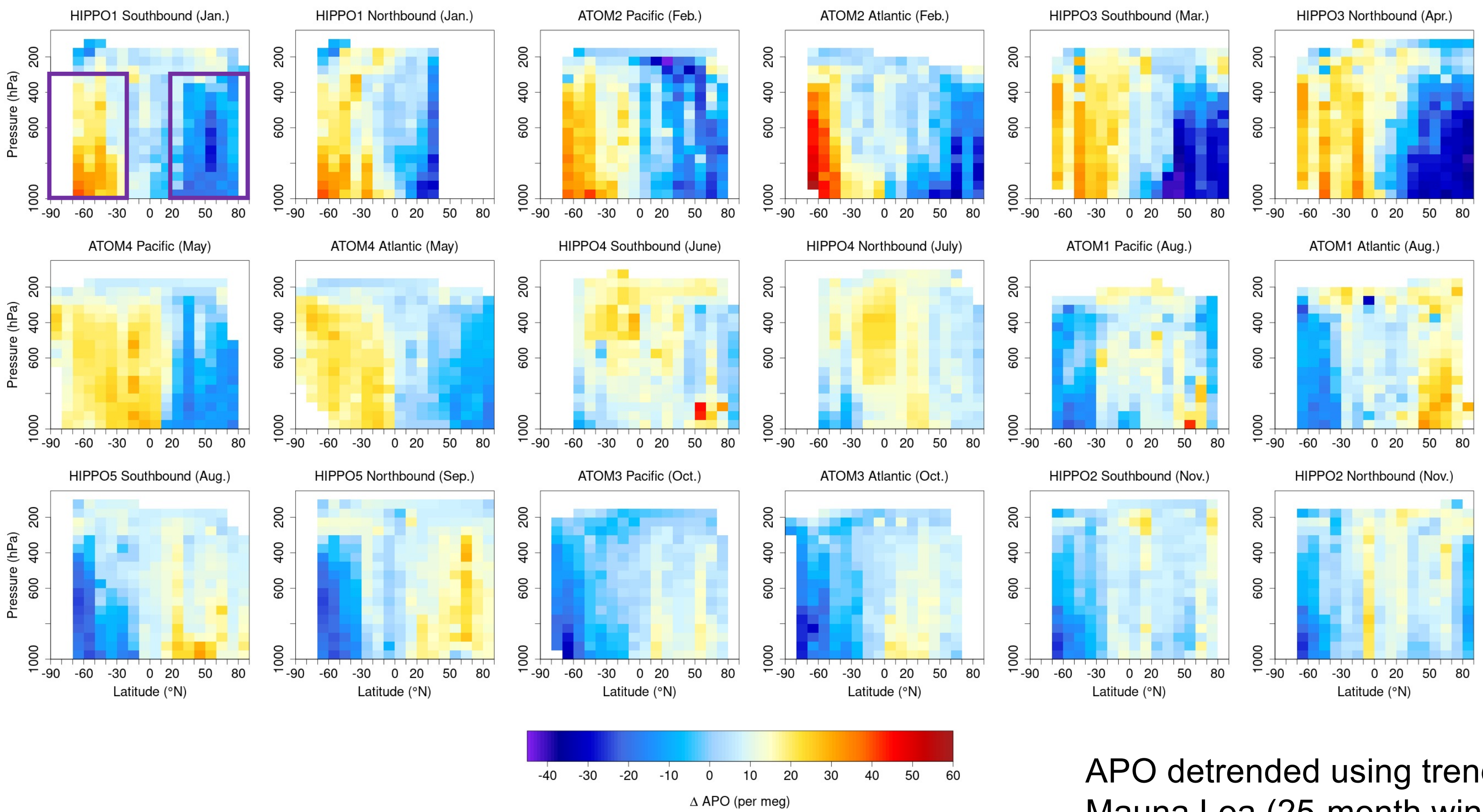
Strong Southern Ocean carbon uptake evident in airborne observations

Matthew C. Long[1*], Britton B. Stephens[1], Kathryn McKain[2,3], Colm Sweeney[3], Ralph F. Keeling[4], Eric A. Kort[5], Eric J. Morgan[4], Jonathan D. Bent[1,4]†, Naveen Chandra[6]‡, Frederic Chevallier[7], Róisín Commane[8], Bruce C. Daube[9], Paul B. Krummel[10], Zoë Loh[10], Ingrid T. Luijkx[11], David Munro[2,3], Prabir Patra[12], Wouter Peters[11,13], Michel Ramonet[7], Christian Rödenbeck[14], Ann Stavert[10], Pieter Tans[3], Steven C. Wofsy[9,15]

Long et al., Science 374, 1275–1280 (2021)   3 December 2021



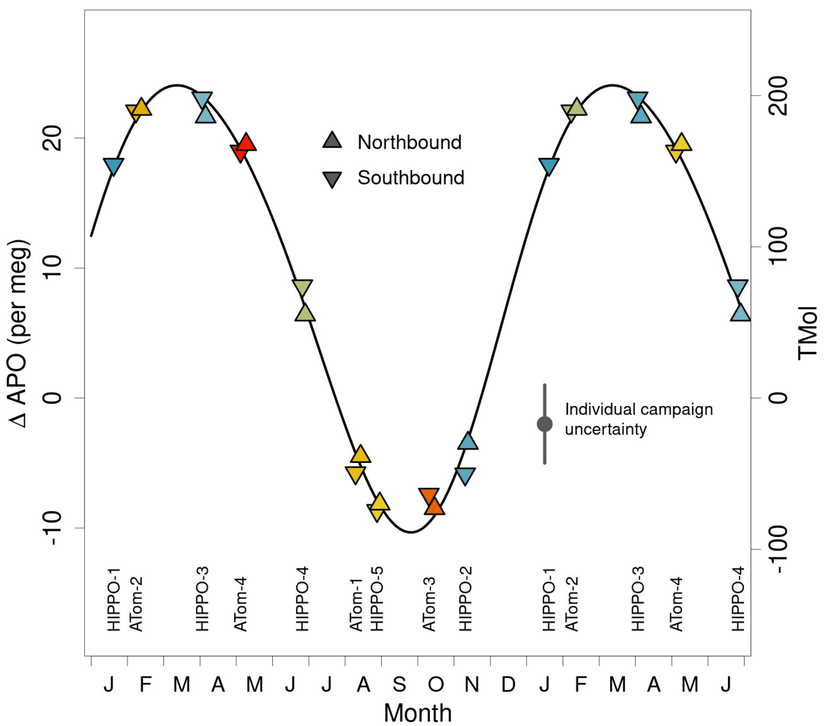
HIPPO and ATom provide 18 global transects



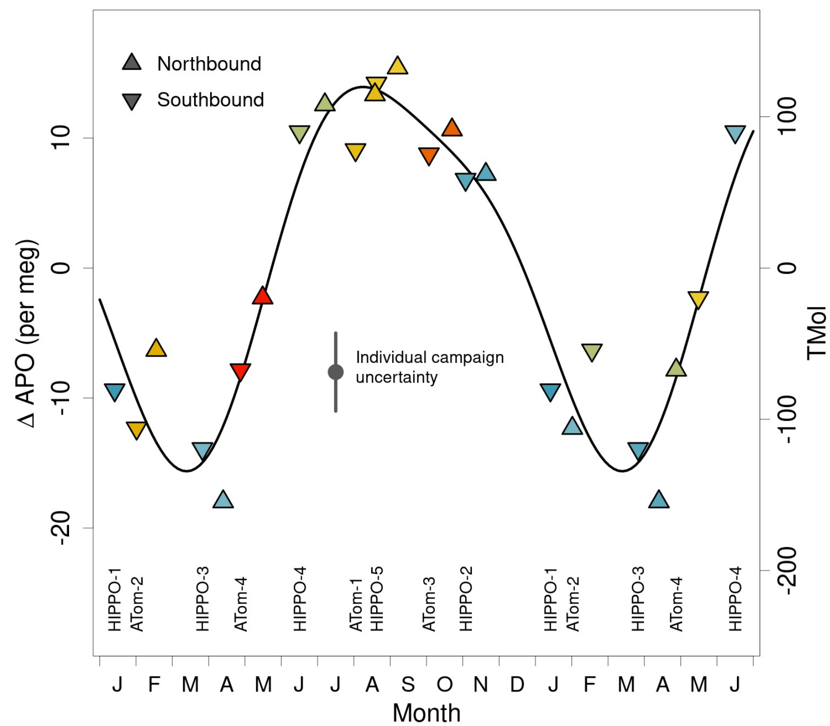
APO detrended using trend fit to Mauna Loa (25-month window)

Tropospheric average APO concentration

Southern Extratropical (> 20 S)

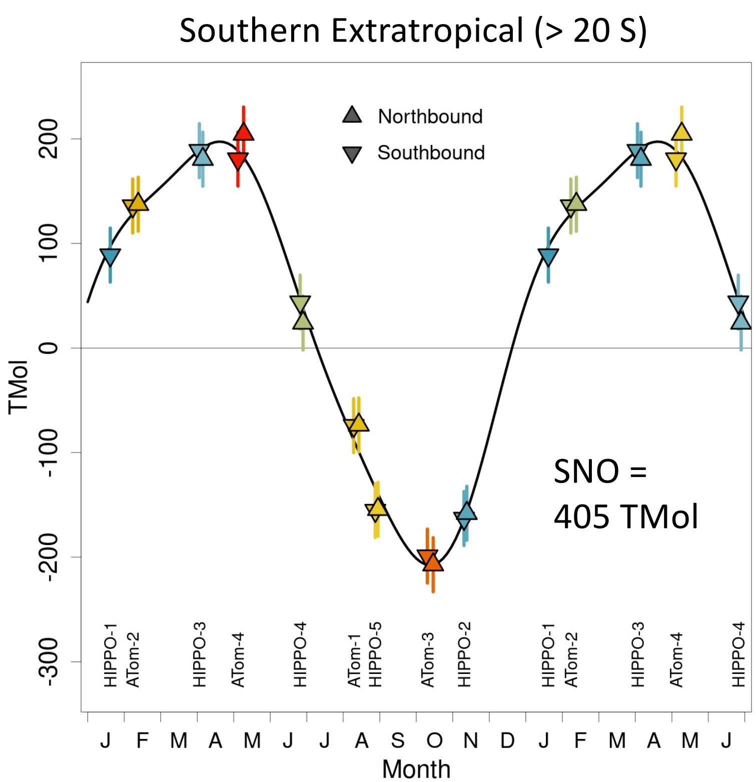


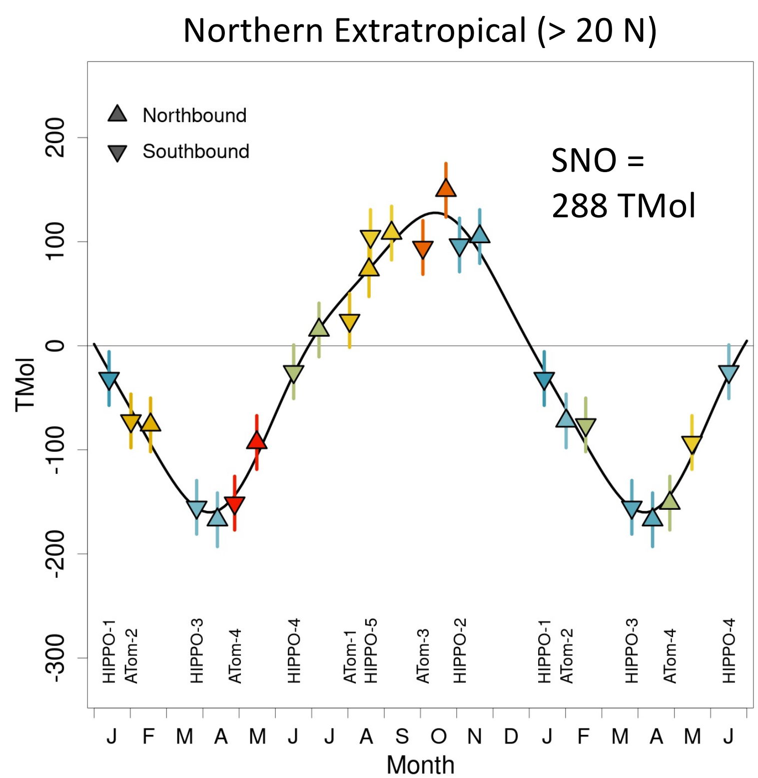
Northern Extratropical (> 20 N)



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

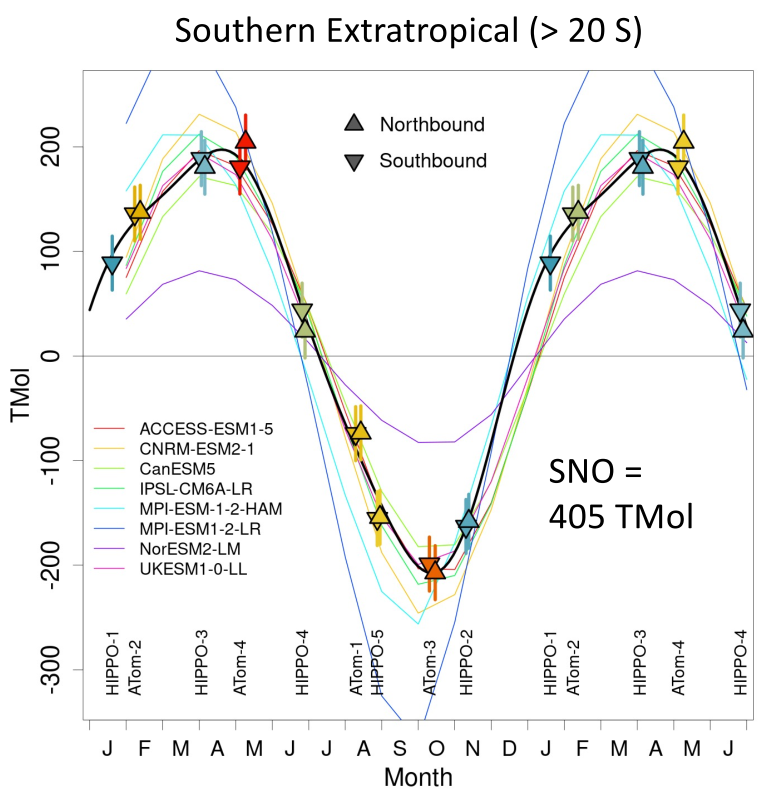
Derived cumulative APO fluxes



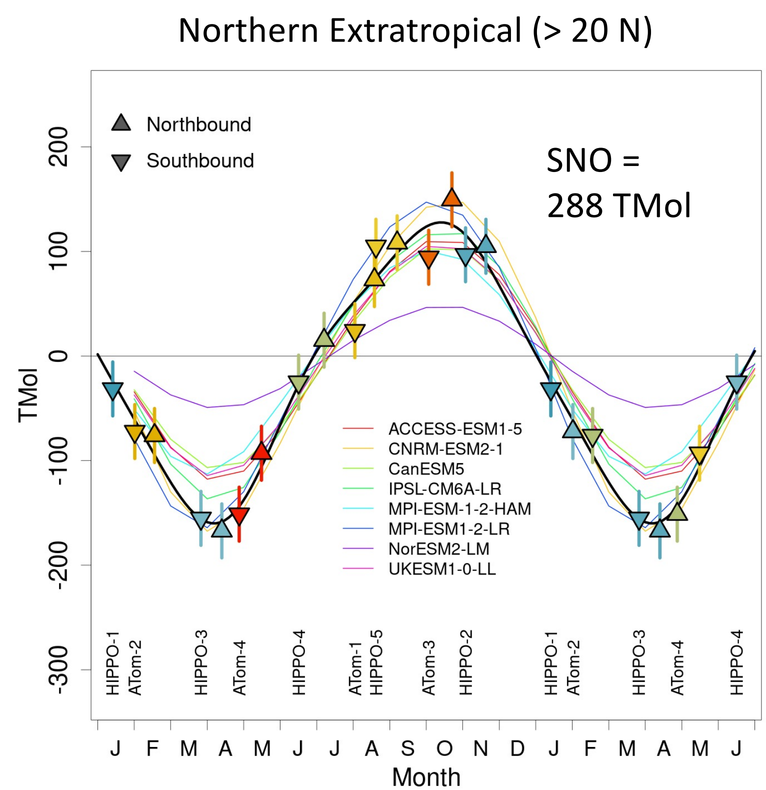


- Amplitude of cumulative APO flux is equivalent to the seasonal net outgassing (SNO) of APO, and with small corrections for CO_2 and N_2 also SNO of O_2. SNO closely tied to seasonal marine productivity.

Cumulative APO flux comparison to CMIP6 ESMs



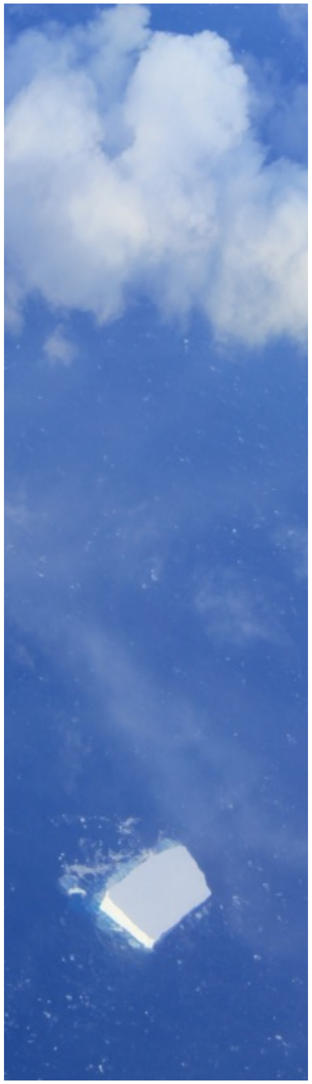
CMIP6 median SNO = 416 Tmol APO



CMIP6 mean SNO = 223 Tmol APO

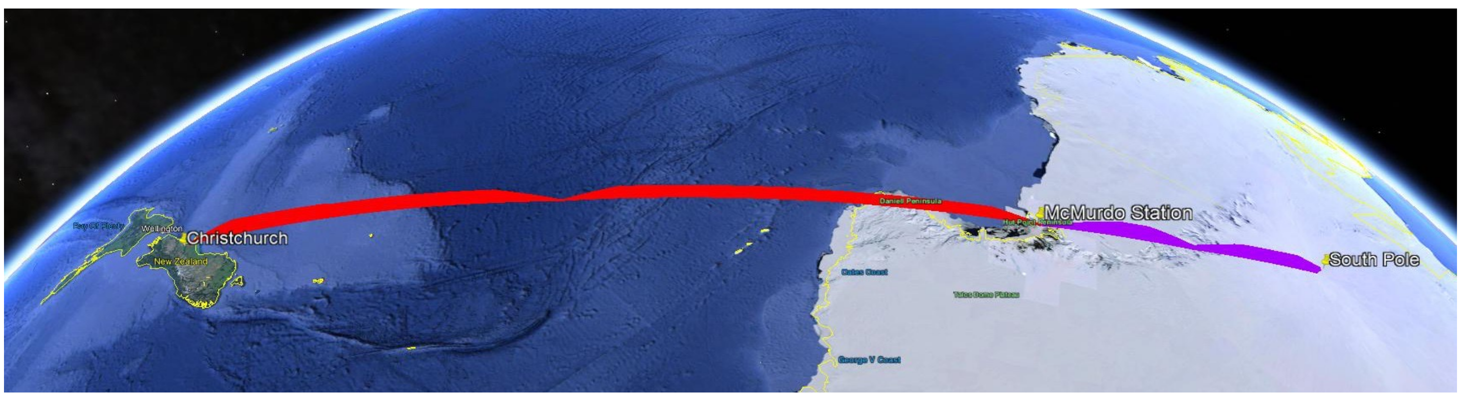
Concluding remarks

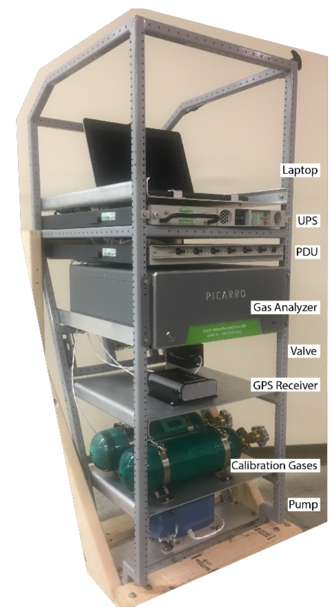
- HIPPO, ORCAS, and ATom provide unique insights into global ocean biogeochemistry
- Data are all publicly available
- NSF/NCAR GV and C-130, and NASA DC-8 are requestable
- A regular program of repeat airborne tomography would be invaluable for assessing carbon-climate feedbacks and validating mitigation efforts
- Funding for multi-year and multi-discipline campaigns remains challenging
- Future work includes a funded NYANG LC-130 measurements and a proposal in development for biannual NSF/NCAR GV deployments



Southern Ocean Carbon Gas Observatory (SCARGO)

- NSF Polar Programs funded project
- B. Stephens / M. Long PIs
- "Roll-on / roll-off" rack and inlet
- Initially measuring CO_2, CH_4, CO, and H_2O
- 139th EAS LC-130s operating between Christhurch, McMurdo Station, South Pole, and north from McMurdo, Nov-Feb
- To quantify gradients, and trends in CO_2 and CH_4





AMELIA

Airborne Mapping the Elements of Life in the Atmosphere

Interdisciplinary Science Team:

NCAR: Britton Stephens (lead PI), Matt Long (co-PI), Adriana Bailey, Dan Amrhein

University of Colorado / NOAA: Kathryn McKain, Colm Sweeney

Scripps Institution of Oceanography: Ralph Keeling, Eric Morgan

University of Washington: Abby Swann

- A new concept for small-scale tomographic GV deployments repeated two times per year for 4.5 years
- A light payload for measuring atmospheric CO_2, O_2, CH_4, H_2O, their isotope ratios, and related tracers