The O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) Study - Punta Arenas, Chile, 15 Jan to 29 Feb 2016


[Image: Jonathan Bent]

Britt Stephens and Matt Long, National Center for Atmospheric Research
with contributions from the ORCAS Science Team

ORCAS Science Team

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Biogenic Reactive Gas Instruments: Eric Apel (NCAR/ACOM), Nicola Blake (UC Irvine), Valeria Donets (U. Miami), Alan Hills (NCAR/ACOM), Becky Hornbrook (NCAR/ACOM), Rich Lueb (NCAR/EOL), Sue Schauffler (NCAR/ACOM), Joanna Casey (CU)

PRISM Remote Sensing: Ernesto Diaz (JPL), Heidi Dierssen (U. Conn.), Robert Green (JPL), Justin Haag (JPL), Ian McCubbin (JPL), Pantazis Mouroulis (JPL), Scott Nolte (JPL), David Thompson (JPL), Byron Van Gorp (JPL), Kate Randolph (U. Conn.), Kat Smith (CU)

Aerosol and Cloud Microphysics Instruments: Minghui Diao (San Jose State), Andrew Gettleman (NCAR/CGD), Jorgen Jensen (NCAR/EOL), Bryan Rainwater (CU), Jeff Stith (NCAR/EOL), Darin Toohey (CU)

Forecasting support: Jim Bresch (NCAR/MMM), Shawn Honomichi (NCAR/ACOM), Jordan Powers (NCAR/MMM)

Atmosphere and Climate Modeling: Abhishek Chatterjee (GMAO), Martin Hoecker-Martinez (U. Mich.), Jean-Francois Lamarque (NCAR/CGD/ACOM), Francis Vitt (NCAR/ACOM/CGD)

Education and Outreach: Alison Rockwell (NCAR/EOL), Teri Eastburn (UCAR), Nikki Lovenduski (CU)

External Collaborators: Nicolas Cassar (Duke), Scott Doney (PALTER), Hugh Ducklow (PALTER), Oscar Schofield (PALTER), Jorge Sarmiento (SOCCOM), Lynne Talley (SOCCOM)

ORCAS was primarily supported by NSF Polar Programs and LAOF. Additional support from NSF Atmospheric Chemistry and NASA Ocean Biology and Biogeochemistry

ORCAS Motivation:

- The Southern Ocean is a large sink for anthropogenic CO_2 with particular sensitivity to climate change
- State-of-the-art Earth System Models diverge for seasonal Southern Ocean air-sea CO_2 and O_2 fluxes, and for Southern Ocean climate-carbon feedbacks
- Atmospheric O_2 provides unique constraints on the biological, thermal, and anthropogenic drivers of Southern Ocean CO_2 exchange

Observational considerations:

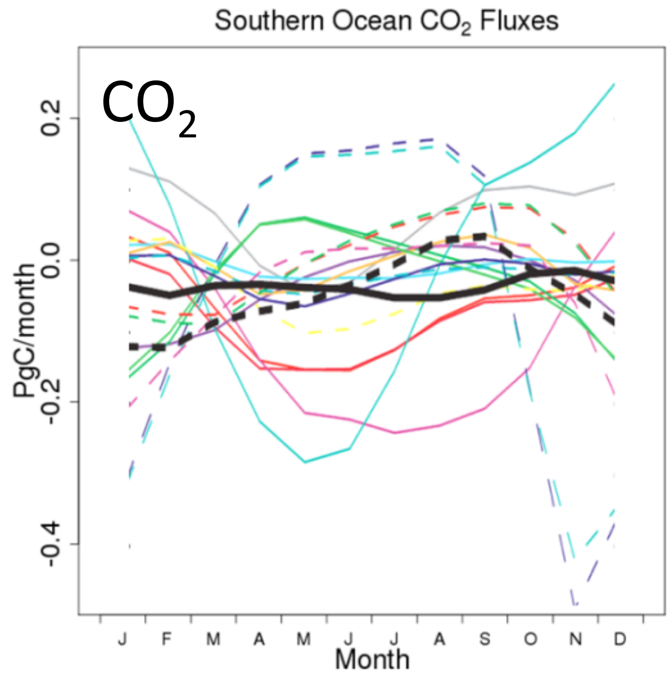
- Both long-term / spatially dispersed and temporally / spatially intensive studies are needed to advance our understanding of the Southern Ocean
- The atmosphere provides an integrated view of air-sea fluxes but surface sites are limited by atmospheric transport uncertainty and sparseness
- Aircraft can measure signals representative of large spatial scales and can overcome problems with atmospheric transport models
- Atmospheric O_2 variations difficult to measure because they are so small, but high precision airborne measurements are now possible

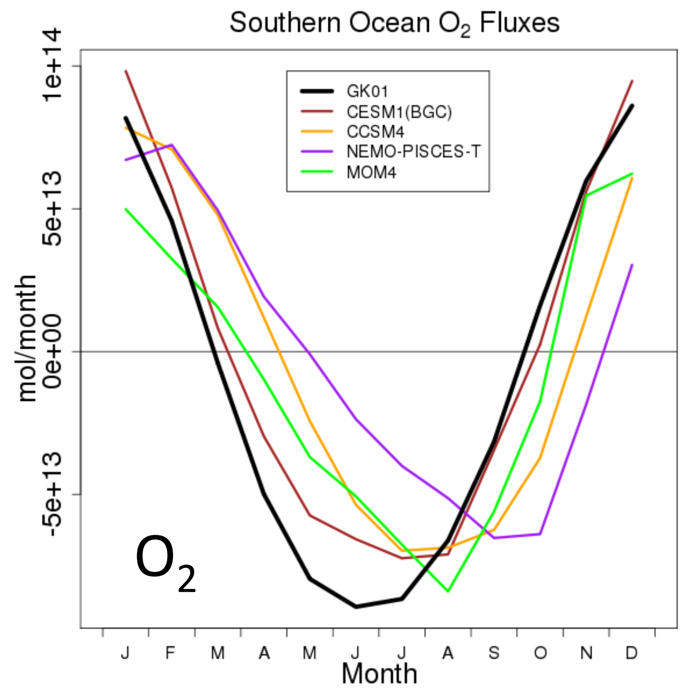
$$\delta(O_2/N_2) = \left(\frac{(O_2/N_2)_{sample}}{(O_2/N_2)_{reference}} - 1 \right) \times 10^6$$

"per meg"

Seasonal CO_2 and O_2 forcings

Annual CO_2 flux ~ -0.4 PgC/yr



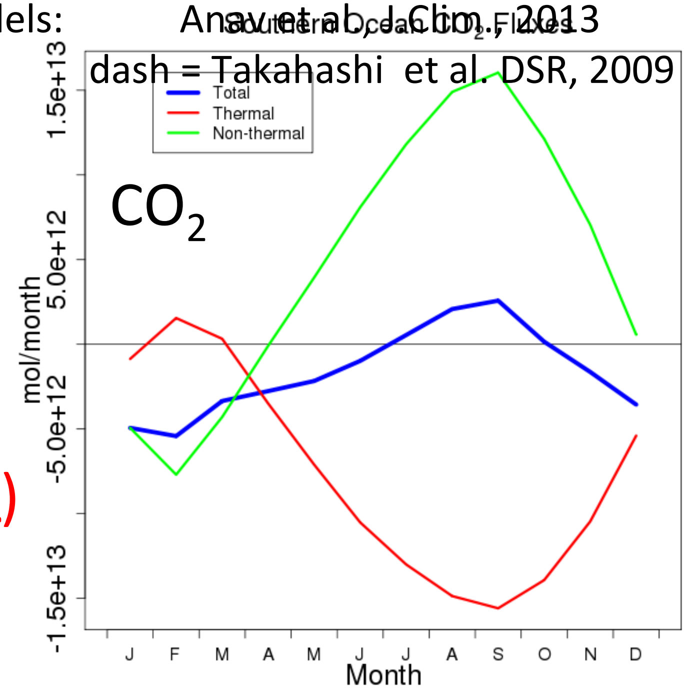


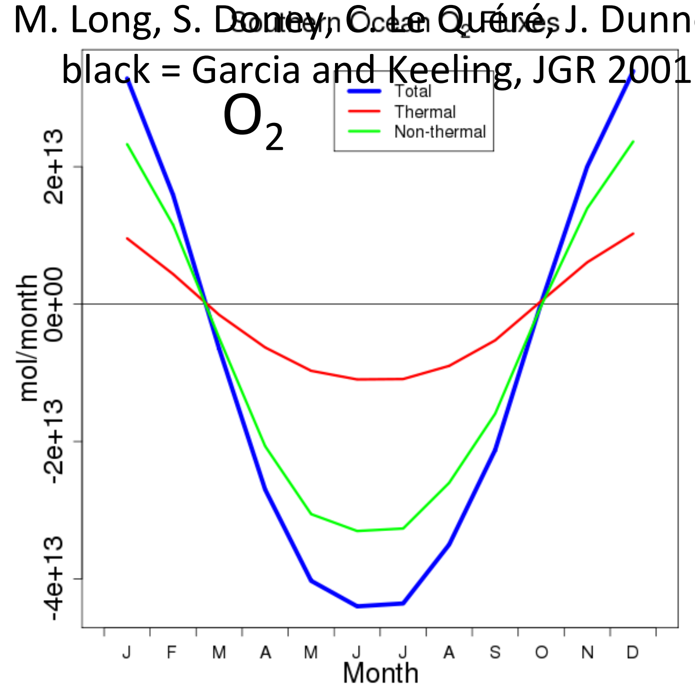
Models: Anav et al. J.Clim., 2013

Obs: dash = Takahashi et al. DSR, 2009

M. Long, S. Doney, C. Le Quéré, J. Dunne

black = Garcia and Keeling, JGR 2001



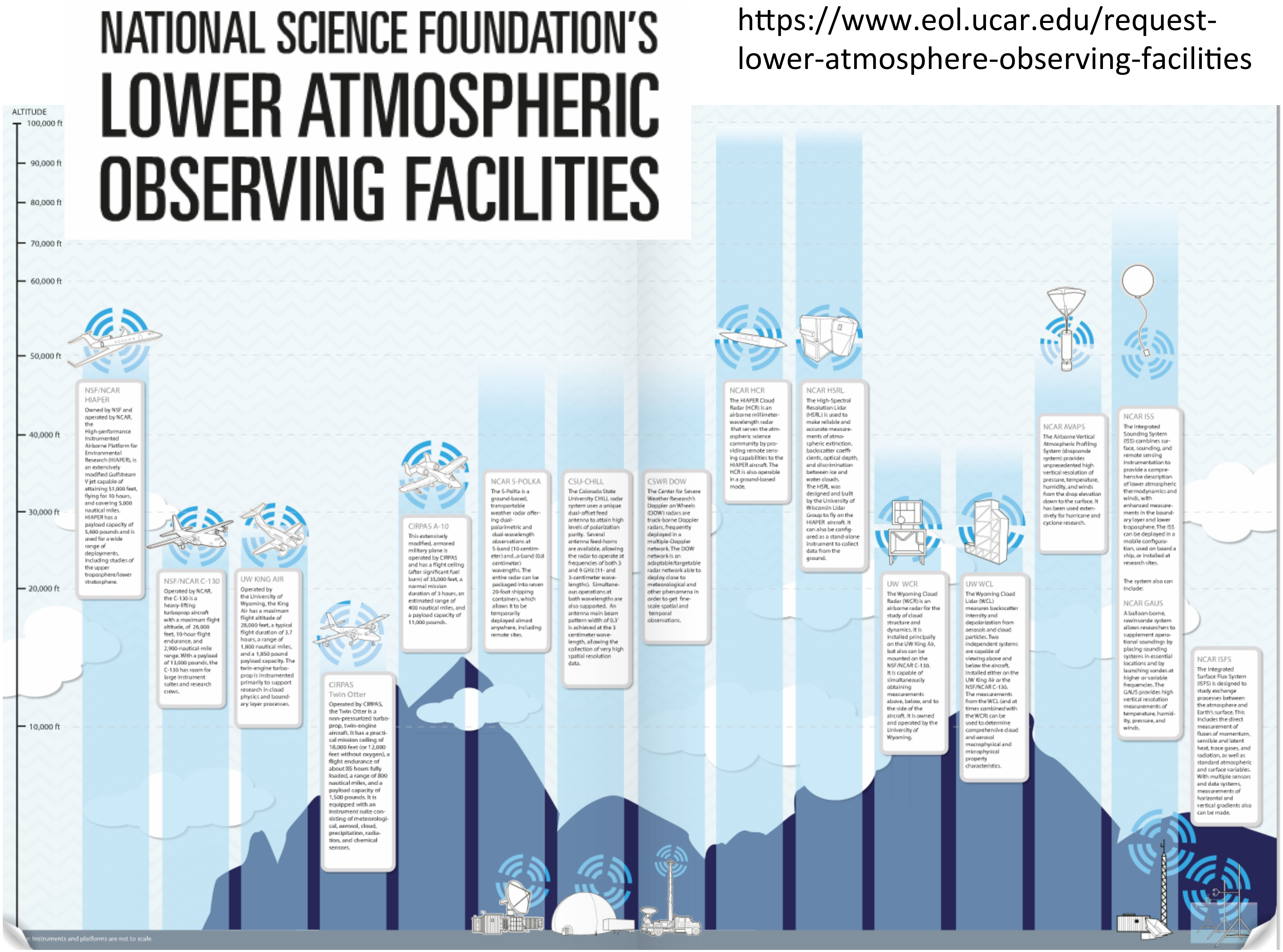


Total (obs)

Thermal (SST, Q)

Non-thermal

https://www.eol.ucar.edu/request-lower-atmosphere-observing-facilities



ORCAS Timeline

- May 2013: original mission concept circulated, refined through rest of 2013
- January 2014: submission of Scientific Program Overview and Experiment Design Overview documents to OFAP
- May 2014: Observing Facilities Assessment Panel meets
- August 2014: NSF approval to proceed to proposal
- October 2014: Science proposal and Facility Request submitted
- February 2015: NSF decision to support campaign
- Jan/Feb 2015: Supplemental proposals submitted
- March 2015: Science Team meeting
- August 2015: Dry run planning meeting
- Nov/Dec 2015: Instrument upload
- Jan/Feb 2016: ORCAS field campaign
  - 19 Research Flights
  - 98.2 Flight Hours
- September 2016: Science Team meeting
- March 1, 2017: Public data release

ORCAS Measurement Objectives:

Large scale

(45-70 S, 0-14 km altitude) atmospheric O_2 and CO_2 distributions, characterizing the size and temporal growth of the zonal atmospheric O_2 plume, and constraining zonal fluxes on monthly to seasonal time scales

Basin scale

Vertical atmospheric O_2 and CO_2 gradient ratios through the mid-troposphere and spatial distributions to support estimation of flux ratios and magnitudes over full campaign time period and spatial extent

Regional scale

Pseudo-Lagrangian flights for localized daily flux estimates and O_2 and CO_2 gradient ratios across the top of the ABL

Plus:

Remote sensing of hyperspectral ocean color over daily flux influence regions and along the Antarctic Peninsula

Biogenic reactive gas measurements to quantify emissions of chemically and radiatively important species

Cloud microphysics measurements to address large discrepancies in climate models

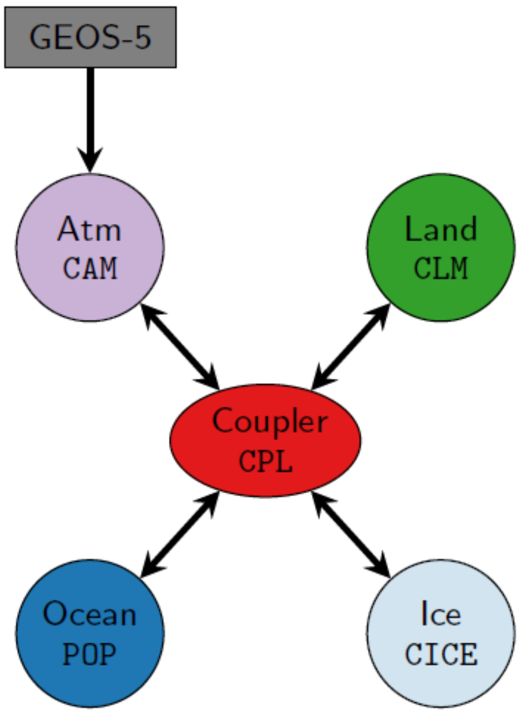
GV Scientific Payload:

Instrument	Measurement	Institution
Airborne Oxygen Instrument (AO2)	$\delta(O_2/N_2)$, CO_2	NCAR EOL
Medusa Flask Sampler	$\delta(O_2/N_2)$, CO_2, $\delta(Ar/N_2)$, $\delta^{13}C$, $\delta^{18}O$, and $\Delta^{14}C$ of CO_2	NCAR/Scripps
Quantum Cascade Laser Spectrometer (QCLS)	CO_2, CH_4, N_2O, CO	Harvard/Aerodyne/NCAR
Picarro	CO_2, CH_4, H_2O	NOAA/CU
Portable Remote Imaging Spectrometer (PRISM)	Hyperspectral water-leaving radiance	JPL
Advanced Whole Air Sampler (AWAS)	Over 80 trace gases, including DMS, OCS, halocarbons, $MeONO_2$, isoprene	NCAR/U. Miami
HIAPER Trace Organic Gas Analyzer (TOGA)	Over 60 VOCs, including nitrate species, DMS, and VSL halocarbons	NCAR
VCSEL, King Probe, RICE, CDP, 2DC, CN, UHSAS, GNI, CLH-2	Cloud microphysics and aerosol size distributions	NCAR, CU

Modeling Tools:

1) Community Earth System Model (CESM)

CAM-SD coupled configuration



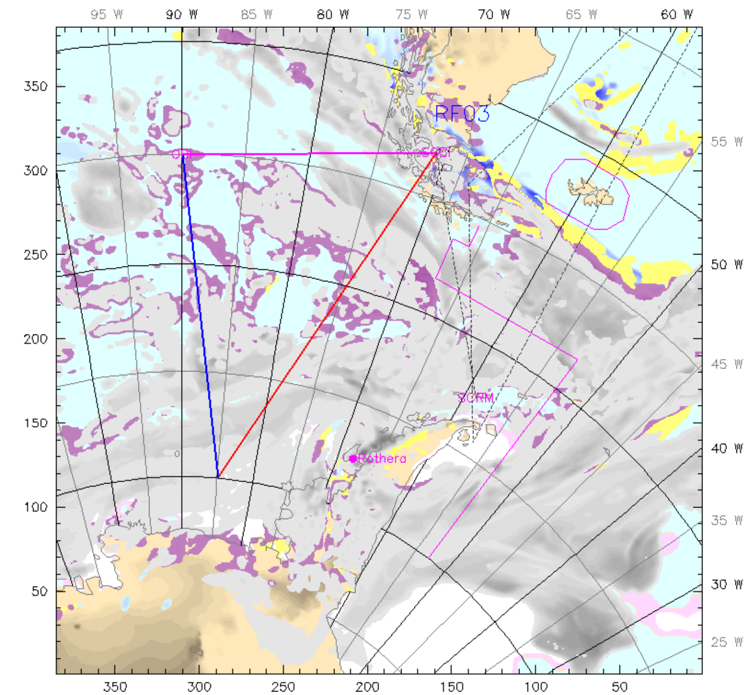
Initialized 3-day forecasts every day: nudge CAM to GEOS-5 forecast model; fully coupled, prognostic ocean ecosystem and air-sea fluxes.

- O_2 and CO_2 distributions;
- Idealized tracers for source regions.

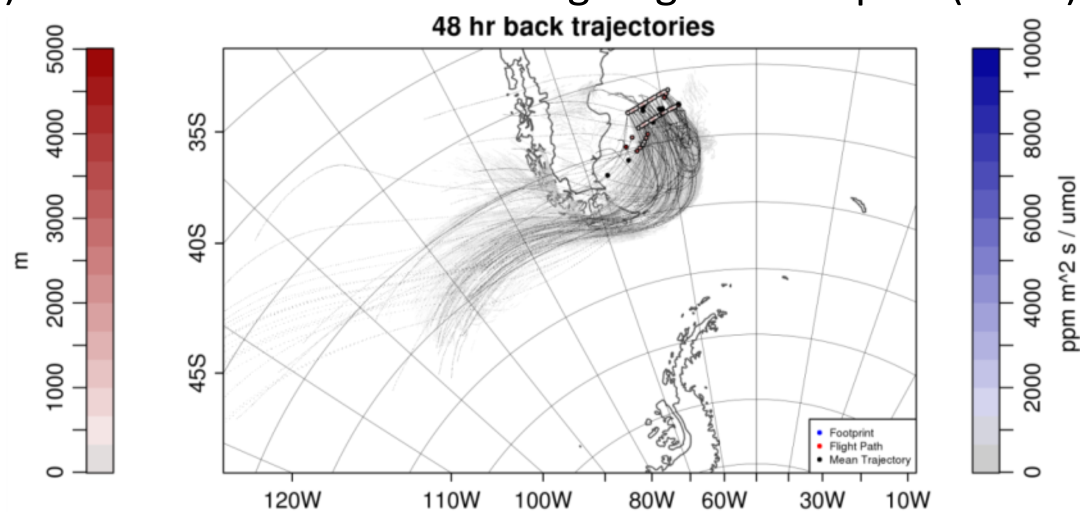
Developed and implemented by Matt Long

2) Antarctic Mesoscale Prediction System (AMPS)

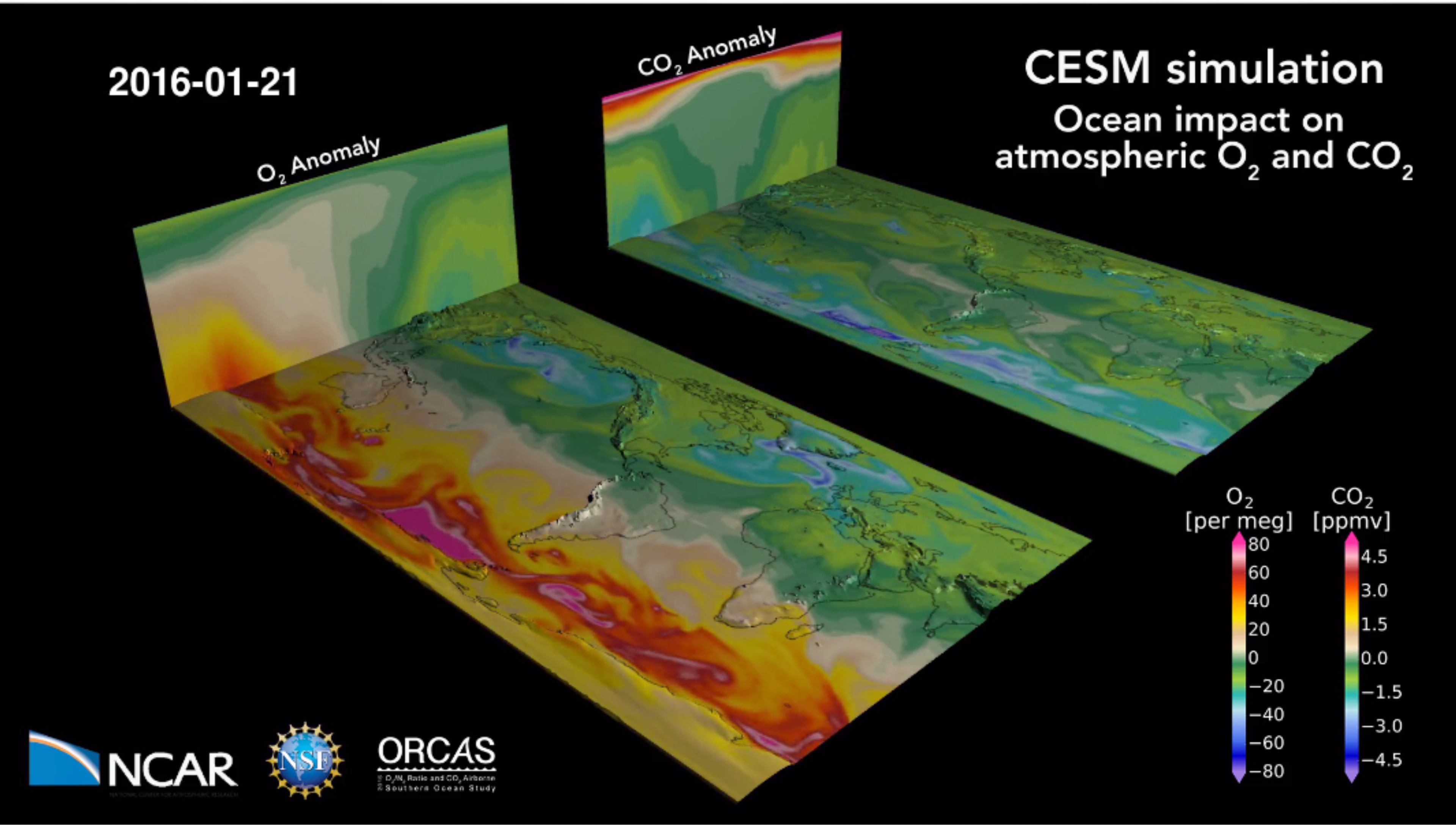
led by Jordan Powers



3) Stochastic Time-Inverted Lagrangian Transport (STILT)

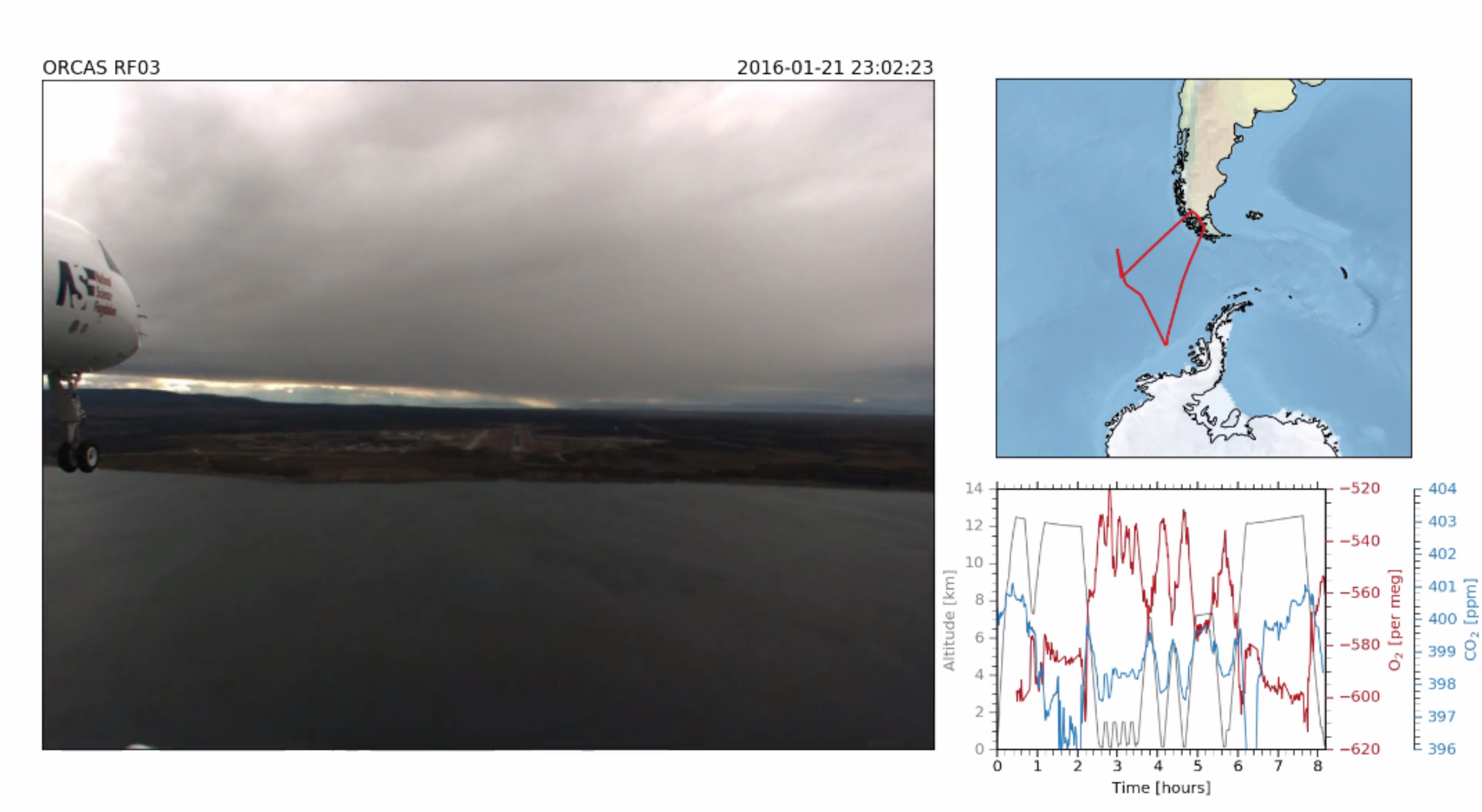


led by Eric Kort and Martin Hoecker-Martinez



https://youtu.be/VUwOAVh6CGQ

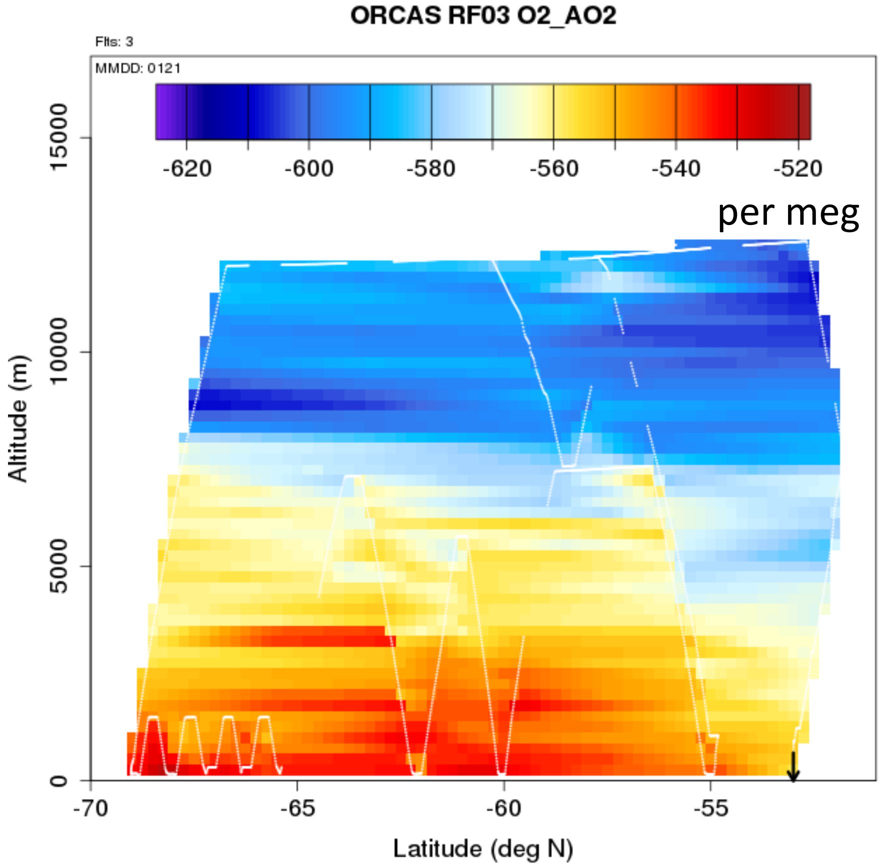
Matt Long, NCAR



https://youtu.be/Df2peaFxUAM

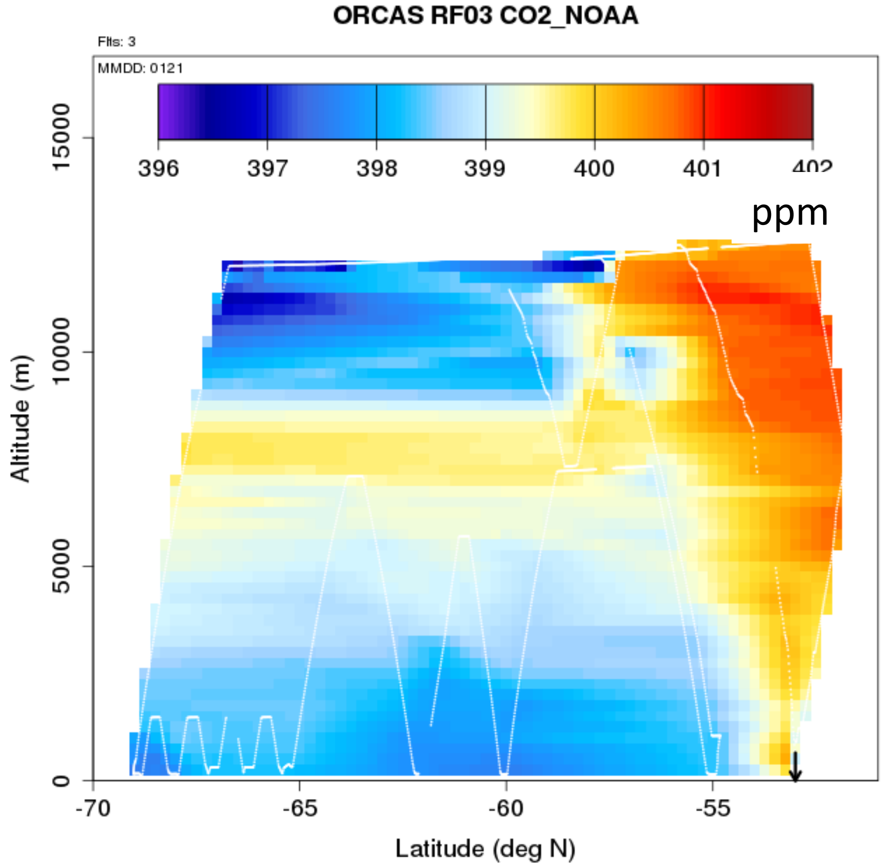
ORCAS Research Flight 3 (RF03) 21 January 2016

O_2



NCAR AO2 Instrument
B. Stephens

CO_2



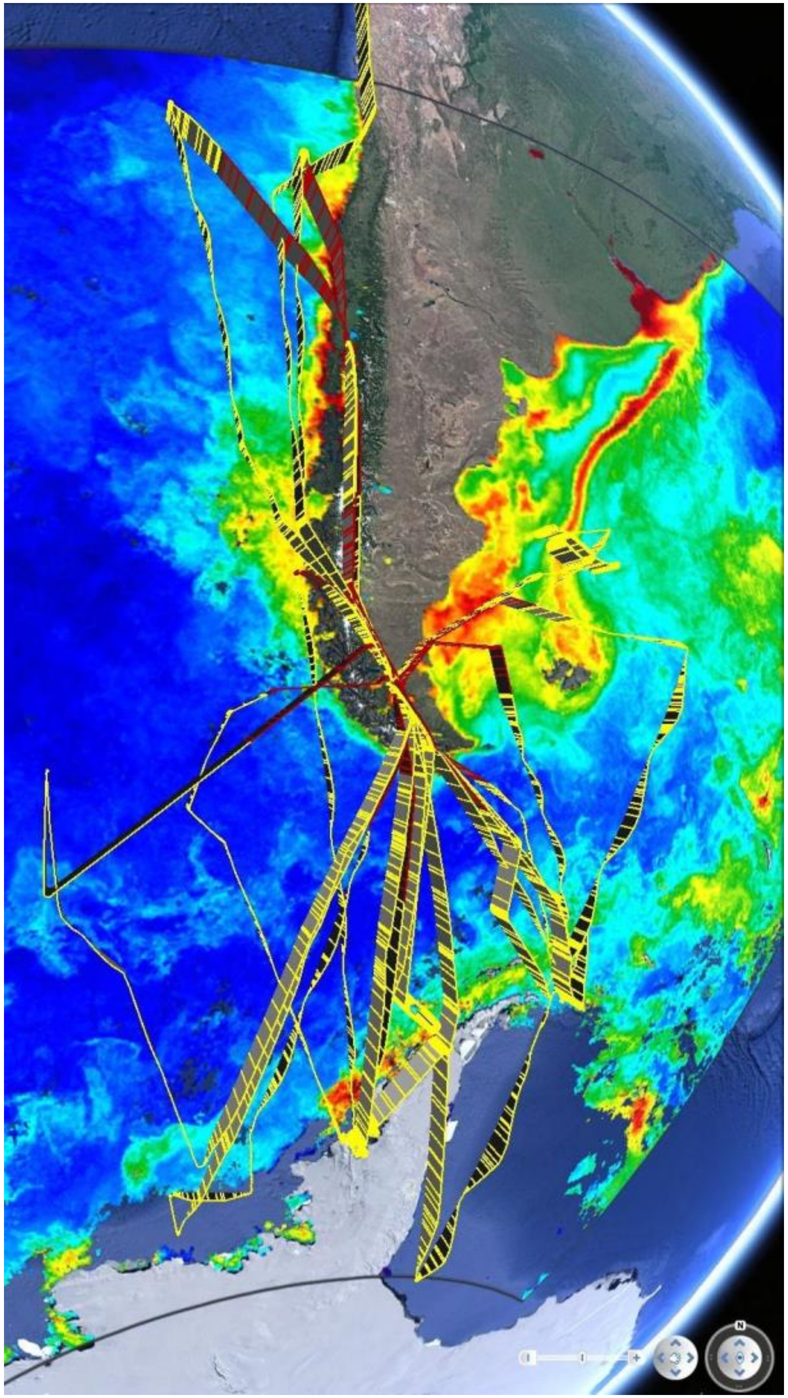
CU / NOAA CO2 Instrument
C. Sweeney

TABLE 1. ORCAS Flights

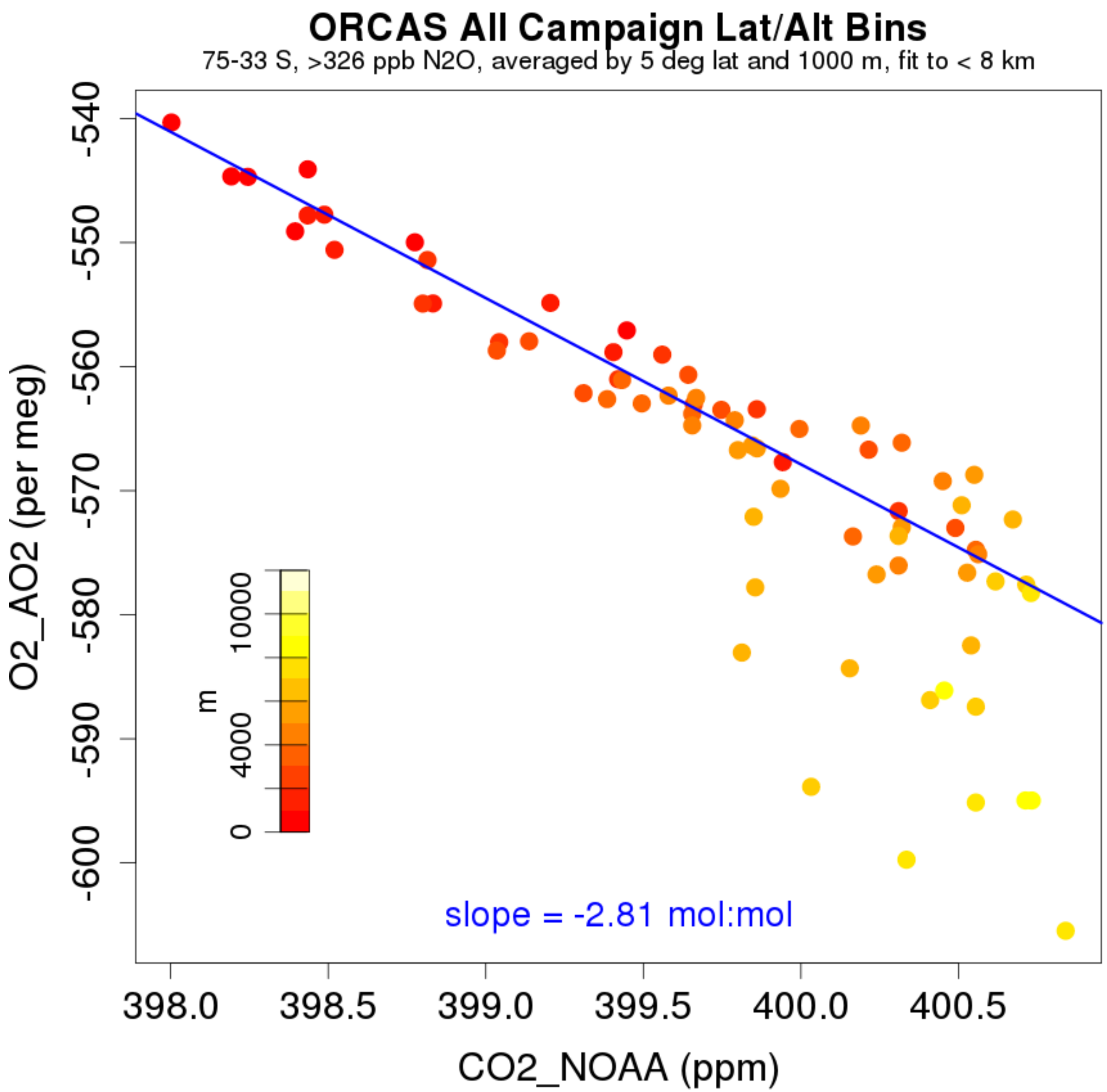
Flight Code[1]	Date	Hours	Route[2]	Objectives
TF01	1/5/2016	4.3	KBJC-Lamont, OK-KBJC	Instrument test flight, TCCON comparison
TF02	1/7/2016	5.5	KBJC-Gulf of Mexico-KBJC	Instrument test flight
FF01	1/11/2016	9.7	KBJC-SCAR	Ferry
FF02	1/12/2016	5.1	SCAR-SCCI	Ferry
RF01	2016-01-15	7.7	SCCI-Marguerite Bay-SCCI	SW large scale survey, remote sensing
RF02	1/18/2016	7.0	SCCI-Elephant Island-SCCI	SE large scale survey, marginal ice zone BL, remote sensing of Patagonian Shelf
RF03	1/21/2016	8.4	SCCI-Bellingshausen Sea-SCCI	W large scale survey, marginal ice zone, OOI node, remote sensing
RF04	1/23/2016	5.7	SCCI-SCTE	NW large scale survey, reposition for winds
RF05	1/25/2016	2.1	SCTE-SCCI	Reposition return
RF06	1/25/2016	6.2	SCCI-PSA-L.M. Gould-SCCI	Remote sensing over Palmer Station and ship, in situ BL comparison to ship
RF07	1/30/2016	7.5	SCCI-Patagonian Shelf-SCCI	Lagrangian budgeting, remote sensing of shelf
RF08	2/5/2016	7.9	SCCI-Bellingshausen Sea-SCCI	SW large scale survey, marginal ice zone
RF09	2/8/2016	4.5	SCCI-SCTE	NW large scale survey, reposition for winds
RF10	2/10/2016	2.0	SCTE-SCCI	reposition return
RF11	2/12/2016	8.2	SCCI-Weddel Sea-SCCI	SE large scale survey
RF12	2/15/2016	2.2	SCCI-SCVD	reposition for winds
RF13	2/17/2016	2.2	SCVD-SCCI	reposition return
RF14	2/18/2016	7.7	SCCI-Elephant Island - Patagonian Shelf-SCCI	SE large scale survey, remote sensing L.M. Gould track
RF15	2/19/2016	2.0	SCCI-SCTE	reposition for winds
RF16	2/22/2016	1.9	SCTE-SCCI	reposition return
RF17	2/24/2016	7.6	SCCI-Antarctic Peninsula-SCCI	SW large scale survey, Lagrangian upwind
RF18	2/25/2016	4.7	SCCI-Elephant Island-SCCI	SE large scale survey, Lagrangian downwind
RF19	2/29/2016	5.9	SCCI-SCAR	NW large scale survey, ferry
FF03	3/1/2016	9.5	SCAR-KBJC	Ferry

[1]TF = Test Flight, FF = Ferry Flight, RF = Research Flight

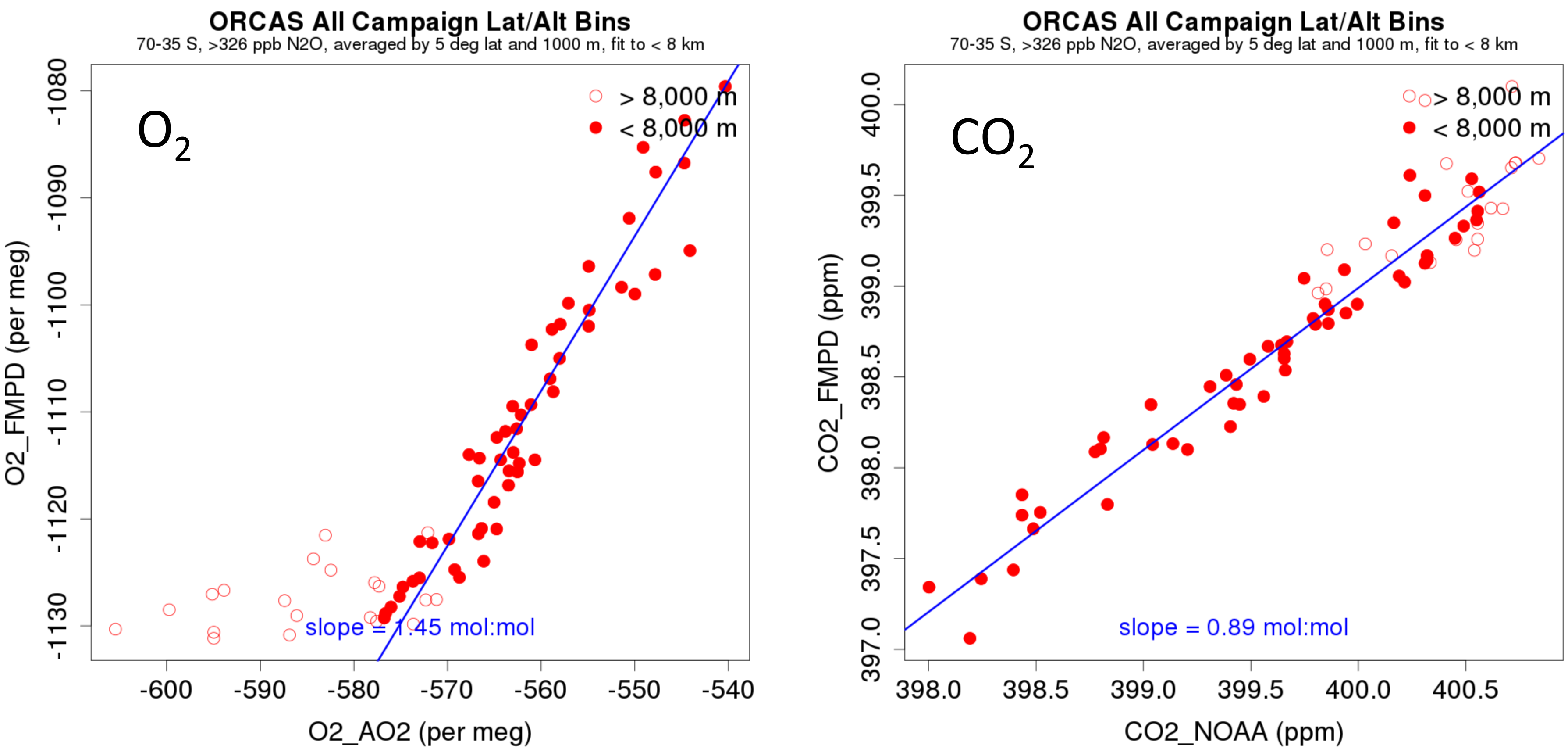
[2]KBJC = Broomfield, CO, SCAR = Arica, Chile, SCCI = Punta Arenas, Chile, SCTE = Puerto Montt, Chile, SCVD = Valdivia, Chile



Whole campaign bin averaged $O_2:CO_2$ relationship

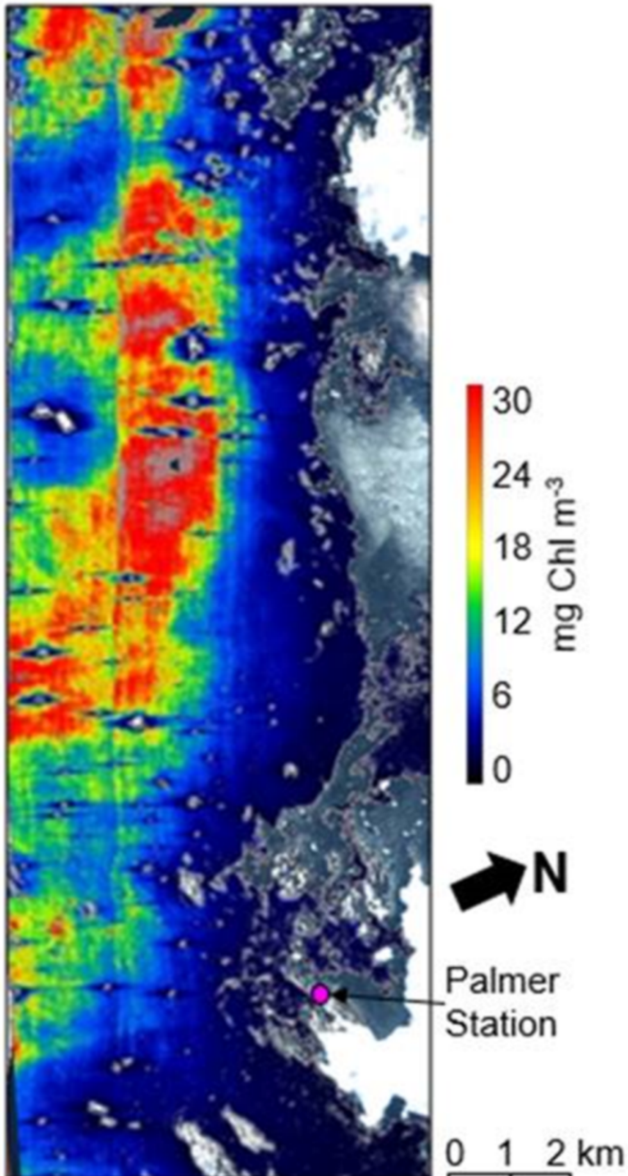


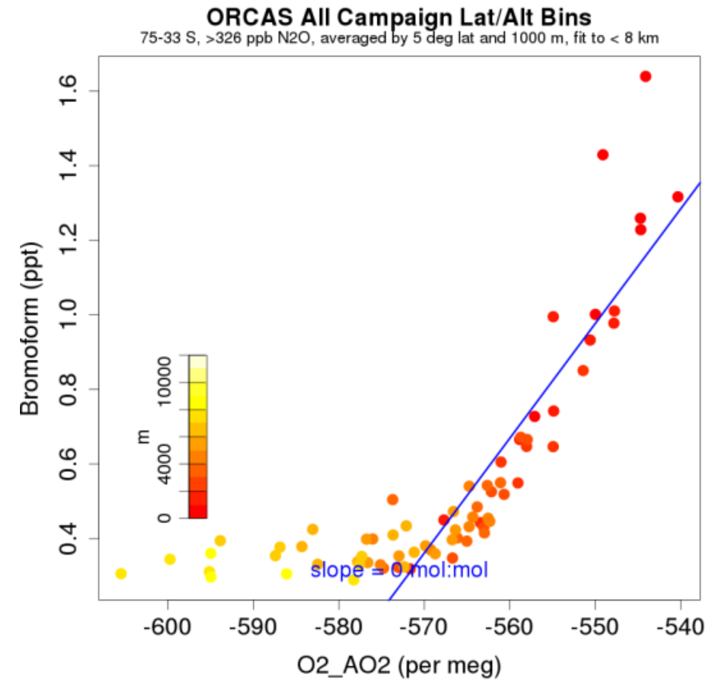
ORCAS whole campaign comparison to CESM forecast model

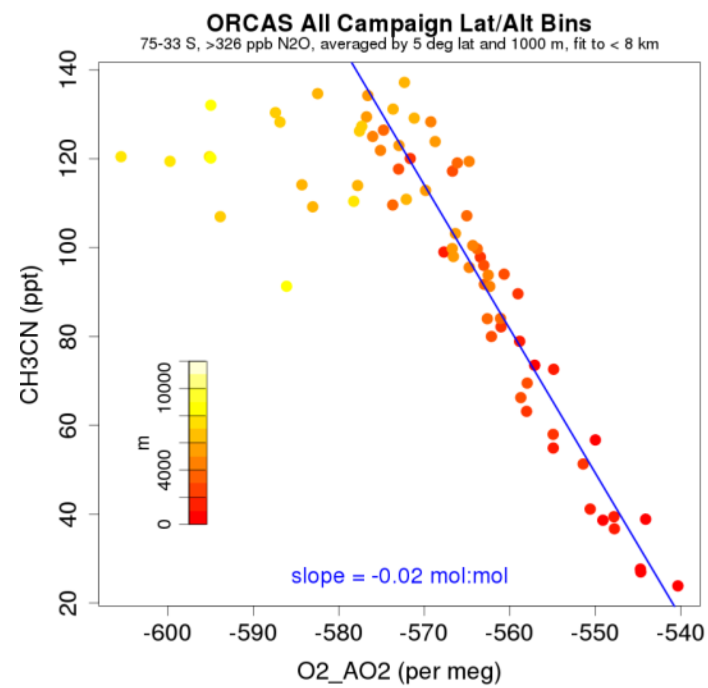


- CO_2 prediction was very close, but O_2 gradients overestimated, suggesting CO_2 agreement for wrong reasons

Example PRISM image and reactive gas relationships to O_2







Summary

- The ORCAS field campaign has successfully completed 19 research flights over 98 hours
- Total amount of O_2 and CO_2 over Southern Ocean well measured and will provide estimates of Seasonal Net Outgassing / Ingassing
- Predominantly negative CO_2:O_2 correlations reflecting the dominance of biological drivers on summertime CO_2 fluxes, and winnowing of CMIP5 seasonal CO_2 cycles
- The CESM forecast product overestimated observed O_2 signals but showed remarkable agreement with CO_2 gradients, which were themselves much stronger than climatological estimates.
- Six week evolutions and spatial distribution of O_2, CO_2, and their ratio are being exploited for further process understanding and model tests
- Other reactive gas, remote sensing, and cloud microphysics results analyses underway
- Potential to leverage many synergistic observations in the region
- Methods developed in ORCAS can be applied at other time of year, and other regions

ORCAS

2016 O_2/N_2 Ratio and CO_2 Airborne Southern Ocean Study

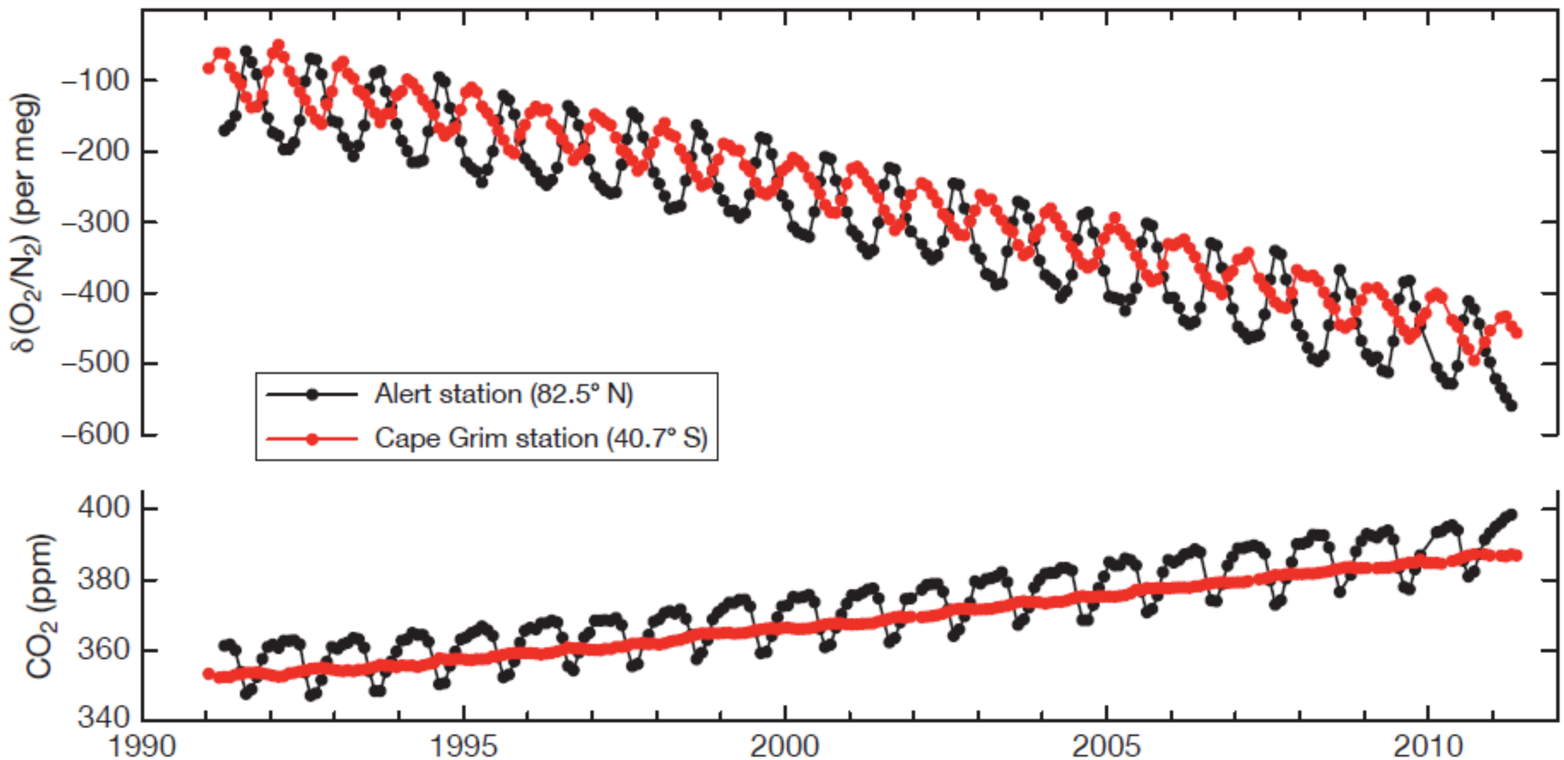
http://www.eol.ucar.edu/field_projects/orcas

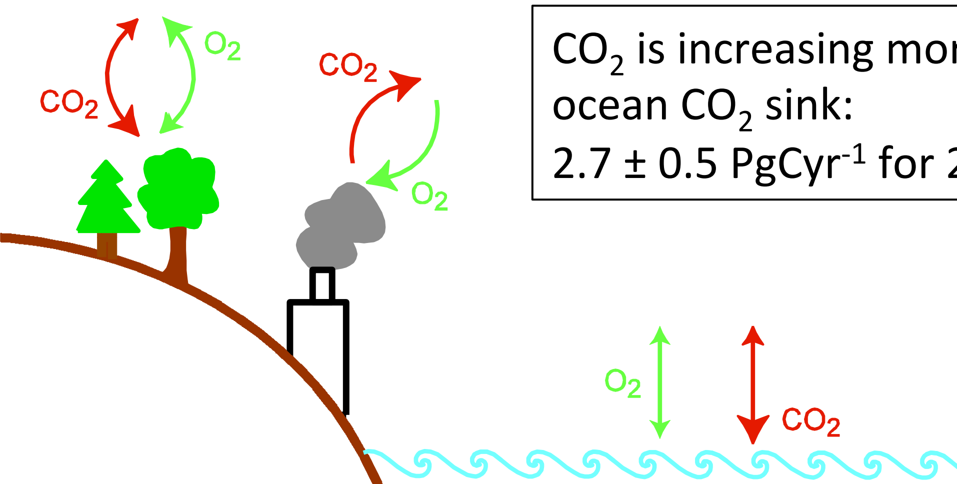
- Synergistic observations include SOCCOM biogeochemical profiling floats; Palmer LTER cruise and DO_2/Ar sampling aboard the NSF ARSV L.M. Gould; pCO_2, DIC, nutrients, and atm. CO_2 and O_2 on the Gould; Palmer Station flasks; NSF OOI Southern Ocean node; biogeochemical gliders; OCO-2 satellite CO_2

Possible talking points:

- ORCAS was motivated by large disagreements in CMIP5 models regarding Southern Ocean CO_2 fluxes, and by HIPPO measurements
- ORCAS was fairly unique in that we had a coupled biogeochemical forecast model running (CESM)
- Example cross-sections from RF03 targeting forecast large plume of O_2, drawdown of CO_2
- Campaign-average O_2:CO_2 ratios well defined, and CESM comparison, though off by 60%, is actually quite good considering around half of CMIP5 models get the sign of this relationship wrong
- Boundary layer CO_2 draw down observed during ORCAS about a factor of 2 greater than predicted by global inverse model calculations – O_2 will provide important constraints on the responsible processes

Scripps O_2 Program





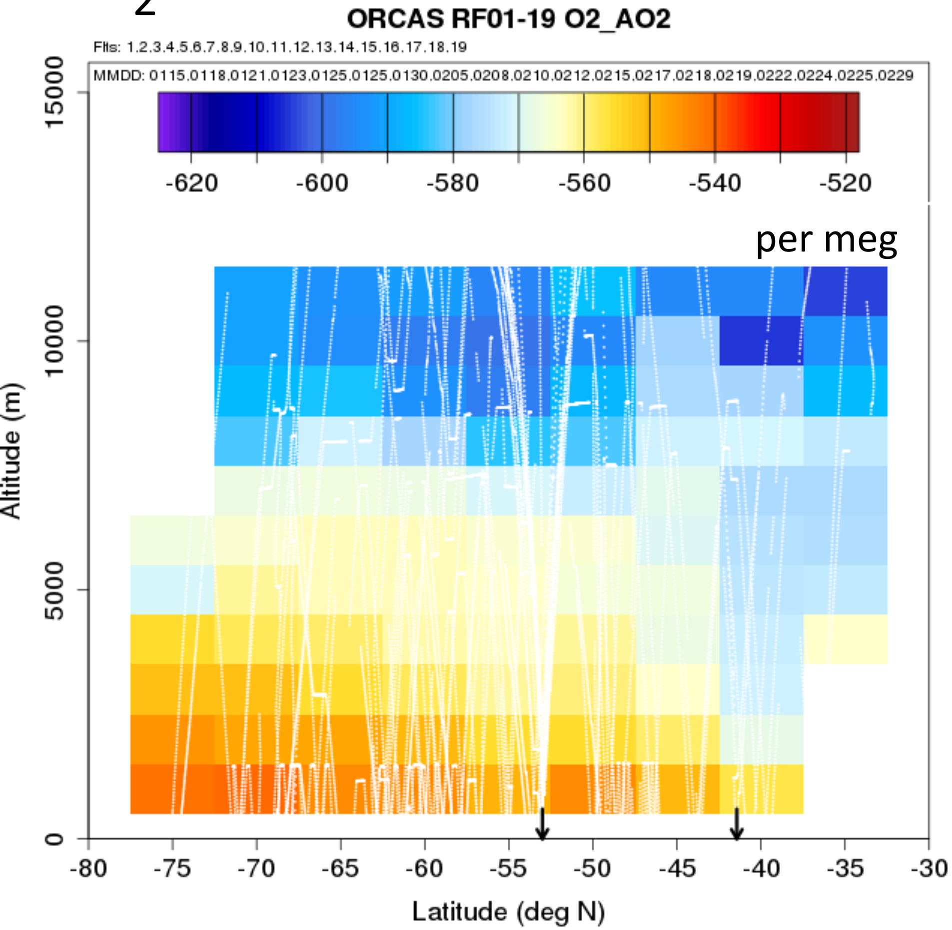
CO_2 is increasing more slowly than O_2 is decreasing because of net ocean CO_2 sink:
2.7 ± 0.5 $PgCyr^{-1}$ for 2000-2010 (Keeling and Manning, TG, 2013).

$\delta(O_2/N_2)=((O_2/N_2)_{sample}/(O$

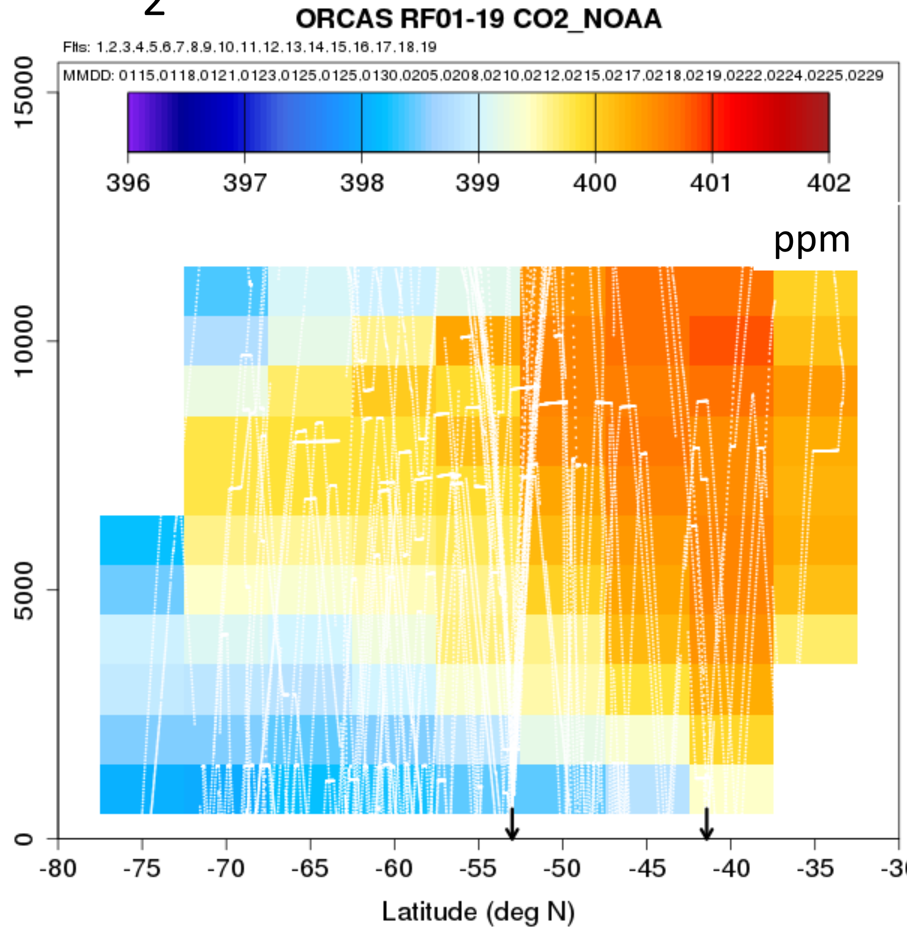
"per meg"

Whole campaign lat/alt bin averages

O_2

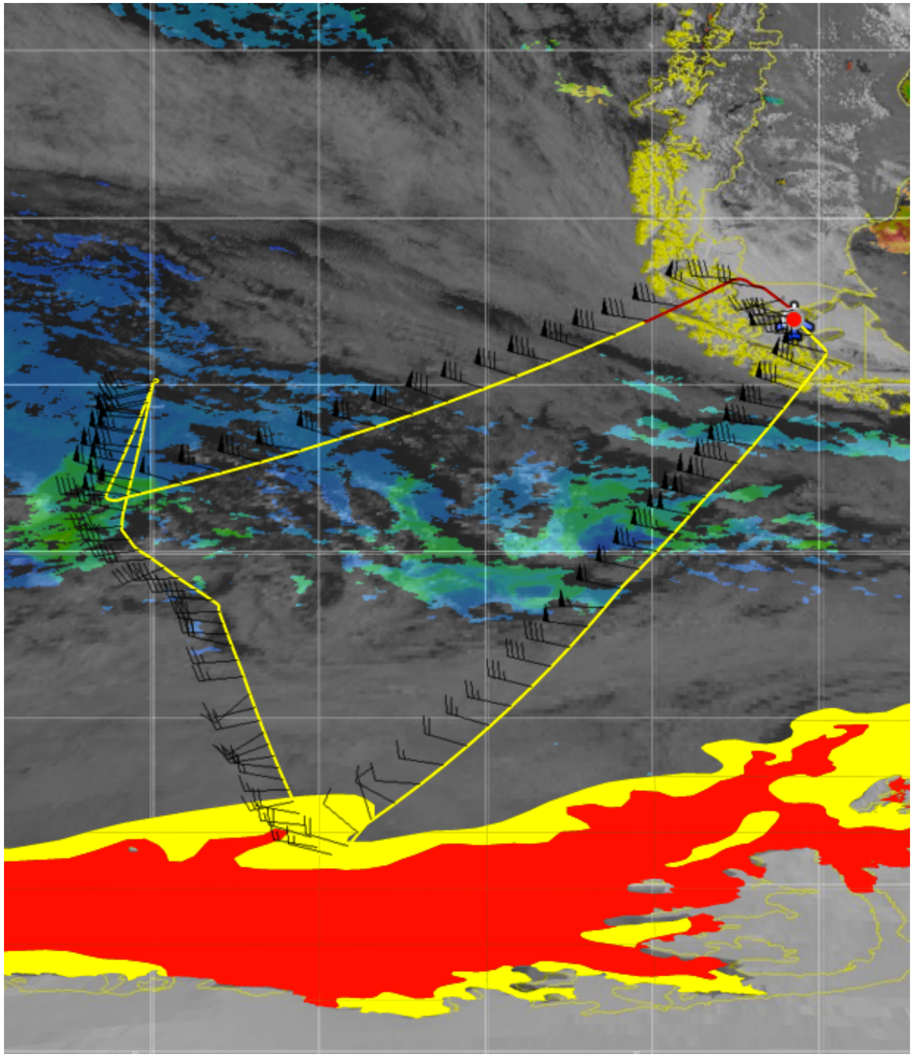


CO_2



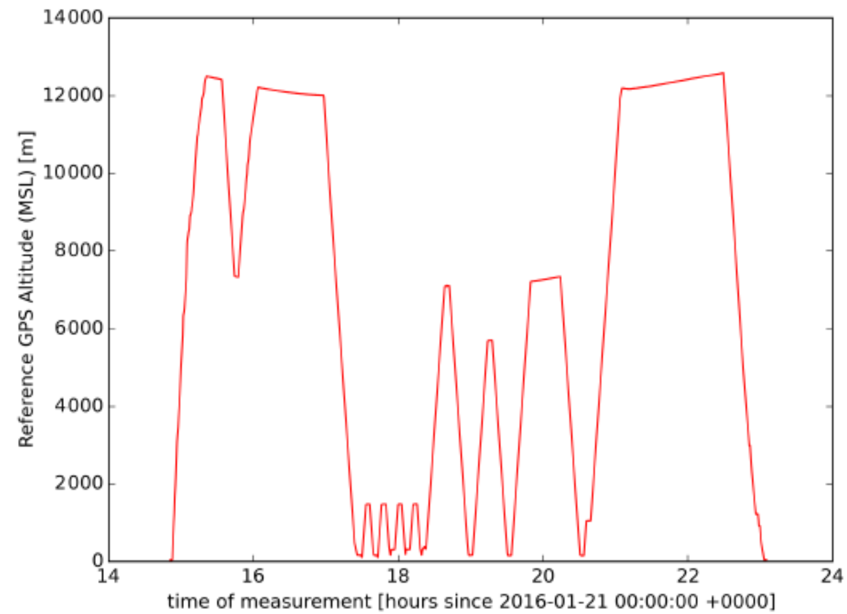
ORCAS Research Flight 3 (RF03)

21 January 2016



wind speed and direction (barbs)
clouds (gray shade)
Chl a (color contour)
marginal (yellow) and pack (red) ice zones

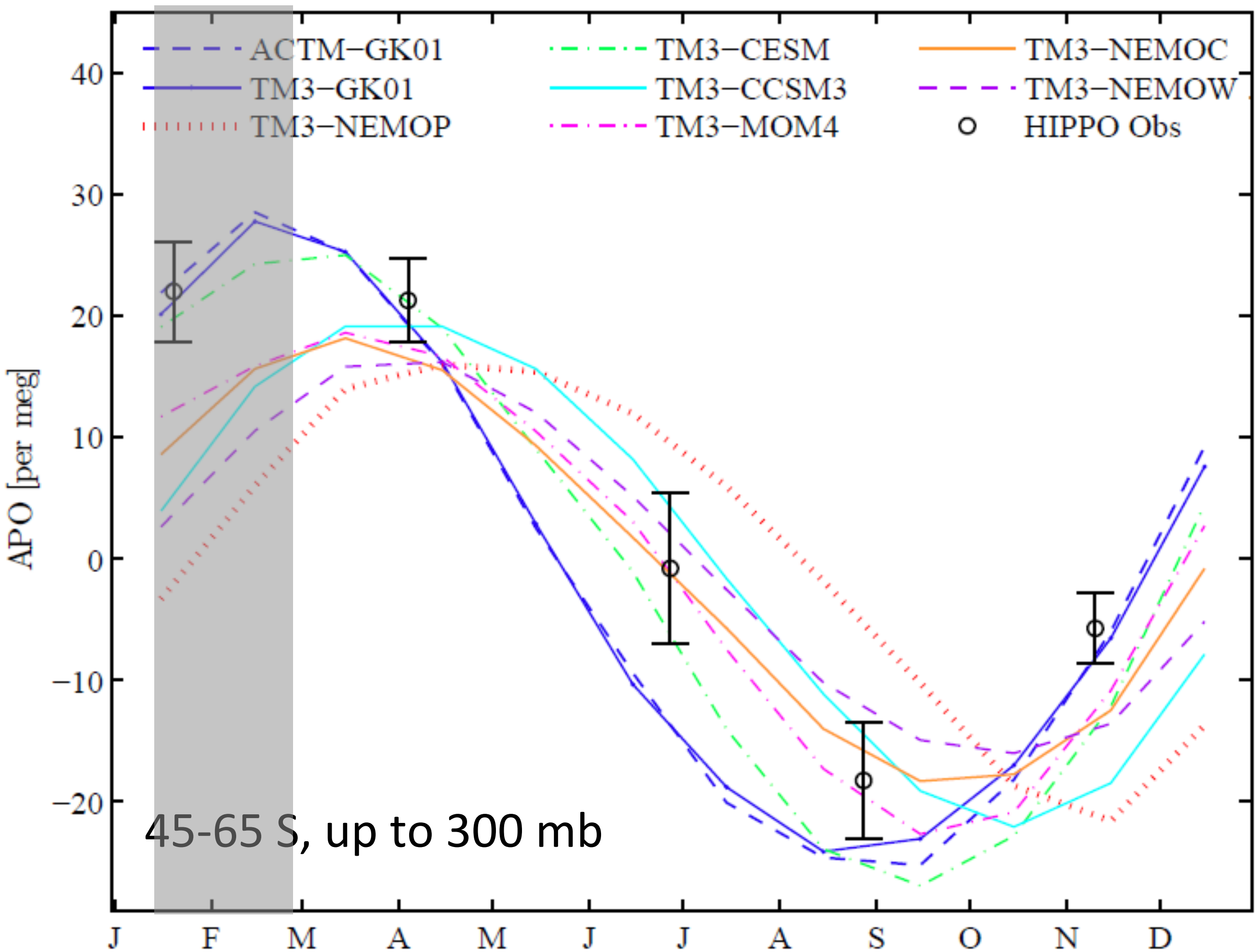
Altitude v. time



Objectives

- Southbound sampling of upper troposphere;
- Marginal ice zone survey at 69S,85W;
- Large scale survey northbound along 90W;
- PRISM remote sensing leg in clear air;
- Profile over OOI node at 55S,90W.

HIPPO Southern Ocean Curtain Averages

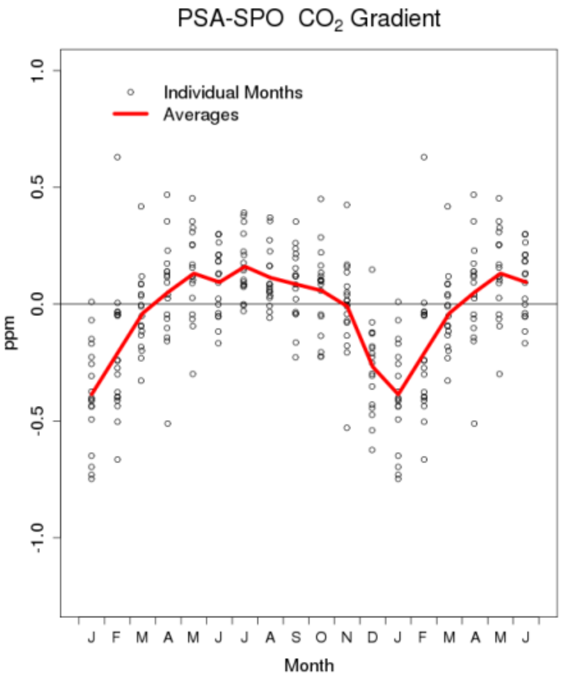


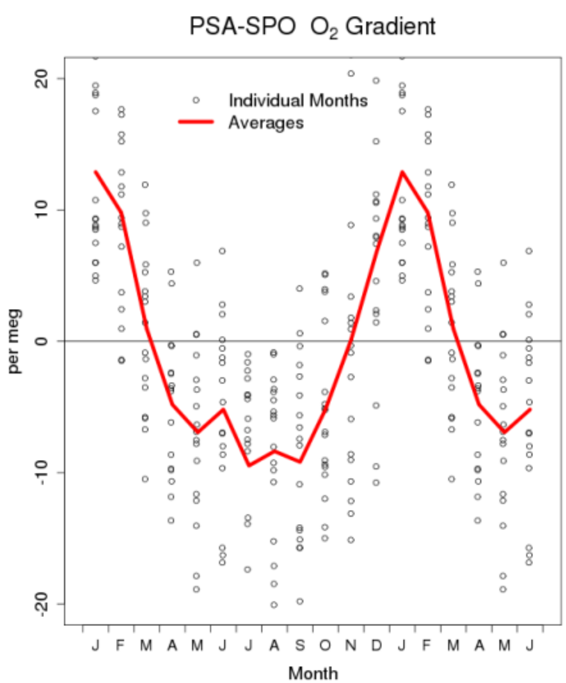
$APO = O_2 + 1.1\ CO_2$

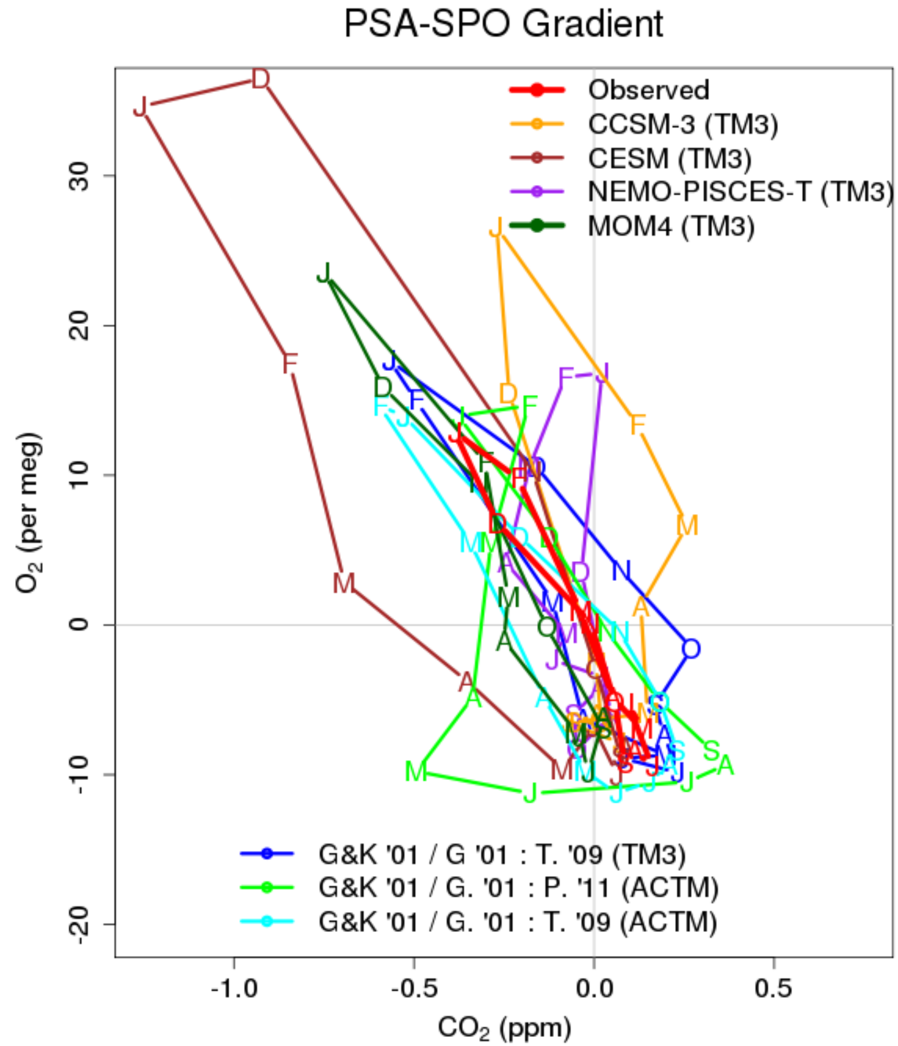
J. Bent, Dissertation, 2014

Scripps Oxygen Network

Palmer Station and South Pole Flasks

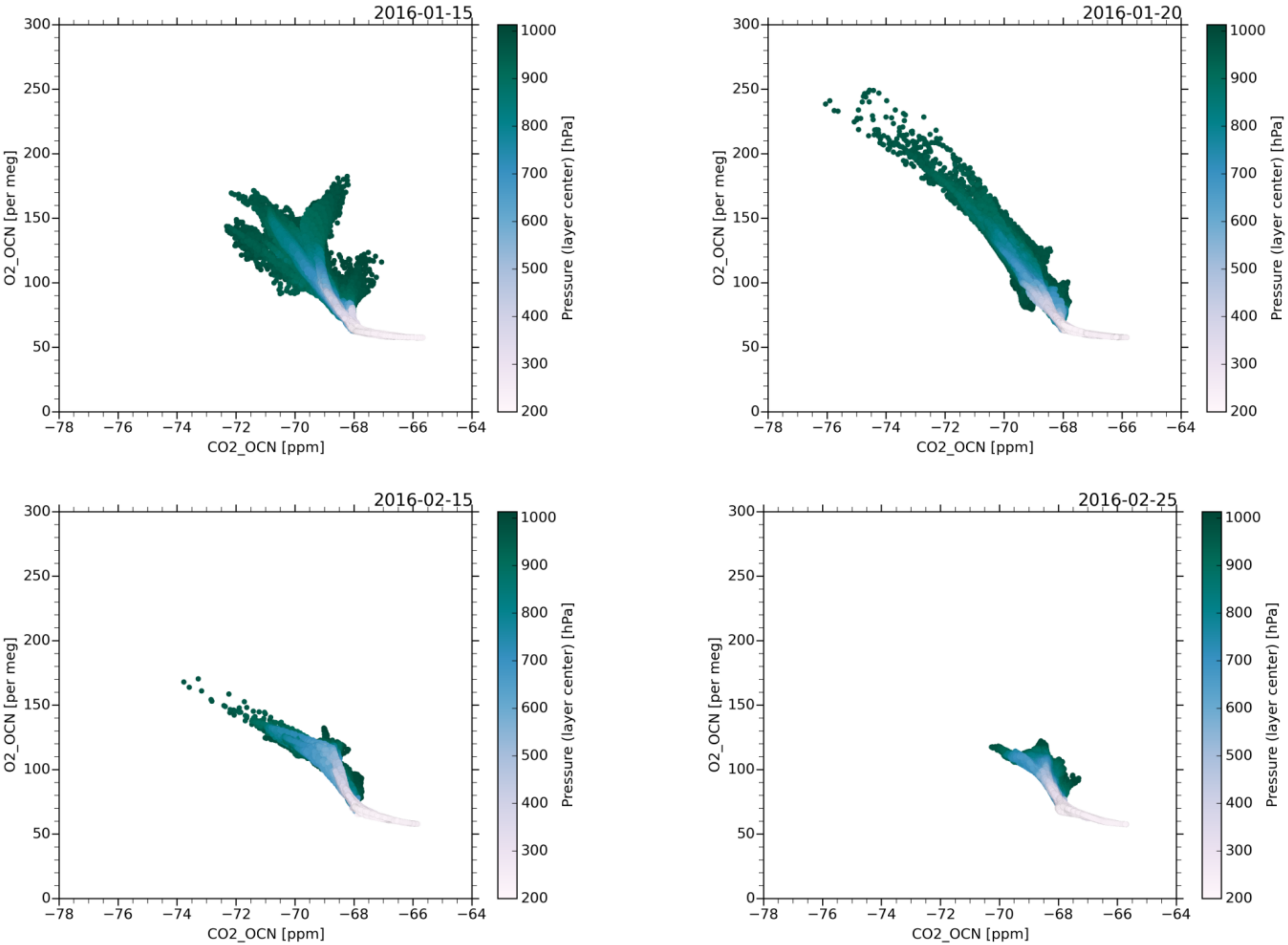






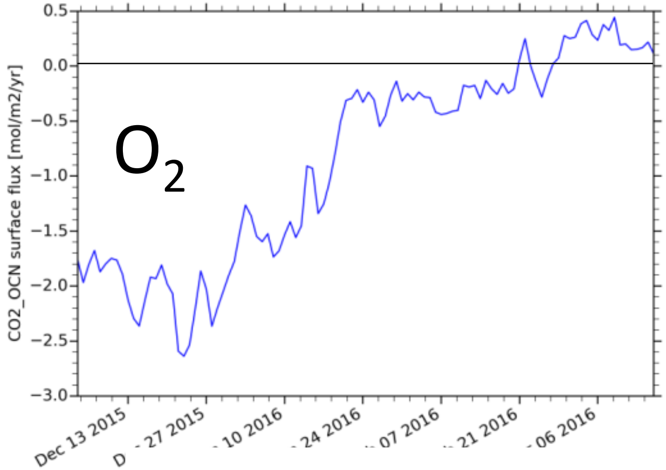
Jan = 0.15 mol CO_2 : mol O_2

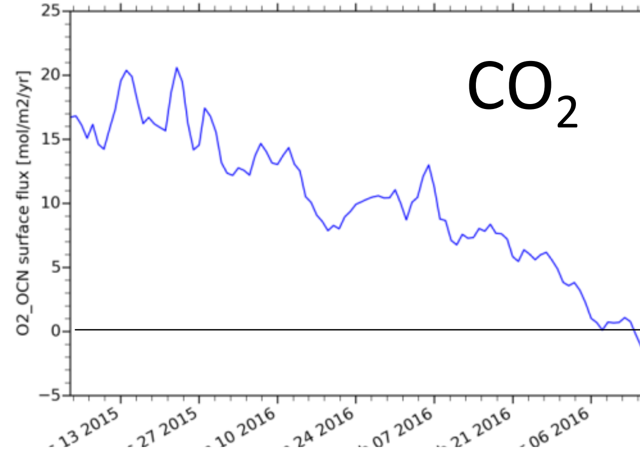
Forecast model predictions, all grid cells over Southern Ocean Easter Pacific sector



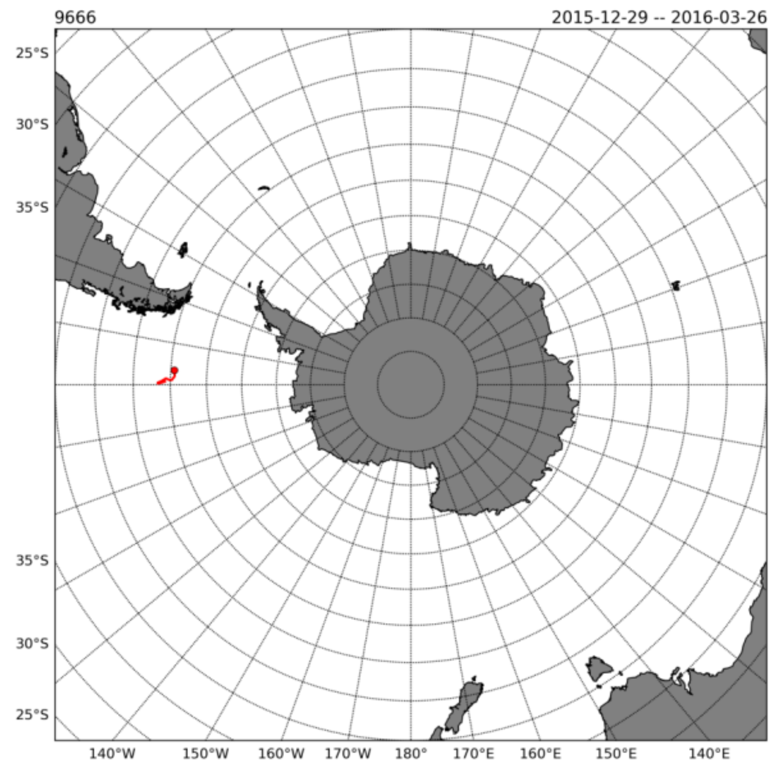
Matt Long, NCAR

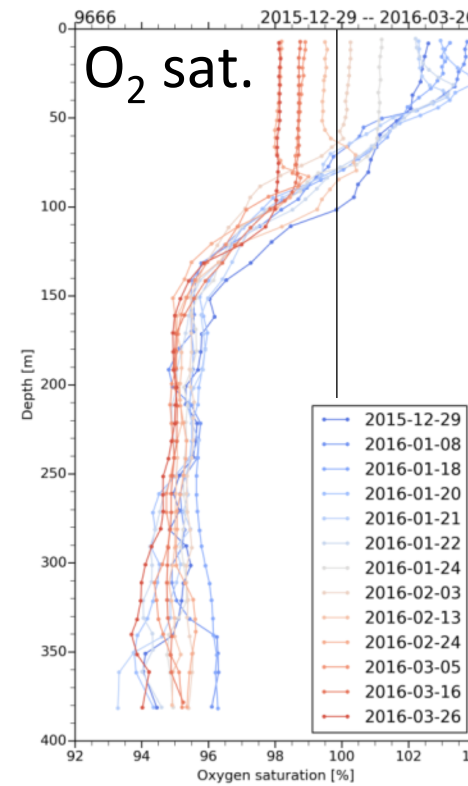
Forecast model predictions, Southern Ocean air-sea fluxes





SOCCOM
Float 9666

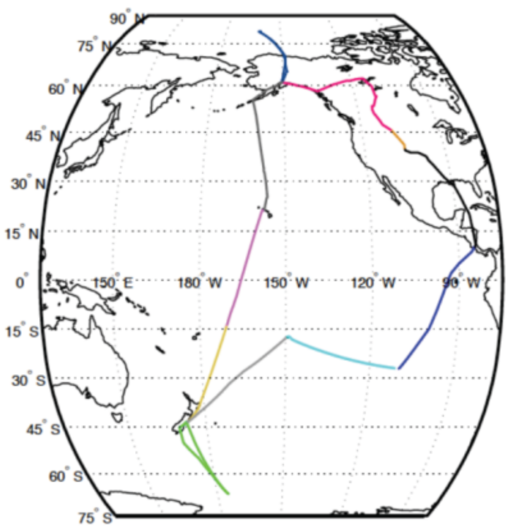


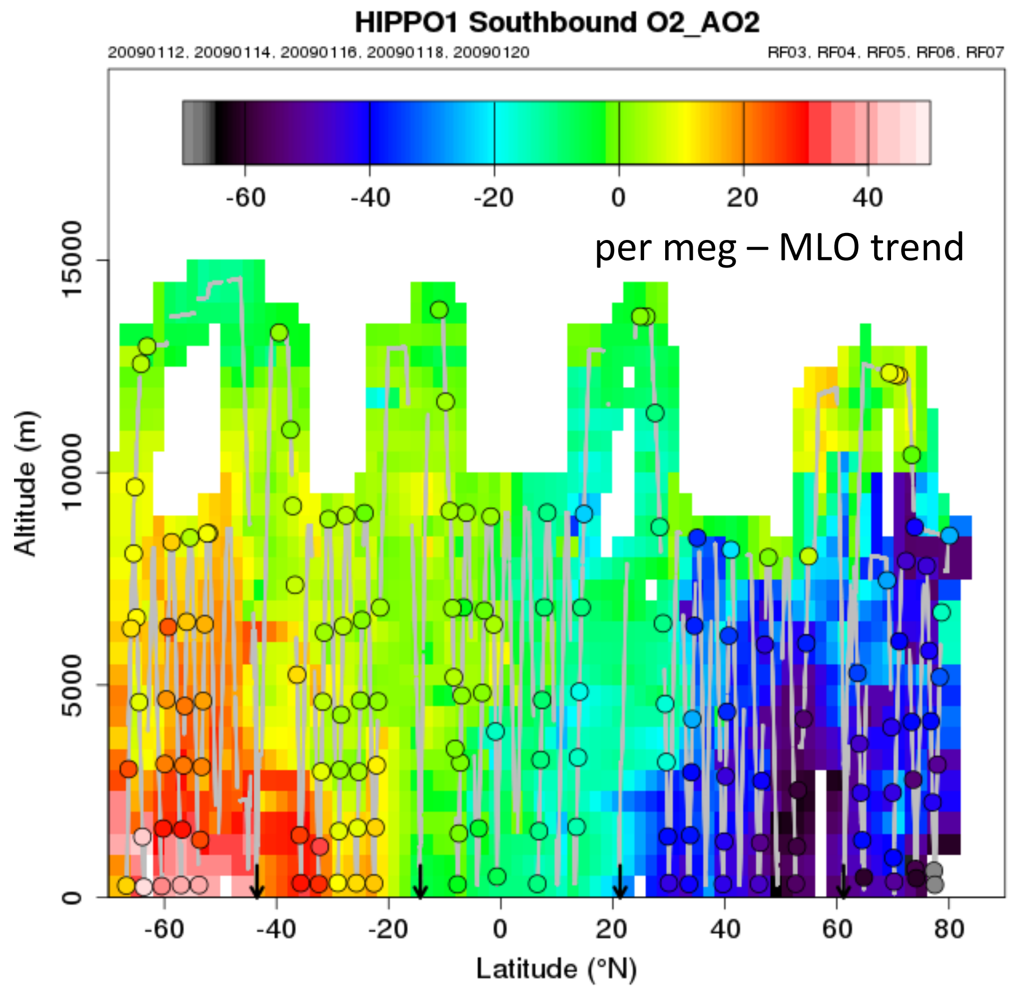


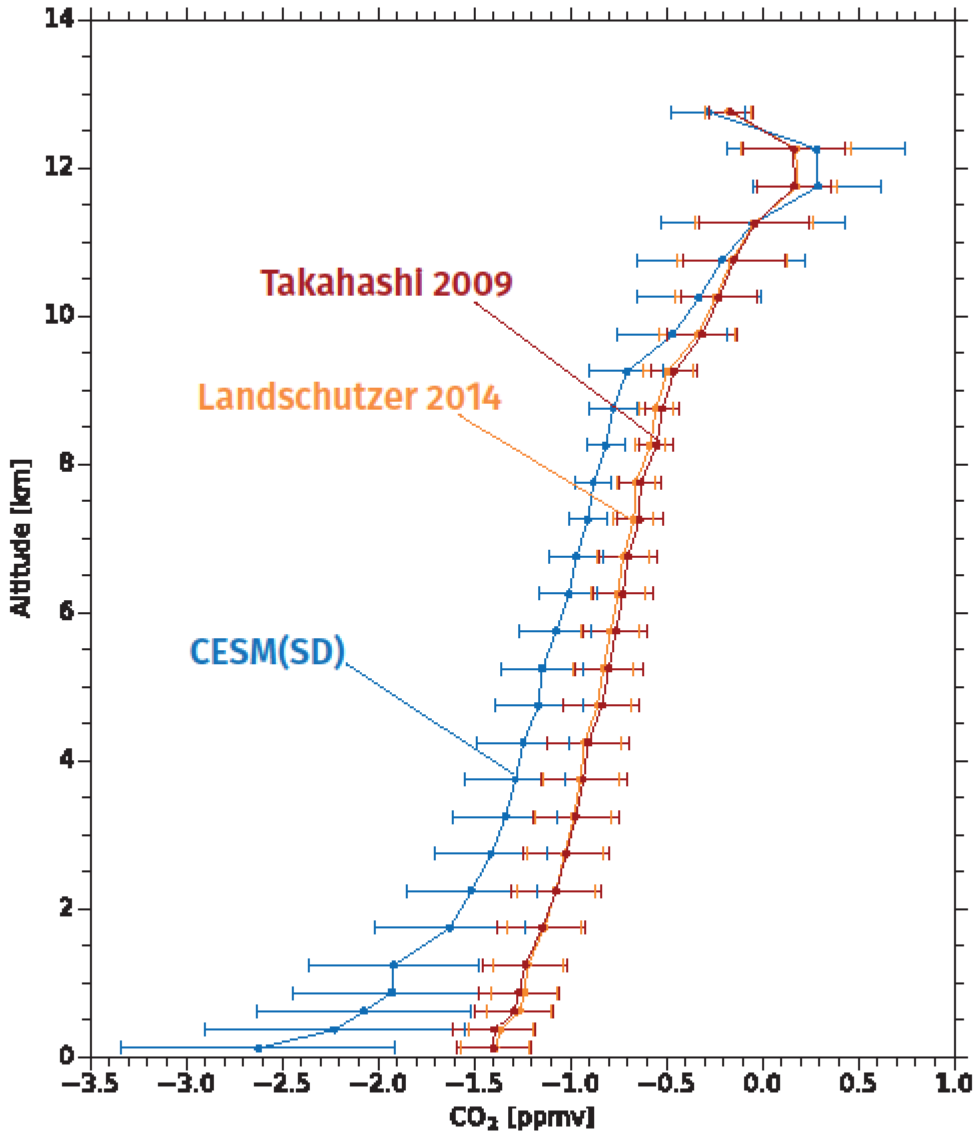
HIAPER Pole-to-Pole Observations

January, 2009

HIPPO1 Flight Track



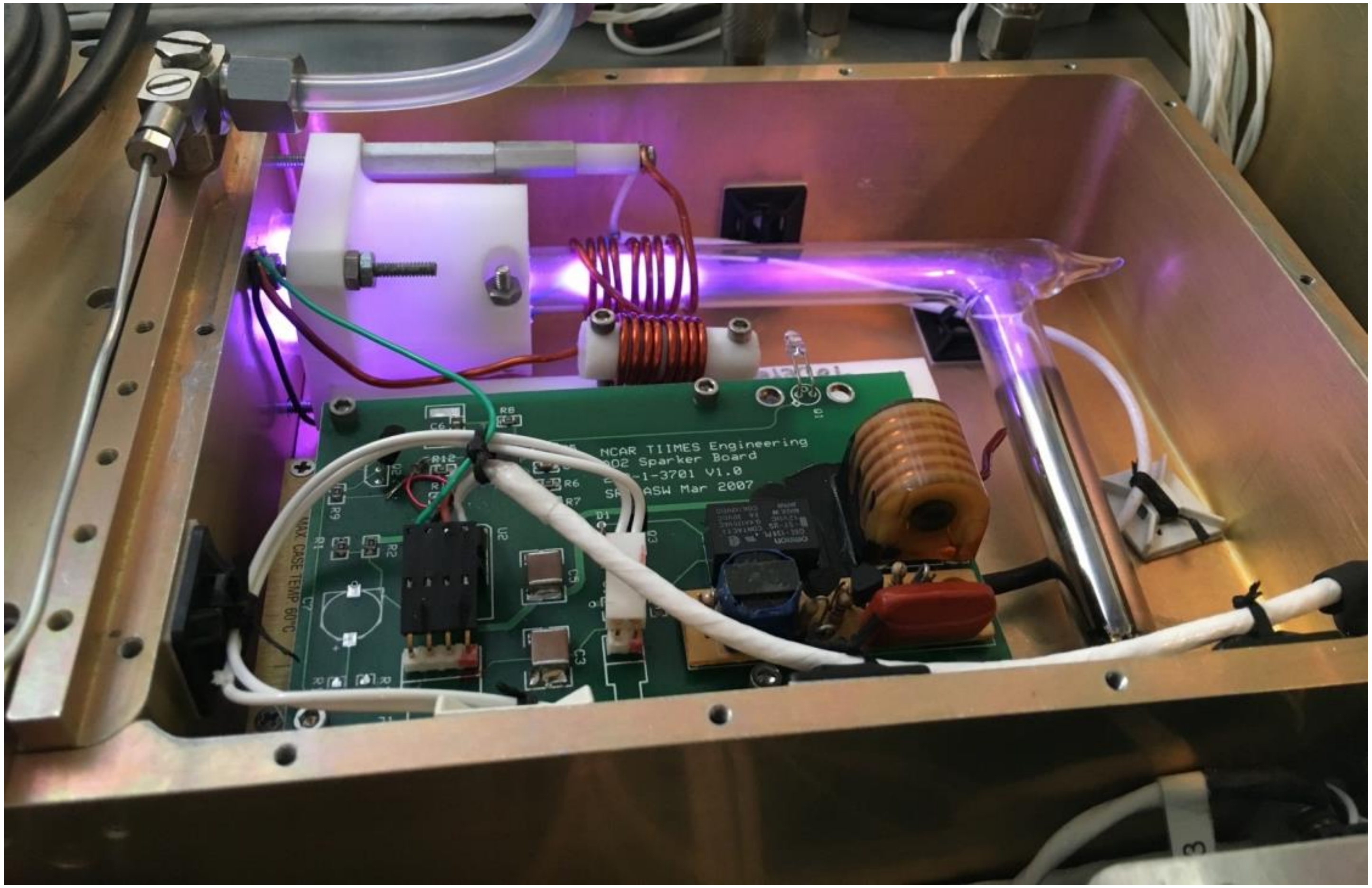




Takahashi 2009
Landschutzer 2014
CESM(SD)
Altitude [km]
CO2 [ppmv]
0
2
4
6
8
10
12
14
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0

NCAR Airborne Oxygen Instrument (AO2)

NCAR/Scripps Medusa Flask Sampler


NCAR TIIMES Engineering
Sparker Board
V1.0
ASW Mar 2007
MAX CASE TEMP 60°C