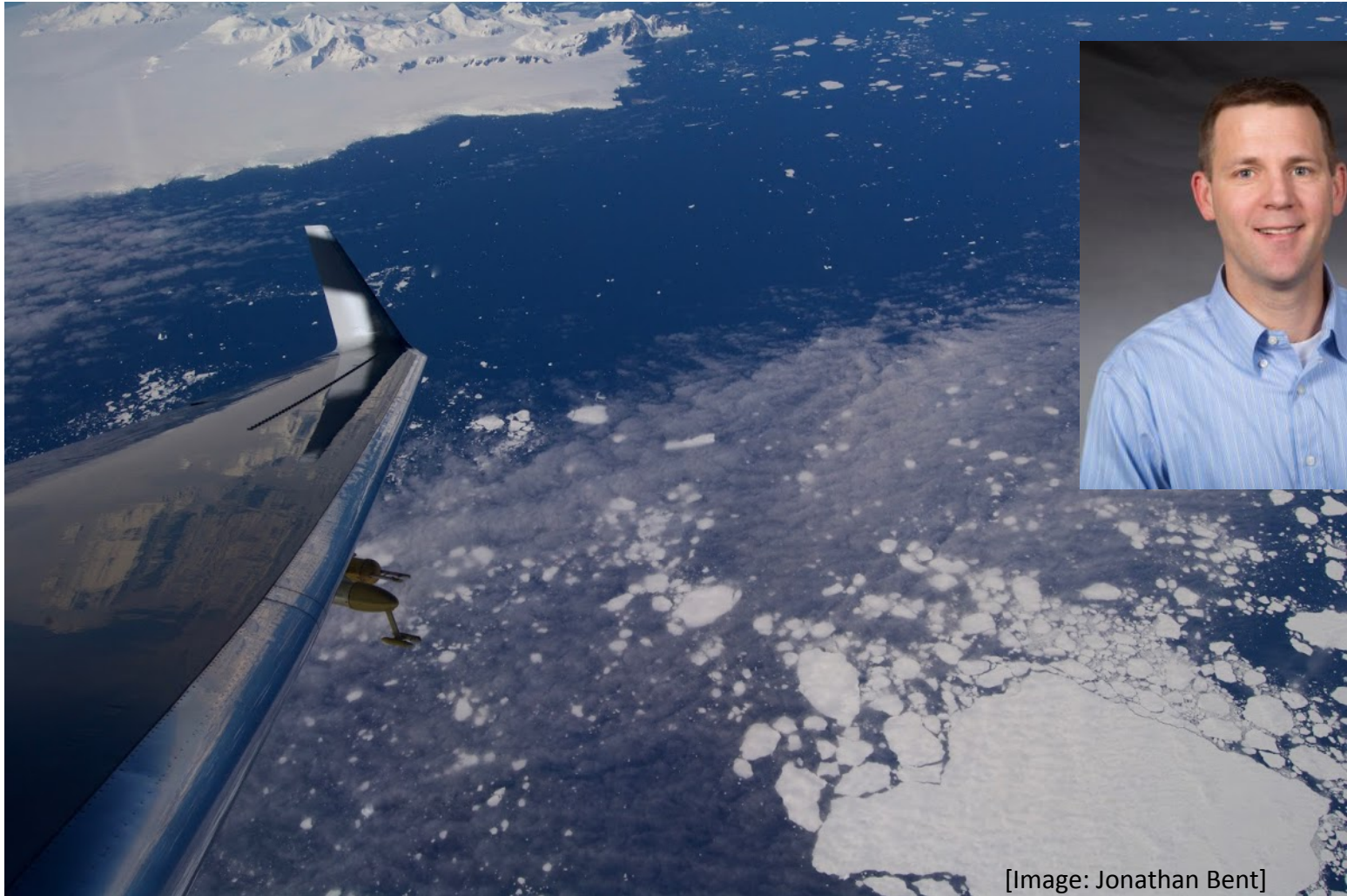


The O₂/N₂ Ratio and CO₂ Airborne Southern Ocean (ORCAS) Study - Punta Arenas, Chile, 15 Jan to 29 Feb 2016



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

ORCAS Science Team

Principle Investigators: Britton Stephens (NCAR/EOL), Matt Long (NCAR/CGD), Ralph Keeling (Scripps), Eric Kort (U. Mich.), Colm Sweeney (CU/NOAA), Elliot Atlas (U. Miami), Michelle Gierach (JPL)

Carbon Cycle Instruments: Jonathan Bent (NCAR/EOL), Bruce Daube (Harvard), Kathryn McKain (CU), Eric Morgan (Scripps), Tim Newberger (NOAA), Mackenzie Smith (U Mich.), Andy Watt (NCAR/EOL), Steve Wofsy (Harvard)

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 CO₂ with particular sensitivity to climate change
- State-of-the-art Earth System Models diverge for seasonal Southern Ocean air-sea CO₂ and O₂ fluxes, and for Southern Ocean climate-carbon feedbacks
- Atmospheric O₂ provides unique constraints on the biological, thermal, and anthropogenic drivers of Southern Ocean CO₂ exchange





Observational considerations:

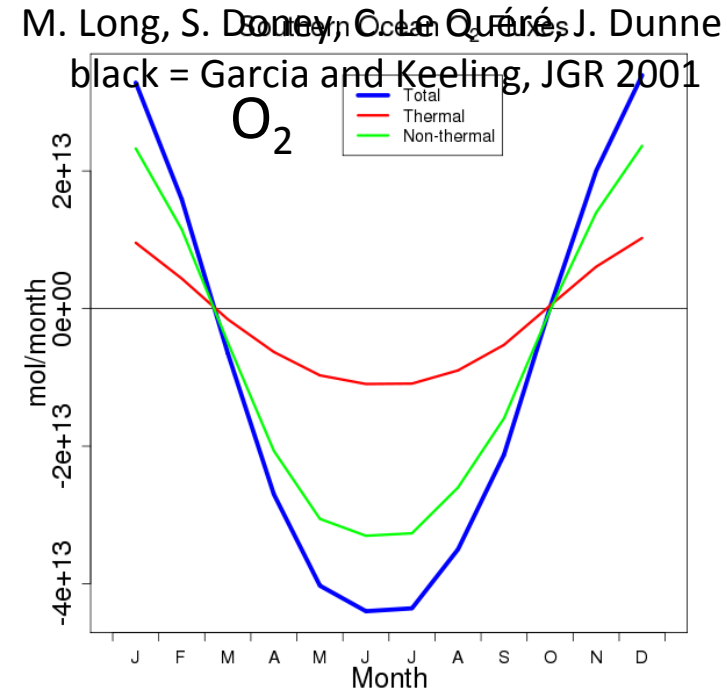
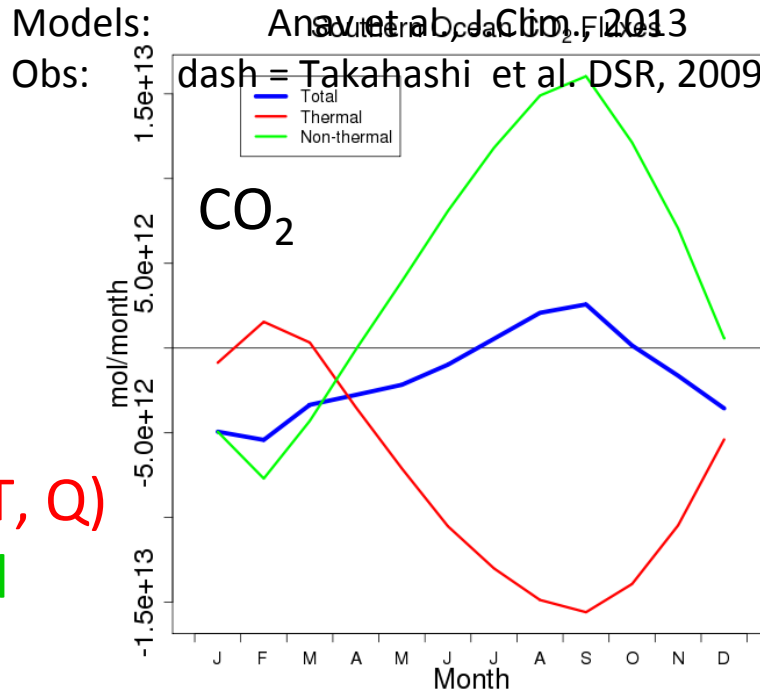
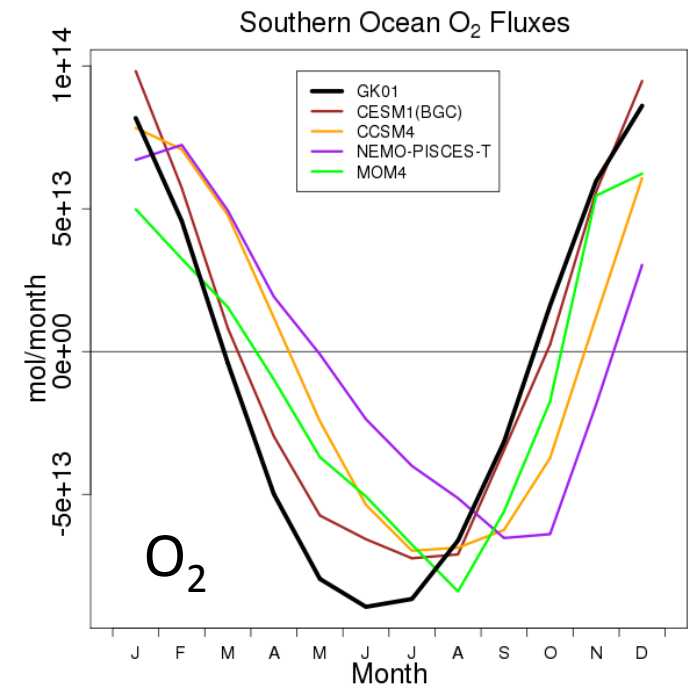
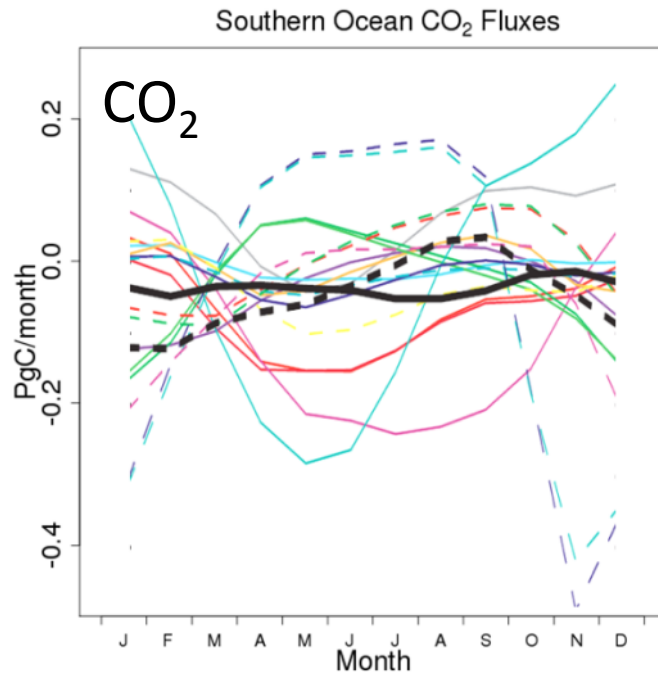
- Both long-term / spatially dispersed and temporally / spatially intensive studies are needed to advance our understanding of the Southern Ocean
- The atmosphere provides an integrated view of air-sea fluxes but surface sites are limited by atmospheric transport uncertainty and sparseness
- Aircraft can measure signals representative of large spatial scales and can overcome problems with atmospheric transport models
- Atmospheric O₂ 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 CO₂ and O₂ forcings

Annual CO₂ flux
~ -0.4 PgC/yr



Total (obs)
Thermal (SST, Q)
Non-thermal

NATIONAL SCIENCE FOUNDATION'S LOWER ATMOSPHERIC OBSERVING FACILITIES

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

ALTITUDE
100,000 ft
90,000 ft
80,000 ft
70,000 ft
60,000 ft
50,000 ft
40,000 ft
30,000 ft
20,000 ft
10,000 ft



NSF/NCAR HIAPER
Owned by NSF and operated by NCAR, the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER), is an extensively modified Gulfstream V jet capable of attaining 51,000 feet, flying for 10 hours, and covering 5,000 nautical miles. HIAPER has a payload capacity of 5,400 pounds and is used for a wide range of deployments, including studies of the upper troposphere/lower stratosphere.



NSF/NCAR C-130
Operated by NCAR, the C-130 is a heavy-lift turboprop aircraft with a maximum flight altitude of 26,000 feet, 19-hour flight endurance, and 2,900 nautical mile range. With a payload of 13,000 pounds, the C-130 has room for large instrument suites and research crews.



UW KING AIR
Operated by the University of Wyoming, the King Air has a maximum flight altitude of 26,000 feet, a typical flight duration of 3.7 hours, a range of 1,800 nautical miles, and a 3,850 pound payload capacity. The twin-engine turboprop is instrumented primarily to support research in cloud physics and boundary layer processes.



CIRRAS Twin Otter
Operated by CBRPNS, the Twin Otter is a non-pressurized turboprop, twin-engine aircraft. It has a practical mission ceiling of 18,000 feet (or 12,000 feet without oxygen), a flight endurance of about 35 hours fully loaded, a range of 800 nautical miles, and a payload capacity of 1,500 pounds. It is equipped with an instrument suite consisting of meteorological, aerosol, cloud, precipitation, radiation, and chemical sensors.



CIRRAS A-10
This extensively modified, armored military plane is operated by CBRPNS and has a flight ceiling (after significant fuel burn) of 35,000 feet, a normal mission duration of 3 hours, an estimated range of 400 nautical miles, and a payload capacity of 11,000 pounds.

NCAR S-POLKA
The S-PolKa is a ground-based, transportable weather radar offering dual-polarimetric and dual-wavelength observations at 6-band (10-centimeter) and 0-band (0.8 centimeter) wavelengths. The entire radar can be packaged into seven 20-foot shipping containers, which allows it to be temporarily deployed almost anywhere, including remote sites.

CSU-CHILL
The Colorado State University CHILL radar system uses a unique dual-offset feed antenna to attain high levels of polarization purity. Several antenna lead-horns are available, allowing the radar to operate at frequencies of both 3 and 9 GHz (11- and 3-centimeter wavelengths). Simultaneous operations at both wavelengths are also supported. An antenna main beam pattern width of 0.3° is achieved at the 3-centimeter wavelength, allowing the collection of very high spatial resolution data.

CSWR DOW
The Center for Severe Weather Research's Doppler on Wheels (DOW) radars, frequently deployed in a multiple-Doppler network, the DOW network is an adaptable, portable radar network able to deploy close to meteorological and other phenomena in order to get fine-scale spatial and temporal observations.



NCAR HCR
The HIAPER Cloud Radar (HCR) is an airborne millimeter-wavelength radar that serves the atmospheric science community by providing remote sensing capabilities to the HIAPER aircraft. The HCR is also operable in a ground-based mode.



NCAR HSRIL
The High-Spectral Resolution Lidar (HSRIL) is used to make reliable and accurate measurements of atmospheric extinction, backscatter coefficients, optical depth, and discrimination between ice and water clouds. The HSRIL was designed and built by the University of Wisconsin Lidar Group in fly on the HIAPER aircraft. It can also be configured as a standalone instrument to collect data from the ground.



UW WCR
The Wyoming Cloud Radar (WCR) is an airborne radar for the study of cloud structure and dynamics. It is installed principally on the UW King Air, but also can be mounted on the NSF/NCAR C-130. It is capable of simultaneously obtaining measurements above, below, and to the side of the aircraft. It is used to determine comprehensive cloud and aerosol microphysical and microphysical characteristics.



UW WCL
The Wyoming Cloud Lidar (WCL) measures backscatter intensity and depolarization from aerosols and cloud particles. Two independent systems are capable of viewing above and below the aircraft, installed either on the UW King Air or the NSF/NCAR C-130. The measurements from the WCL (and at times combined with the WCR) can be used to determine comprehensive cloud and aerosol microphysical and microphysical characteristics.



NCAR AVAPS
The Airborne Vertical Sounding System (AVAPS) provides unprecedented high vertical-resolution of pressure, temperature, humidity, and winds from the drop altitude down to the surface. It has been used extensively for hurricane and cyclone research.



NCAR ISS
The Integrated Sounding System (ISS) combines surface, sounding, and remote sensing instrumentation to provide a comprehensive description of lower atmospheric thermodynamic and winds, with enhanced measurements in the boundary layer and lower troposphere. The ISS can be deployed in a mobile configuration, used on board a ship, or installed at research sites.

The system also can include:

NCAR GAUSS
A balloon-borne, rawinsonde system allows researchers to supplement operational soundings by placing sounding systems in essential locations and by launching sondes at higher or variable frequencies. The GAUSS provides high vertical resolution measurements of temperature, humidity, pressure, and winds.

NCAR ISFS
The Integrated Surface Plus System (ISFS) is designed to study exchange processes between the atmosphere and Earth's surface. This includes the direct measurement of fluxes of momentum, sensible and latent heat, trace gases, and radiation, as well as standard atmospheric and surface variables. With multiple sensors and data systems, measurements of horizontal and vertical gradients also can be made.

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 O₂ and CO₂ distributions, characterizing the size and temporal growth of the zonal atmospheric O₂ plume, and constraining zonal fluxes on monthly to seasonal time scales

Basin scale

Vertical atmospheric O₂ and CO₂ 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 O₂ and CO₂ 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:

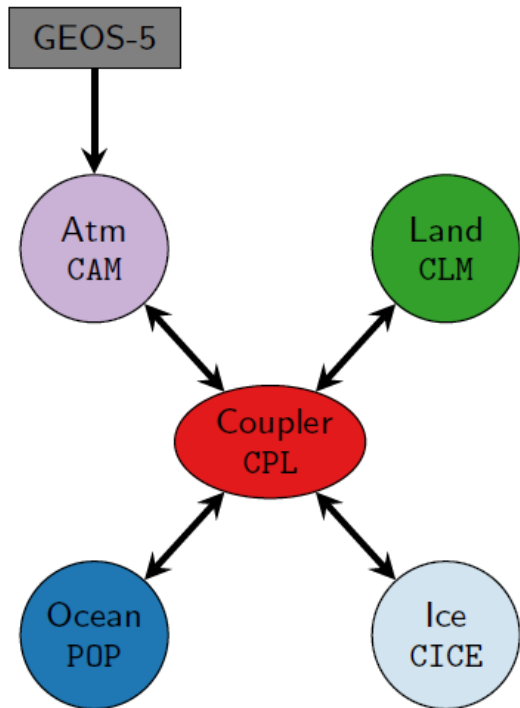


Instrument	Measurement	Institution
Airborne Oxygen Instrument (AO2)	$\delta(\text{O}_2/\text{N}_2)$, CO_2	NCAR EOL
Medusa Flask Sampler	$\delta(\text{O}_2/\text{N}_2)$, CO_2 , $\delta(\text{Ar}/\text{N}_2)$, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and $\Delta^{14}\text{C}$ of CO_2	NCAR/Scripps
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

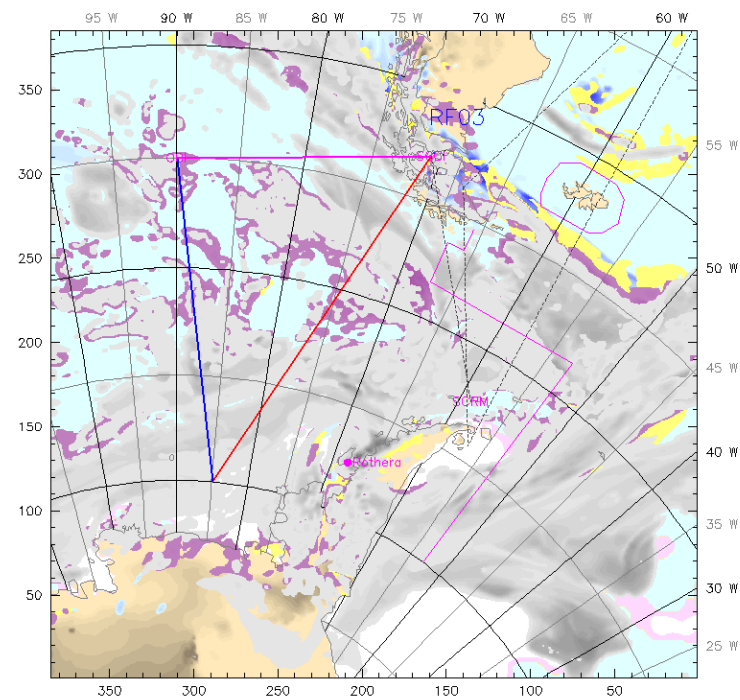


Initialized 3-day forecasts every day:
 nudge CAM to GEOS-5 forecast model;
 fully coupled, prognostic ocean ecosystem
 and air-sea fluxes.

- ▶ O₂ and CO₂ distributions;
- ▶ Idealized tracers for source regions.

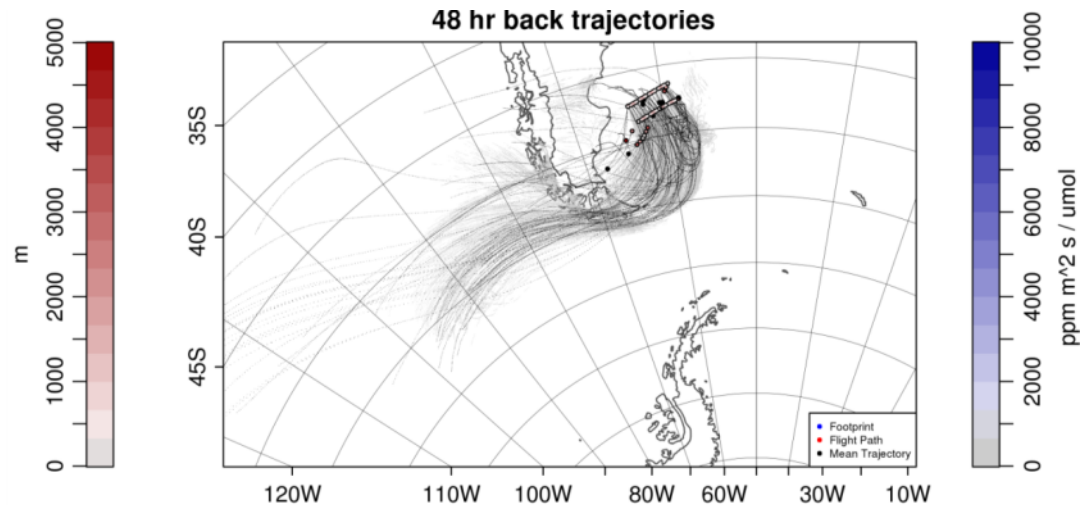
Developed and implemented by Matt Long

2) Antarctic Mesoscale Prediction System (AMPS)



led by
 Jordan
 Powers

3) Stochastic Time-Inverted Lagrangian Transport (STILT)

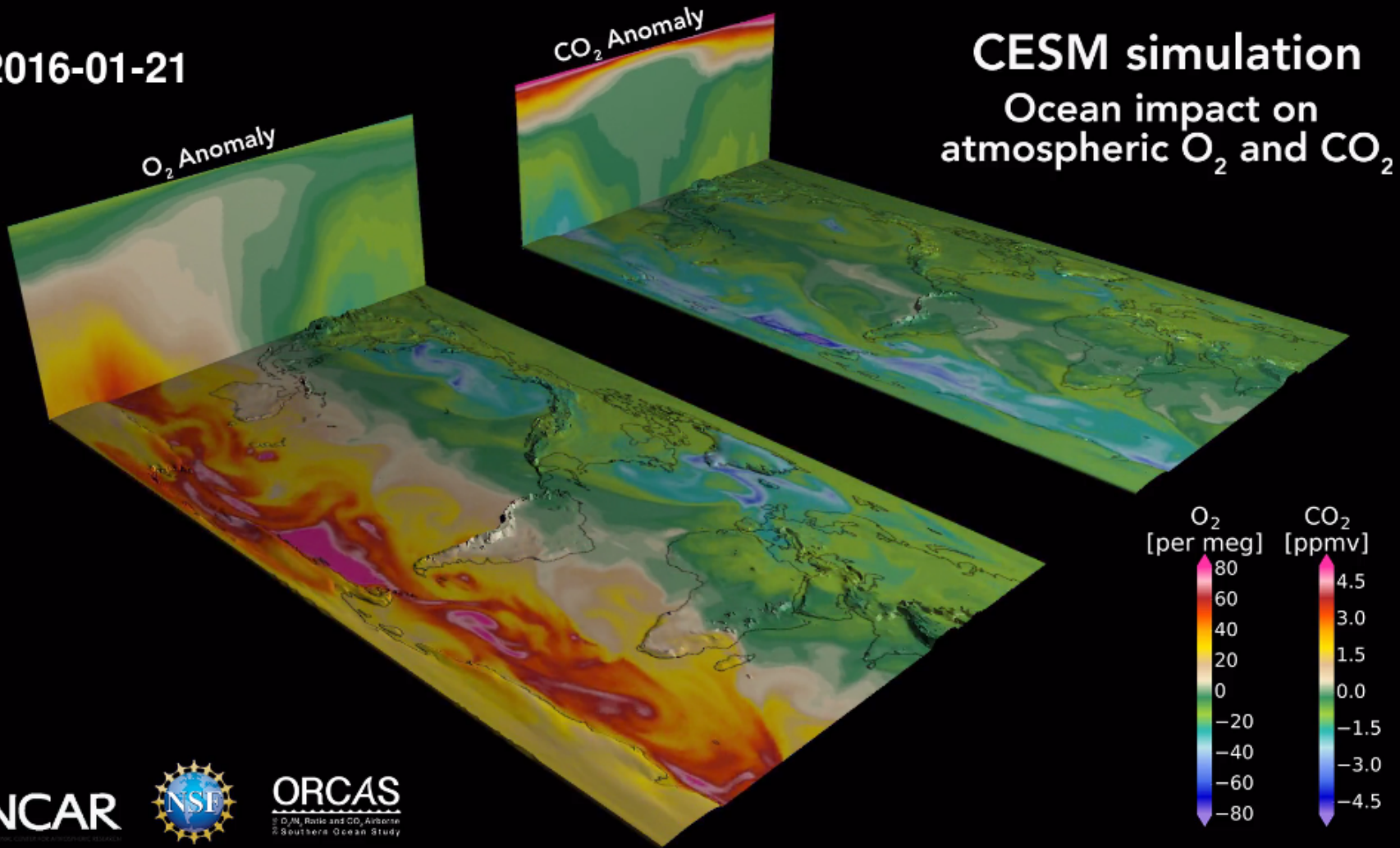


led by Eric Kort and Martin Hoecker-Martinez

2016-01-21

CESM simulation

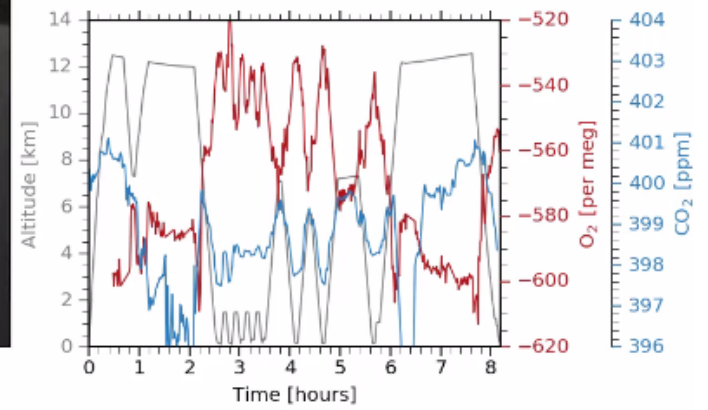
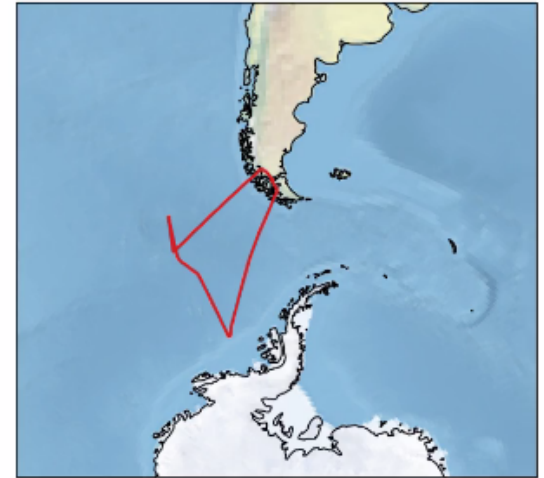
Ocean impact on atmospheric O_2 and CO_2



ORCAS
O₂, CO₂, and CO₂ Airborne
Southern Ocean Study

ORCAS RF03

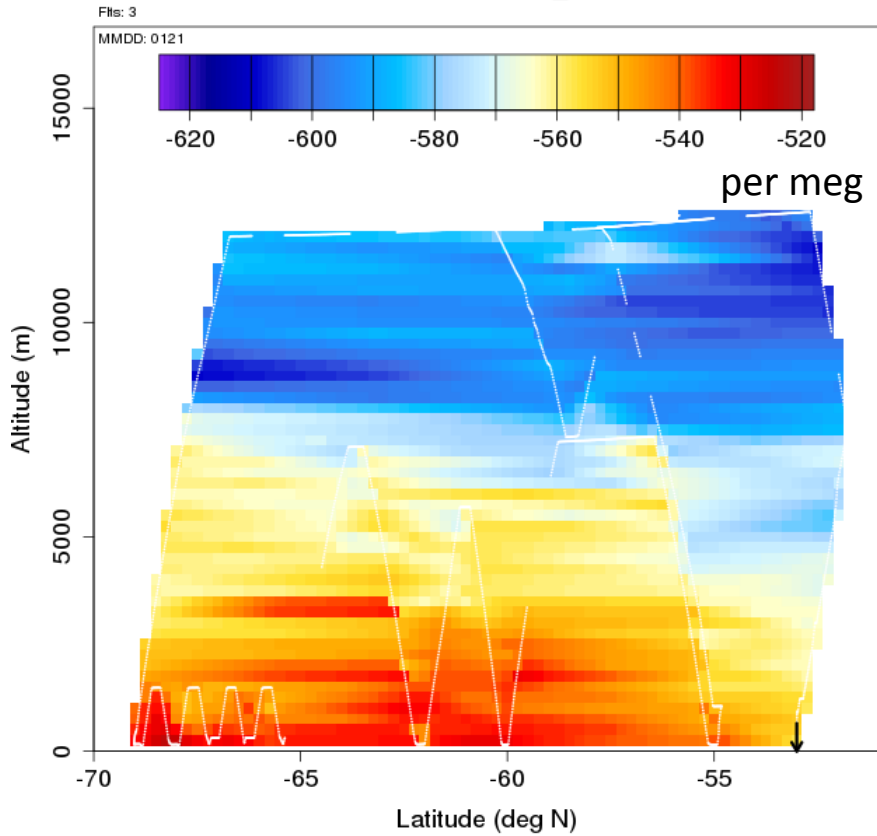
2016-01-21 23:02:23



<https://youtu.be/Df2peaFxUAM>

O₂

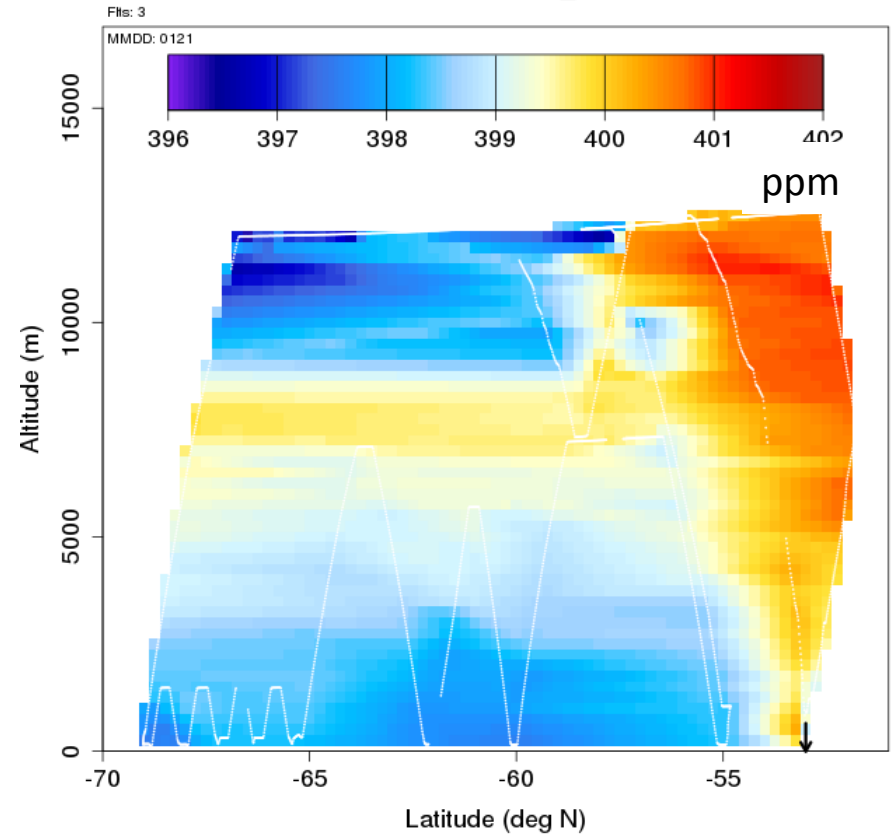
ORCAS RF03 O2_AO2



NCAR AO2 Instrument
B. Stephens

CO₂

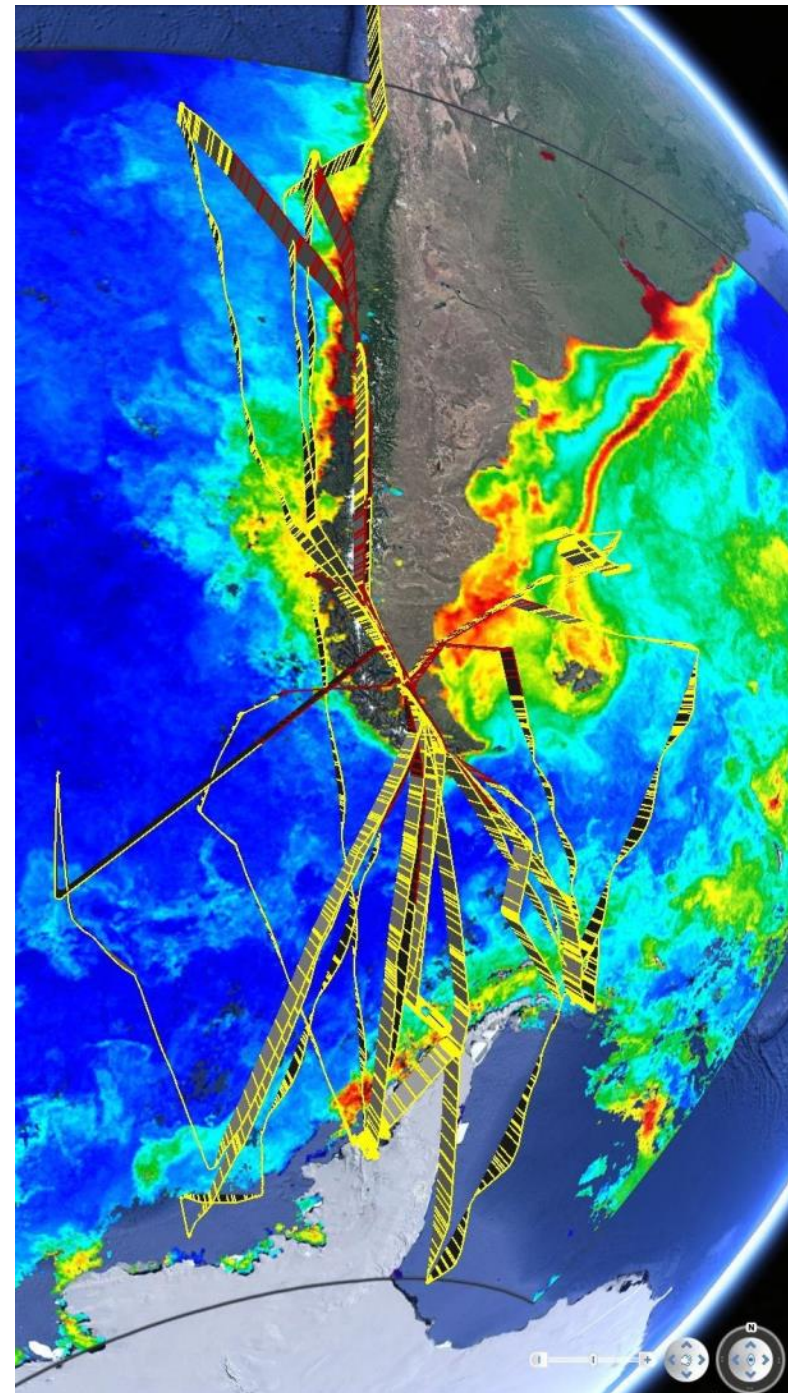
ORCAS RF03 CO2_NOAA



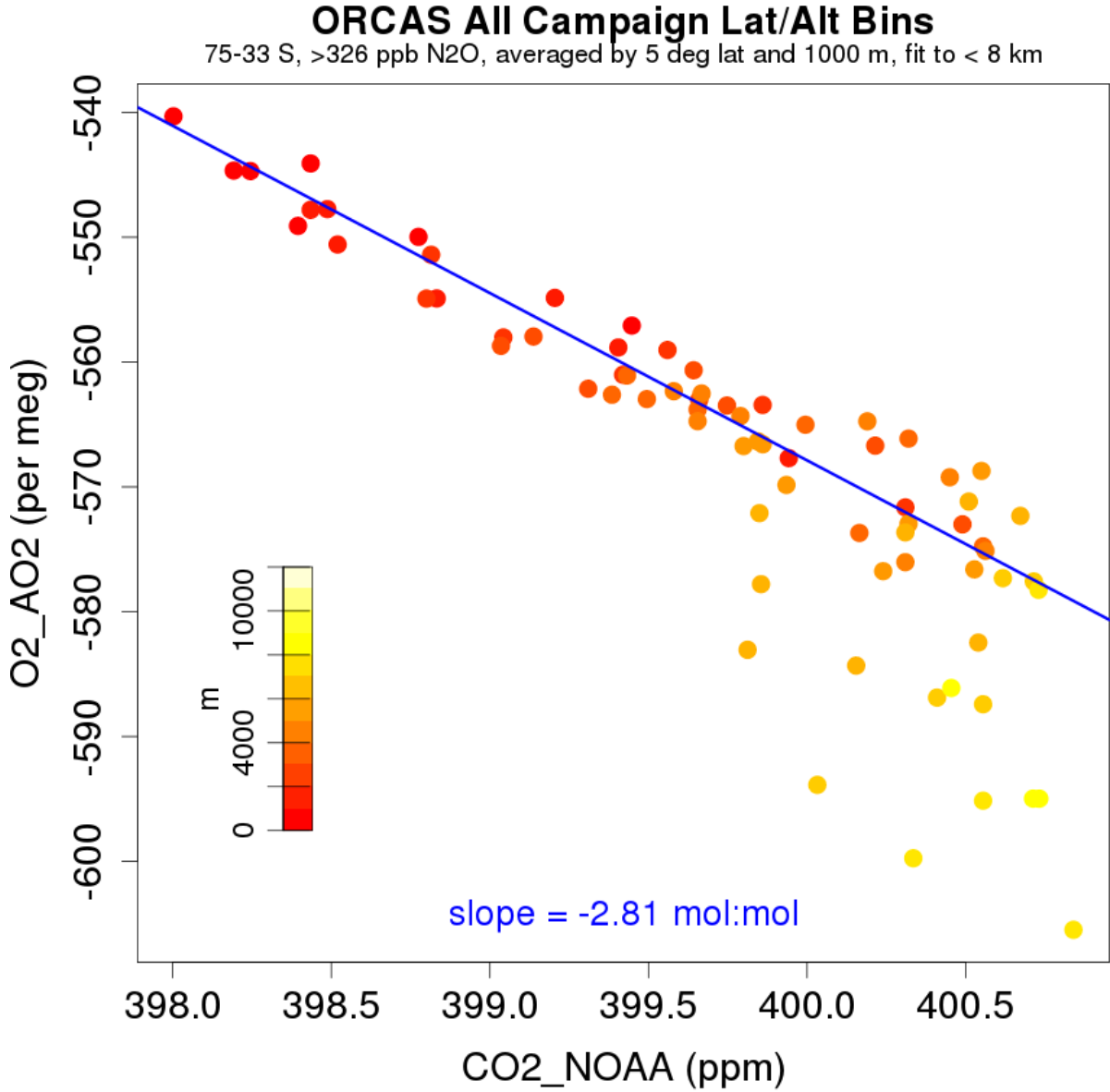
CU / NOAA CO2 Instrument
C. Sweeney

TABLE 1. ORCAS Flights

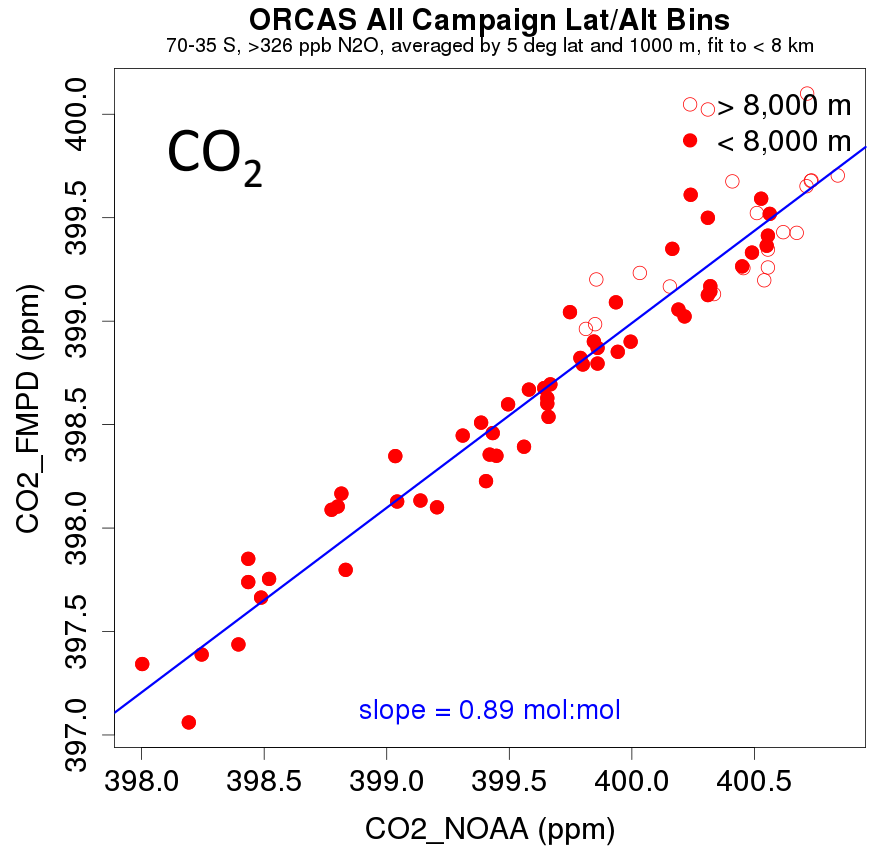
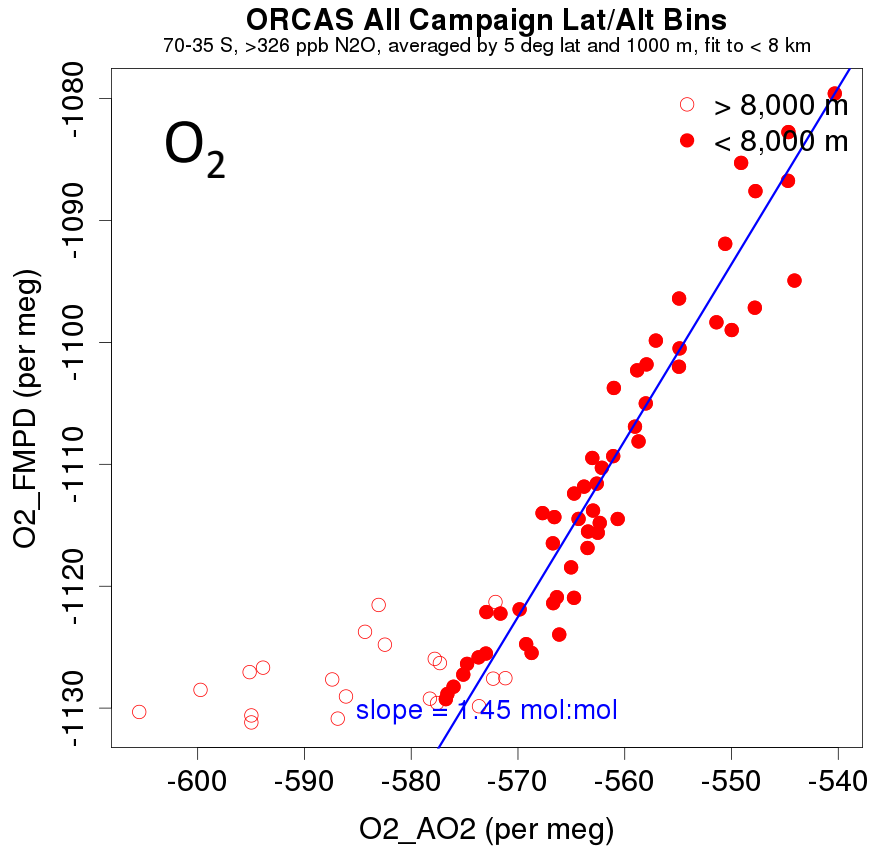
Flight Code ¹	Date	Hours	Route ²	Objectives
TF01	1/5/2016	4.3	KBJC-Lamont, OK-KBJC	Instrument test flight, TCCON comparison
TF02	1/7/2016	5.5	KBJC-Gulf of Mexico-KBJC	Instrument test flight
FF01	1/11/2016	9.7	KBJC-SCAR	Ferry
FF02	1/12/2016	5.1	SCAR-SCCI	Ferry
RF01	2016-01-15	7.7	SCCI-Marguerite Bay-SCCI	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

¹TF = Test Flight, FF = Ferry Flight, RF = Research Flight²KBJC = Broomfield, CO, SCAR = Arica, Chile, SCCI = Punta Arenas, Chile, SCTE = Puerto Montt, Chile, SCVD = Valdivia, Chile

Whole campaign bin averaged O₂:CO₂ relationship

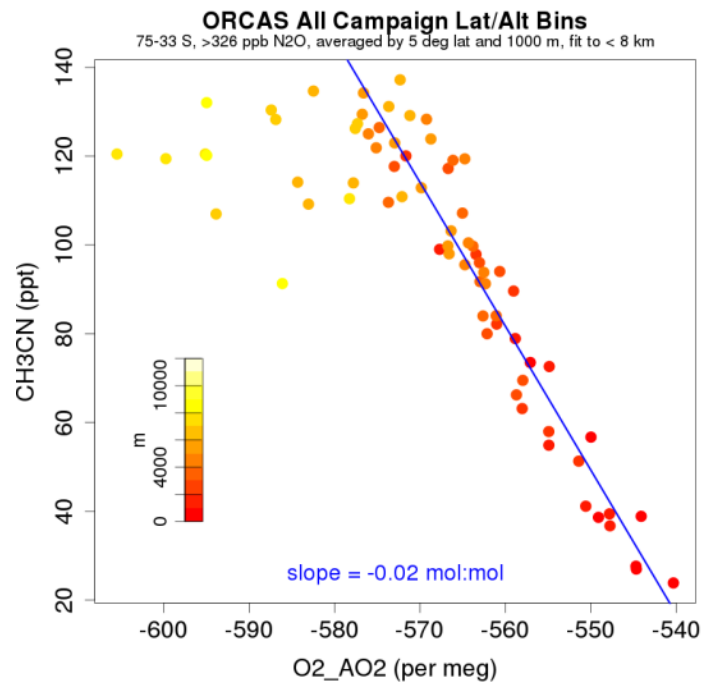
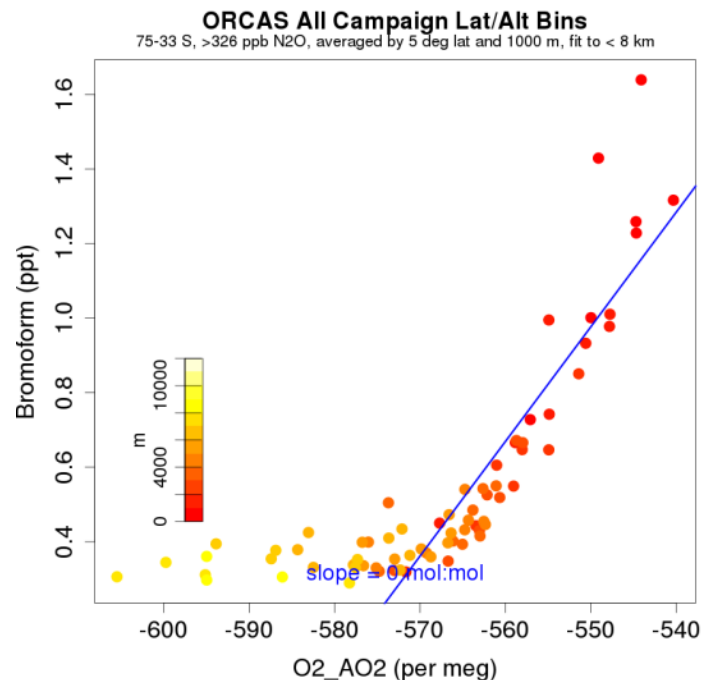
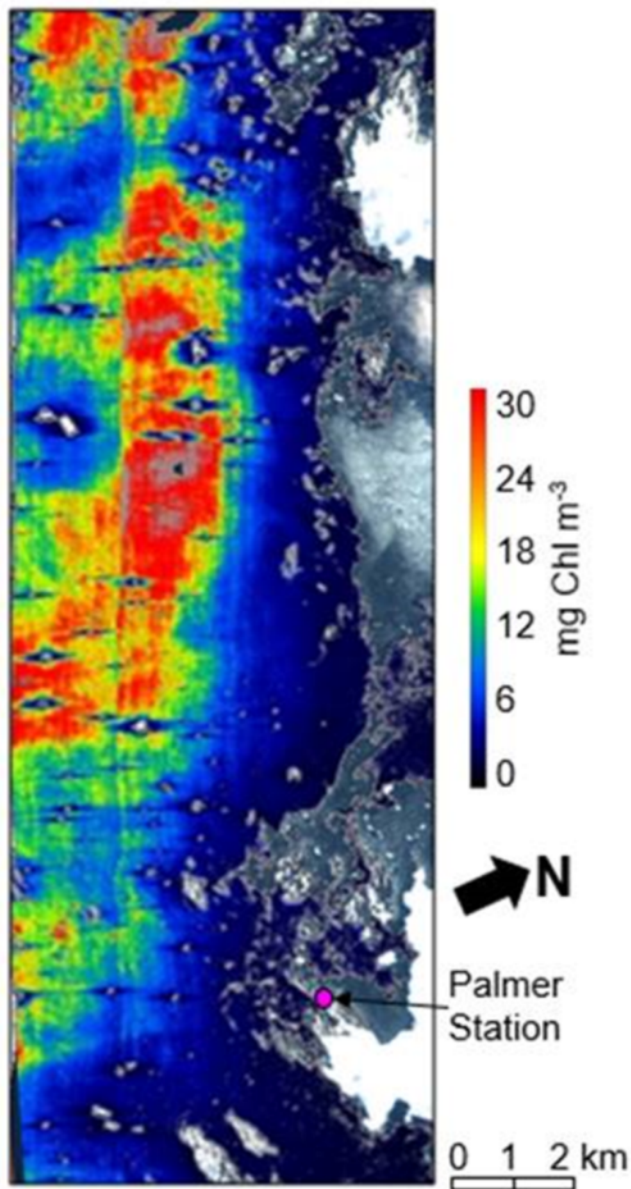


ORCAS whole campaign comparison to CESM forecast model



- CO₂ prediction was very close, but O₂ gradients overestimated, suggesting CO₂ agreement for wrong reasons

Example PRISM image and reactive gas relationships to O₂



Summary

- The ORCAS field campaign has successfully completed 19 research flights over 98 hours
- Total amount of O₂ and CO₂ over Southern Ocean well measured and will provide estimates of Seasonal Net Outgassing / Ingassing
- Predominantly negative CO₂:O₂ correlations reflecting the dominance of biological drivers on summertime CO₂ fluxes, and winnowing of CMIP5 seasonal CO₂ cycles
- The CESM forecast product overestimated observed O₂ signals but showed remarkable agreement with CO₂ gradients, which were themselves much stronger than climatological estimates.
- Six week evolutions and spatial distribution of O₂, CO₂, 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 O₂/N₂ Ratio and CO₂ Airborne
Southern Ocean Study

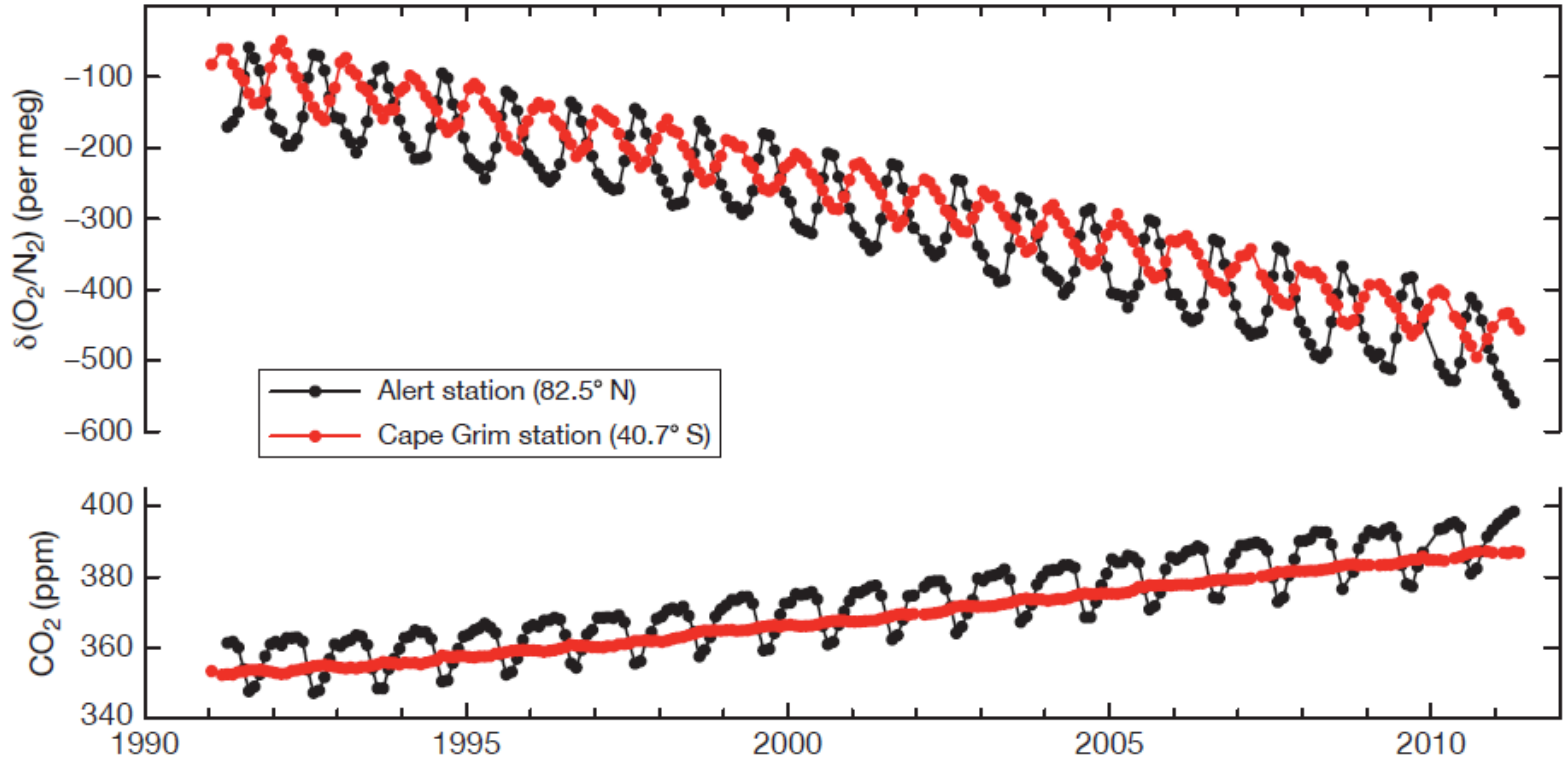
[http://
www.eol.ucar.edu/
field_projects/orcas](http://www.eol.ucar.edu/field_projects/orcas)

- 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 CO₂ 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 O₂, drawdown of CO₂
- Campaign-average O₂:CO₂ 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 CO₂ draw down observed during ORCAS about a factor of 2 greater than predicted by global inverse model calculations – O₂ will provide important constraints on the responsible processes

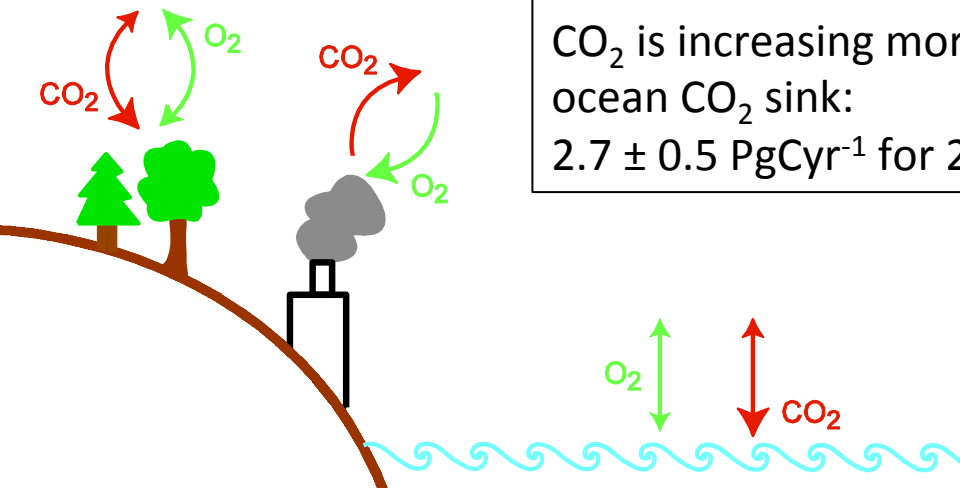
Scripps O₂ Program



CO₂ is increasing more slowly than O₂ is decreasing because of net ocean CO₂ sink:
 $2.7 \pm 0.5 \text{ PgCyr}^{-1}$ for 2000-2010 (Keeling and Manning, TG, 2013).

$$\delta(\text{O}_2/\text{N}_2) = ((\text{O}_2/\text{N}_2)_{\text{sample}} / (\text{O}_2/\text{N}_2)_{\text{reference}}) - 1$$

“per meg”



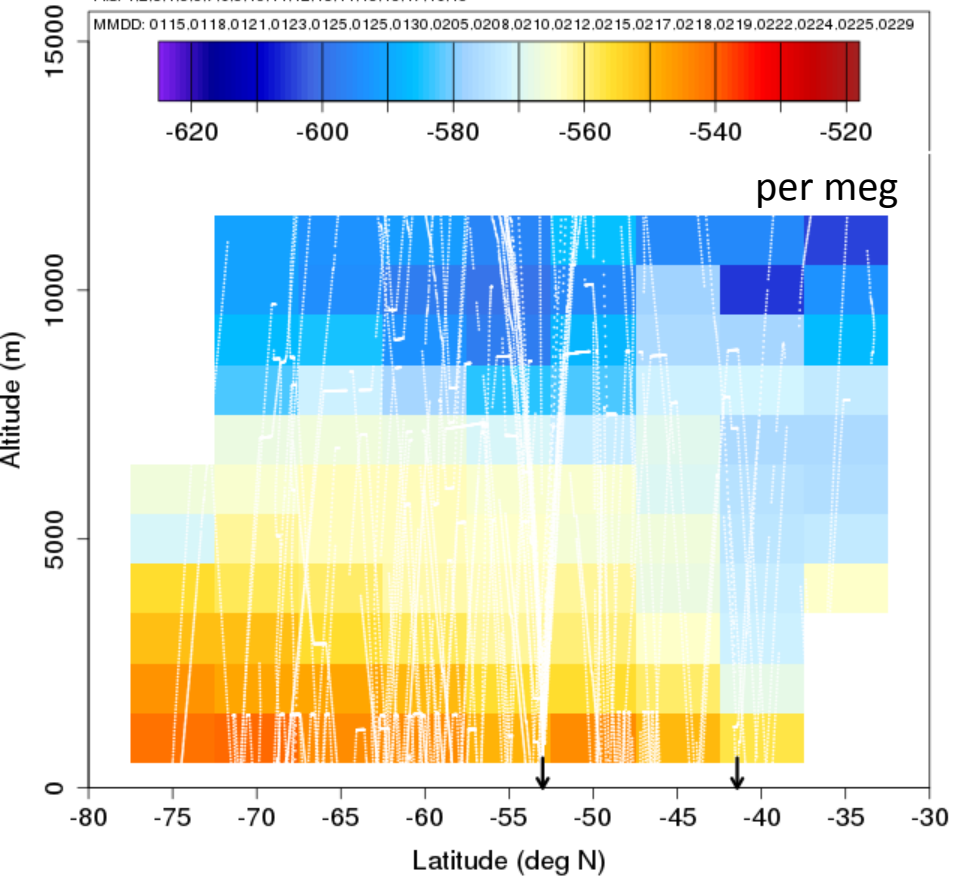
Whole campaign lat/alt bin averages

O₂

ORCAS RF01-19 O2_AO2

Files: 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19

MMDD: 0115,0118,0121,0123,0125,0125,0130,0205,0208,0210,0212,0215,0217,0218,0219,0222,0224,0225,0229

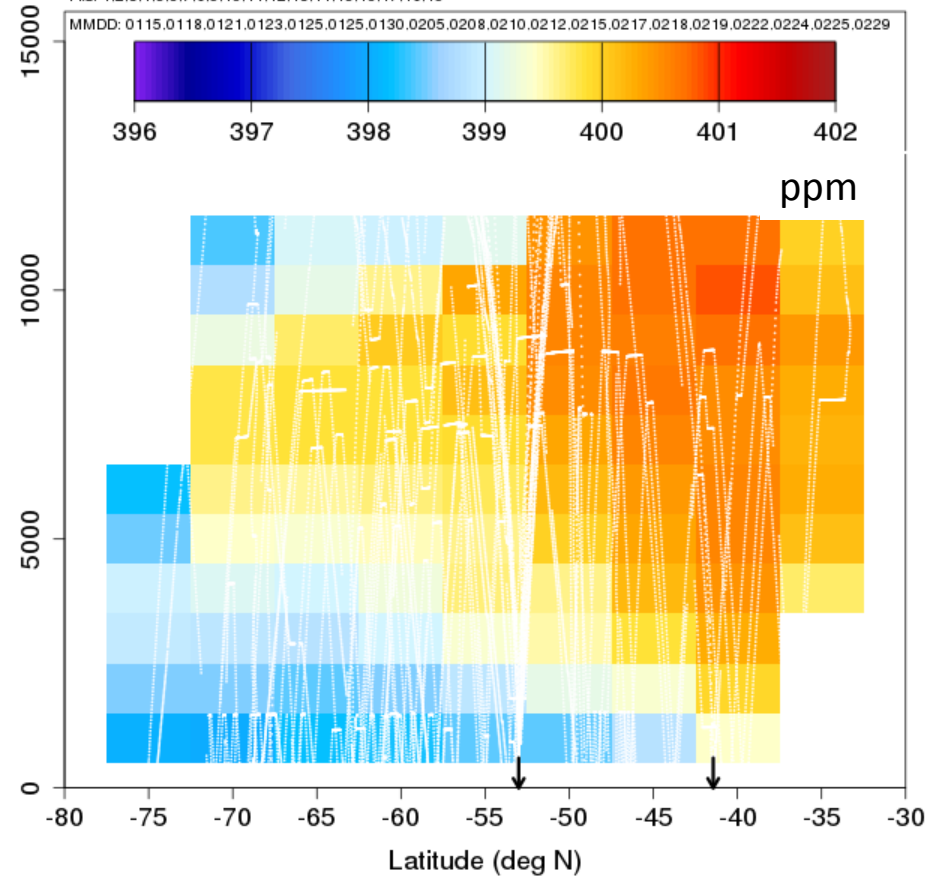


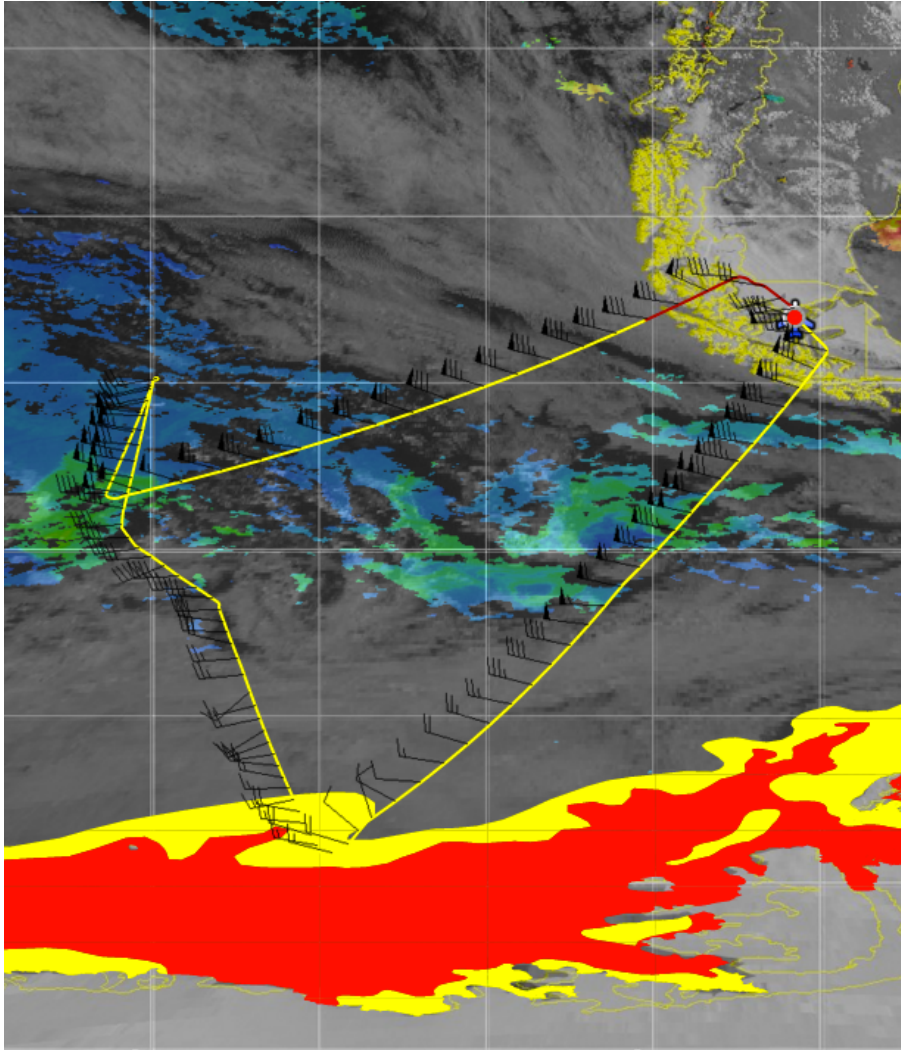
CO₂

ORCAS RF01-19 CO2_NOAA

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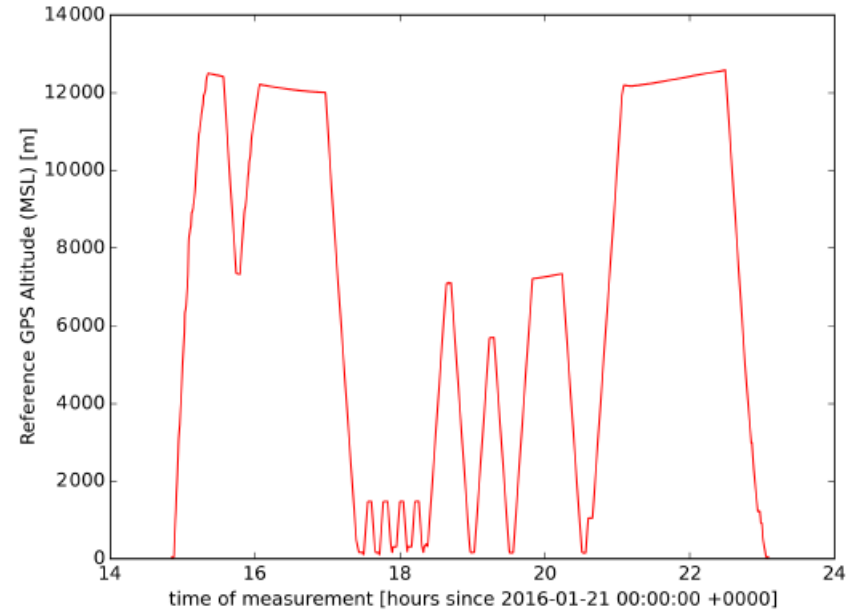
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wind speed and direction (barbs)
clouds (gray shade)
Chl a (color contour)
marginal (yellow) and pack (red) ice zones

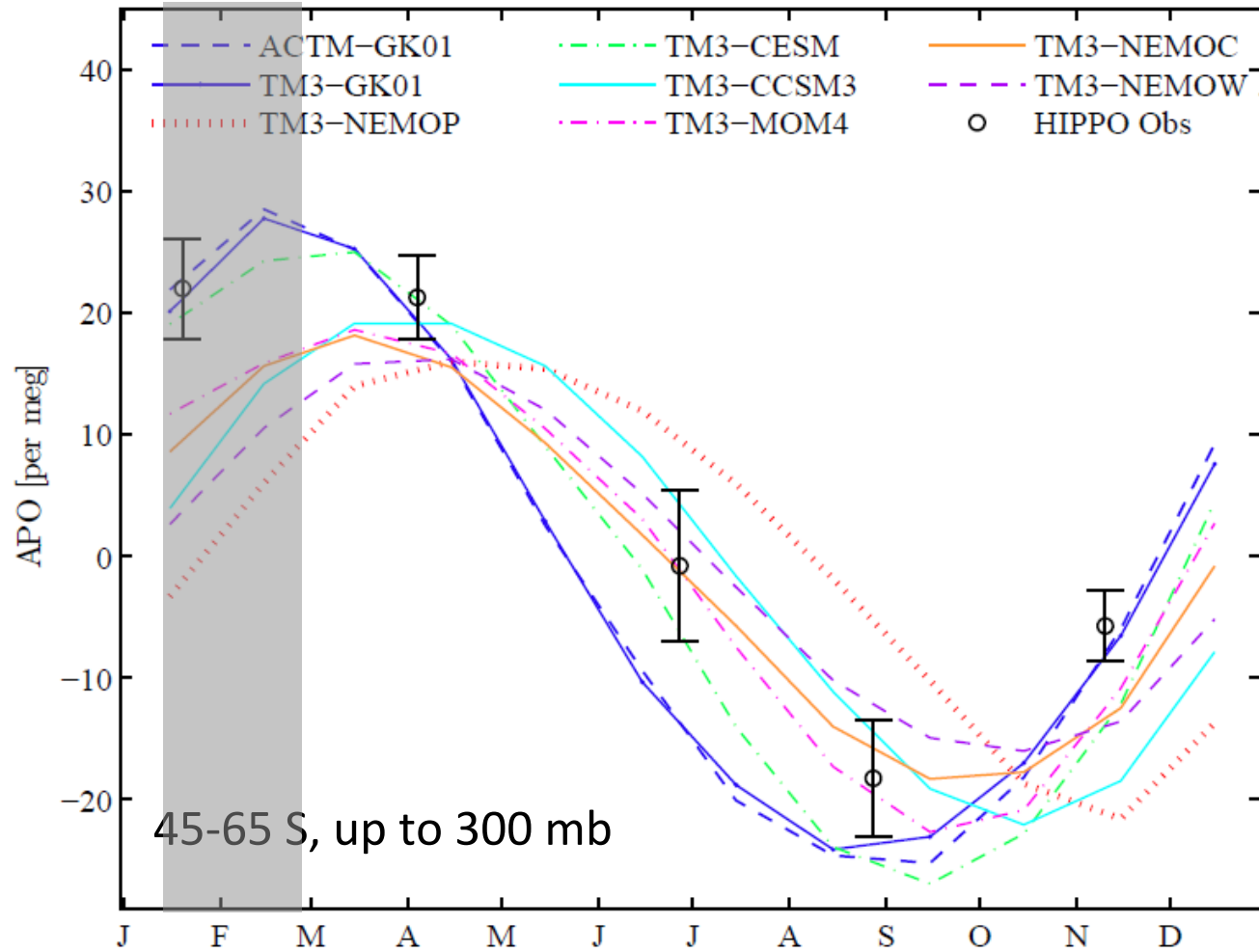
Altitude v. time



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.

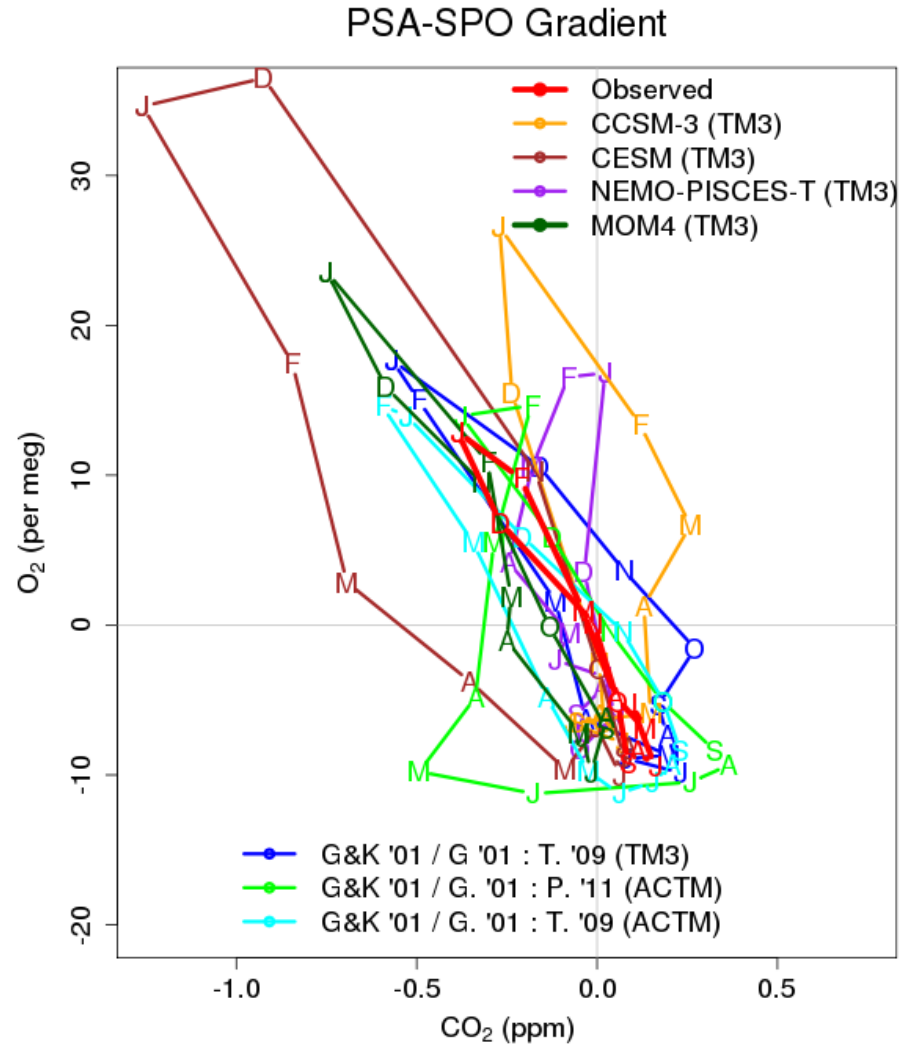
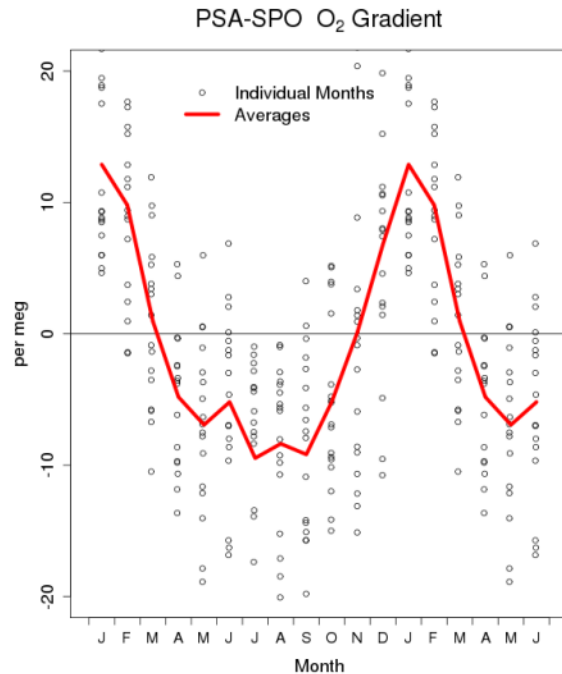
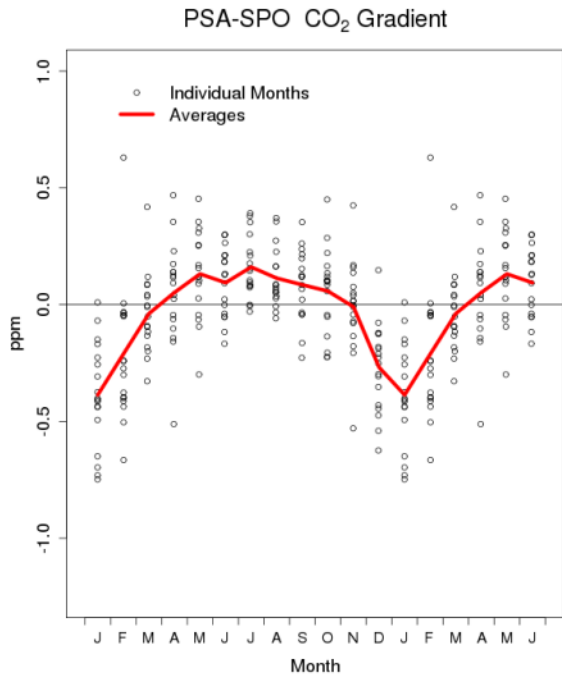
HIPPO Southern Ocean Curtain Averages



$$\text{APO} = \text{O}_2 + 1.1 \text{CO}_2$$

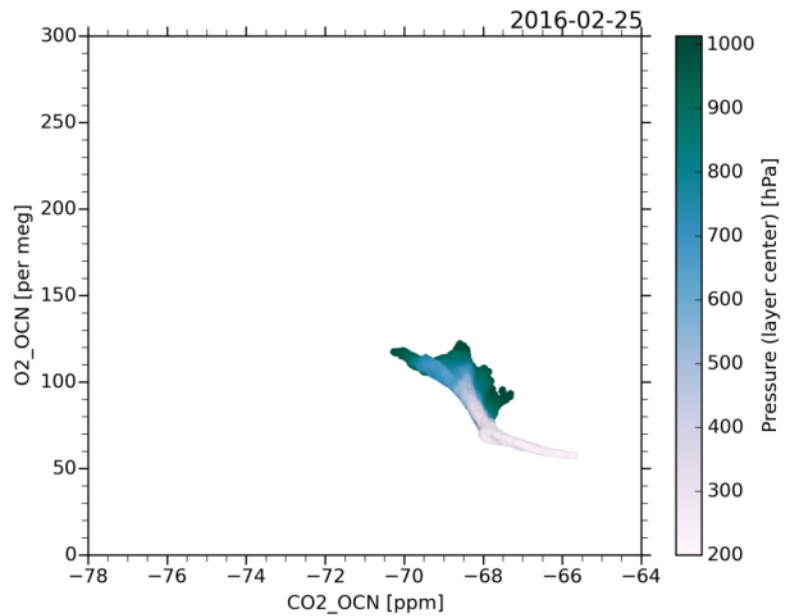
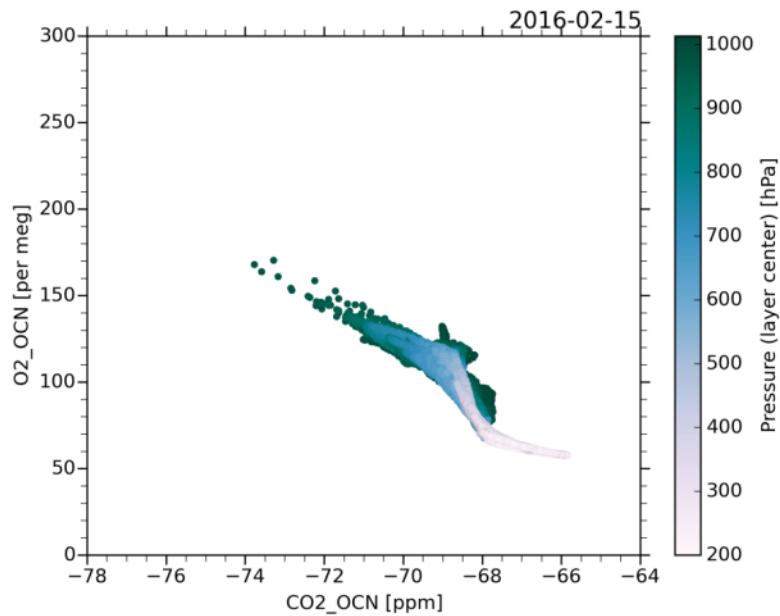
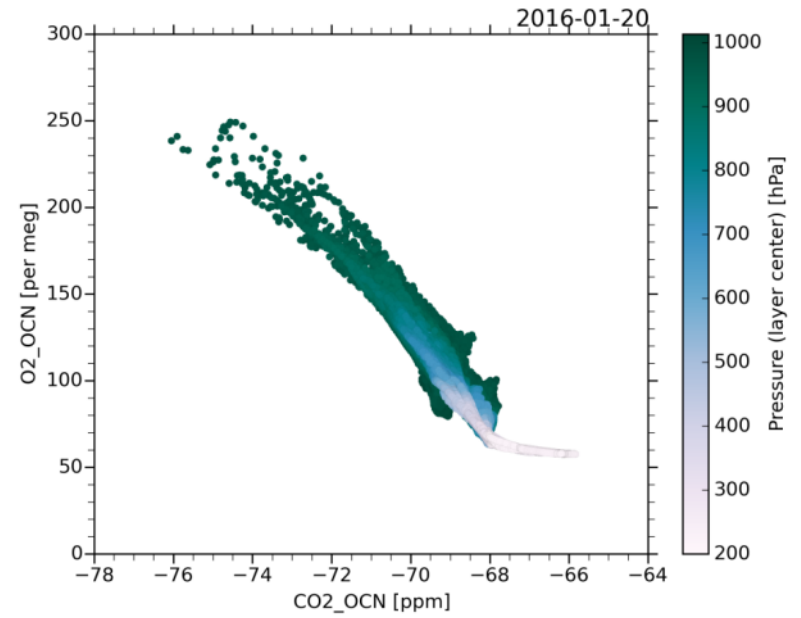
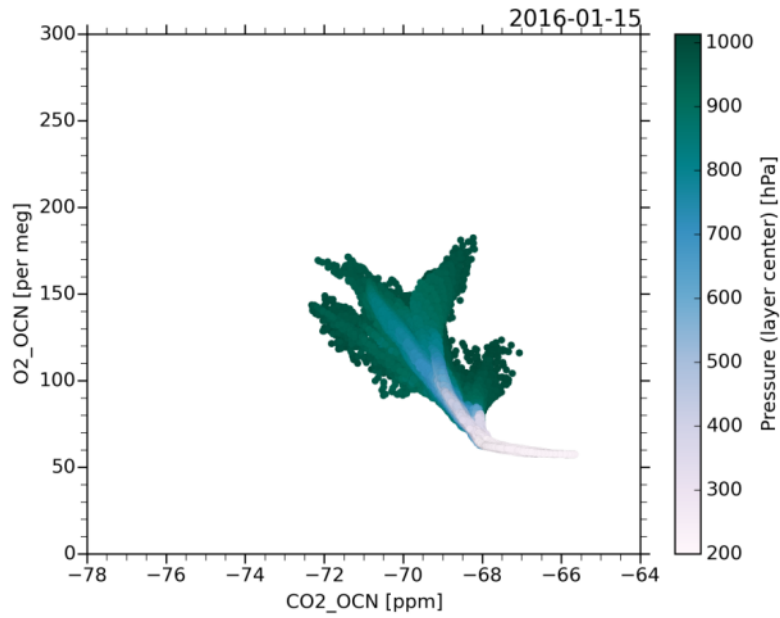
J. Bent, Dissertation, 2014

Scripps Oxygen Network Palmer Station and South Pole Flasks

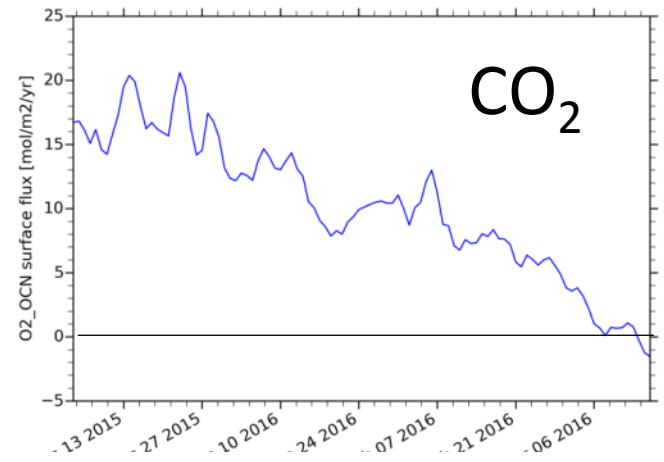
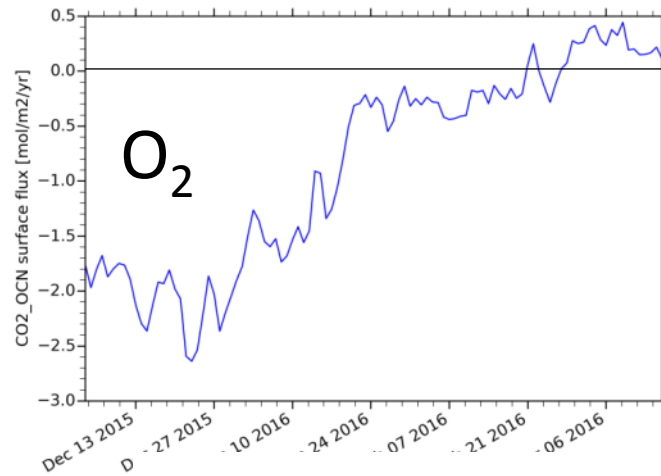


Jan = 0.15 mol CO₂ : mol O₂

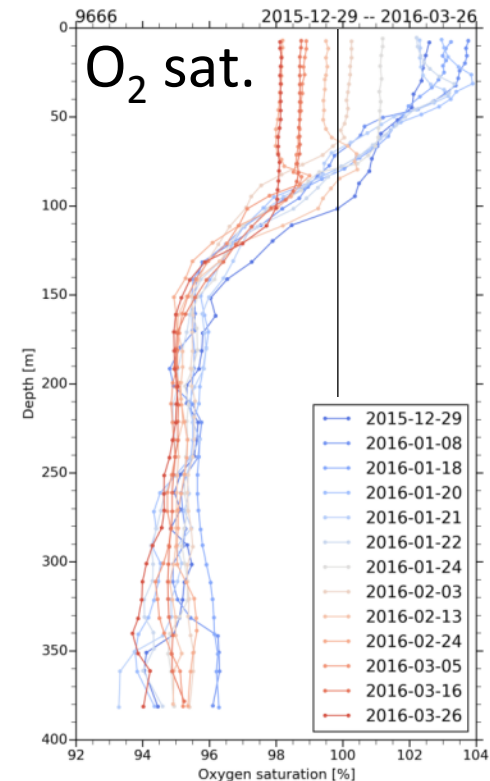
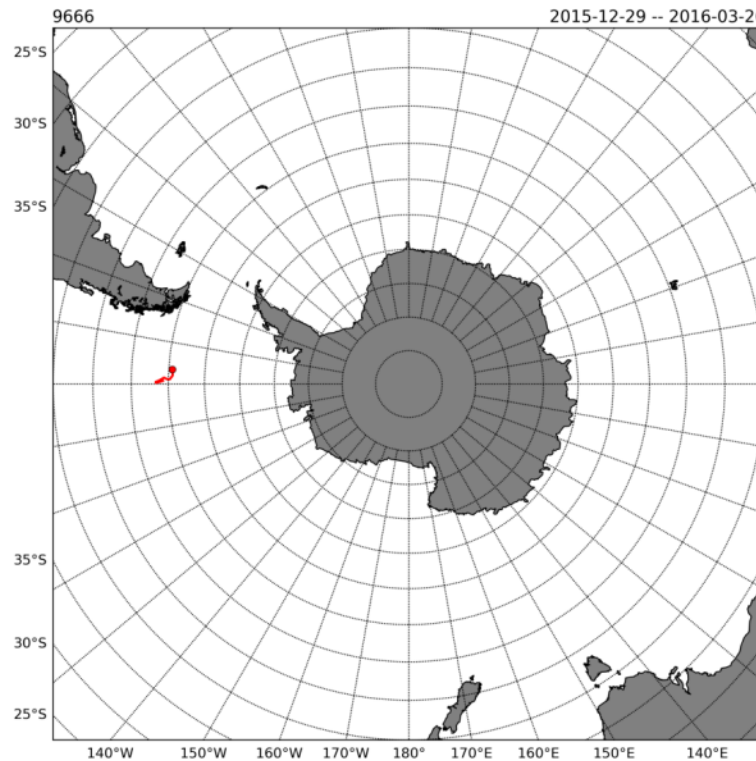
Forecast model predictions, all grid cells over Southern Ocean Easter Pacific sector



Forecast model predictions, Southern Ocean air-sea fluxes



SOCCOM
Float 9666



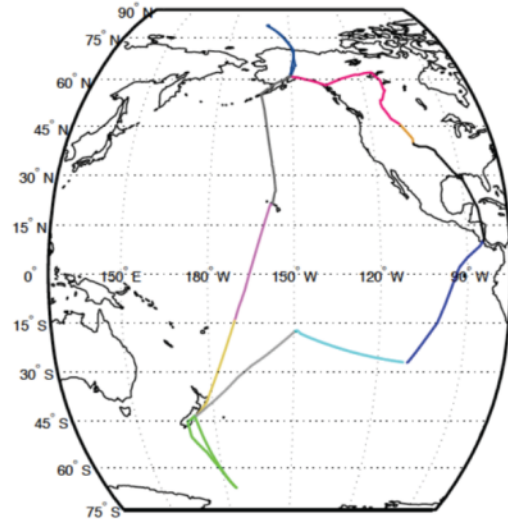


HIAPER

Pole-to-Pole
Observations

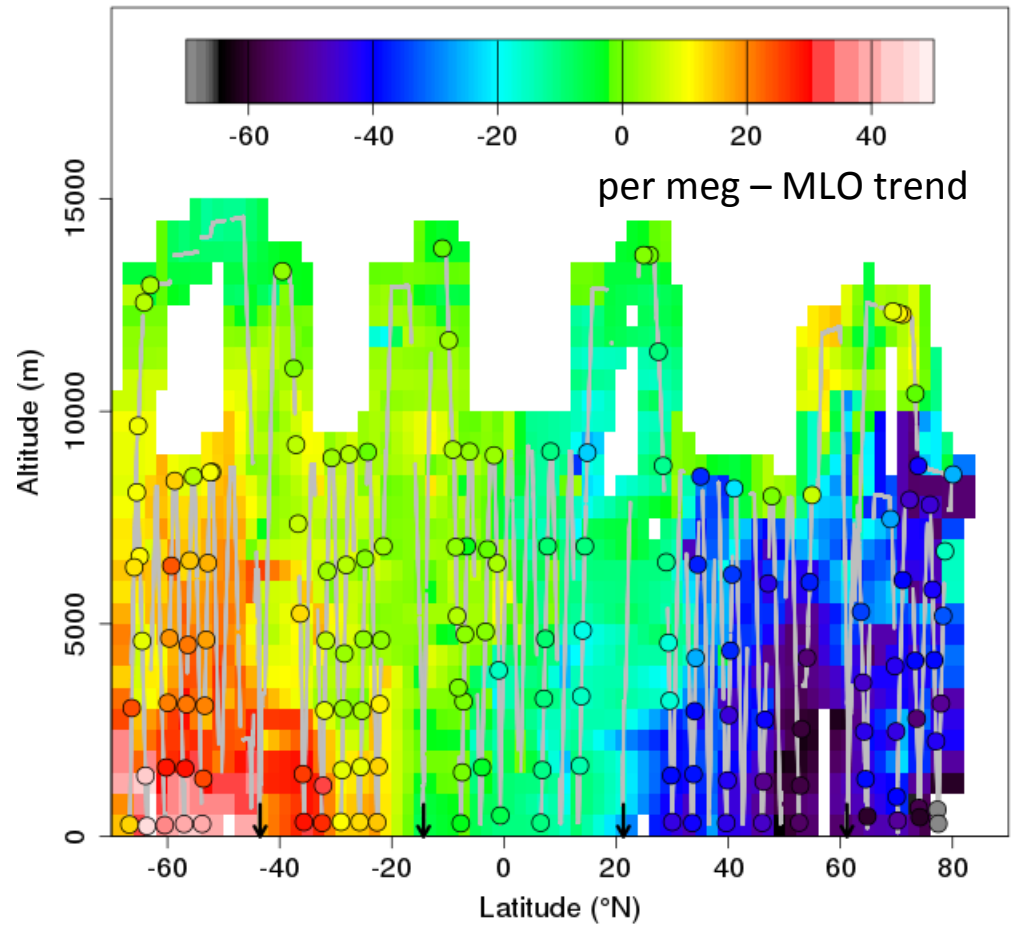
January, 2009

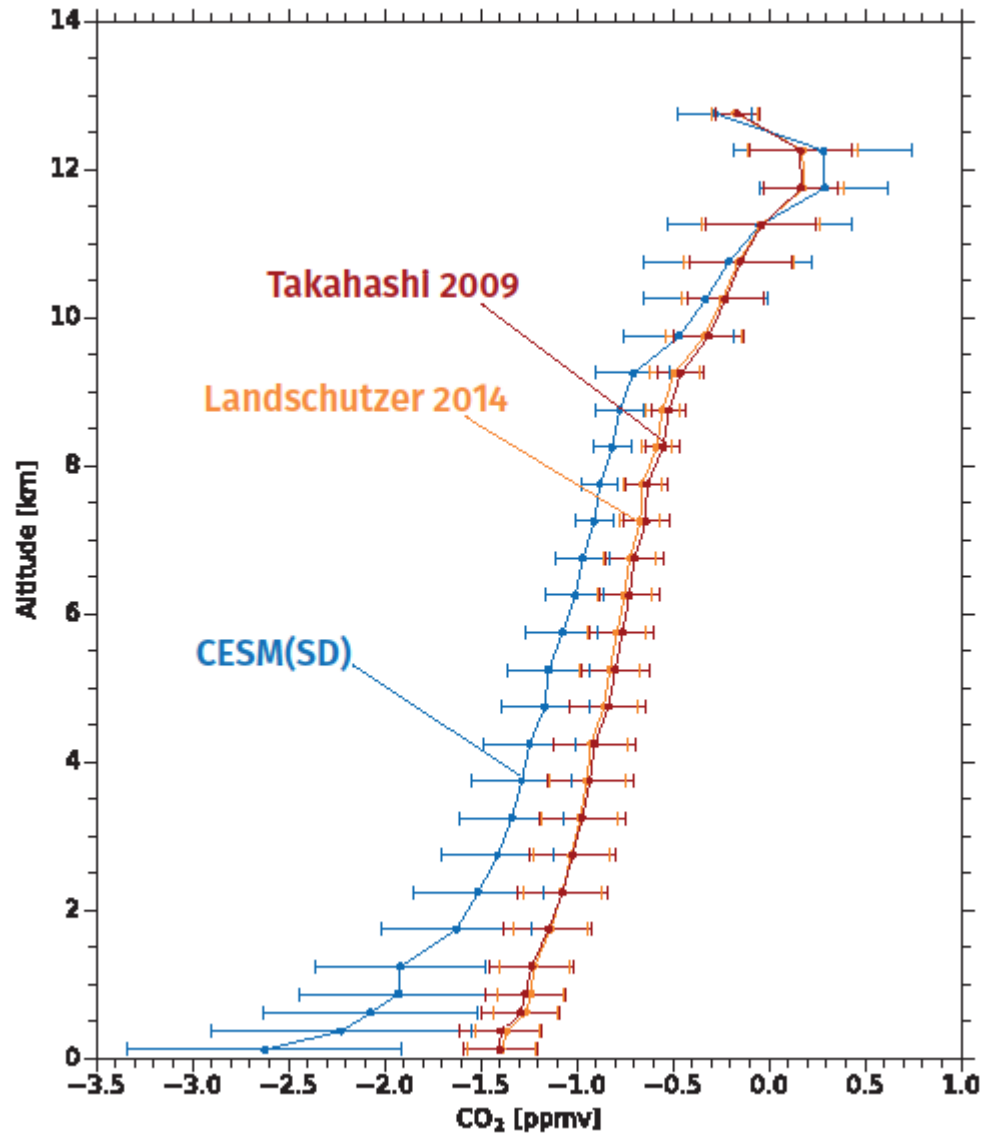
HIPPO1 Flight Track



HIPPO1 Southbound O2_AO2

20090112, 20090114, 20090116, 20090118, 20090120 RF03, RF04, RF05, RF06, RF07





NCAR Airborne Oxygen Instrument (AO2)

NCAR/Scripps Medusa Flask Sampler



