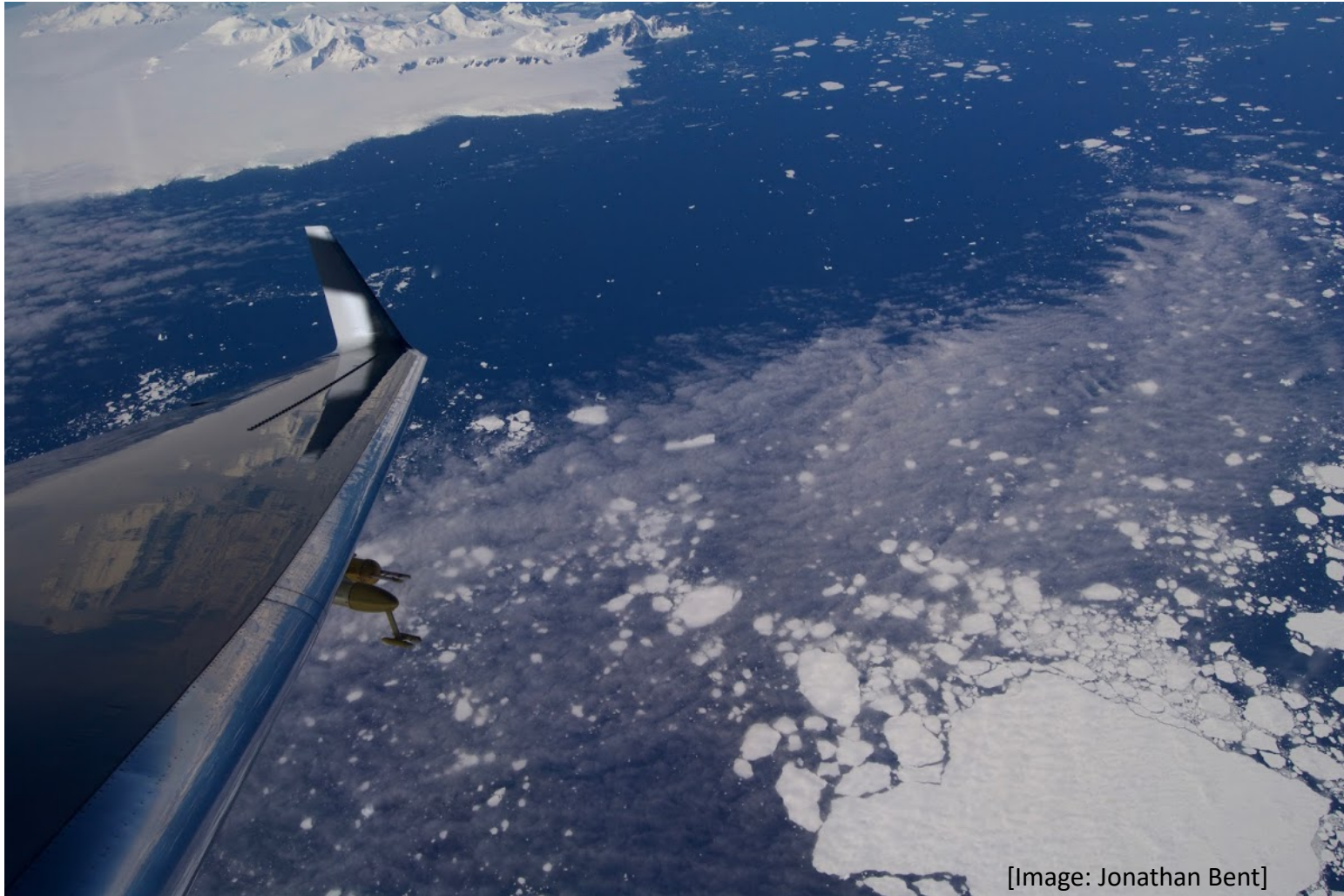


Recent NSF Supported Airborne Oceanography Campaigns and Future Directions



[Image: Jonathan Bent]

Outline:

1) NSF Lower Atmospheric Observing Facilities

- NCAR C-130
- NCAR GV
- Request process

2) Past campaigns

3) O₂/N₂ Ratio and Southern Ocean (ORCAS) Study

4) Future Plans



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

WHAT IS THE VERTICAL RANGE OF THE LOWER ATMOSPHERIC OBSERVING FACILITIES?



NSF/NCAR HAAPER
Owned by NSF and operated by NCAR, the High-performance Instrumented Airborne Platform for Environmental Research (HAAPER) is an extensively modified Gulfstream V jet capable of attaining 51,000 feet, flying for 10 hours, and covering 5,000 nautical miles. HAAPER has a payload capacity of 5,000 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 30,000 feet, 10-hour flight endurance, and 2,800-nautical-mile range. With a payload of 13,000 pounds, the C-130 has space 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 20,000 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.

NCAR S-POLKA
The S-POLKA is a ground-based, transportable weather radar offering dual-polarimetric and dual-wavelength observations at S-band (10 centimeter and 2-band (58 centimeter) wavelengths). The entire radar can be moved 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 feed-horns are available, allowing the radar to operate at frequencies of both 3 and 9 GHz (11- and 3-centimeter wavelength). 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 are truck-borne Doppler radars, frequently deployed in a multiple-Doppler network. The DOW network is an adjustable/variable radar network able to deploy close to meteorological and other phenomena in order to get fine-scale spatial and temporal observations.



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



NCAR HSRL
The High-Spectral Resolution Lidar (HSRL) is used to make reliable and accurate measurements of atmospheric extinction, backscatter coefficients, optical depth, and discrimination between ice and water clouds. The HSRL was designed and built by the University of Wisconsin Lidar Group to fly on the HAAPER aircraft. It can also be configured as a stand-alone 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 primarily 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 owned and operated by the University of Wyoming.



UW WCL
The Wyoming Cloud Radar (WCL) measures backscatter intensity and depolarization from aerosols and cloud particles. Two independent systems are capable of viewing above and below the aircraft. The measurements from the WCL (and at times combined with the WCR) can be used to determine comprehensive cloud and aerosol microphysical and microphysical property characteristics.



NCAR AWAPS
The Airborne Vertical Atmospheric Profiling System (AWAPS) 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 thermodynamics 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 GALS
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 GALS provides high vertical resolution measurements of temperature, humidity, pressure, and winds.

NCAR ISF5
The Integrated Surface Flux System (ISF5) 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.

* Instruments and platforms are not to scale.

C130 Research Aircraft



- 10 Hours Endurance
- 23,000 lb (13,000 with max fuel) payload
- Range 3100 nautical miles
- 26,000 ft max altitude (7.9 km)

Photo courtesy of Tony Clarke,
Univ. of Hawaii

NSF/NCAR G-V Aircraft



- Six under-wing hardpoints
- Up and down co-aligned 21-inch optical viewports
- Multiple aperture/inlet locations
- 6000 lb science payload
- 6000 nautical miles
- 51,000 ft max altitude (15.5 km)



<https://www.eol.ucar.edu/aircraft-instrumentation>

I.State Parameters Including Temperature, Wind and Position

- A. Temperature, Ambient Air
- B. Humidity, Ambient Air
- C. Pressure, Ambient Air
- D. Winds
- E. Water vapor isotopes

II.Properties of Clouds and Hydrometeors

- A. Liquid Water Content
- B. Cloud Droplet Spectrometers
- C. Ice, Drizzle, and Precipitation Probes
- D. Remote Sensors

III.Gas Concentrations

- A. Ozone
- B. Carbon Dioxide, Methane, Carbon Monoxide, Nitrous Oxide
- C. Oxygen
- D. Flask Sampling Systems

IV. Aerosol Particles

- A. Condensation Nucleus Counter (Water or Butanol) (CN)
- B. Aerosol-Particle Spectrometers
- C. Chemical, Optical, or Other Properties of Aerosols
- D. Remote Sensors
- E. Special Inlet: Solid Diffuser Aerosol Inlet (SDI)

V. Radiation

- A. Upwelling and Downwelling Irradiance
- B. Actinic Flux
- C. Remotely Sensed Surface Temperature

VI. Other

- A. HIAPER Modular Inlet (HIMIL; "HIMIL" inlets)
- B. Digital Imagery (camera or video)
- C. Satellite Communications System (SATCOM)
- D. Optical viewports
- E. Dropsondes

Example NCAR C-130 Campaigns

Gulf of Tehuantepec Experiment - 2004

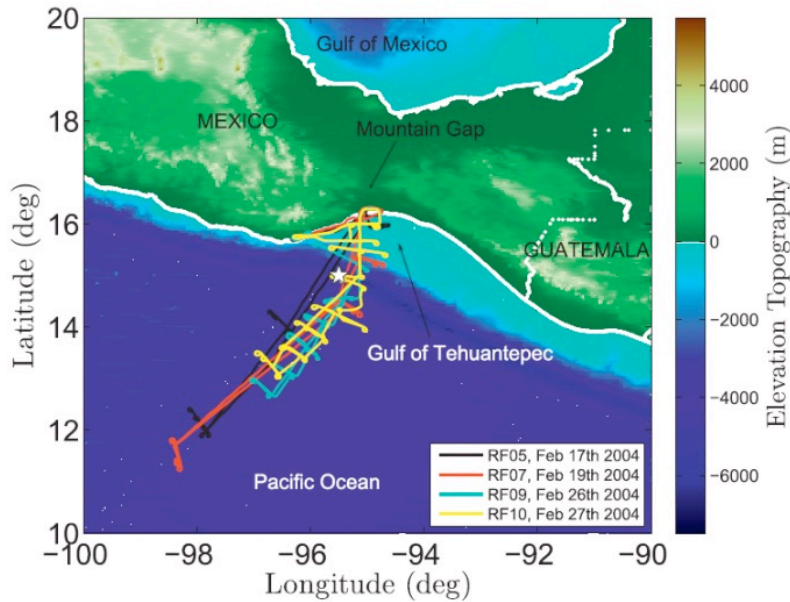
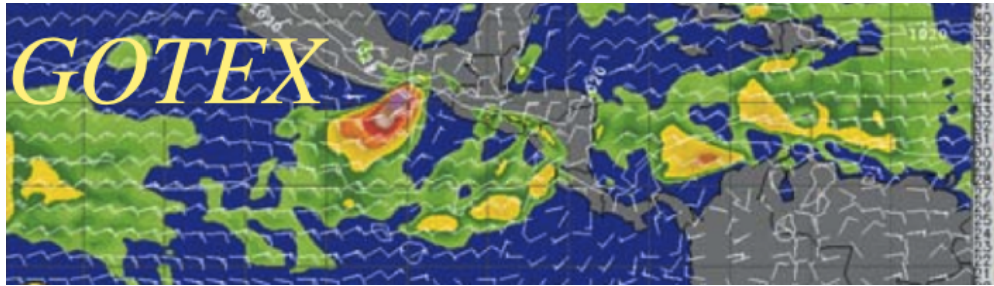
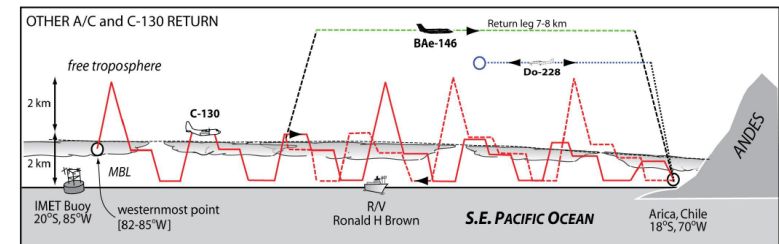
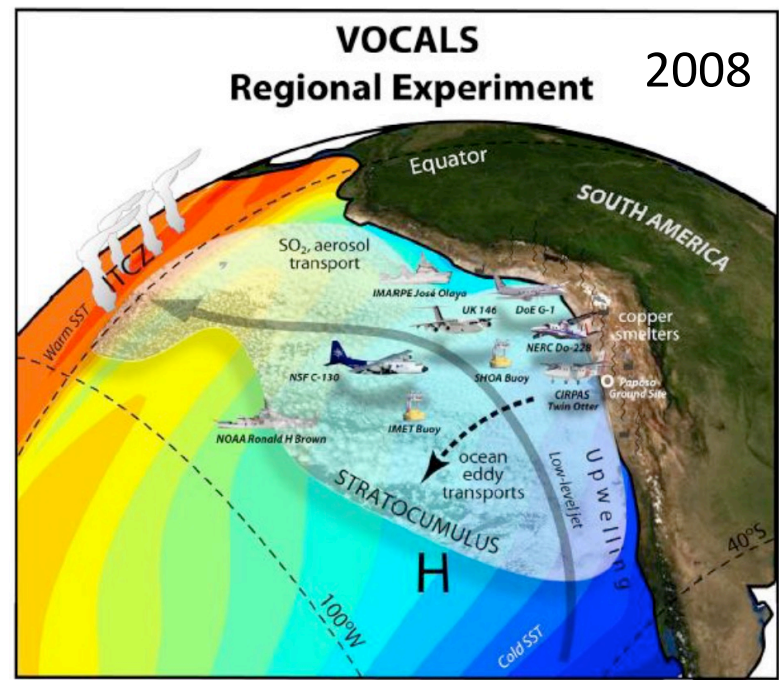


FIG. 2. GOTEX flight tracks from research flights 05, 07, 09, and 10. The white star corresponds to the location of wind time series shown in Fig. 3.

Romero and Melville, JPO, 2010



HIPPO

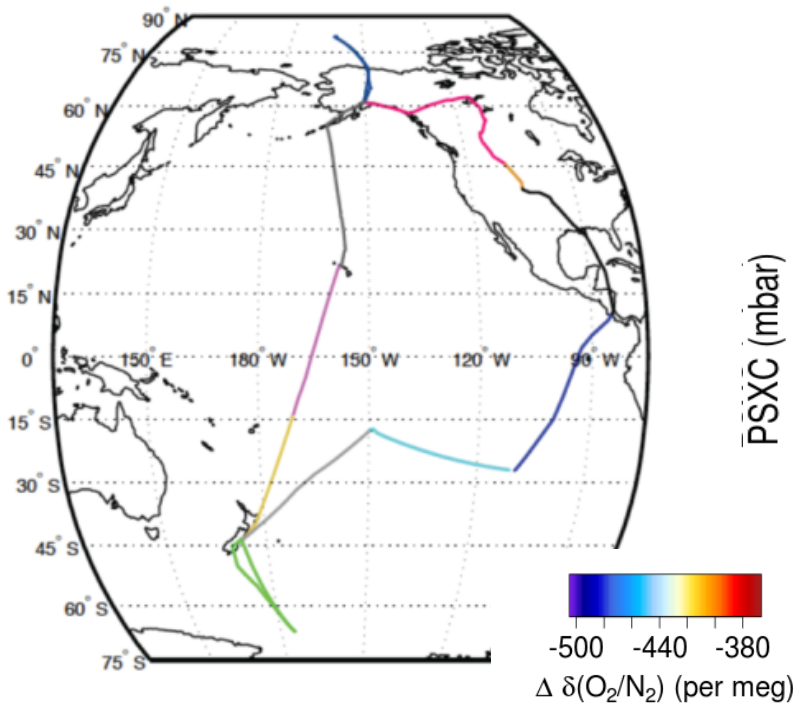
2009-2011



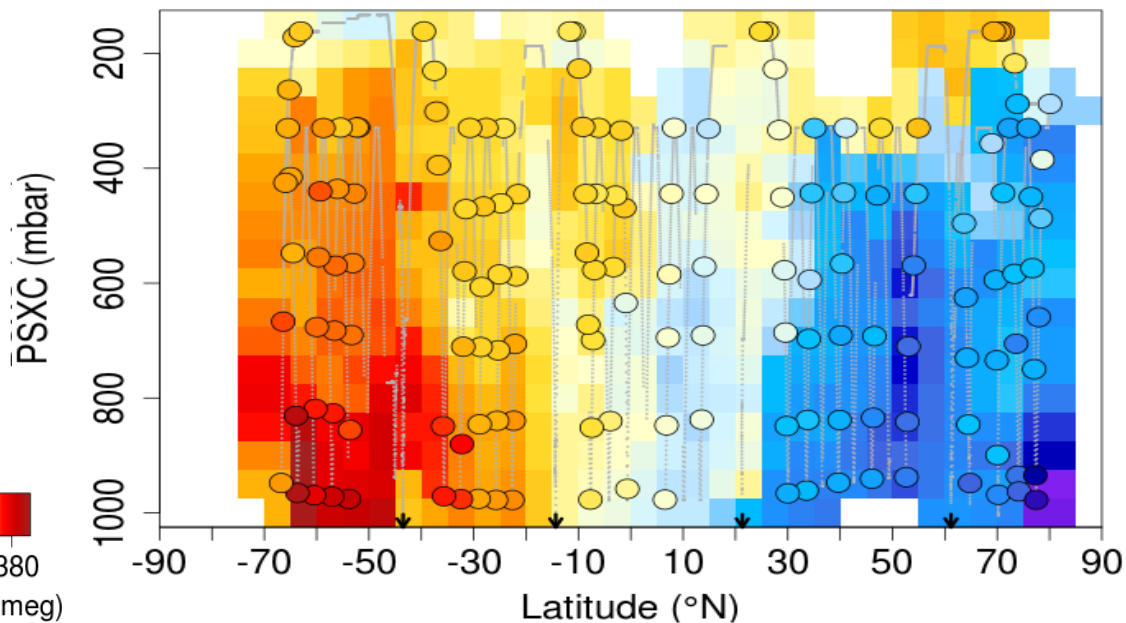
HIAPER

Pole-to-Pole
Observations

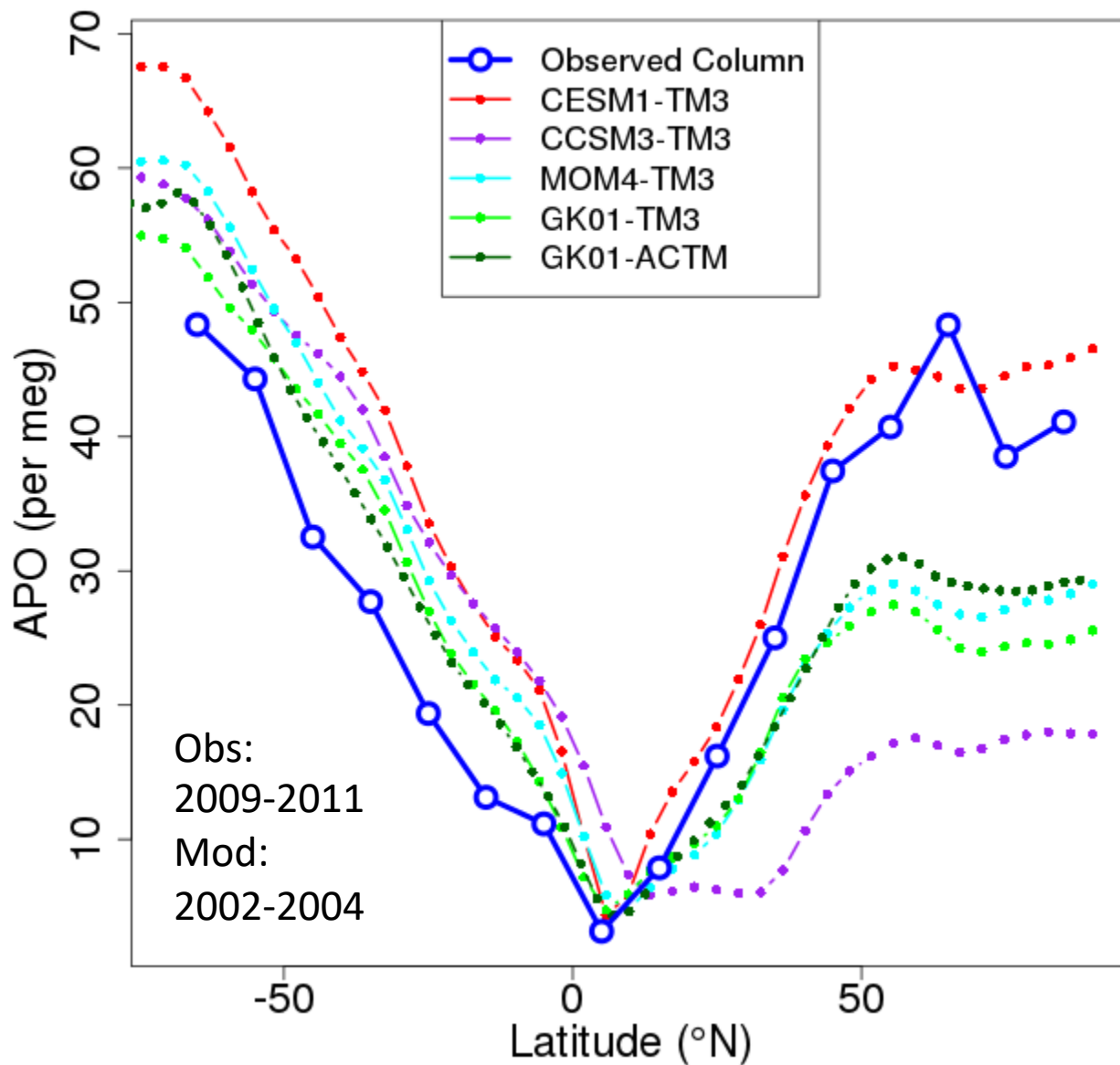
- PIs: Harvard, NCAR, Scripps, NOAA
- Global and seasonal survey of CO₂, O₂, CH₄, CO, N₂O, H₂, SF₆, COS, CFCs, HCFCs, O₃, H₂O, CO₂ isotopes, Ar, black carbon, and hydrocarbons (over 90 species).
- NSF / NCAR Gulfstream V
- Five 3-week campaigns over 3 years, across Pacific between 87 N and 67 S
- www.eol.ucar.edu/field_projects/hippo



HIPPO1 January 2009 Atmospheric O₂



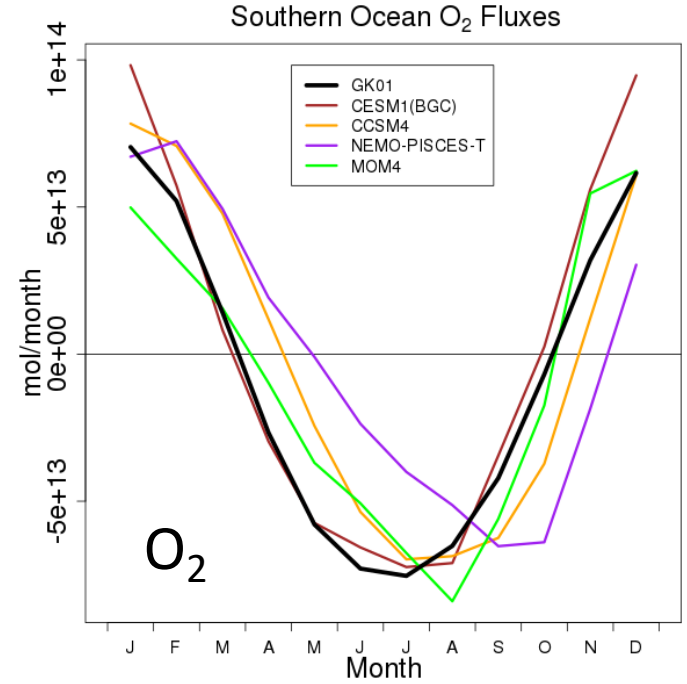
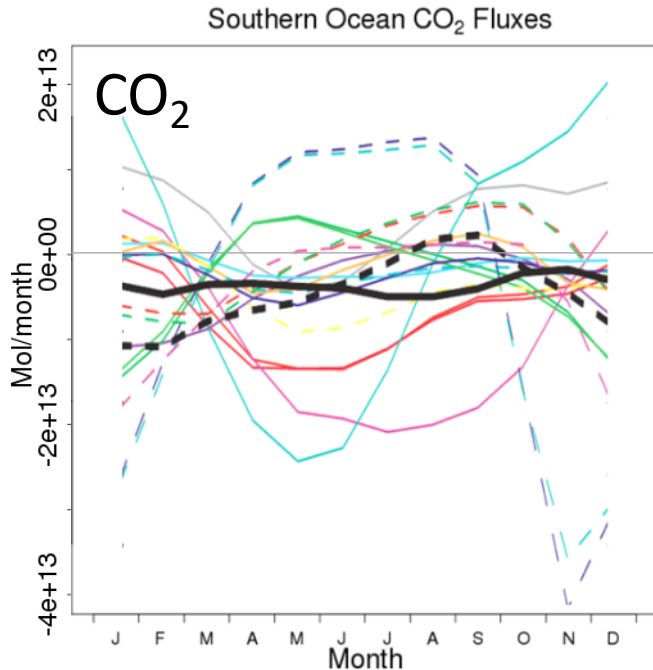
HIPPO Seasonal APO Amplitudes



Obs:
2009-2011
Mod:
2002-2004

$APO = O_2 + CO_2 = \text{“oceanic oxygen”}$

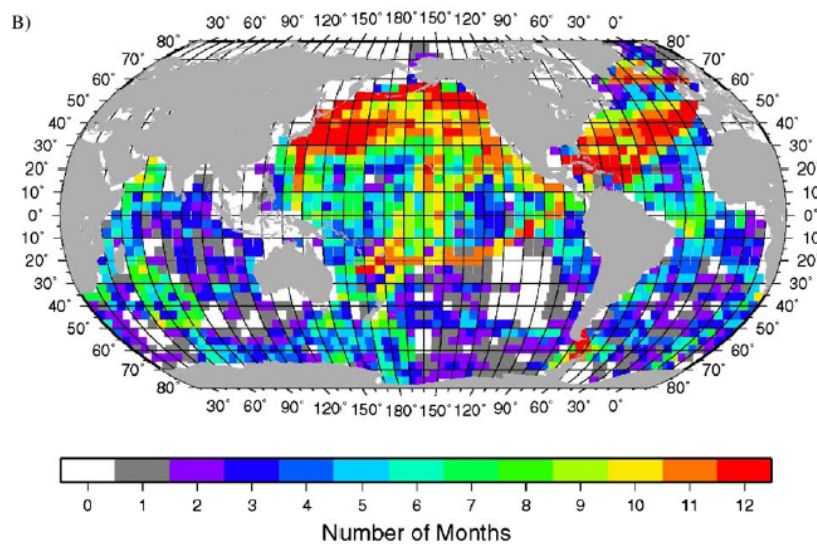
Seasonal CO₂ and O₂ fluxes (S of 44 S)



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

pCO₂ coverage



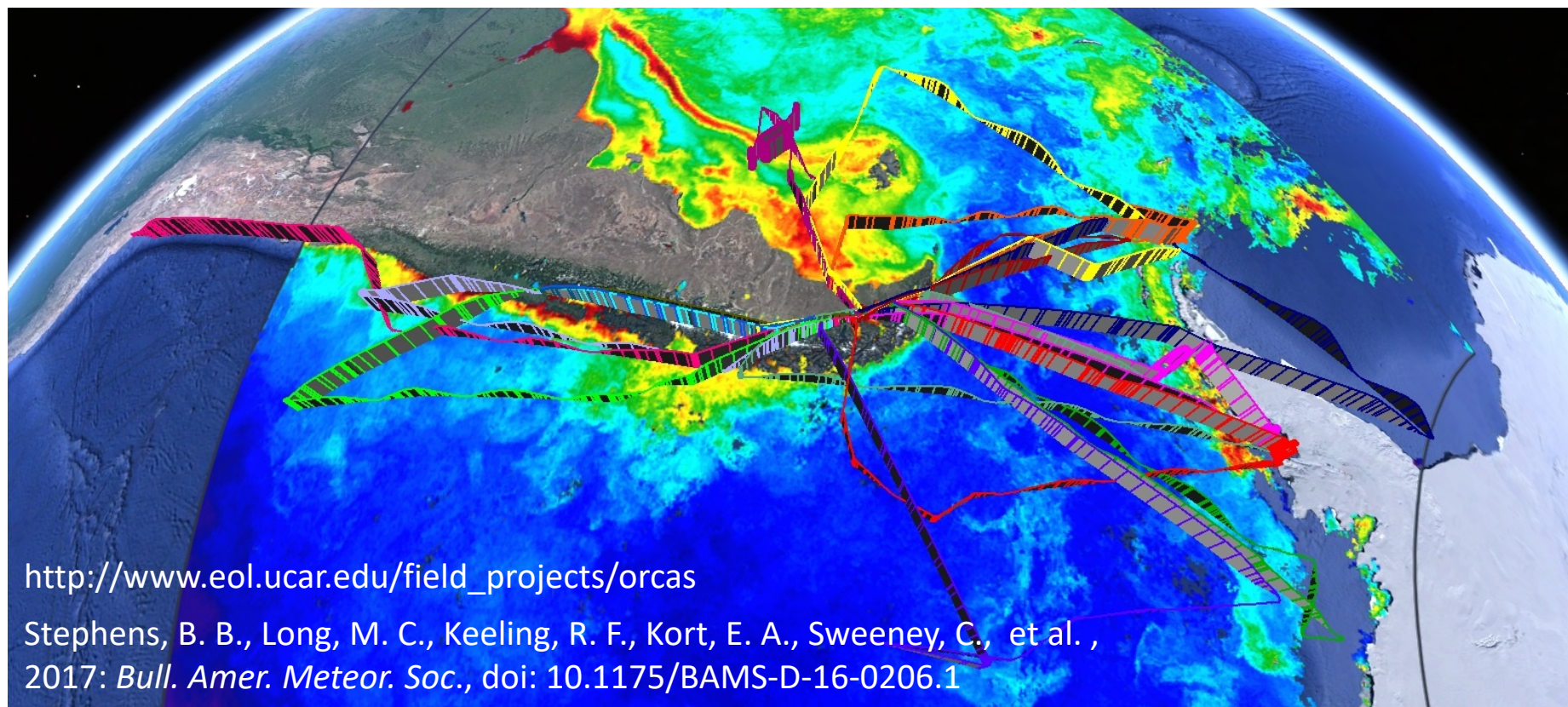
Takahashi et al.,
 DSR, 2009

ORCAS

2016 O₂/N₂ Ratio and CO₂ Airborne
Southern Ocean Study



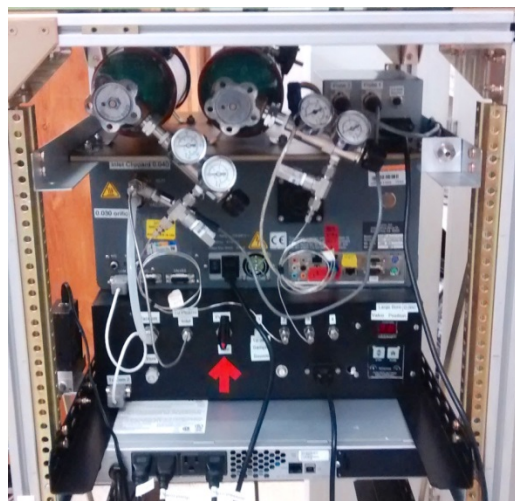
NSF/NCAR GV
Punta Arenas, Chile
15 Jan to 29 Feb 2016



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

Stephens, B. B., Long, M. C., Keeling, R. F., Kort, E. A., Sweeney, C., et al.,
2017: *Bull. Amer. Meteor. Soc.*, doi: 10.1175/BAMS-D-16-0206.1

GV Scientific Payload:

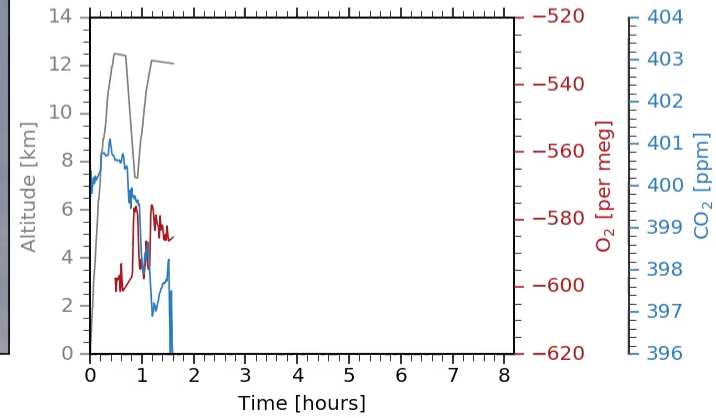


Instrument	Measurement	Institution
Airborne Oxygen Instrument (AO2)	$\delta(\text{O}_2/\text{N}_2)$, CO_2	NCAR EOL
Medusa Flask Sampler	$\delta(\text{O}_2/\text{N}_2)$, CO_2 , $\delta(\text{Ar}/\text{N}_2)$, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and $\Delta^{14}\text{C}$ of CO_2	NCAR/Scripps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

ORCAS Research Flight 3

ORCAS RF03

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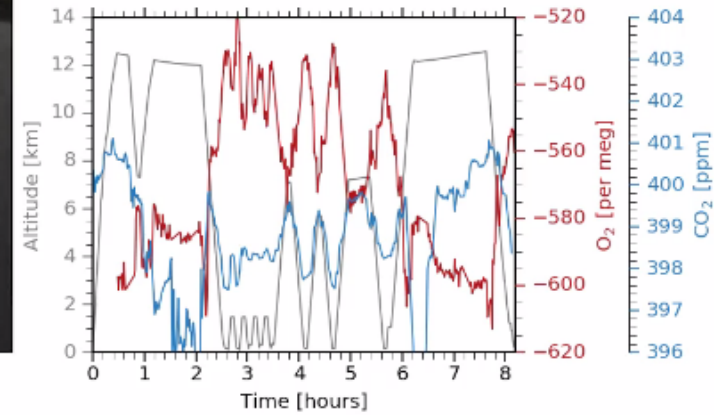


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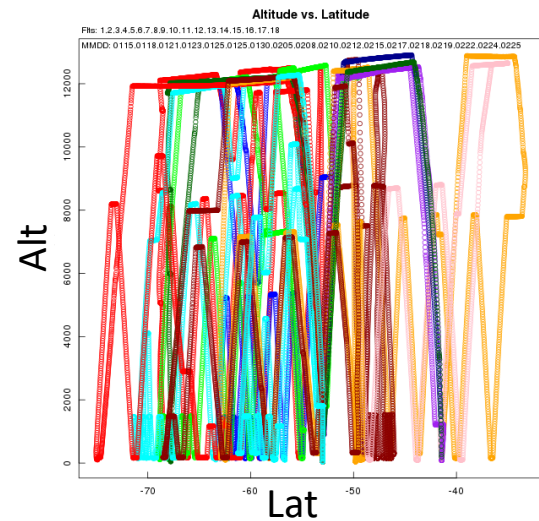
ORCAS Research Flight 3

ORCAS RF03

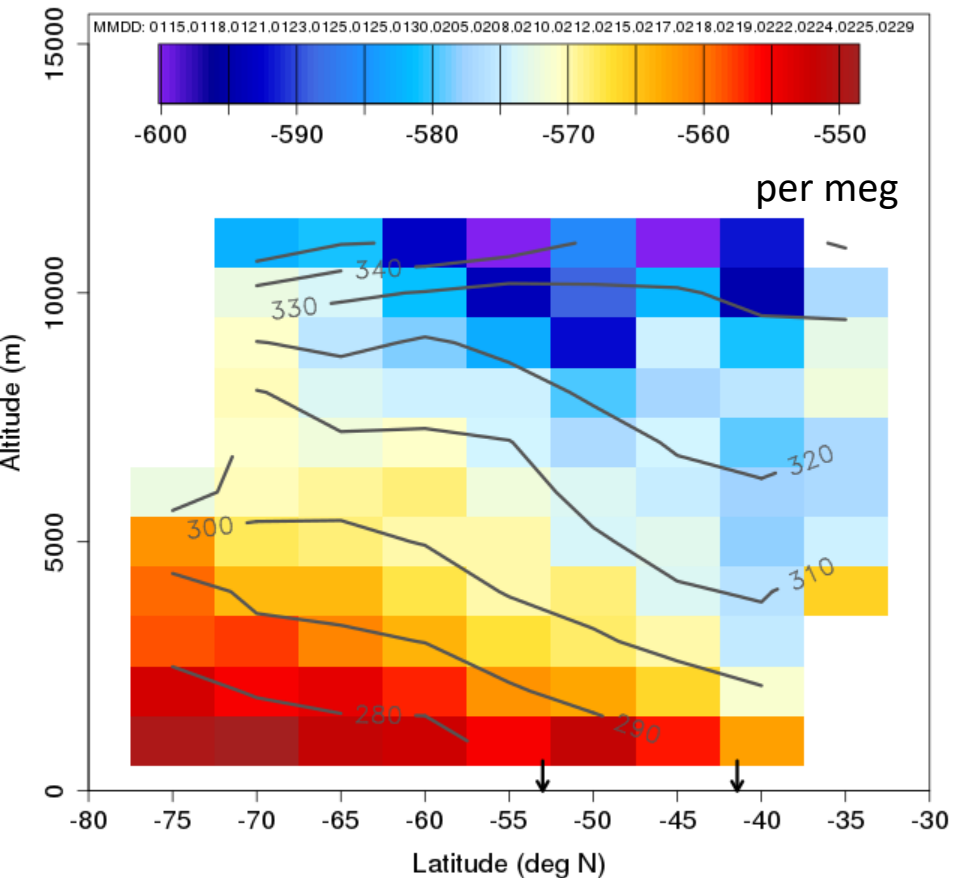
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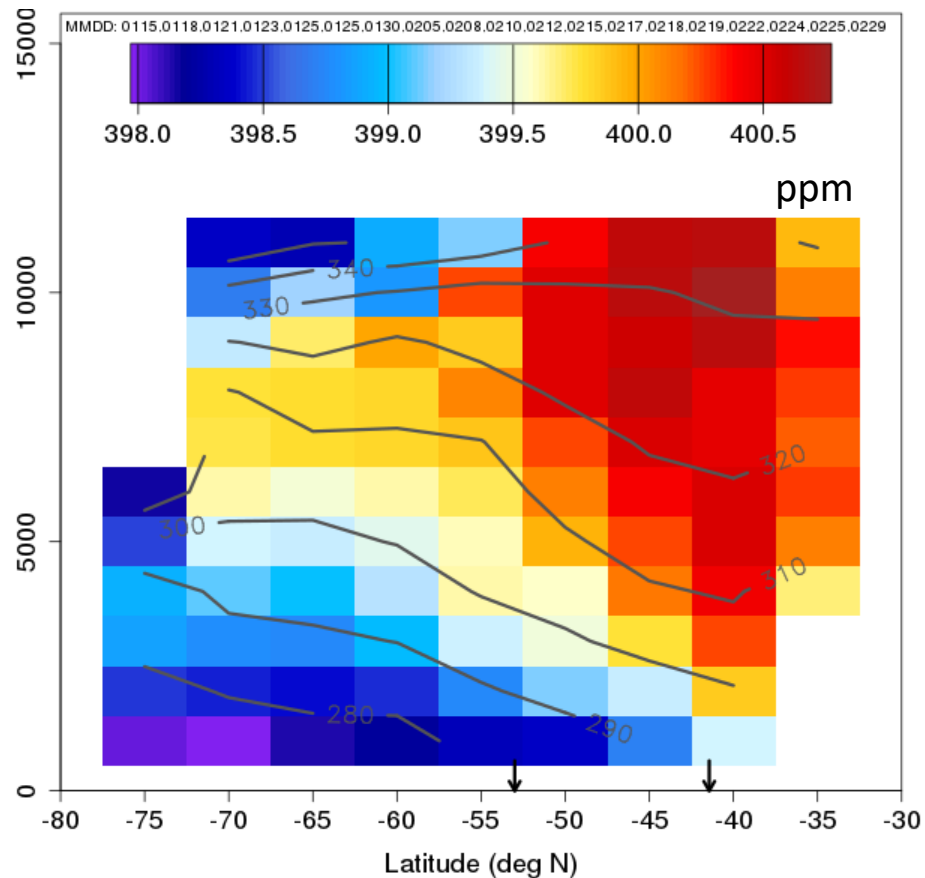
Whole campaign latitude /altitude bin averages



O₂



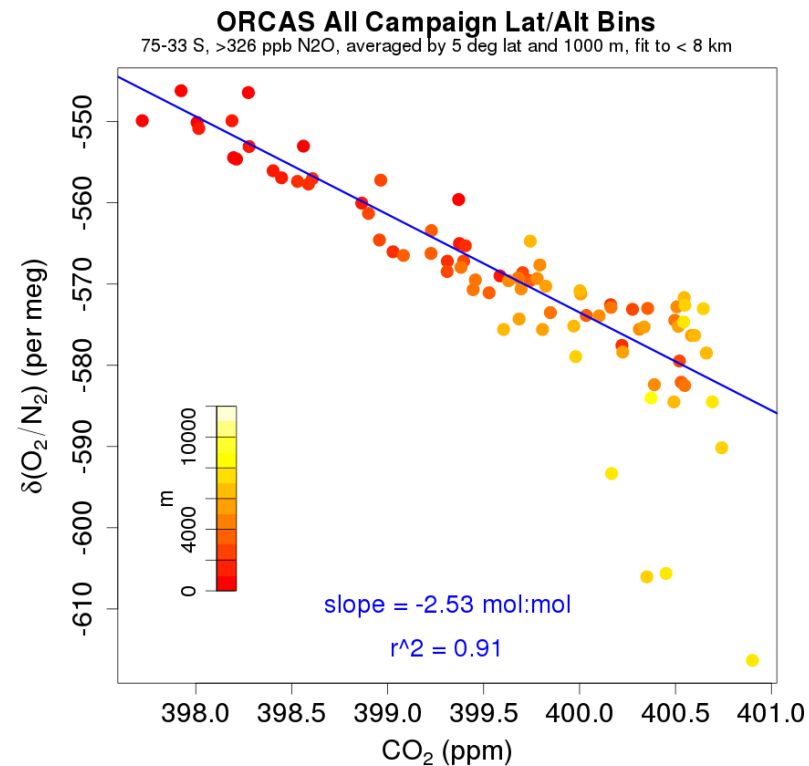
CO₂



ORCAS Highlights

- Negative $O_2:CO_2$ correlations revealed the dominance of biological drivers on summertime CO_2 fluxes
- $O_2:CO_2$ ratio and mean O_2 and CO_2 gradients suggest CESM overestimates summertime O_2 outgassing and climatologies underestimate summertime CO_2 ingassing
- Halogenated VOCs correlate with O_2 indicating biogenic source and providing new model tests
- ESM evaluation of supercooled liquid cloud distributions
- Development of methods for remotely sensing depth-resolved chlorophyll fluorescence

Whole campaign bin averaged $O_2:CO_2$ relationship



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 CO₂, CH₄, CO, and H₂O
- 139th EAS LC-130s operating between Christchurch, McMurdo Station, South Pole, and north from McMurdo, Nov-Feb
- To quantify gradients, and trends in CO₂ and CH₄



UAS Activities

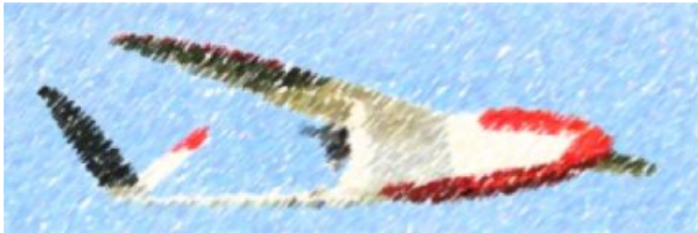
THE NCAR/EOL COMMUNITY WORKSHOP ON UNMANNED AIRCRAFT SYSTEMS FOR ATMOSPHERIC RESEARCH

21-24 February 2017
Boulder, Colorado, USA
Final Report 6 February 2018

Senior Editor:
Holger Vömel (NCAR/EOL)

Workshop Report Authors:
B.M. Argrow (CU), D. Axisa (DMT), P. Chilson (OU), S. Ellis (NCAR/EOL), M. Fladeland (NASA/AMES), E.W. Frew (CU), J. Jacob (OSU), M. Lord (NCAR/EOL), J. Moore (NCAR/EOL), S. Oncley (NCAR/EOL), G. Roberts (UCSD), S. Schoenung (BAERI), C. Wolff (NCAR/EOL)

[Download the Final Workshop Report](#)

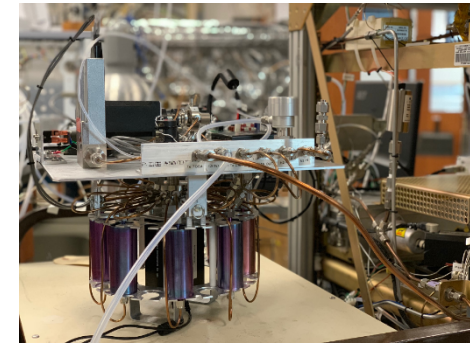


Reference:

H. Vömel, B.M. Argrow, D. Axisa, P. Chilson, S. Ellis, M. Fladeland, E.W. Frew, J. Jacob, M. Lord, J. Moore, S. Oncley, G. Roberts, S. Schoenung, C. Wolff, 2018: NCAR/EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research, UCAR/NCAR Earth Observing Laboratory, <https://doi.org/10.5065/D6X9292S>

Whole-air Airborne Sampler - Pilotless (WASP)

Developed by
Lizzy Asher



- Collects 8 air canisters per flight (may collect ≤ 15)
- Measured on the NCAR TOGA fast GCMS instrument
- VOC measurements range < 10 ppt - ~ 50 ppb
- 1Hz T, RH, P, 2D winds, system P and flow
- Computer programed or piloted flights

Summary

- NSF aircraft have been used for past and ongoing oceanographic campaigns
- NSF aircraft are requestable by the community and come with a wide array of instrumentation
- Engineering, flight planning, data management, outreach, and logistical support are also available
- The ORCAS campaign provided insights into the biogeochemical drivers of Southern Ocean air-sea gas exchange not possible from shipboard measurements
- NCAR EOL is interested in pursuing further synergies and eager to provide future support to the oceanographic research community



[Image: Jonathan Bent]



Courtesy of Alec Chin (ARSV L.M. Gould)



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

NCAR Airborne Oxygen Instrument (AO2)

NCAR/Scripps Medusa Flask Sampler

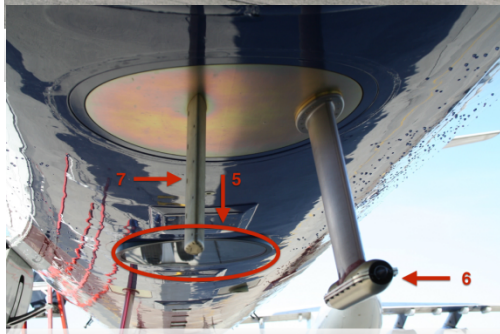
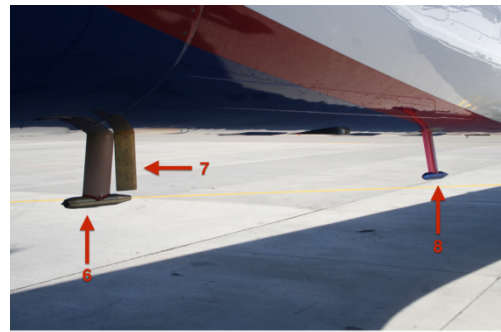
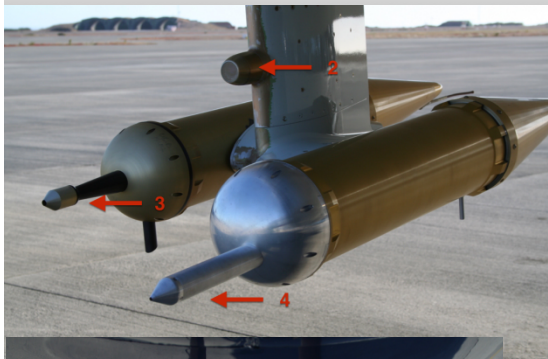




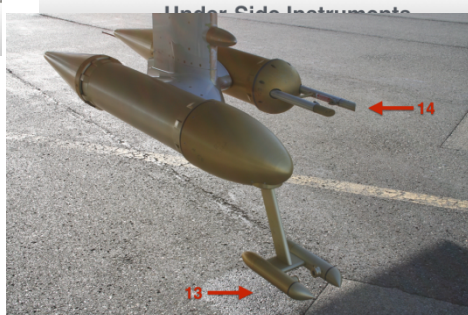
NSF/NCAR HIAPER Right-side



NSF/NCAR HIAPER Left-side



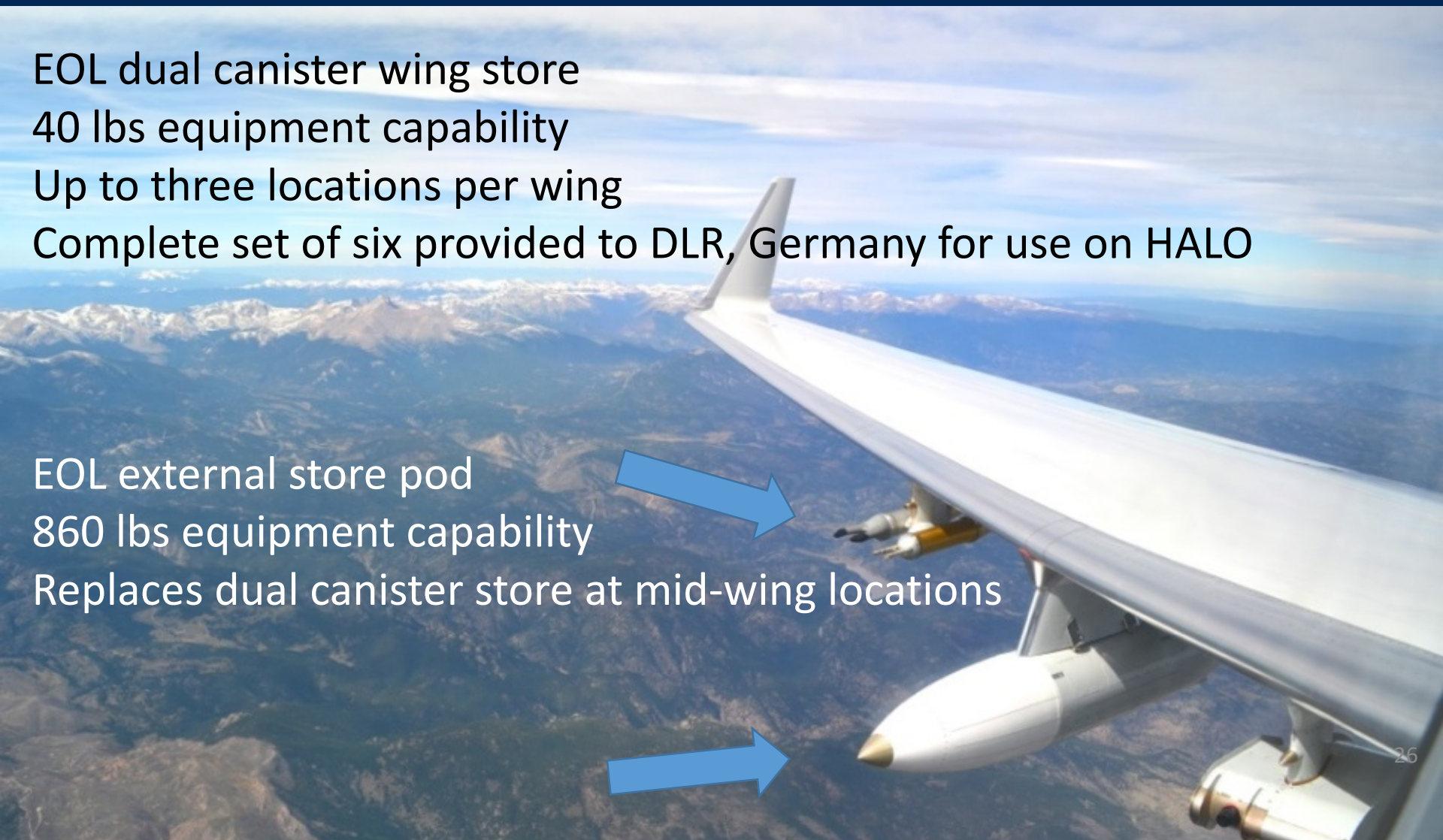
Under-Side Instruments



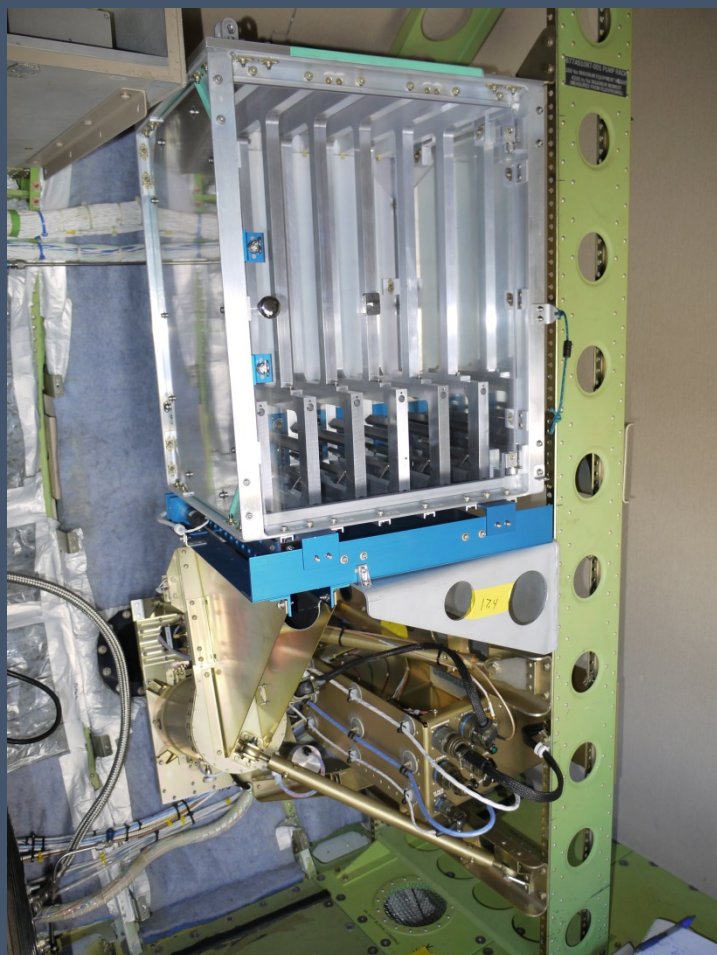
Left Wing-Mounted Instruments

EOL dual canister wing store
 40 lbs equipment capability
 Up to three locations per wing
 Complete set of six provided to DLR, Germany for use on HALO

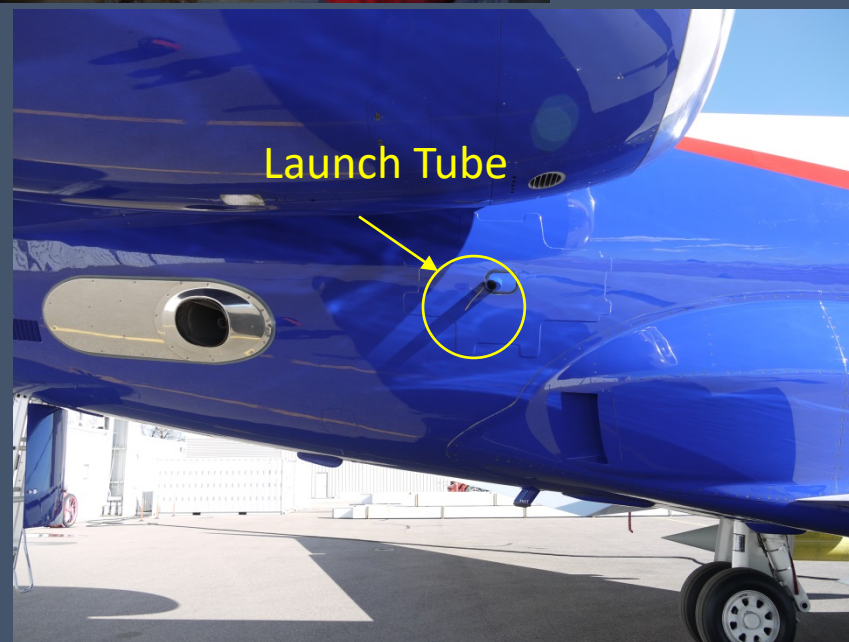
EOL external store pod
 860 lbs equipment capability
 Replaces dual canister store at mid-wing locations

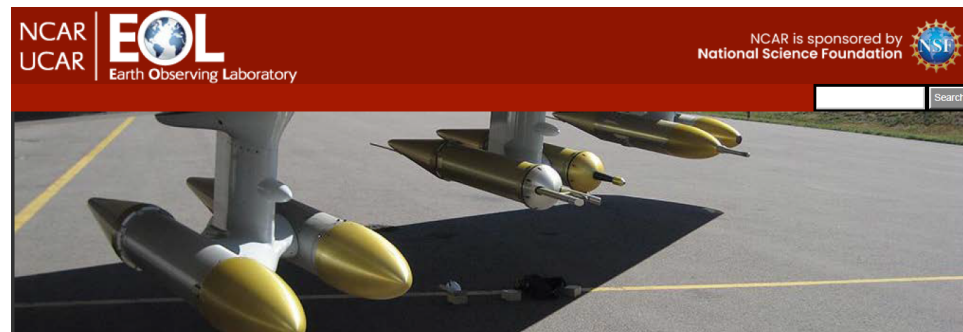


G-V Automated Dropsonde Launcher



AVAPS[®]
Data System





Files & Brochures

HAIS_brochure_2017.pdf

INSTRUMENTS AVAILABLE ON NCAR-OPERATED RESEARCH AIRCRAFT

Aircraft Instrumentation

I. State Parameters Including Temperature, Wind and Position

A. Temperature, Ambient Air

1. Heated (Deiced) Total / Ambient Temperature Sensor (ATHx-TTHx)
2. High Rate Ambient Temperature Sensor (RTF1-ATF1)
3. Radiometric Sensors
 - a. OPHIR-III Air Temperature Radiometer (Ophir) Decommissioned
 - b. In-Cloud Air Temperature Radiometer (ITR)
4. Remote Sensors
 - a. Microwave Temperature Profiler (MTP)
 - b. GNSS Instrument System for Multi-static and Occultation Sensing (GISMOS)
 - c. AVAPS Dropsonde (AVAPS)

B. Humidity, Ambient Air

1. Thermo-electronic Dew Point Sensor (DPx)
2. Buck Instruments Model CR-2 Cryogenic Hygrometer (CR2)
3. Ultraviolet Absorption Hygrometer (UVH)
4. Vertical Cavity Surface-Emitting Laser Hygrometer (VCSEL)
5. Open-Path Laser Hygrometer (OPLH) Decommissioned

C. Pressure, Ambient Air

1. Ambient Static Pressure (PSFx)

D. Wind

Obtained from the addition of the relative-wind vector and aircraft-velocity vector using the following sensors:

1. Gust Measurements (Wind Relative to the Aircraft)
 - a. Dynamic Pressure (QCX; at pitot-tube inlet)
 - b. Radome Gust Probe for 3-D Wind Measurements (ADIFR-BDIFR-QCRC)
 - c. All Weather Wind Gust Pod (TASX; anti-iced for all-weather capability)
 - d. Laser Air Motion Sensor (LAMS; remote measurement ahead of disturbed airflow)
2. Aircraft Motion Relative to the Earth
 - a. Inertial Navigation System, A.K.A Inertial Reference Unit (IRU)
 - b. Global Positioning Systems
 - i. Research Global Positioning System (GPS; standard)
 - ii. Differential GPS Ground Station (DGPS; highest accuracy, depends on a reference station)

3. Position of the aircraft

- a. Inertial Navigation System, A.K.A Inertial Reference Unit (IRU)
- b. Global Positioning Systems
 - i. Research Global Positioning System (GPS; standard)
 - ii. Differential GPS ground station (DGPS; highest accuracy, depends on a reference station)
- c. Radar Altimeter (RALT; height above the surface underlying the aircraft)

E. Time

1. Time Server (Time)

F. Other Related Measurements

1. Cabin Pressure (PCAB)
2. Cabin Temperature at ADS Rack Location (TCAB)
3. Instrument Exhaust Gas Dump Pressure (PDump; pressure in the gas-dump manifold, this outlet is used as outlet for sampling lines)

II. Properties of Clouds and Hydrometeors

A. Liquid Water Content

1. King Probe Liquid Water Sensor (CSIRO)
2. Gerber Liquid Water Probe (PVM-100 or XGLWC) Decommissioned
3. Rosemount Icing Detector (RICE; supercooled liquid water sensor)
4. (also obtained as a derived quantity from distrometers listed below)

B. Cloud Droplet Spectrometers

1. Forward Scattering Spectrometer Probe, Model 100 (FSSP-100) Decommissioned
2. Forward Scattering Spectrometer Probe, Model 300 (FSSP-300) Decommissioned
3. Cloud Droplet Probe (CDP)
4. (see also the SID2H, 2DC, and 3V-CPI)

C. Ice, Drizzle, and Precipitation Probes

1. Two-Dimensional Optical Array Cloud Probe (2DC or 2D-OAP)
2. Two-Dimensional Optical Array Precipitation Probe (2DP) Decommissioned
3. Small Ice Detector, Version 2 for HIAPER (SID2H) Decommissioned
4. Three-View Cloud Particle Imager (3V-CPI) Decommissioned
5. Holographic Detector for Clouds (HOLODEC)
6. Two-Dimensional, Stereo, Particle Imaging Probe (2D-S)

D. Remote Sensors

1. HIAPER cloud radar (HCR)
2. (see also HSRL below and MTP above)

III. Gas Concentrations

A. Ozone

1. Nitric Oxide Chemiluminescence Ozone Instrument (FO3_ACD)
2. RAF Ozone Photometer (OP-1 or OP-2; Photometric Ozone)
3. Thermo Environmental Instruments Model 49 Ozone Analyzer (TECO) Decommissioned

B. Carbon Dioxide

1. Picarro Instrument for Airborne Measurement of CO₂ and CH₄ (CO₂_PIC, CH₄_PIC)
2. Quantum Cascade Laser Spectrometer (QCLS; also measures CO, CH₄, N₂O) Decommissioned
3. (see also AO2 and flask-sampling systems below)

C. Whole Air Sampling Systems

1. Advanced Whole Air Sampler (AWAS)
2. NCAR/Scripps Medusa Flask Sampler (Medusa)

D. Other Gases

1. Aero-Laser VUV Resonance Fluorescence Carbon Monoxide (COMR_AL; See also QCLS above) Decommissioned
2. 2-Channel Chemiluminescence (NO-NO₂)
3. Airborne Oxygen (AO2)
4. Georgia Tech Chemical Ionization Mass Spectrometer (GTCIMS; nitric acid and other species)
5. Trace Organic Gas Analyzer (TOGA; many organic species)

IV. Aerosol Particles

A. Condensation Nucleus Counter (Butanol) (CN)

B. Aerosol-Particle Spectrometers

1. Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)
2. Signal Processing Package - 200 for Passive Cavity Aerosol Spectrometer Probe (SPP-200 or PCASP-1)
3. Radial Differential Mobility Analyzer (RDMA) Decommissioned
4. Scanning Mobility Particle Spectrometer (SMPS) Decommissioned
5. HIAPER Aerosol Spectrometer Probe, Optical Particle Counter (OPC, HASP)

C. Chemical, Optical, or Other Properties of Aerosols

1. Time-of-Flight Aerosol Mass Spectrometer (TOF-AMS; composition) Decommissioned
2. Counter-flow Virtual Impactor (CVI; samples selected for size)
3. Integrating Nephelometer (Neph; wet and dry, radiative properties) Decommissioned
4. Giant Nuclei Impactor (GNI; collector of giant/ultra-giant particles on slides for analysis)

D. Remote Sensors

1. High Spectral Resolution Lidar (HSRL)

E. Special Inlet: Solid Diffuser Aerosol Inlet (SDI)

V. Radiation

A. Upwelling and Downwelling Irradiance

1. HIAPER Airborne Radiation Package (HARP)
2. Broadband Radiometers (Pyrometers and Pyranometers)

B. Actinic Flux

1. HIAPER Airborne Radiation Package (HARP)

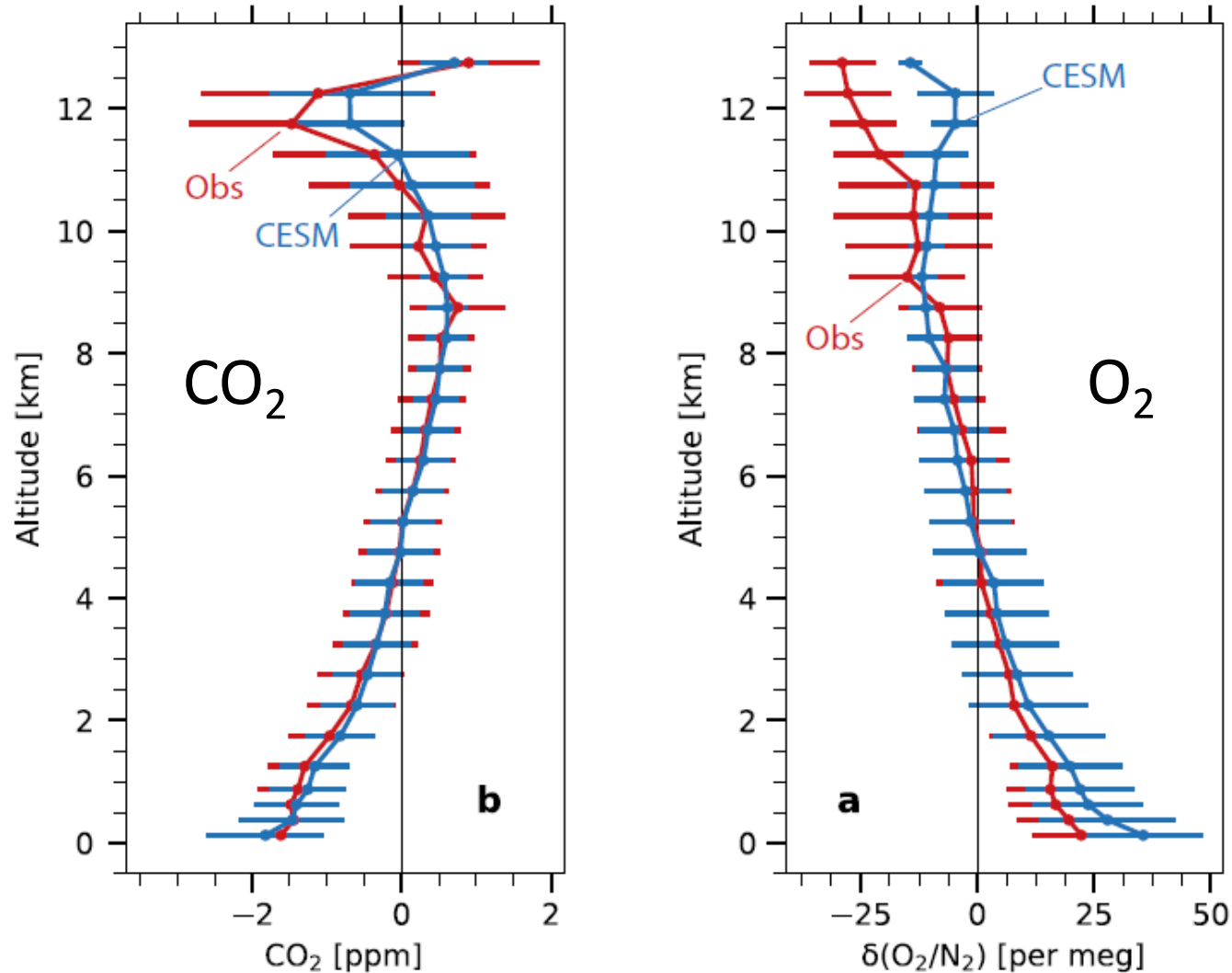
C. Remotely Sensed Surface Temperature

1. Heimann Infrared Radiation Pyrometer (KT19)

VI. Other

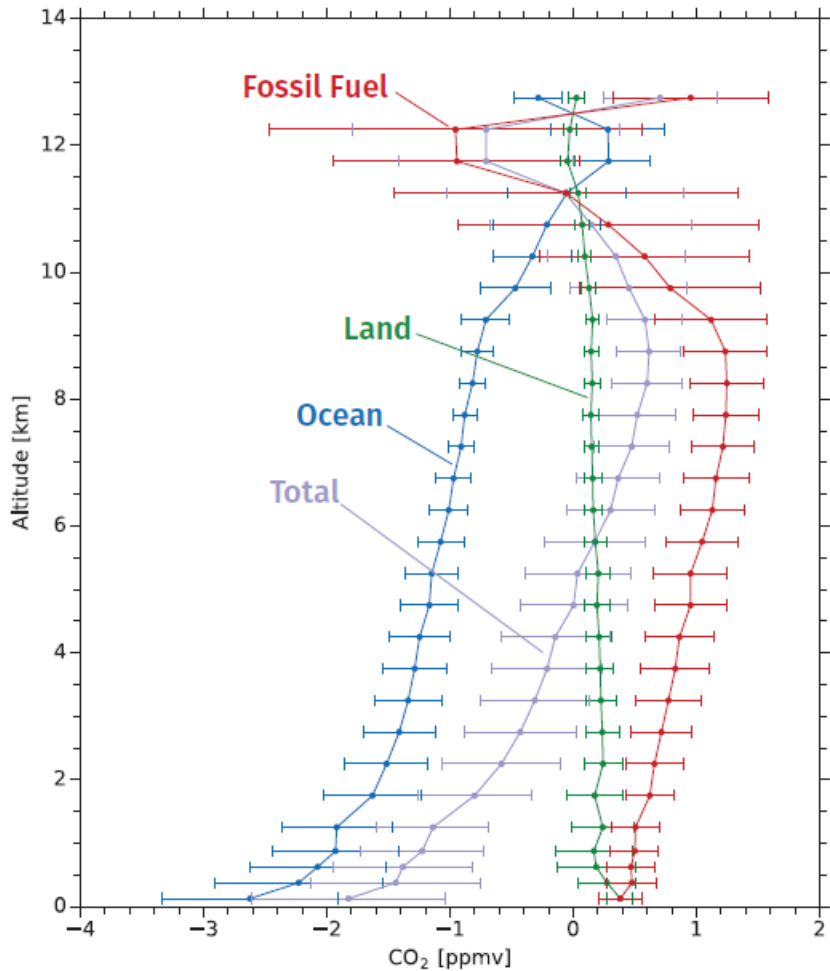
- A. HIAPER Modular Inlet (HIMIL; "HIMIL" inlets)
- B. Digital Imagery (camera or video)
- C. Satellite Communications System (SATCOM)

CESM(SD) Compared to Observations

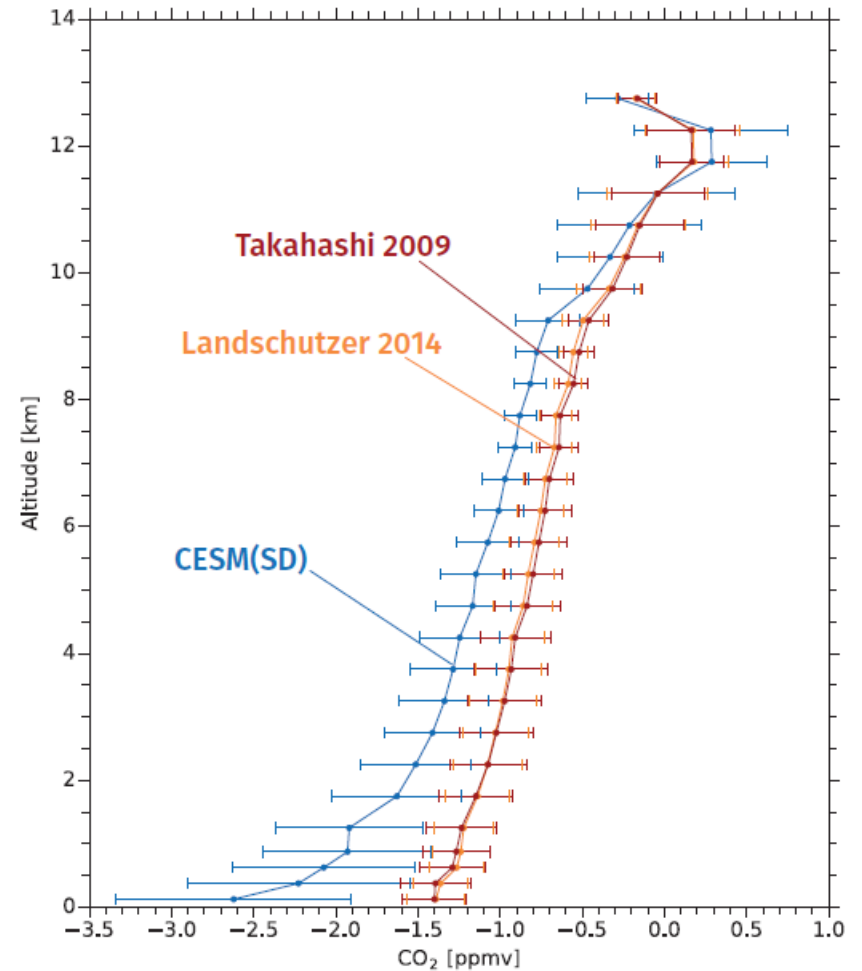


- Model matches CO₂ gradient but overestimates O₂ gradient from 5 km by 50%
- Implies CO₂ right for wrong reason, such as compensating overestimates of both biological and thermal forcing

CESM(SD) CO₂ Components



CESM(SD) Ocean CO₂ Comparison



ORCAS take-home points:

- strong negative O₂:CO₂ correlation, but with relatively small slope
- CESM(SD) matches CO₂ but not O₂ gradients
- CAM vertical CO₂ gradients ~ 2X larger than expected from pCO₂ flux estimates