Southern Ocean Gas Exchange Experiment Science Plan

Collated by David Ho

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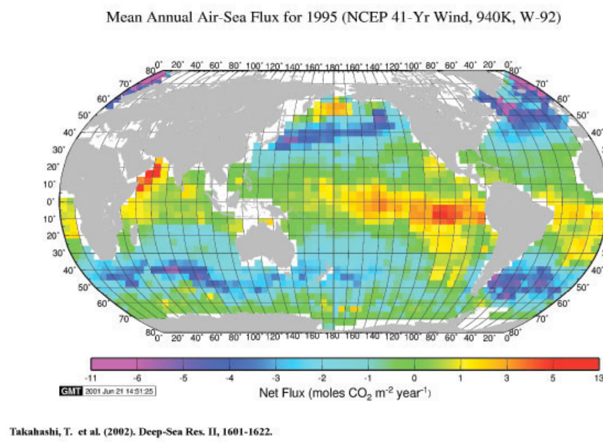
Southern Ocean Gas Exchange Experiment (SO GasEx)

Given the paucity of data, there is a clear need to quantify gas transfer velocities at wind speeds in excess of 10 m s^{-1} [e.g., see *Ho et al.*, 2006]. The Southern Ocean represents an obvious candidate for reliably finding these wind speeds – see discussion below of regional physical, chemical and biological properties. While it is true that high wind speeds and a large ΔpCO_2 signal can be found in other oceanic regions, such as the north Pacific in boreal winter, the Southern Ocean is of interest because of its status as a globally significant but poorly sampled CO_2 sink [*Takahashi et al.*, 2002]. As alluded to in the list of research objectives below, it is entirely possible that the Southern Ocean CO_2 flux is governed by factors unique to this ocean, other than wind speed and ΔpCO_2. If this is the case, parameterizations developed elsewhere will not be applicable to the Southern Ocean, and will continue to lead to large errors in our estimates of the global air-sea CO_2 flux.



Mean annual air-sea CO_2 flux for 1995 calculated from the ΔpCO_2climatology and using the wind speed gas exchange parameterization of *Wanninkhof* [1992]. Figure from *Takahashi et al.* [1999].

The main research objectives for SO GasEx are to answer the following questions:

- What are the gas transfer velocities at high winds?
- What is the effect of fetch on the gas transfer?
- How do other non-direct wind effects influence gas transfer?
- How do changing pCO_2 and DMS levels affect the air-sea CO_2 and DMS flux, respectively in the same locale?
- Are there better predictors of gas exchange in the Southern Ocean other than wind?
- What is the near surface horizontal and vertical variability in turbulence, pCO_2, and other relevant biochemical and physical parameters?
- How do biological processes influence pCO_2 and gas exchange?
- Do the different disparate estimates of fluxes agree, and if not why?
- With the results from Southern Ocean GasEx, can we reconcile the current discrepancy between model based CO_2 flux estimates and observation based estimates?

References

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Science Implementation

In order to investigate the questions and problems posed in the research objectives of SO GasEx, a series of projects are planned, which roughly fall into the following categories:

	Research Projects	Method
1	Direct measurements of CO_2 and DMS Fluxes	Air-sea CO_2 (NDIR) and DMS (APIMS) flux systems
2	Integrated Gas Transfer Velocities with Deliberate Tracers (SF_6 and ^3He)	Continuous and discrete SF_6 systems (GCs) and He isotope mass spec
3	Bulk Meteorology and Turbulent Fluxes (winds, momentum, water vapor, temp, IR, Solar radiation, etc.)	Sonic anemometer, thermometer, pyranometer, pyrgeometer
4	Surface and Near-surface Ocean Processes (Large waves, directional wave field; currents; oceanic surface turbulence, oceanic shear, oceanic stratification, bubbles)	Shipboard radar; microwave altimeter. ADV, MAV, thermister chain, video camera, noble gases (mass spec)
5	Core CO_2 and Hydrographic Measurements (DIC; pCO_2; Talk, temp, sal, O_2)	SOMMA/DICE, NDIR, titration, CTD, Winkler
6	Surface and Subsurface pCO_2 and DIC Variability	Shipboard underway pCO_2 system (NDIR), SAMI, CARIOCA, SuperSoar
7	Primary production; New production	^{14}C and ^{15}N incubations, O_2/Ar (MIMS)
8	Nutrients (NO_2^-, NO_3^-, NH_4^+, PO_4^{3-} and H_4SiO_4)	Nutrient autoanalyzer

The specific projects and their main objectives are:

Quantifying air-sea gas exchange at high wind speeds using a dual gas tracer ($^3He/SF_6$) technique during the Southern Ocean Gas Exchange Experiment (*David Ho and Peter Schlosser, LDEO, Rik Wanninkhof, NOAA/AOML*)

- **Main objective**: To obtain spatially (order of 10-100 km^2) and temporally (order of one day) integrated measurements of gas transfer velocities, constrain vertical exchange across pycnocline, and tag water for Lagrangian experiment.

Southern Ocean air-sea carbon dioxide exchange (*Wade McGillis and Chris Zappa, LDEO; Jim Edson and Penny Vlahos, University of Connecticut*)

- **Main objective:** To measure CO_2 fluxes between the atmosphere and ocean, and characterize surface waves using shipboard radar and altimeter.

Measurement and parameterization of air-sea gas transfer over the Southern Ocean in GasEx-III (*Chris Fairall, NOAA/ESRL; Detlev Helmig, University of Colorado*)

- **Main objective:** To provide meteorological reference data.

Measurement and parameterization of air-sea DMS transfer over the Southern Ocean in GasEx-III (*Barry Huebert and Byron Blomquist, University of Hawaii*)

- **Main objective:** To measure DMS fluxes between the atmosphere and ocean.

Measurement of seawater DMS during SO GasEx (*Steve Archer, Plymouth Marine Laboratory*)

- **Main objective:** To obtain measurements of seawater DMS.

CO_2 and hydrographic measurements during the GasEx-III Experiment (*Dick Feely, Chris Sabine and Greg Johnson, NOAA/PMEL; Rik Wanninkhof and Molly Baringer, NOAA/AOML*)

- **Main objective:** To provide core measurements including: ADCP, CTD/O_2-based temperature, salinity, and oxygen, water-sample based TCO_2, TA, O_2, and pCO_2, as well as underway measurements of salinity, temperature, and pCO_2.

Measurement of nutrients during the Southern Ocean Gas Exchange Experiment (GasEx III) (*Jia-Zhong Zhang, NOAA/AOML*)

- **Main objective:** To measure inorganic nutrients (phosphate, nitrate, nitrite, ammonium and silicic acid) from hydrographic casts.

Closing the mixed layer carbon budget during Southern Ocean GasEx (*Burke Hales and Pete Strutton, Oregon State University; Dave Hebert and David Ullman, University of Rhode Island*)

- **Main objective:** To close the mixed layer carbon budget based on high-resolution sampling of TCO_2, pCO_2, POC, DOC, O_2 and NO_3 combined with incubations for productivity and ADCP and microstructure-based transport rates.

Quantifying the surface physical controls on CO_2 transfer during the Southern Ocean Gas Exchange Experiment (*Will Drennan, University of Miami*)

- **Main objective:** To measure near surface physics using the ASIS buoy.

Autonomous multi-parameter measurements from a drifting buoy during the SO GasEx Experiment (*Chris Sabine, NOAA/PMEL, Michael DeGrandpre, University of Montana, Wade McGillis, LDEO, Chris Zappa, LDEO*)

- **Main objective:** To make a set of physical, geochemical, and biological measurements from a drogued drifter.

Gas tracers of productivity and bubble-mediated gas exchange during the SO GasEx Experiment (*Roberta Hamme, University of Victoria; Michael Bender, Princeton University; Steve Emerson, University of Washington*)

- **Main objective:** To use oxygen and inert gases to infer net community production and bubble dynamics.

On the distribution of colored dissolved organic matter in the Southern Ocean and the potential for photoproduction of CO_2 and CO (*Carlos Del Castillo, Johns Hopkins University, Richard Miller, NASA Stennis Space Center, Watson Gregg, NASA Goddard Space Flight Center, Tom Haine, Francis Monaldo, and Donald Thompson, Johns Hopkins University*)

- **Main Objective:** To make underway measurements of CDOM and solar irradiance.

Phytoplankton absorption and carbon dioxide drawdown in the Southern Ocean: A consortium of observations (*John Marra, Bob Vaillancourt, and Ajit Subramaniam, LDEO*)

- **Main Objective:** To measure phytoplankton spectral absorption, CDOM absorption, and perform ^{14}C incubation studies.

Optical properties in the Southern Ocean: In situ and satellite observations in support of Southern Ocean Carbon Program (*ZhongPing Lee, Alan Weidemann, Paul Martinolich, and Wesley Goode, Naval Research Lab*)

- **Main Objective:** To measure optical properties in the Southern Ocean using various methods.

Optical properties in the Southern Ocean: In situ measurements of phytoplankton absorption using the pFPT-TR instrument in support of the Southern Ocean Carbon Program (*Bruce Hargreaves, Lehigh University*)

- **Main Objective:** To measure phytoplankton absorption.

Differentiating sources of backscattering in the Southern Ocean: Calcite, bubbles, and other optical constituents (*Heidi Dierssen, University of Connecticut, Barney Balch, Bigelow Laboratory, Michael Twardowski, WET Labs, Inc., and Penny Vlahos, University of Connecticut*)

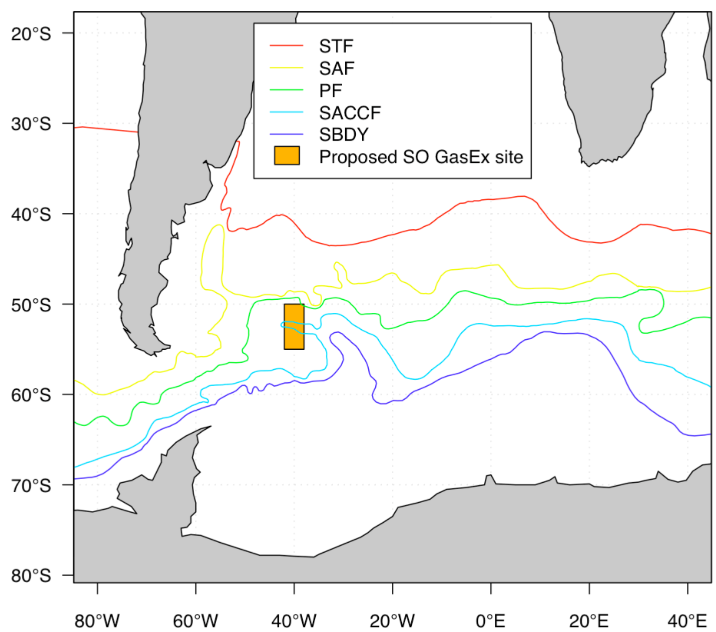
- **Main Objective:** To determine sources of backscattering in the water.

Study Site Selection

As we have learned from previous gas exchange studies in the open ocean, the study site selection is critical to ensure the success of the experiment. The general study area of SO GasEx in the southwest Atlantic was chosen to satisfy the following criteria:

- Have a ΔpCO_2 of at least 40 µatm to ensure a large enough signal to noise for direct eddy-covariance measurements of CO_2.
- Be a relatively stable water mass (i.e., relatively weak currents and low mesoscale eddy variability) to allow $^3He/SF_6$ patch to be followed for up to 25 days.
- Have mixed layer depth of less than 50 to 70 m to constrain the tracers.
- Have relatively high wind speeds, long fetch and large waves.
- Proximity to South American ports to minimize transit time.

Significant variability is known to occur in the Southern Ocean and so pre-tracer injection surveys along with remote sensing products of ocean color, altimetry and SST will be essential for final site refinement within the study area.



Map showing the general study location of SO GasEx.

For the direct CO_2 flux measurements, the region must be sufficiently homogeneous to not cause artifacts, that is, the pCO_2 should be nearly constant within its oceanic and atmospheric footprint. The flux "footprint" is a function of wind speed, stability, boundary layer height, and surface roughness. For a typical measurement in neutral conditions from the bow tower of the ship (20 m above sea level), roughly 80% of the measured flux will originate from the surface about 300-600 m upwind. In one-half hour of sampling moving slow ahead into the wind, this footprint will cover ca. 500 m more of the ocean surface. The region should be a large pCO_2 sink to ensure a large enough signal to noise for direct CO_2 flux measurements.

For the $^3He/SF_6$ dual tracer measurements, the region should be a relatively stable water mass and have a mixed layer depth of less than 50-70 m to prevent shearing of the tracer patch or rapid dilution of the tracers.

Cruise Narrative

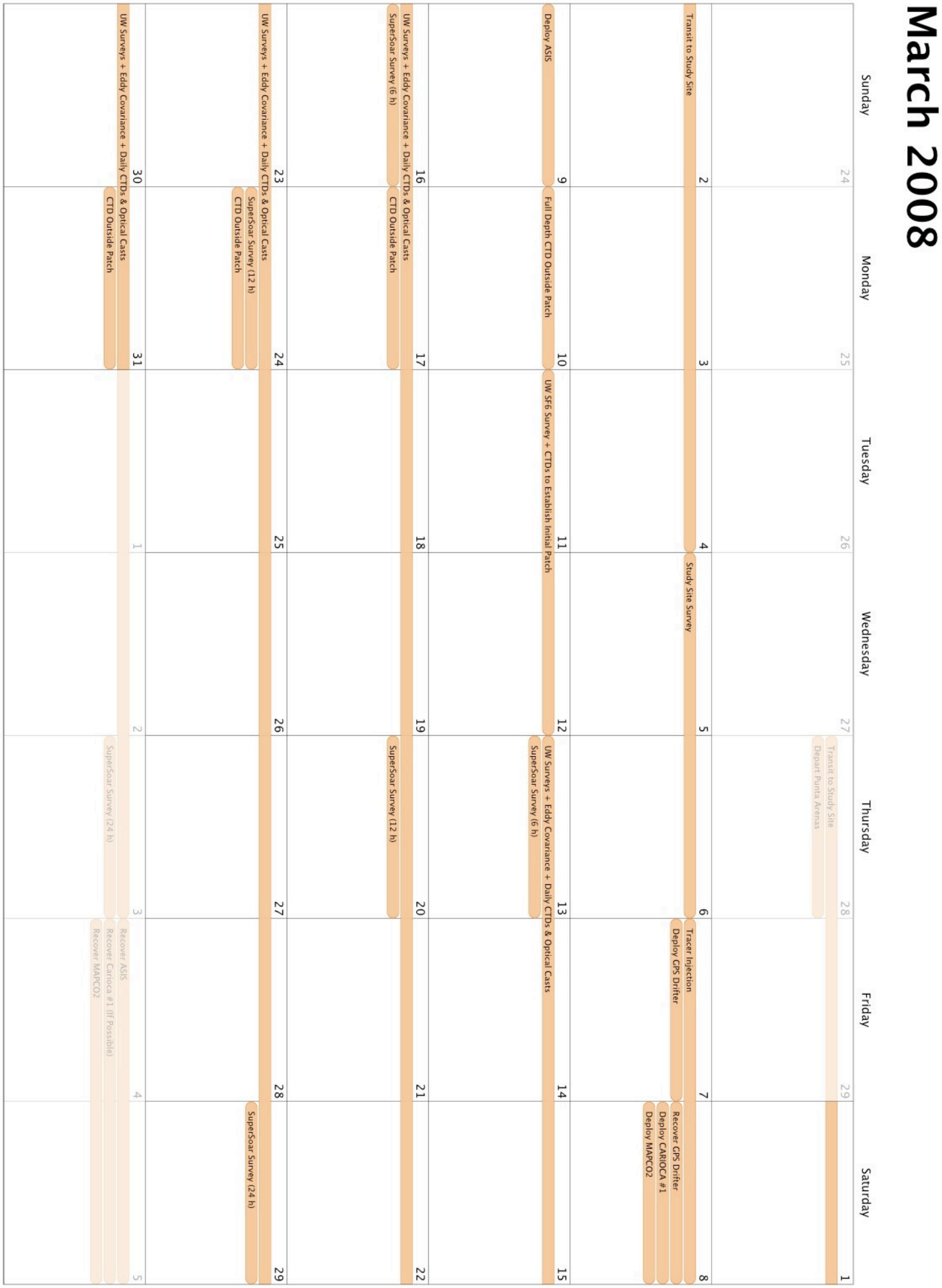
The ship will leave Punta Arenas on Feb 28, 2008. Transit time to the study region is 5 days. During the transit, the 4000L tank on the aft deck will be filled with seawater and then infused with SF_6 and ^3He. Once we arrive on site, we will conduct a 24-48 h site survey using the criteria described in the "Site Selection" section using CTDs and/or SuperSoar, underway measurements, and remote sensing data. After we have located our study site, we will deploy a GPS drifter, around which the tracer release will be conducted in order to keep us in a Lagrandian framework. The tracers will be injected in an expanding hexagonal pattern around the GPS drifter over the next 24 h, during which time the uncontaminated seawater intake will be shutdown to prevent contaminating the line with tracers.

At the end of the tracer release, we will retrieve the GPS drifter, and deploy the MAPCO2 buoy and one of the CARIOCA buoys in the tracer patch. The ship will then steam upstream of the tracer patch, and deploy the ASIS buoy. At this time, the ship's uncontaminated seawater intake will be turned on. We will then conduct a CTD over the entire depth of the water column outside the patch.

Systematic (i.e., lawnmower pattern) surveys of the tracer patch will commence uninterrupted over the next 24-48 h, punctuated by CTDs for SF_6 and ^3He near the center of the patch every 12 h. After this survey to establish the initial condition, our routine experiment will begin. This includes: continuous underway measurements of SF_6, pCO_2, O_2/Ar, and fluorescence, direct eddy-covariance measurements of CO_2 and DMS fluxes when the ship is facing into the wind, periodic deployments of the SuperSoar for towyo measurements (see calendar for frequency), 11a CTD cast to 500 m for $^3He/SF_6/CO_2$/hydrography and, 4a CTD cast to 500 m for $^3He/SF_6/CO_2$/hydrography and productivity, and a noon CTD casts to 200 m for biology, followed by casts of the various optical packages (IOP Cage, FRRF, MVSM, and HTSRB). The bow of the ship should face into the wind if possible on all these casts to facilitate the eddy-covariance measurements. Once a week, we will conduct a CTD cast to 500 m outside the patch.

During the experiment, it might be necessary to adjust the position of the MAPCO2 buoy, and if it is determined that the ASIS buoy has drifted too far from the patch, it will be retrieved and dismantled. At the end of the experiment, we will retrieve the MAPCO2 buoy, the ASIS buoy (if necessary), and CARIOCA buoy #1 (if feasible). The ship will head to Montevideo, and we will deploy the CARIOCA buoy(s) in the SAZ. The ship will arrive in Montevideo on April 9, 2008.

Cruise Calendar



April 2008

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
30 UW Surveys + Eddy Covariance + Daily CTDs & Optical Casts	31 CTD Outside Patch	1	2	3 SuperSoar Survey (24 h)	4 Recover Carioca #1 (If Possible) Recover MAPCO2 Recover ASIS	5
6 Transit to Montevideo	7 Deploy CARIOCAs in SAZ	8	9 Arrive Montevideo	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	1	2	3

Cruise Participants

First	Last	Email	Affiliation	Task
Steve	Archer	stda@pml.ac.uk	Plymouth Marine Lab.	DMS
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Dave	Hebert	hebert@gso.uri.edu	Univ. of Rhode Island	Turbulence/mixing
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Sarah	Purkey	sarah.purkey@noaa.gov	Univ. of Washington	CTD/O_2
Mike	Rebozo	mrebozo@rsmas.miami.edu	Univ. of Miami	ASIS
Matt	Reid	mcr@ldeo.columbia.edu	LDEO	Underway SF_6
Chris	Sabine	chris.sabine@noaa.gov	NOAA/PMEL	Co-Chief Sci
Paul	Schmieder	schmied@ldeo.columbia.edu	LDEO	^3He
Pete	Strutton	strutton@coas.oregonstate.edu	Oregon State U.	SuperSoar chem/optics
Kevin	Sullivan	kevin.sullivan@noaa.gov	NOAA/AOML	Discrete SF_6
Bob	Vaillancourt	vaillanc@ldeo.columbia.edu	LDEO	FRRF
Chris	Zappa	zappa@ldeo.columbia.edu	LDEO	Waves/Turbulence

Appendix 1. SO GasEx Project Summaries

These are summaries of individual project objectives and work plan, written by the individual PIs.

Quantifying air-sea gas exchange at high wind speeds using a dual gas tracer ($^3He/SF_6$) technique during the Southern Ocean Gas Exchange Experiment

David Ho (LDEO of Columbia University)
Peter Schlosser (LDEO of Columbia University)
Rik Wanninkhof (NOAA/AOML)

Objectives:
Our primary objective is to constrain the gas transfer velocities during SO GasEx through a dual gas tracer release (SF_6 and ^3He) into the surface mixed layer. From the change in ratio of these gases over time, a robust and spatially (order of 100 km) and temporally (order of one day) integrative gas transfer velocity can be determined. The measurements can be used to validate the higher frequency but more uncertain micrometeorological flux measurements of CO_2 (McGillis, PI) and DMS (Huebert, PI). The deliberate tracer injection is also critical for water column studies by creating a virtual lab beaker in the ocean. The tracers delineate the parcel of water that will be studied extensively to determine the controls of surface water CO_2 levels and other climate relevant gases. From the change in SF_6 concentration, corrected for gas exchange, a quantitative estimate of dilution can be obtained that is critical to produce mass balances of carbon in the patch (Feely, PI). From the continuous real-time measurements of SF_6 in the surface water it can be determined when the ship is in the patch for the biogeochemical studies and rate measurements. Select stations will also be occupied outside the patch to fully quantify the effect of dilutions on mass balances and rate measurements.

Work plan:
We will fill a 4000 L tank situated on the fantail with seawater, and infuse it with ^3He and SF_6 over a period of 24-48 hours. We will create the tracer patch by injecting the tracer-infused seawater over a 12-h period in a hexagonal pattern of approximately 5-km diameter.

Subsequently we will map the tracer patch over time in its horizontal and vertical extent to determine the effective horizontal and vertical diffusion. From $^3He/SF_6$ ratios collected with depth at regular intervals (every 12 h) throughout the experiment, the gas transfer velocity will be determined.

For each ^3He sample, about 40 ml of water will be collected in copper tubes sealed by stainless steel pinch-off clamps at each end and stored for ^3He analysis to be performed in the Noble Gas Laboratory at Lamont-Doherty Earth Observatory (LDEO). ^3He samples will be collected from CTD casts close to the center of the tracer patch as determined by the underway SF_6 measurements. SF_6 samples will be collected in 550 ml borosilicate glass bottles, and measured onboard the ship using a purge-and-trap GC/ECD system. We plan to collect 300 ^3He and 700 SF_6 samples.

The sampling plan is to collect depth profiles for $^3He/SF_6$ samples at two CTD stations per day (total number of in-patch stations: ca. 30). We plan to collect ca. 10 samples per CTD station: 4 in the mixed layer, (i.e., at depth intervals of ca. 25 meters), four in the seasonal pycnocline and two below the pycnocline. These vertical profiles will typically be collected close to the center of the SF_6 patch, as determined by the surface water SF_6 survey. For background measurements we request 3 stations outside the patch during the experiment.

To determine the extent of the patch we request near-continuous mapping surveys every 5 days lasing about 24 hours utilizing shipboard ADCP and near-real time surface SF_6 concentrations to design an adaptive surveying scheme. The ship tracks will be determined by the SF_6 survey group and navigation called to the bridge.

Southern Ocean Air-Sea Carbon Dioxide Exchange

Wade McGillis (LDEO of Columbia University)
Chris Zappa (LDEO of Columbia University)
James Edson (University of Connecticut)
Penny Vlahos (University of Connecticut)

Objectives:

- Work as an atmospheric and ocean physics consortium to provide all project experimentalists, modelers, and remote sensing researches with the best possible meteorological data during the experiment;
- To investigate the processes controlling of air-sea gas exchange at high winds;
- To improve our parameterizations of the gas transfer velocity through consideration of these processes. In particular, the dependence of the gas transfer velocity on wind speed, wind stress, atmospheric stability, sea state, and wave breaking will be investigated;
- Determine the spatial and temporal distribution of various persistent organic pollutants in the Southern Ocean air and surface waters;
- To investigate the structural changes in DOM from surface to deep waters and how this varies temporally;
- To enhance air-sea CO_2 studies with determination of the DIC C-13 signatures in surface waters.

Work plan:

- In collaboration with Drs. Fairall (NOAA/ESRL), Helmig (NOAA CIRES/University of Colorado), and Huebert (University of Hawaii), momentum, sensible, latent, ozone, DMS, and CO_2 direct covariance flux systems (DCFS) will be deployed on the forward jackstaff of the NOAA ship Ronald H. Brown. These measurements will be combined with a variety of infrared gas analyzers (IRGAs) to directly measure the flux of CO_2 between the atmosphere and ocean. These systems will be run continuously and we request that the ship be pointed into the wind (i.e., a relative wind within +/- 60 degrees of bow-on) whenever possible for valid flux estimates.
- Additional mean meteorological measurements will be made in collaboration with Fairall's group to quantify the wind speed and direction; air temperature, relative humidity and pressure; and downwelling infrared and solar radiation.
- A WaMoS wave measurement system will be setup on the ship to remotely estimate directional wave spectra. This uses Doppler Radar mounted from the ship.
- A nadir-looking microwave radar in conjunction with an accelerometer will provide a point measurement of the wave field including quantifying significant wave height.
- Two high-resolution cameras will be mounted on either side of the deck above the bridge to provide wave-breaking statistics;
- High volume air samples will be collected over 24-hours during both steam time to and from the station and at the station. While on station several diurnal samples will also be collected;
- On station, every other day, approximately 8-L of water during daily hydrocasts will be collected at 3 depths (surface, mid, bottom) for DOM structural characterization studies. This can be during either the afternoon or mid-night casts but must be consistent. We will also investigate a diurnal signal in the surface water DOM that would require an additional 8-L of surface water during sampling days 12 hours prior to or post sampling.
- Surface water (4 L) through the in-line system will be collected every 4th day to determine POPs concentrations;
- DOC/POC/DIC-C13 and nutrients will be collected at all depths during both daily hydrocasts requiring a total of 500 milliliters per depth.

Measurement and Parameterization of Air-Sea Gas Transfer over the Southern Ocean in GasEx-III

Chris Fairall (NOAA Earth System Research Laboratory)
Detlev Helmig (University of Colorado INSTAAR)

Objectives:

- Work as an atmospheric and ocean physics consortium to provide all project experimentalists, modelers, and remote sensing researches with the best possible meteorological reference data during the experiment;
- To investigate the processes controlling of air-sea gas exchange at high winds;
- To improve our parameterizations of the gas transfer velocity through consideration of these processes. In particular, the dependence of the gas transfer velocity on wind speed, wind stress, atmospheric stability, sea state, and wave breaking will be investigated;

Work plan:

- In collaboration with Drs. McGillis (LDEO), Edson (UConn), and Huebert (University of Hawaii), momentum, sensible, latent, ozone, DMS, and CO_2 direct covariance flux systems (DCFS) will be deployed on the forward jackstaff of the NOAA ship Ronald H. Brown. These measurements will be combined with a variety of infrared gas analyzers (IRGAs) to directly measure the flux of CO_2 between the atmosphere and ocean. These systems will be run continuously and we request that the ship be pointed into the wind (i.e., a relative wind within +/-60 degrees of bow-on) whenever possible for valid flux estimates.
- Additional mean meteorological measurements will be made to quantify the wind speed and direction; air temperature, relative humidity and pressure; and downwelling infrared and solar radiation (ESRL seagoing flux/meteorology system).
- A Riegl laser wave sensor will be operated from the jackstaff to record surface waves.

Measurement and Parameterization of Air-Sea DMS Transfer over the Southern Ocean in GasEx-III

Barry Huebert (University of Hawaii)
Byron Blomquist (University of Hawaii)

Objectives:

Flux of trace sulfur gases, chiefly dimethylsulfide (DMS), from the ocean surface contributes to the formation of aerosols and cloud condensation nuclei in remote marine environments. Several theoretical and empirical approaches have been used to develop predictive models. Comparison with direct measurements is the best way to adjudicate between competing approaches and refine gas transfer theory to the degree required by global climate models. This project seeks to advance our understanding of gas exchange using direct eddy covariance flux measurements of dimethylsulfide.

This is a three-year effort to deploy measurement systems for DMS flux: Atmospheric Pressure Ionization Mass Spectrometers using an Isotopically Labeled Standard (APIMS-ILS). Close collaboration with colleagues measuring seawater concentrations of DMS is necessary for us to derive exchange velocities from our flux measurements. Other ancillary measurements of physical ocean properties and tracer flux data will provide a rich database for examining the principle factors controlling gas exchange.

Work plan:

Chris Fairall has offered additional space in the NOAA lab van for us to install the APIMS system for DMS. Power requirements for our van are as before: 20 amps 440 volt/3 phase and connection to the ships compressed air system. No water requirements. We require as much time as possible with the ship bow into the wind, but have no other specific operational requirements.

CO_2 and Hydrographic Measurements During the GasEx-III Experiment

Dick Feely (NOAA/PMEL)
Chris Sabine (NOAA/PMEL)
Rik Wanninkhof, (NOAA/AOML)
Greg Johnson (NOAA/PMEL)
Molly Baringer (NOAA/AOML)

Objectives:

PMEL and AOML scientist will provide core measurements including: ADCP, CTD/O_2-based temperature, salinity, and oxygen, water-sample based TCO_2, TA, O_2, and pCO_2, as well as underway measurements of salinity, temperature, and pCO_2. We will also compare the airside measurement of gas transfer velocities with CO_2 mass balances in the ocean in the tracer patch that will also contain the drifting buoys. In addition, we will use the results of the GasEx III experiment to develop algorithms to determine the air-sea flux of CO_2 in the southeastern Atlantic utilizing the satellite-data.

Work plan:

During the GasEx III cruise our group will make underway air and water measurements of pCO_2, conduct CTD/rosette casts twice daily (nominally noon and midnight), and process the shipboard ADCP data. The CTD/rosette package will include 24-Niskin-type bottles. Water samples will be collected twice daily from these sample bottles and analyzed for DIC, TA, pCO_2, O_2, and salts.

Measurement of Nutrients During the Southern Ocean Gas Exchange Experiment (GasEx III)
Jia-Zhong Zhang (NOAA/AOML)

Objectives:
We propose to measure inorganic nutrients (phosphate, nitrate, nitrite, ammonium and silicic acid) from hydrographic casts and from biological production experiments during GasEx-III.

Work plan:
Concentrations of dissolved nitrite (NO_2^-), nitrate (NO_3^-), ammonium (NH_4^+), phosphate (PO_4^{3-}) and silicic acid (H_4SiO_4) will be measured using an automated continuous flow analyzer with air-segmented flow and colorimetric detection. The five-channel autoanalyzer consists one 24-channel Ismatek peristaltic pump and five high precision ThermoSeparation monochrometers. It has been modified from original Alpkem Flow Solution Model 3000 autoanalyzer for oceanographic application. The original autosampler has been replaced with a CETAC 510 high speed autosampler to allow a 50 ml of sample volume required for simultaneous 5-channel analysis. Large sample volume also minimizes the potential sample contamination. The original plastic mixing blocks have been replaced with micro-glass coils for convenience in monitoring the flow and trouble shooting if required. Software in commercial instrument is designed for freshwater analysis in which deionized water (nutrient free) is usually used as wash solution. Custom software developed for digitally logging and processing the chromatographs in our autoanalyzer allows the correction of refractive index and background nutrients in Low Nutrient Seawater that must be used as wash solution and matrix for standards in accurate seawater analysis.

Gas tracers of productivity and bubble-mediated gas exchange during the SO GasEx Experiment

Roberta Hamme (University of Victoria)
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Objectives:

Our objectives for this project are threefold. First, we will determine Net Community Production while on site using the O_2/Ar mass balance method. Measurements will be made continuously on the ship's seawater inflow by a membrane inlet mass spectrometer (MIMS) and by an optode O_2 sensor, while discrete samples from Niskin casts will be collected for high accuracy measurements to calibrate the system. Discrete samples for Gross Production by the triple oxygen isotope method will also be collected. Second, we will use inert gas tracers to constrain bubble dynamics through continuous and discrete measurements of the N_2/Ar ratio, which is an effective measure of bubble injection. Third, discrete samples will be collected to measure dissolved Ne, N_2, Ar, Kr and Xe concentrations and Ar isotopes by high accuracy mass spectrometric methods. This suite of gases has a large range of solubilities and temperature dependencies. The combination of all of these gases will enable us to separate the influences of multiple processes on the gases, including temperature change, bubble-mediated gas exchange by different mechanisms, and atmospheric pressure variation.

Work plan:

The MIMS and optode system require a continuous flow from the ship's seawater intake system at a rate of 3-5 L/min. We will need to collect discrete samples from regularly scheduled Niskin casts. MIMS calibration samples would be collected from the surface bottle on a maximum of four casts per day. Profiles of discrete samples would be collected at less regular intervals timed with events of interest. Sampling for these gases can take 5-10 minutes per Niskin, and is normally done just after oxygen samples are taken. It is important that the water in the Niskin not be exposed to a headspace for long intervals before our sampling, so we ask that others sampling a cast not get too far ahead of our sampling. Because of the time constraints, we would sample no more than eight Niskins on single cast. Water requirements are small, less than 250mL for a single sample, less than 1L if we collected samples for all the gases.

Autonomous Multi-parameter Measurements from a Drifting Buoy During the SO GasEx Experiment

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Chris Zappa (LDEO of Columbia University)

Objectives:
Our specific objectives for the 3-years of this project are to 1) modify a recently developed low profile, high payload buoy to act as a drogued drifter for the SO GasEx Experiment; 2) instrument the drifter with a variety of autonomous instruments capable of making a coordinated set of physical, geochemical, and biological measurements at high temporal resolutions to provide a key component in the study of processes controlling air-sea CO_2 exchange; 3) Integrate the multi-parameter measurements into a mass balance study of the surface ocean carbon system (in conjunction with shipboard water column studies) to provide an independent assessment of air-sea gas exchange; 4) evaluate the physical and biogeochemical mechanisms leading to short-term variability in air-sea gas exchange; and 5) evaluate potential biases in CO_2 flux estimates from high resolution data sets (e.g. CO_2 moorings) arising from the use of traditional gas exchange parameterizations. The basic hypothesis driving this study is that short-term variability in carbon system and physical parameters has a significant impact on gas exchange and the estimation of carbon mass balances on time scales of days to weeks.

Work plan:
We wish to deploy a drogued buoy in the center of the dye patch as soon as practical after the patch has been made. It should take about 2 hours to deploy the drifter. There is a possibility that during the course of the experiment that the drifter will move out of the patch. If this happens then we will want to recover the drifter and redeploy back in the center of the patch. There is a GPS system on the buoy and we will have satellite communication with the buoy so we can locate it at any time during the experiment. Recovery could take 3 hours from the time that the ship reaches the buoy. We anticipate doing this no more than once per week (hopefully less) during the experiment. We will need to recover the drifter at the end of the experiment.

Closing the carbon budget in the mixed layer during Southern Ocean GasEx

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Dave Hebert (University of Rhode Island)
David Ullman (University of Rhode Island)

Objectives:

Our goals are to provide the spatially and temporally comprehensive, high-resolution measurements of concentrations, biological rates, and physical transports that will allow rigorous closure of the carbon budget within the patch. Our efforts will consist of the following major themes:

1. Operation of the SuperSoar towed undulating sampling/sensing vehicle, including full-suite CTD measurements and high-volume sampling pump. In situ measurements will include dual T/S sensor pairs, O_2, beam-c, chlorophyll fluorescence, CDOM fluorescence, and PAR.
2. Operation of the TOMASI microstructure instrument aboard the SuperSoar, which will measure microstructure temperature and conductivity and provide estimates of vertical turbulent mixing rates.
3. Incubation of C and N isotope-labeled samples from SuperSoar and CTD rosette for constraint of primary and new productivity in the patch.
4. High-speed continuous shipboard measurement of nitrate, pCO_2, and TCO_2 in the sample stream provided by the SuperSoar.
5. Analysis and display of shipboard ADCP data for quantification of lateral transport, and progressive-vector estimation of patch and drifter trajectories.
6. Processing and dissemination of the SuperSoar/TOMASI data.
7. In addition, we will be providing sample splits to D. Ho for tracer analysis and 3-D quantification of the patch volume.

Work plan:

Our proposed work plan is to deploy the SuperSoar/TOMASI every 2 to 5 days, for durations ranging from 6-24 hours, as described below and as allowed by the ship's schedule. It is absolutely essential to our project goals that we be able to sample the patch exhaustively (e.g. 4-5 lines spanning the patch) on each deployment.

Early in the evolution of the patch when it is small and sharply defined, these surveys will be short duration (6 hours) at low speed (~2 kts) and should be relatively frequent (every 2 to 3 days). During this period the concentration of tracer (SF_6) will be changing rapidly and it is important that we characterize that change at relatively high temporal resolution. Later in the experiment when the patch has spread and tracer concentration is changing more slowly, the deployments will need to be longer (24 hours) at higher speeds (6 kts), but may not need to happen as frequently (e.g. once every 5 days).

Deployment/recovery during the low-speed surveys will be rapid, under 30 minutes for each. Deployment/recovery for the higher-speed deployments will be slower, 30 minutes to an hour, as full cable lengths are paid out and optimal ship speeds are attained.

We will provide our own water samples from the SuperSoar, but will need a way to accommodate excess water (2 GPM) continuously during in-water operations. During cruises on the Thomas G Thompson, a utility sink was set up in the main lab that drained into a gray-water tank that could be pumped out. During a 2003 cruise on the Revelle, a sink in the main lab was plumbed to drain directly overboard.

Quantifying the surface physical controls on CO_2 transfer during the Southern Ocean Gas Exchange Experiment

Will Drennan (RSMAS, University of Miami)

Objectives:

The proposed work will:

- Provide an Air-Sea Interaction Spar (ASIS) buoy to explore the role of physics in the lower atmosphere and surface ocean on ocean-atmospheric CO_2 fluxes during the Southern Ocean Gas Exchange experiment.

- Perform continuous measurements of the (1) air-sea fluxes of momentum, heat, water vapor, and CO_2, (2) mean atmospheric properties and boundary layer stability, (3) surface wave characteristics (2D spectra and slopes), as well as sea spray aerosol and bubbles, and (4) TKE dissipation rate, currents and temperature, in the near surface of the ocean.

- Develop a parameterization for the gas exchange velocity in terms of physical forcing parameters (including wind speed, TKE dissipation, stability, surface waves).

Work plan:

Deploy the ASIS buoy from the Brown in the vicinity of the study site. The buoys will be free drifting, drogued so as to remain as close to the study site as possible. ASIS would remain deployed for three-four weeks, and then be recovered. Deployment and recovery will each take about 4 hours (daytime hours).

On the distribution of colored dissolved organic matter in the Southern Ocean and the potential for photoproduction of CO_2 and CO

Carlos Del Castillo (Johns Hopkins University)
Richard Miller (NASA Stennis Space Center)
Watson Gregg (NASA Goddard Space Flight Center)
Tom Haine (Johns Hopkins University)
Francis Monaldo (Johns Hopkins University)
Donald Thompson (Johns Hopkins University)

Objectives

We propose to use several remote sensing techniques, field and laboratory measurements, and DA modeling to answer the following questions:

1. What is the annual variability in abundance and distribution of CDOM in the SO?
2. What physical processes control the abundance and distribution of CDOM?
3. How much CO_2 and CO is produced from the photolysis of CDOM?

Work plan

Question 1 will be answered using historical ocean color data from SeaWiFS, MODIS-AQUA, and MERIS. We will use field and laboratory measurements, and radiative transfer modeling to develop a regional CDOM algorithm for the SO. The algorithm will be use to reprocess imagery from the aforementioned sensors from launch trough 2008, and the data will be merged to reduce the effect of prevalent cloud cover in the region.

Fieldwork involves collection of water samples for CDOM analysis, optical casts, and underway measurements of CDOM.

Question 2 will be answered through a combination of ocean circulation modeling and remote sensing. The ocean circulation model and data assimilation system will be developed for the GasEx cruise region from existing, similar, setups in the subpolar North Atlantic ocean. A package to simulate upper ocean CDOM will be included. From this perspective CDOM, is, essentially, a passive tracer with (complex) sources and sinks. The sources and sinks will be treated as weakly constrained parameters to be determined in the DA The model will use inputs from field measurements, and from remote sensing estimates of wind vectors, SSH, and SST, and photolysis loss term for CDOM. The model will be run retrospectively, and resulting CDOM field maps will be compared with remote in-situ and remote sensing measurements of CDOM.

Question 3 will be answered in two modalities. In the first approach, we will estimate the photoproduction of CO_2 and CO along the cruise track using underway measurements of CDOM, solar irradiance, radiative transfer modeling, and published values of photoproduction quantum efficiencies (Φ) for the gases. In the second approach we will use remote sensing estimates of CDOM (question 1), solar irradiance, radiative transfer modeling and published values of Φ to produce historical maps of CO_2 and CO photoproduction.

Phytoplankton absorption and carbon dioxide drawdown in the Southern Ocean: A consortium of observations

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Bob Vaillancourt (LDEO of Columbia University)
Ajit Subramaniam (LDEO of Columbia University)

Team Objectives:

- To improve the estimation/modeling of primary production in the Southern Ocean
- To test the hypothesis that primary production can be best estimated/modeled from spectral absorption of phytoplankton rather than using chlorophyll a concentration.
- To quantify and minimize uncertainties in estimates of phytoplankton absorption in order to parameterize photosynthesis models from in situ and satellite data.

LDEO Cruise Objectives:

- To measure phytoplankton spectral absorption concentrated on 25 mm GF/F filters (measured before and after extracting/bleaching pigments) over the spectral range 350-750 nm using the traditional filter pad transmission (FPT) method.
- To calculate phytoplankton spectral absorption of captured water samples based on pigment reconstruction of HPLC pigment concentrations.
- To compare phytoplankton absorption by the above 2 methods to same measured by Hargreaves and Lee.
- To measure daily-integrated CO_2 uptake by phytoplankton using ^{14}C-bicarbonate tracer.
- To measure photosynthesis-irradiance and transient fluorescence responses of phytoplankton using ^{14}C-bicarbonate tracer by method of P vs. E experiments in photosynthetron and FRR fluorometry. Water column daily PP can be derived from the PvsE parameters and compared to daily PP measured above.
- To measure CDOM absorption by method of capillary wave guide spectrophotometry.

Work plan and sampling requirements:

- We will collocate our optical sampling and measurements with similar measurements made by Hargreaves and Lee to enable direct comparison of method efficacies.
- Water for daily CO_2 uptake incubations will be captured from CTD bottle casts in early morning hours from several depths from surface to bottom of euphotic zone. Water for P vs. E experiments will be captured about an hour prior to local noon from similar depths. The sample timing is essential as there is a natural variation in PE parameters over the diurnal cycle, and these variations must be minimized by timing experiments near local noon on each day they are performed.
- FRR fluorometry will be measured on seawater captured from the 11am bottle cast (Vaillancourt) and analyzed in FRR fluorometer on benchtop under ambient temperature conditions. Both whole and filtered seawater will be analyzed to assess the contribution of CDOM fluorescence to the phytoplankton signal. The FRR fluorometer and C6 instrument (Hargreaves) will be set-up in the ship's lab with access to flowing seawater for instrument cooling, and a sink for waste flow.

Optical properties in the Southern Ocean: In situ and satellite observations in support of Southern Ocean Carbon Program

ZhongPing Lee (Naval Research Lab)
Alan Weidemann (Naval Research Lab)
Paul Martinolich (Naval Research Lab)
Wesley Goode (Naval Research Lab)

Objectives:

- The overall objective is to improve the estimation/modeling of primary production in the southern ocean
- To quantify uncertainties of phytoplankton absorption derived from observation of ocean color (both in situ and from satellite sensor)
- To refine/improve remote-sensing algorithms for optical properties of the southern ocean

Work plan:

- Spectral remote-sensing reflectance will be measured over the ship with handheld spectralradiometer
- Water's volume scattering function will be measured from pumped water samples and from profiles
- Aerosol optical density will be measured with a sunphotometer (Microtops II)
- Water's optical properties and phytoplankton absorption coefficients will be derived from measured remote-sensing reflectance, and these properties will be compared with data from water sample measurements (taken by collaborators)
- Satellite (MODIS-Aqua and/or SeaWiFS, MERIS) data will be processed and be compared with in situ measurements

Optical Properties in the Southern Ocean: In situ measurements of phytoplankton absorption using the pFPT-TR instrument in support of the Southern Ocean Carbon Program
Bruce Hargreaves (Lehigh University)

Team Objectives:

- To improve the estimation/modeling of primary production in the Southern Ocean
- To test the hypothesis that primary production can be best estimated/modeled from spectral absorption of phytoplankton rather than using chlorophyll a concentration.
- To quantify and minimize uncertainties in estimates of phytoplankton absorption in order to parameterize photosynthesis models from in situ and satellite data.

Hargreaves' Cruise Objectives:

- To measure phytoplankton spectral absorption concentrated on 25 mm GF/F filters from 1-2 L discrete water samples (measured before and after extracting/bleaching pigments) over the spectral range 250-850 nm using an improved filterpad method (pFPT-TR instrument). The primary method of removing pigments will be 1-minute exposure to bleach (hypochlorite), but some comparisons may be made to the alcohol extraction method when sufficient resources (sample volumes and time) are available.
- To support water column and surface water characterization of bio-optical properties at sampling stations with a multisensor fluorescence profiler (Turner Designs C6 with sensors for Chl-a, CDOM, phycoerythrin, temperature, pressure/depth).
- To characterize fluorescence relative to CDOM UV absorption and DOC concentration, and chlorophyll a fluorescence and red peak absorption with extracted chlorophyll a concentration for different phytoplankton communities encountered over the ship's course.

Work plan:

- Will apply the above measurements of phytoplankton spectral absorption to all discrete water samples used by the NASA team for the partial or complete suite of measurements and primary production incubations using water collected from CTD rosette casts and from water pumped to the laboratory from the ship's seawater intake port while underway. Sample schedule/depth to be determined by others.
- Will support water column characterization at sampling stations by adding the C6 profiler to Vaillancourt's FRR instrument. In profiling mode this instrument logs data internally at 1-second intervals and is self-contained with battery pack. It is rated to 600 m depth.
- Will support surface water characterization while underway by using the C6 instrument in the laboratory in flow-through mode (equipped with flowcap and sensor wipers and downstream from debubbler provided by others) to monitor phytoplankton and CDOM along the ship's course. In flowthrough mode it can either log data or send it through a serial (RS-232) cable at programmable time intervals.

Differentiating sources of backscattering in the Southern Ocean: Calcite, bubbles, and other optical constituents

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Michael Twardowski (WET Labs, Inc.)
Penny Vlahos (University of Connecticut)

Objectives:

Satellite-derived remote sensing reflectance from the southern ocean is higher than most of the world's oceans. We propose to evaluate the following hypotheses for the high reflectance:

- Southern Ocean waters contain high levels of backscattering materials such as Particulate Inorganic Carbon (PIC) from coccolithophores
- High reflectance is primarily due to the excessive amounts of bubbles produced by consistently high winds in this region.
- High reflectance is due to enhanced bbp from other organic particles (e.g., specialized groups of phytoplankton, organic detritus that may include POC created by bubble dissolution associated with breaking waves)
- The standard atmospheric correction algorithms, including the whitecap/foam corrections, are not accurate in this region and result in overestimates of Rrs.

Work plan:

- Conduct an extensive field effort to measure a suite of bio-optical parameters and provide real-time imagery support to the field campaign
- Develop a backscattering budget that partitions the contributions due to:
    a. Bubbles
    b. Calcite, including coccolithophores and detached coccoliths
    c. Other phytoplankton and organic detritus
    d. Other mineral particles (polydisperse)
- Determine whether optical closure is achieved between measured R_{rs} (both in the field and from satellite) and that derived theoretically using our measured backscattering, VSF, and absorption properties
- Refine algorithms that use ocean color satellite imagery to estimate significant carbon pool components, including phytoplankton chlorophyll, calcite, and POC. Depending on results from satisfying previous objectives, this may involve developing a wind-based algorithm to estimate and correct for the bubble contribution to R_{rs} and/or using results from the existing calcite algorithm or refinements thereof to account for the calcite interference in other biogeochemical algorithms