Implementation Strategies
Southern Ocean Gas Exchange Experiment (GasEx III)

Background

In order to constrain CO_2 uptake by the ocean and terrestrial biosphere on seasonal time scales, it is essential to quantify the ocean-atmosphere and atmosphere-biosphere CO_2 fluxes. Accurate knowledge of CO_2 uptake by the world's oceans is critical for predicting future atmospheric CO_2 levels and ocean acidification. Oceanic CO_2 uptake together with the atmospheric growth rate and fossil fuel emissions also offer a robust constraint on terrestrial CO_2 fluxes, which are singularly difficult to quantify due to their spatial and temporal variability.

The principle of determining air-sea CO_2 fluxes is straightforward. The flux, F_{CO2}, is defined as:

$$F_{co2} = k\, \alpha\, \Delta pCO_2$$

where k is the gas transfer velocity, α is the solubility of CO_2, which is well quantified as a function of temperature and salinity [*Weiss*, 1974], and ΔpCO_2 is difference in partial pressure of CO_2 between the ocean and the atmosphere. The ΔpCO_2 can be measured from a variety of platforms such as ships of opportunity [*Cooper et al.*, 1998], drifters [*Hood et al.*, 2001], and moorings [*Friederich et al.*, 1995]. Currently planning is underway to optimally utilize these platforms, together with modeling, extrapolation algorithms, and remote sensing to determine global pCO_2 fields on seasonal time scales. The first global climatology of ΔpCO_2 has been produced by *Takahashi et al.* [1997], and updated by *Takahashi et al.* [2002], based on more than 20 years of data. Our long-term goal will be to obtain seasonal fluxes on annual time scale to discern interannual variability.

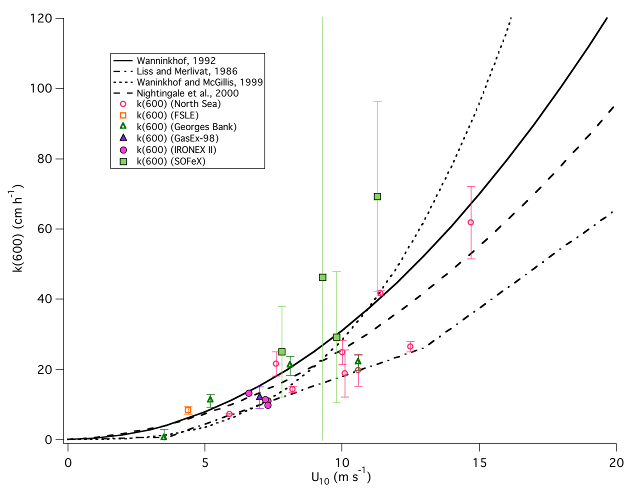

Figure 1. Figure showing wind speed/gas transfer parameterizations of Wanninkhof and McGillis [1999], Wanninkhof [1992], Liss and Merlivat [1986], and Nightingale et al. [2000b]. Also shown are results of $^3He/SF_6$ dual tracer experiments conducted in coastal and shelf areas, as well as the open ocean. Solid symbols = open ocean experiments; open symbols = coastal and shelf experiments. The North sea data are from Nightingale et al. [2000b], FSLE data from Wanninkhof et al. [1997], GasEx-98 from, Georges Bank data are from Wanninkhof et al. [1993], and reanalyzed by Asher and Wanninkhof [1998], IRONEX data are from Nightingale et al. [2000a], and SOFeX data are from Wanninkhof et al. [2004].

A US-led program to use process studies to improve quantification of air-sea CO_2 fluxes and the gas transfer velocity was initiated in 1998. So far, two large-scale studies have been conducted, one in the North Atlantic (GasEx-98) and one in the Equatorial Pacific (GasEx-2001). One of the main goals of these efforts is to be able to quantify transfer velocities on regional scale from remote sensing such that, combined with regional ΔpCO_2, global air-sea CO_2 fluxes can be determined. A systematic approach will be followed to accomplish this goal that involves the following steps:

- Make direct flux measurements in the field to obtain short-term local CO_2 fluxes/gas transfer velocities.
- Reconcile direct CO_2 flux measurement with integrated measurements of gas transfer velocities using $^3He/SF_6$ dual tracer technique.
- Understand the mechanisms controlling ocean mixed layer pCO_2 on short time and space scales.
- Elucidate the forcing functions controlling gas transfer.
- Relate forcing functions to parameters that can be detected by remote sensing.

While the goal is straightforward, the implementation relies heavily on innovative measurements. Direct flux observations from moving platforms are extraordinarily difficult to make, and quantifying small-scale variability will require new approaches and new instrumentation. A brief summary of previous gas exchange experiments follows. Southern Ocean GasEx seeks to build on these experiments and extend previous results to a high wind environment in a globally significant region of CO_2 flux.

GasEx I: GasEx-98

GasEx-98 was conducted in a warm core eddy in the North Atlantic in 1998. During this study, direct CO_2 flux measurement were made successfully for the first time in the open ocean, while factors controlling short time scale pCO_2 variations were determined. The CO_2 direct co-variance measurements gave robust estimates of gas exchange up to winds of 15 m s^{-1}, and the measurements were in agreement with the flux profile measurements of CO_2 and DMS in the marine boundary layer. The direct flux results were validated with the waterside measurements using the $^3He/SF_6$ dual-deliberate tracer technique. An analysis of the CO_2 co-variance data along with global constraints using bomb ^{14}C invasion supports a cubic relationship with wind speed [*Wanninkhof and McGillis*, 1999; *McGillis et al,* 2001]. If such a relationship holds over most of the ocean it will have a major impact on estimates of CO_2 uptake based on air-sea CO_2 disequilibria by increasing oceanic CO_2 uptake by 40 % due to lower exchanges in the outgassing regions that have lower winds and higher uptake in the windier high latitudes using a quadratic dependence.

GasEx II: GasEx-2001

The next process study (GasEx-2001) took place in the Equatorial Pacific in 2001. It offered a contrast with GasEx-98 in that the region is a strong CO_2 source with relatively low wind speeds, while the North Atlantic has relatively higher winds and a large CO_2 sink. Measurements of CO_2 fluxes were made using the co-variance method and CO_2 and DMS fluxes using the profile flux method (see publications in the GasEx-2001 JGR special issue). The direct flux results were reconciled with mass balance of TCO_2 [*Sabine et al.*, 2004]. During the experiment, processes controlling air-sea CO_2 exchange under low wind conditions were examined. Diurnal changes in biogeochemistry of carbon dioxide and air-sea gas exchange rates were also determined. Furthermore, GasEx-2001 involved intensive measurements of biogeochemical and physical processes in the lower atmosphere and surface ocean mixed layer using a variety of innovative platforms (e.g., ASIS, LADAS, SPIP, SkinDeep). Studies included surfactant concentrations, surface wave roughness, and surface infrared imagery.

The results of the two process studies differed. While GasEx-98 showed a strong wind speed dependence of gas transfer velocities at high wind speeds and a weaker dependence at lower wind speeds, GasEx-2001 showed the opposite, albeit over a narrower and lower wind speed range. These differences are attributed to the fact that factors other than wind-generated turbulence affect gas exchange over the open ocean. The high gas transfer velocities measured during GasEx-98 could be caused by bubble enhanced turbulence and exchange. The results from GasEx-2001 showing enhanced gas fluxes could be attributed to increased near-surface shear due to the diurnal heating effects (see e.g. *McGillis et al.*, [2004] and other publications in the GasEx-2001 JGR special issue). This difference between GasEx-98 and 2001 raises the intriguing question of whether effects other than those that are parameterized by wind speed have a significant effect on gas transfer over the ocean, and calls for additional process studies in other regimes.

Why the Southern Ocean?

There is a clear need to quantify the gas transfer velocity at wind speeds in excess of 10 m s $^{-1}$. 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.

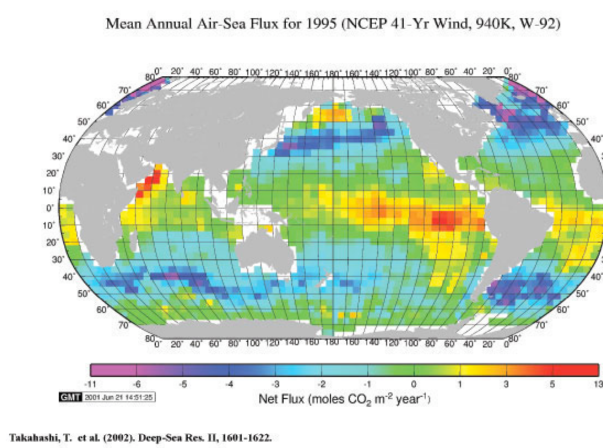

Figure 2. Mean annual air-sea CO_2 flux for 1995 calculated from the ΔpCO_2climatology and using the wind speed gas exchange parameterization of Wanninkhof [1992]. Figure from Takahashi et al. [2002].

GasEx III: Southern Ocean GasEx

The research objectives for Southern Ocean GasEx are to answer the following questions:

- What are the gas transfer velocities at high winds (10 to 20 m s^{-1})?
- What is the effect of fetch on the gas transfer?
- How do other non-direct wind effects (whitecaps, possibly surfactants) 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, DMS and other relevant biochemical and physical parameters?
- Do the estimates of fluxes from in-water and multiple air-side observations 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?

Implementation

The proposed Southern Ocean GasEx study will look at both the controls on air-sea gas exchange and on pCO_2. Projects focusing on extrapolating the findings to remote sensing and projects investigating turbulent fluxes of heat, momentum, water vapor, and other gases in the marine boundary layer are particularly desirable.

State-of-the-art high frequency measurements of meteorology and surface waves will be necessary to interpret the results and to perform the direct flux measurements both by gradient and eddy co-variance techniques. Fluxes of gases with different diffusivity and solubility could be useful in constraining the factors controlling gas transfer.

Investigations on the controls of pCO_2 should include bulk characterization of the advective fluxes of dissolved inorganic and organic components, loss of particulate material, and changes in the upper water column during the experiment. Such a mass balance is critical to ensure that the individual components have been quantified correctly. Use of $^3He/SF_6$ deliberate tracers is an extremely useful way to tag the water mass, particularly in the energetic region of the Southern Ocean.

Accurate high-resolution profiles near the surface of pCO_2 and/or CO_2 proxies in air and water would be desirable to determine near-surface gradients and the influence on CO_2 fluxes. Moreover, since we aim to determine gas transfer velocities from direct flux measurements, accurate ΔpCO_2 measurements, which require knowledge of pCO_2 right below the interface, are essential. The study is also an opportune time to investigate subgrid variability combining surveys on 10-km scales and observations from (possibly expendable) drifters with chemical sensors.

Timing

The study is proposed for austral summer 2008 (December through February), when low pCO_2 (hence high ΔpCO_2) and favorable weather conditions will be conducive for this challenging study. The mixed layer should be shallow during this time, which will facilitate the use of the $^{3}He/SF_6$ dual tracer and other mass balance techniques to determine gas transfer velocities.

Study site criteria

As in previous studies, the study site selection is critical to ensure the success of the experiment. The study site should satisfy the following criteria:

- Have wind speeds, fetch and waves that are representative of the Southern Ocean.
- Have a delta pCO_2 of at least 40 µatm.
- Have a mixed layer depth of less than 50-70 m.
- Have relatively weak currents and low mesoscale eddy variability.

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

Based on inspection of available satellite and *in situ* data, the region in the Atlantic Sector of the Southern Ocean should be a good choice for the process study. Biological productivity is higher in this region than in the SE Pacific, generating a ΔpCO_2 of ca. -40 to -60 µatm in the austral summer, *cf* a ΔpCO_2 of *at most* -30 µatm in the SE Pacific. The more favorable ΔpCO_2 in the Atlantic should satisfy the minimum gradient necessary to make a direct CO_2 flux measurement with confidence. Climatological wind speeds in the region during the austral summer range is 10 ± 3 m/s, the mean significant wave height in the 1990's was ca. 3 m, and the mixed layer depth in the region is ca. 50 m. Eddy Kinetic Energy (EKE), a measure of the degree of variability due to eddies, current meanders and fronts, is relatively high in the Southern Ocean, and even during austral summer EKE > 500 cm^2/s^2 can be found in the Atlantic sector. However, altimetry measurements of EKE suggest these high values are most commonly associated with the Malvinas Confluence region and just to the north of the SubAntarctic Front, and are relatively quiescent elsewhere in the Atlantic sector. Nonetheless, significant variability is known to occur in the Southern Ocean and so pre-process study surveys along with remote sensing products of ocean color, altimetry and SST will be essential for final site selection.

Logistic resources

The process study would last approximately 23 days, which combined with relatively long transit times to port (Punta Arenas, Chile) would require approximately 35 days of ship time. The study would require a Class I vessel to accommodate all the individual projects. NOAA SHIP RONALD H. BROWN would be the preferred vessel because of its extensive infrastructure of direct benefit to the project such as the underway CO_2 measurement system, air sounding devices, and a sturdy bow mast. As in the previous two campaigns, extensive logistic and organizational support prior and during the cruise is necessary to accommodate the disparate science requirements for the proposed work.

We anticipate that the research will be co-funded by NOAA, NSF and NASA. During the past two campaigns, the projects benefited tremendously from the collaborative efforts of academic and federal scientists. For example, on GasEx-98 approximately half of the participants were funded from sources other than NOAA, and on GasEx-2001 approximately one third of the participants were funded from sources other than NOAA. NSF and NASA supported the other participants. The success of this project was in large part due to contributions of interagency support.

Multi-agency and international participation

Although this campaign could be undertaken as a single ship process study, the payback could be greatly increased by a significant increase in number of observing platforms. Because of the basic insights gleaned on robust measurements of fluxes during GasEx-98 and GasEx-2001, a larger study is warranted to fully explore the biogeochemical and physical controls on gas transfer. It is envisioned that an optimal study would include two ships. To fully utilize different techniques to determine gas transfer velocities and fluxes, and to incorporate remote sensing, and to deploy innovative techniques to study air-sea fluxes, a truly comprehensive campaign would be required. We are currently exploring collaboration with international partners.

More Information

A community website, constructed as a design and implementation forum, for the SO GasEx study, is located at <http://duck-rabbit.ldeo.columbia.edu/so_gasex/>.

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