The Australian Integrated Marine Observing System Southern Ocean Time Series Facility

T. W. Trull, E. Schulz, S. G. Bray, L. Pender, D. McLaughlan, B. Tilbrook, M. Rosenberg, T. Lynch
Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, CSIRO Marine and Atmospheric Research, and Bureau of Meteorology
PB 80, Hobart, TAS 7001 Australia

***Abstract*- The CSIRO, Bureau of Meteorology, University of Tasmania, and Antarctic Climate and Ecosystems CRC operate the Integrated Marine Observing System (IMOS) Southern Ocean Time Series (SOTS) facility with funding from the National Collaborative Research Infrastructure Strategy (NCRIS)– a set of moorings designed to quantify physical, chemical, and biological processes important to the transfer of heat, moisture, momentum, oxygen and carbon dioxide between the atmosphere and ocean. There are 3 mooring platforms at the SOTS site near 140ºE, 47ºS in ~4500m water depth, in the Subantarctic Zone (SAZ) ~36 hours by ship southwest of Tasmania: i) the Southern Ocean Flux Station (SOFS) – a large surface tower buoy that focuses on meteorological measurements, ii) the Pulse surface mixed layer mooring focusing on biological nutrient and carbon transformations using sensors and an automated water sampler, and iii) the deep SAZ sediment trap mooring (below 1000m depth) that quantifies sinking carbon fluxes to the ocean interior and returns particle samples for a broad range of biogeochemical studies. Additional applications include evaluation of wave models, calibration of isotopic proxies for past ocean conditions, and quantification of impacts of ocean acidification on foraminiferal zooplankton.**

I. Introduction

Australians have long led research into the importance of Antarctica and the Southern Ocean in the global climate system [1, 2]. The Southern Ocean encircles Antarctica and covers approximately 77 million km^2, or 22% of the surface of the world ocean. It connects the Pacific, Atlantic and Indian oceans and allows heat and other properties to be redistributed, influencing temperature and rainfall patterns [3, 4]. Subduction of surface waters occurs over vast areas, pumping heat, freshwater and gases into the deep ocean, and controlling the supply of nutrients to a large proportion of the global surface ocean [5, 6]. The Southern Ocean is responsible for nearly 40% of the global uptake of anthropogenic CO_2 [7], and the Southern Ocean is also thought to have had a dominate role in changes in global climate and atmospheric CO_2 levels over the past few 100,000 years [8]. Understanding the exchange of heat and carbon dioxide between the ocean and atmosphere in the Southern Ocean is critical to progress in climate and carbon cycle science, and an area in which the international community looks to Australia for leadership.

The region is remote and logistically challenging and is therefore one of the least sampled of all the world oceans. A comparison of a number of current turbulent heat flux climatologies (Fig.1) and models of CO_2 exchange with the atmosphere (Fig. 2) shows significant discrepancies with uncertainties as large as the mean values, particularly in the Southern Ocean.

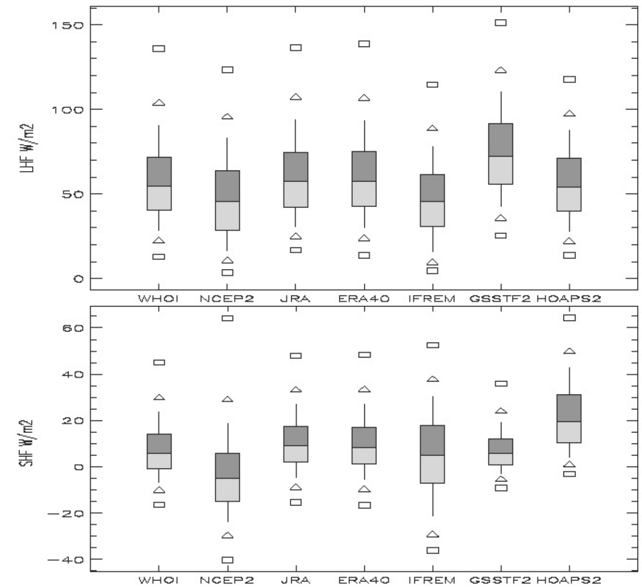

Figure 1. Box plots showing latent (top) and sensible (bottom) heat flux from seven monthly air-sea flux products in the Southern Ocean (40S-60S, 0E-360E) for the period March 1992 – December 2000. Percentiles represented are 1st (square), 5th (triangle), 10th (whisker), 25th (box bottom), 50th (central bar), 75th (box top), 90th (whisker), 95th (triangle), and 99th (square). Products represented are WHOI, NCEP2, JRA, ERA40, IFREM, GSSTF2 and HOAPS2 [44].

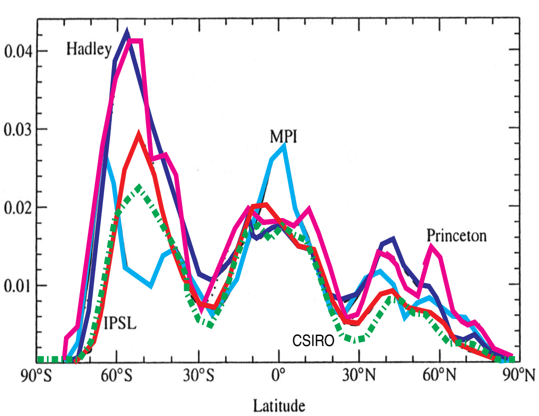

Figure 2. Comparison of models of air-sea CO2 exchange showing large uncertainty in Southern Ocean [9].

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The lack of long-term in-situ observations in the Southern Ocean is at the core of this uncertainty. In addition many of the processes that control heat and CO_2 exchange with the atmosphere, as well as carbon and oxygen transfer to the ocean interior show variability on a wide range of timescales – from diel cycles driven by insolation, to weekly variations in response to weather systems, to seasonal cycles influenced by heat accumulation driven ocean stratification, to interannual variations driven by basin-scale ocean-atmosphere oscillations such as the El Niño – Southern Oscillation and the Southern Annular Mode [10-13]. Indeed, the ability to assess decadal ocean responses to elevated atmospheric CO_2 requires correction for seasonal cycles, which is currently extremely difficult for the Southern Ocean because of a lack of in-ocean observations [14].

Ship-based observations are simply insufficient and uneconomical to obtain the observations required to deconvolute these effects and thus to obtain insights into anthropogenically driven change. As an example, Fig. 3 shows that 9 years of nutrient and pCO_2 observations obtained from ships in the Subantarctic Zone during a period of intensive work by CSIRO and the Antarctic CRC falls far short of constraining the seasonal cycle of production and gas exchange, and undoubtedly confounds interannual and seasonal variations.

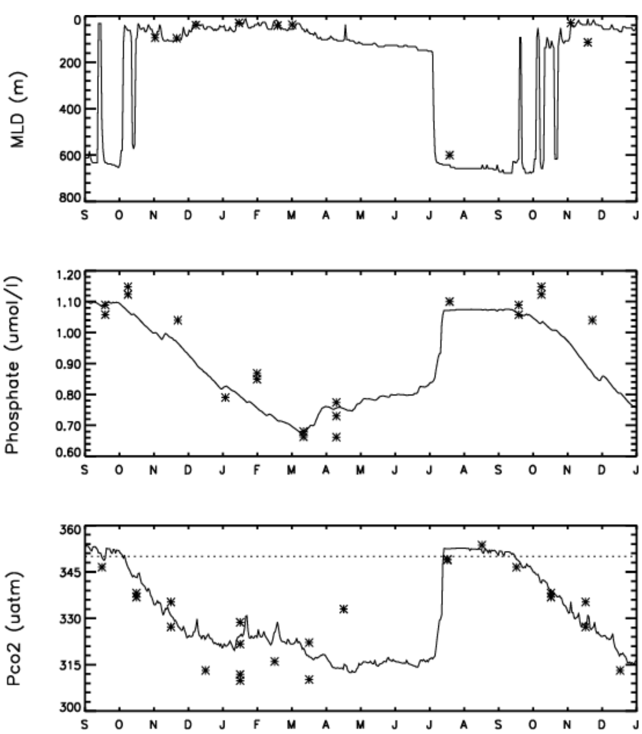

Figure 3. Comparison of mixed layer model of upper ocean properties to all data available from a decade of ship-based observations in the SAZ southwest of Tasmania. The variability of summer values may reflect interannual variability and prevents improvement of the seasonal biogeochemical model parameterizations. (Wang, Matear, Trull, and Tilbrook, unpublished).

There is a mounting global effort to obtain the required high-frequency observations from key regions of the global ocean. The time-series programs at Station P (PAPA; [15]), Bermuda (BATS; [16, 17]) and Hawaii (HOTS; [18-20]) have led this effort and identified "regime shifts" in ocean physics and their coupling to marine ecosystems. Other sites are under development, e.g. in the Canaries by the UK and Germany and in the northwest Pacific by Japan, with plans for many more sites being coordinated internationally via the OceanSITES program (www.oceanSITES.com). For logistic and financial reasons both these new programs and the existing programs are moving from personnel-based shipboard observations towards automated systems (in particular towards moored instruments and sampling systems). Successful examples include the installation of the HALE-ALOHA system in Hawaii (hahana.soest.hawaii.edu/hot/hot_jgofs.html), the ANIMATE program in the Canaries (www.soc.soton.ac.uk/animate) and perhaps the most highly instrumented moored system to date deployed at the K2 site in the northwest Pacific [21].

The Sub-Antarctic Zone is a key region in need of this scale of observation. As the site of formation of Sub-Antarctic Mode and Antarctic Intermediate waters, it is recognized as a major player in the uptake of anthropogenic CO_2 [7, 13, 14], in the ventilation of oxygen into the deep ocean [22], in the supply of nutrients to surface waters throughout the southern hemisphere and well into the northern hemisphere [5], and as a region that has shown changes over the past few decades that demonstrate a response to climate warming [23, 24].

II. SOTS FACILITY OBJECTIVES

The Integrated Marine Observing System (IMOS) Southern Ocean Time Series (SOTS) facility seeks to provide sustained observations in the Sub-Antarctic Zone to address these issues of fundamental ocean physics and chemistry, climate change, carbon cycling, and biogeochemical controls on marine productivity. SOTS is based on the application of automated technologies to these problems. It is built on the successes of the ACE CRC with deep-ocean automated observations of currents and sinking particle fluxes for the quantification of the biological carbon pump (the movement of carbon to the ocean interior by sinking particles; [25-27]) , and the development of paleo-proxies for the interpretation of past climate cycles [28-34]. Interestingly, these efforts in the SAZ (and globally) have led to the unexpected situation that knowledge of the synoptic to seasonal timescale variations in carbon fluxes is generally better in the deep sea than it is in the surface mixed layer where the exchange with the atmosphere and primary production occur. This is clear from comparing Fig. 4, that shows the variations observed by the SAZ sediment trap mooring below 1000m from a single year to the sparse coverage at the surface obtained over 9 years (Fig. 3).

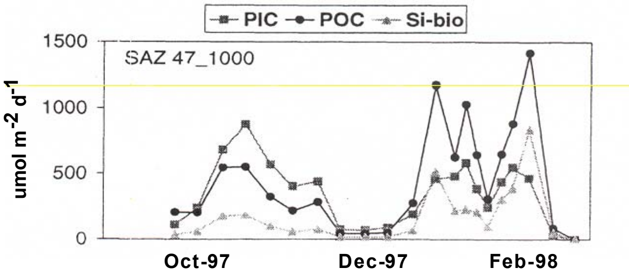

Figure 4. Seasonal cycle of biogenic materials to deep ocean moored sediment traps in the SAZ [27]. Note the short pulses that account for large fractions of the total annual flux.

SOTS seeks to change this situation by deploying moorings capable of obtaining physical, chemical, and biological measurements and samples on similar timescales for the surface ocean. SOTS will also continue to deploy the SAZ sediment trap mooring to examine the coupling of surface and deep processes in the control of carbon transports.

The choice of the SAZ site reflects:
1. scientific objectives as described in the Introduction.
2. the rarity of any sustained observations in the Southern Ocean - the proposed SOTS site is 1 of only 3 proposed for the Southern Ocean as recognized by the Global Ocean Observing System and the OceanSITES programs, and the only one with a track record of automated observations.
3. existing and ongoing supporting observational programs, including:
   i) the ongoing World Ocean Circulation Experiment/ Climate Variability Southern Ocean SR3 Repeat Sections
   ii) ongoing French resupply vessel *Astrolabe* repeat expendable bathythermograph (XBT) transects, recently expanded to include more biological and chemical measurements under the IMOS Ship of Opportunity underway observations program
   atmospheric observations at Cape Grim
   iii) previous detailed shipboard process studies in 1997-8 (SAZ Project; [35]) and January 2007 (SAZ-SENSE; www.cmar.csiro.au/datacentre/saz-sense/)
4. logistic synergies - specifically opportunities to use Australian Marine National Facility research vessel *Southern Surveyor* and Australian research and resupply icebreaker *Aurora Australis* to service the moorings

Examples of specific (and sometimes competing) hypotheses to be tested include:

1. seasonal stratification and its effect on mean light levels dominates the control of phytoplankton production; conversely the effect of warming on production is negligible.
2. episodic mixing controls air-sea CO_2 exchange
3. episodic mixing or supply of iron controls primary production.
4. supply of total CO_2 from below the mixed layer determines the seasonality in the air-sea flux
5. export as observed in deep sediment traps can be predicted from surface production
6. seasonal oxygen and carbon dioxide observations can be used to determine the relative roles of the biological and solubility pumps.
7. the surface ocean is well mixed, and remotely sensed sea surface temperature is representative of a deeper mixed layer that controls net primary production
8. for a given wind speed, air-sea heat, momentum, and moisture fluxes are enhanced compared to other oceans due to consistently large waves
9. seasonal heat fluxes have little influence on the Australian seasonal forecast which is dominated by tropical conditions

III. SOTS Facility Methods

A. SAZ sediment trap mooring

This is essentially standard deep ocean technology based on conical traps with a rotating carousel of cups that collect sinking particle flux samples with ~weekly resolution in summer and monthly in winter. We have successful experience with the methodology [27] and our results are routinely used in global compilations [36]. In addition we sometimes use novel sediment traps that measure particle sinking rates [26, 37], and we distribute samples to support a wide range of investigations.

B. PULSE biogeochemistry mooring

The basic mooring platform is innovative technology of our own design to address the problem of how to obtain surface mixed layer measurements from a highly energetic location. Previous efforts have applied two basic approaches:

1. use a very stiff-mooring that rises from the sea-floor to hold a package of instruments in the mixed layer (i.e. ~50 meters below the surface). The advantage is that exposure to waves and wind is reduced. Disadvantages include lack of any data until retrieval, and the difficulty of deploying a mooring to exactly the right bottom depth (i.e. to with ~20 in a depth of ~4500m). This second problem, as compounded by deployments from a ship that does not hold its head easily at low speed (*Aurora Australis* as an icebreaker and expeditioner transport ship has a shallow keel and high sides) led us to reject this option and

2. use a large surface float on a very strong mooring. Prior to receiving IMOS funding this option was too expensive for us to contemplate. It is the approach that will now be used for the SOFS mooring (see below), but importantly – mass

added in the mixed layer does add risk to this type of mooring – which has generally been deployed with instruments only within the surface float.

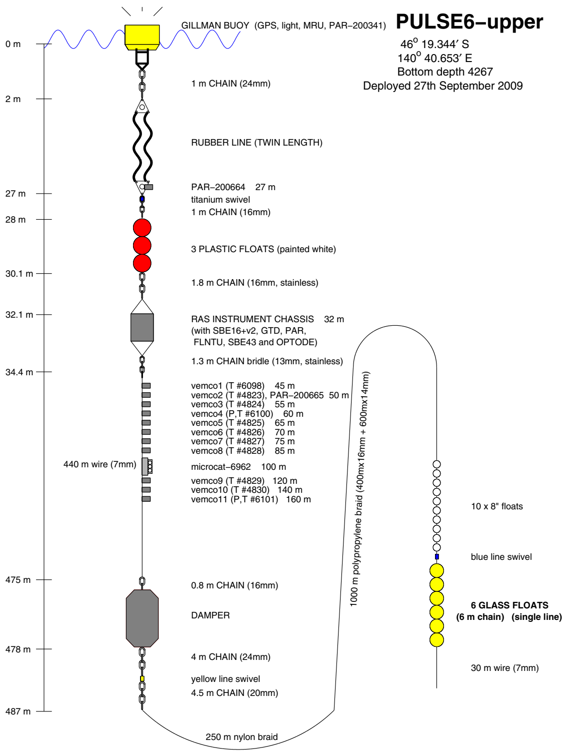

Figure 5. Top section of Pulse-6 mooring indicating elastic tether, inertial mass damper, and s-tether.

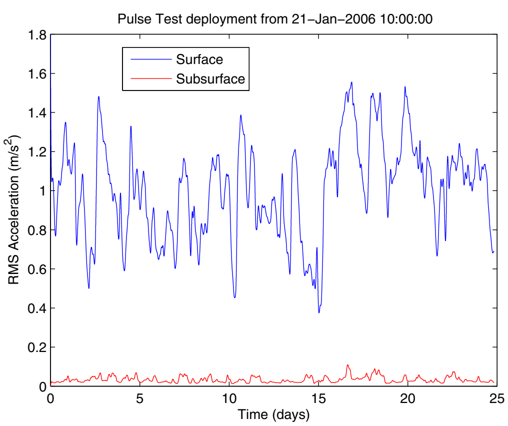

Figure 6. Results from PULSE Test showing excellent protection of subsurface instrument package from surface wave forces

Our solution is a hybrid design that combines a small surface float (that defines the depth, and allows some data transmission) that suspends the mixed-layer instrument package via elastic links that decouple the package from the surface float motions (Fig. 5). This surface assembly is then linked to the deeper stiff mooring by an s-shaped tether that provides some leeway in terms of deployment to the targeted bottom depth. Successful test deployments in 2008-9 (see www.imos.org.au -under Facility 3. SOTS for engineering results as transmitted live to the internet via the Iridium telecommunications network) demonstrated that this does protect the instruments and keeps them within the desired depth range (Fig. 6). The s-tether design allows the surface float to move within a large "watch-circle", which provides an indication of current direction and intensity (Fig. 7).

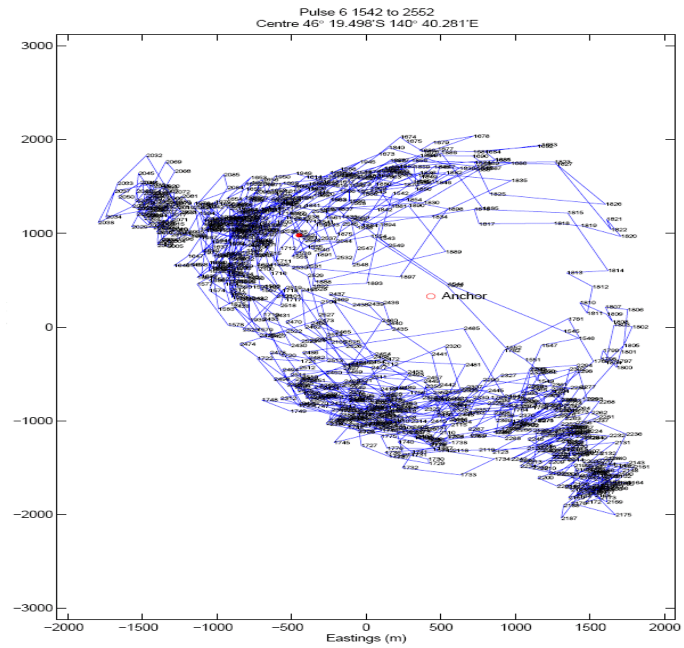

Figure 7. Movement of Pulse-6 surface float about anchor position

We deployed the first fully instrument version, Pulse-6, in Sept. 2009 for recovery in March 2010. To meet the goals of defining biogeochemical processes important to carbon cycling the Pulse-6 mooring has a wide range of sensors and also a sample collection device. The parameters measured and associated sensors have been used in many shipboard studies and consist of:

1. T,S: Seabird 16+ CTD
2. Photosynthetically Active Radiation Sensor: Alec Electronics
3. Suspended phytoplankton (fluorescence) and total particles (backscatter): Wetlabs FLNTUS
4. Dissolved oxygen concentrations: Aanderaa optode and SBE-43 electrode
5. Total dissolved gases: Pro-oceanus Gas Tension Device
6. Water samples: Mclane RAS-500 48x0.5L samples

The first 4 instruments are familiar to most oceanographers and their ability to obtain reliability data with the necessary sensitivity was recently demonstrated for our target region during the SAZ-SENSE voyage (papers in review and data are available on line on the SAZ-SENSE website). The combination of 4 and 5 can yield biological oxygen production based estimates of primary production (e.g. as done with moored instruments off Hawaii [38], and similar instruments in recent Southern Ocean shipboard surveys [39]. Instrument 6 has been used for a full season successfully on a mooring in the North Pacific [21]. It allows for dissolved nutrients, dissolved inorganic carbon and alkalinity to be determined, to aid in distinguishing biological from physical contributions to carbon transports. It can also collect samples for phytoplankton identification to connect the biogeochemical processes to the ecosystem structures that control them. These measurements provide more information on how and why nutrient stoichiometries in the Subantarctic Southern Ocean have sometimes been observed to differ strongly from global averages [40, 41]. This suite of instruments requires twice-yearly servicing due to the high frequency of measurements (ranging from nearly continuous to 1 sample per week) and the need to address bio-fouling on some of the sensors. A second set of instruments 1-4, and a pCO2 system provided by NOAA (C. Sabine collaboration) are also housed in the SOFS mooring for real-time data transmission by the Iridium network.

C. SOFS meteorological flux mooring

The SOFS mooring is based on a standard meteorological mooring with a surface float and small tower, modified for the extreme Southern Ocean conditions (Fig. 8).

Figure 8. SOFS-1 surface meteorological buoy.

The tower carries twin meteorological systems that measure long and short-wave radiation, sea-level pressure, atmospheric temperature, humidity, PAR and wind which will fully capture all the components necessary to obtain total heat flux. Atmospheric and surface water CO_2 will also be measured (NOAA C. Sabine collaboration). Surface wave spectra will be measured using a motion reference unit, allowing the modulation of fluxes by waves to be examined. In addition, a partial replicate of the Pulse sensor package will be sampling biogeochemical properties in the surface mixed layer. PAR will be measured at 10m intervals down to 50m to capture extinction coefficients. The mooring will also measure ocean properties including surface salinity and temperature at approximately 10m intervals in the mixed layer to 100m depth to fully document mixed layer dynamics. Meteorological and surface ocean data will be transmitted via satellite, while sub-surface data will be retrieved during ship visits.

IV. SOTS Additional applications

While the focus of the SOTS facility is on physical, chemical, and biological processes affecting climate and carbon uptake over seasonal timescales, other applications are easily supported. Examples include:

i) determination of relationships between surface ocean properties and the composition of sinking particles, and thus calibration of "paleo-proxies" for the interpretation of sedimentary records of climate and biogeochemical cycles [28-34]

ii) studies of the impact of ocean acidification from the uptake of anthropogenic CO2 on Southern Ocean organisms, e.g. the demonstrated thinning of the carbonate shells of foraminiferal zooplankton [42].

iii) determination of wave amplitudes from the motion reference unit installed in the Pulse surface float, for comparison to wave models [43]

Acknowledgments

SOFS-1 was built under the direction of Dr. Robert Weller at Woods Hole Oceanographic Institution (WHOI). WHOI engineer Jeff Lord assisted with its deployment. Chris Sabine (NOAA) provided the SOFS-1 pCO_2 system.

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