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Introduction to Special Section: SAZ Project

T. W. Trull

Peter N. Sedwick
Old Dominion University, Psedwick@odu.edu

F. B. Griffiths

S. R. Rintoul

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Introduction to special section: SAZ Project

T. W. Trull, P. N. Sedwick, F. B. Griffiths,[1] and S. R. Rintoul[1]

Antarctic Cooperative Research Centre, Hobart, Tasmania, Australia

Abstract. Oceanographic processes in the subantarctic region contribute crucially to the physical and biogeochemical aspects of the global climate system. To explore and quantify these contributions, the Antarctic Cooperative Research Centre (CRC) organized the SAZ Project, a multidisciplinary, multiship investigation carried out south of Australia in the austral summer of 1997-1998. Here we present a brief overview of the SAZ Project and some of its major results, as detailed in the 16 papers that follow in this special section.

1. Introduction

The Southern Ocean plays an important role in the global oceanic overturning circulation and its influence on the carbon dioxide contents of the atmosphere. Deep waters upwelled to the surface are rich in nutrients and carbon dioxide. Air-sea interaction modifies the upwelled deep waters to form bottom, intermediate, and mode waters, which transport freshwater, oxygen, and carbon dioxide into the ocean interior. The overall effect on atmospheric carbon dioxide is a balance between outgassing from upwelled deep waters and uptake via both dissolution in newly formed waters (sometimes referred to as the solubility pump) and the transport of photosynthetically formed organic carbon to depth in settling particles (referred to as the biological pump). Determining the variations in the overturning circulation and the associated carbon fluxes in the past and their response to increased anthropogenic emissions of carbon dioxide in the future is essential to a full understanding of the controls on global climate. At present the upwelled nutrients are incompletely used. Low light in deep wind-mixed surface layers, lack of the micronutrient iron, and other factors restrict phytoplankton production so that Southern Ocean surface waters represent the largest high-nutrient, low chlorophyll (HNLC) region in the world.

The subantarctic region is central to these linkages between circulation, carbon transports, and climate. Circumpolar fronts divide the Southern Ocean into several oceanographic zones [e.g., *Orsi et al.*, 1995]. The Subantarctic Zone (SAZ) extends south from the Subtropical Front (STF), the boundary of the Southern Ocean with the subtropical gyres, to the deep-reaching Subantarctic Front (SAF), which carries the most intense transport of the Antarctic Circumpolar Current. The Polar Frontal Zone (PFZ) lies just to the south of the SAZ and extends from the SAF to the Polar Front, a subsurface temperature minimum that marks the northernmost extent of Antarctic waters. Together the SAZ and PFZ make up the subantarctic region. The SAZ alone represents more than half the areal extent of the Southern Ocean [*Orsi et al.*, 1995] and is the site of the formation of both subantarctic Mode and Antarctic Intermediate Waters [*McCartney*, 1977; *Talley*, 1996], which connect the upper and lower components of the overturning circulation [*Sloyan and Rintoul*, 2001a, 2001b]. SAZ surface waters exhibit carbon dioxide partial pressures (pCO_2) well below atmospheric levels, and thus the SAZ acts as a large sink (~1 Gt C yr^{-1}) for atmospheric CO_2 [*Metzl et al.*, 1999]. Algae accumulations are relatively large in the PFZ in summer and moderate throughout the year in the SAZ, with both regions showing generally higher chlorophyll concentrations than ice-free circumpolar waters in the Antarctic Zone [*Moore et al.*, 2000]. This phytoplankton production fuels organic carbon export to the deep sea that is currently close to or above the global median in both the SAZ and PFZ [*Honjo et al.*, 2000; *Trull et al.*, this issue].

Changes in the overturning circulation and carbon transports in the subantarctic region feature strongly in interpretations of past climate change and expectations of future climate change. Increased carbon export in the subantarctic region appears to have contributed to lowered atmospheric carbon dioxide levels during the Last Glacial Maximum [*Kumar et al.*, 1995; *François et al.*, 1997; *Sigman et al.*, 1999]. Future carbon uptake in the subantarctic region appears likely to decrease in response to global warming because of reduction in the global overturning circulation, which affects both the biological and solubility pumps [*Sarmiento and LeQuere*, 1996; *Matear and Hirst*, 1999]. This reduction may already affect the properties of Subantarctic Mode and Antarctic Intermediate Waters formed in the SAZ [*Wong et al.*, 1999; *Banks et al.*, 2000], including a reduction in the transport of oxygen to the ocean interior [*Matear et al.*, 2000].

Despite the recognized importance of the subantarctic region to carbon transports, until recently, there had been few studies of biogeochemical processes in the region. Important issues to be resolved included the relative contributions of the biological and solubility pumps to low pCO_2 in surface waters; the overall magnitude of uptake of atmospheric CO_2 and its response to anthropogenically elevated atmospheric carbon dioxide concentrations; the magnitudes and controls on

[1]Also at CSIRO Marine Research, Hobart, Tasmania, Australia.

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primary production, including the role of iron and silicate availability and the nature of ecosystem changes when iron is added; and the magnitude and controls on particulate carbon export to the deep sea. Quantitatively, describing these processes in the modern ocean is a first step toward predicting their role in and response to climate change.

2. Design of the SAZ Project

To address these questions, the Antarctic CRC organized the SAZ Project, a study of biogeochemical processes along ~140°E longitude from ~40° to 55°S latitude, i.e., from the STF southward across the SAZ and SAF, and well into the PFZ. This enabled direct comparison of biogeochemical processes between the SAZ and the PFZ. Both regions exhibit HNLC characteristics but with a very important difference between the two. In the PFZ, phosphate, nitrate, and silicate levels all remain high until at least midsummer in surface waters, but in the SAZ, silicate is low throughout the year [*Trull et al.*, 2001; *Rintoul and Trull*, this issue]. The two zones differ in other factors that strongly affect primary production. SAZ surface waters are typically 8°-12°C in summer, while PFZ waters are closer to 4°-7°C. In winter, SAZ mixed layers can exceed 400 m, but PFZ mixed layers remain shallower than 200 m [*Rintoul and Trull*, this issue]. The two zones exhibit different algal communities, with diatoms prevalent in the PFZ and coccolithophores, flagellates, and cyanobacteria more common in the SAZ [*Odate and Fukuchi*, 1995; *Wright et al.*, 1996; *Kopczynska et al.*, this issue]. Full knowledge of the availability of iron in the two regions is not in hand, but SAZ and PFZ surface waters appear to have low levels of dissolved iron in middle and late summer, with somewhat higher values near the STF [*Sedwick et al.*, 1997, 1999].

The main field work for the SAZ Project occurred in the 1997-1998 austral summer, and included several components: (1) a dedicated marine science cruise carried out in March 1998 using the Australian icebreaker *Aurora Australis,* which undertook multiday process stations and ondeck incubation studies at sites in the STF, SAZ, SAF, and PFZ, (2) a simultaneous survey of a large meander of the SAF from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) research vessel *Southern Surveyor,* (3) deployment of moored sediment traps and current meters in the SAZ, SAF, and PFZ from September 1997 to February 1998, and (4) underway collection of surface water and particle samples from Antarctic resupply vessels throughout the 1997-1998 austral summer.

A map of the main *Aurora Australis* and *Southern Surveyor* cruise tracks is provided by *Rintoul and Trull* [this issue], and the mooring locations are shown by *Trull et al.* [this issue]. Additional resupply voyage tracks are shown by *McNeil et al.* [this issue]. The field programs combined standard hydrographic determinations of temperature, salinity, dissolved nutrients, and oxygen with extensive additional study of water column properties important to primary and export production. Carbon measurements included pCO_2, alkalinity, dissolved inorganic carbon (DIC), dissolved organic carbon, particulate inorganic carbon, particulate organic carbon (POC), and the stable carbon isotopic compositions of DIC, POC, and individual organic carbon compounds. Dissolved and total dissolvable iron were measured, and the major and trace element contents of suspended particles were examined. Phytoplankton studies included pigment analyses, flow cytometry, microscopy, fast repetition rate fluorometry, ^{14}C-based estimates of primary production as a function of irradiance, and ^{15}N-based estimates of new production. In addition to the water column studies, shipboard incubation experiments were undertaken to explore phytoplankton responses to varying levels of iron, macronutrients, and light.

Design of the SAZ Project drew strongly on knowledge of the region developed from previous field programs. A detailed view of water mass properties and circulation was available from six repeats of the World Ocean Circulation Experiment (WOCE) SR3 hydrographic section from Tasmania to Antarctica [*Rintoul and Bullister*, 1999; *Rintoul and Sokolov*, 2001; *Trull et al.*, 2001; *Yaremchuk et al.*, 2001; *Rintoul and Trull*, this issue]. The development of the seasonal thermocline was known from repeat expendable bathythermograph sections carried out using the French Antarctic resupply ship *l'Astrolabe* [*Rintoul et al.*, 1997]. A preliminary view of biogeochemical processes was available from previous Australian programs [*Sedwick et al.*, 1997; *Clementson et al.*, 1998] including measurements from both the CSIRO ship *Southern Surveyor* and the U.S. National Oceanic and Atmospheric Administration (NOAA) ship *Discoverer* during the first Aerosol Characterization Experiment (ACE-1) [*Griffiths et al.*, 1999]. The pCO_2 observations obtained on many of these voyages [*Metzl et al.*, 1999; B. Tilbrook, unpublished data, 2001] played a key role in developing the regional focus of the SAZ Project. The subantarctic focus of the SAZ Project was designed to complement other major biogeochemical studies in the Southern Ocean that focused on the Polar Front or farther south, including the U.S. Antarctic Enviroment and Southern Ocean Process Study (AESOPS) program [*Smith et al.*, 2000], the French KERFIX and ANTARES programs [*Jeandel et al.*, 1998; *Gaillard*, 1997], and the European Joint Global Ocean Flux Study (JGOFS) programs in the Atlantic sector [*Turner et al.*, 1995; *Smetacek et al.*, 1997; *Bathmann*, 1998]. Direct collaboration was also developed with two programs that focused farther north: the French ANTARES 4 program in the Indian Ocean [*Blain et al., 2001; Sedwick et al., 2001*] and National Institute of Water and Atmospheric Research (NIWA) research programs east of New Zealand [*Boyd et al.*, 1999; *Nodder and Northcote*, 2001].

3. Results of the SAZ Project

This collection of 16 papers presents some of the major results from the SAZ Project. A few SAZ Project results have already been published [*Sedwick et al.*, 1999; *Church et al.*, 2000], and others will be forthcoming (including results of the *Southern Surveyor* meander survey, measurements of primary and new production, phytoplankton pigments, and near-surface sinking particle fluxes). The papers presented here provide new information and insights into the biogeochemistry, carbon transports, and controls on primary production in the Australian subantarctic region. *McNeil et al.* [this issue] determined the accumulation of anthropogenic carbon dioxide in Subantarctic Mode Water over a 30 year period by comparison with historical DIC results and by extrapolation estimated that the circumpolar SAZ accumulates 0.07-0.08 Gt C yr^{-1}. This is ~10% of the total annual uptake of atmospheric carbon dioxide estimated from surface pCO_2 observations and wind speed-based transfer coefficients [*Metzl* *et al.*, 1999]. *Lourey and Trull* [this issue] document the magnitude of seasonal biological nitrate and phosphate depletion in surface waters and find that it is high in both the SAZ and PFZ, considering the relatively low levels of biomass accumulation. Comparison of their results to the pCO_2 observations suggests that the biological pump dominates the seasonal variations in pCO_2, with only a minor contribution from the thermally driven solubility pump. The *Lourey and Trull* [this issue] estimates of particulate carbon export from the nutrient depletion observations are similar in magnitude to the total carbon uptake from the atmosphere estimated by *Metzl et al.* [1999], implying that both vertical mixing and particulate transports contribute importantly to the deep penetration of atmospheric CO_2 into Subantarctic Mode Water and hence the ocean interior.

Examination of the SAZ Project results for the SAZ and PFZ reveals some surprises, which are important to the assessment of Southern Ocean ecosystem controls on POC export. *Lourey and Trull* [this issue] found that seasonal nitrate depletion in SAZ surface waters was nearly twice that in the PFZ, although phosphate depletion was only ~20% higher (owing to a much lower than Redfield ratio for nitrate to phosphate depletion in the PFZ). The higher nutrient depletion in the SAZ than in the PFZ is consistent with higher primary production (F. B. Griffiths, unpublished data, 2001), but the explanation may be more complex. On the basis of a modeling study, *Wang et al.* [this issue] suggest that the SAZ–PFZ difference in nutrient depletion is the result of greater nutrient resupply in the PFZ, rather than higher export production in the SAZ. This view is supported by greater accumulations of suspended barite, a proxy for organic carbon export, in middepth waters in the PFZ than in the SAZ [*Cardinal et al.*, this issue]. However, uncertainties in both the modeled magnitude of nutrient resupply and the reliability of barite as a proxy for export production leave open the question of which zone, the SAZ or PFZ, exports more POC from surface waters.

Whatever the relative magnitude of organic carbon export from surface waters in the SAZ and PFZ, the deep sediment trap results demonstrate that organic carbon export to the deep sea is similar in the two zones or perhaps somewhat higher in the SAZ [*Trull et al.*, this issue]. This is an unexpected result given recent assessments of the ecosystem control of carbon export, which suggest that diatom-dominated ecosystems such as occur in the PFZ are more likely to export large amounts of organic carbon from surface waters than are ecosystems dominated by smaller nondiatom phytoplankton such as occur in the SAZ [*Buesseler*, 1998; *Boyd and Newton*, 1999; *Laws et al.*, 2001]. Reconciliation of these results may lie in understanding the efficiency of carbon remineralization in mesopelagic waters. Specifically, it is possible that the silicate-rich particles departing PFZ waters more readily lose their organic carbon at mesopelagic depths than do the carbonate-rich particles exported from the SAZ [*Trull et al.*, this issue]. Alternatively, mesopelagic feeders may more effectively repackage carbon for deep transport in the SAZ than in the PFZ. In either case, further study of mesopelagic controls on deep carbon export, and not just export production from surface waters, will be required to assess the probable response of the subantarctic region biological pump to climate change.

Shipboard phytoplankton incubations undertaken during the March 1998 cruise investigated the controls on phytoplankton growth in the PFZ, SAZ, and near the STF. Low iron availability clearly limited community growth in the SAZ and near the STF [*Sedwick et al.*, 1999; *Hutchins et al.*, this issue], although low light availability was possibly the primary limitation in the deeply mixed waters of the PFZ [*Boyd et al.*, this issue]. Silica availability affected community growth and species composition within the SAZ, but, importantly, the low ambient silicate levels (~1 μM) did not prevent a significant community response to iron addition, including an increase in the abundance of small pennate diatoms [*Hutchins et al.*, this issue]. Iron, light, and silicate availability all affected algal production of particulate dimethylsulfoniopropionate and dimethyl sulfide, sulfur species potentially involved in the control of cloud condensation in the atmosphere [*DiTullio et al.*, this issue]. The roles of iron and silica in the control of algal growth have been further examined in collaborative studies between the SAZ Project and the French ANTARES 4 program [*Blain et al.*, 2001; *Sedwick et al.*, 2001].

Insights gained from the shipboard incubation experiments and measured water column properties have also assisted in the interpretation of algal biomass production and distribution within the study region, including the presence of deep subsurface maxima in chlorophyll and biogenic silica in the PFZ [*Parslow et al.*, this issue; *Quéguiner*, this issue], low rates of biogenic silica production and unusual silicate uptake kinetics [*Quéguiner*, this issue], the possible role of photoadaptation in the distribution of phytoplankton and the overall bio-optical properties of subantarctic waters [*Clementson et al.*, this issue]; the role of algal growth rate in affecting the paleoproxy relationship between dissolved carbon dioxide concentrations and the ^{13}C content of suspended organic matter [*O'Leary et al.*, this issue], and the distribution of inorganic and organic forms of arsenic [*Featherstone et al.*, this issue].

4. Comparison With Other Southern Ocean Sectors

Comparison of SAZ Project results with the results from other recent Southern Ocean studies is just beginning, but already clear, differences have been noted. Much lower levels of algal biomass develop south of Australia [*Trull et al.*, 2001; *Rintoul and Trull*, this issue] than in either the 170°W region studied by the U.S. AESOPS program or in the Atlantic sector [*Comiso et al.*, 1993; *Moore et al.*, 2000]. The seasonality of export as determined by deep sediment traps also differs, with both spring and summer peaks in the Australian sector, in contrast to a single summer maximum in the 170°W region [*Honjo et al.*, 2000; *Trull et al.*, this issue]. The origin of these differences is not yet clear. There are several possible influences. Insolation differs because of the relatively northward positions of the circumpolar fronts in the sector south of Australia [*Orsi et al.*, 1995]. Sea ice can reach the Polar Front in winter in the South Atlantic and the 170°W region but is confined much farther south in the Indian sector [*Gloersen et al.*, 1993; *Worby et al.*, 1998]. Upstream landmass sources of iron are more distant in the Australian sector [*Comiso et al.*, 1993; *de Baar et al.*, 1995]. Frontal structures may also play a role. South of Australia, the Polar Front divides into two branches, and the broad quiescent region between them exhibits nutrient depletions and biomass accumulations that are distinct from the regions to the north or south [*Trull et al.*, 2001; *Parslow et al.*, this issue]. Determining the origins of the different biogeochemical characteristics of the different sectors of the Southern Ocean will require additional synthesis, modeling, and experiments, but already, it is clear that the Australian results will enhance the overall understanding of Southern Ocean processes. In addition to the observations presented here, there has been considerable progress in the development of quantitative models for mixed layer dynamics and the seasonal cycles of production and export in the SAZ and PFZ [*Wang and Matear*, this issue; *Wang et al.*, this issue].

5. Continuing Programs

Some components of the SAZ Project are continuing. The deployment of sediment traps at the SAZ and PFZ sites has continued annually since 1998, and the Antarctic CRC is considering extending the mooring program to include other sites and surface instruments as a small step toward the establishment of Southern Ocean times series observations. Many of the issues raised by the SAZ Project will be investigated in November 2001 in conjunction with a Climate Variability and Predictability program (CLIVAR) repeat occupation of the WOCE SR3 section. This voyage will extend the SAZ Project multidisciplinary approach farther south into the Antarctic and Marginal Ice Zones, including a springtime reexamination of iron availability and carbon uptake at the site of the Southern Ocean Iron Release Experiment [*Boyd et al.*, 2000; *Trull et al.*, 2001]. Development of this work includes active collaboration with New Zealand, French, Belgian, U.S., and Japanese investigators. We hope that this compilation of results will further stimulate collaborative investigation and synthesis of Southern Ocean biogeochemistry.

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F. B. Griffiths, S. R. Rintoul, P. N. Sedwick, and T. W. Trull, Antarctic CRC, GPO Box 252-80, Hobart, Tasmania 7001, Australia. (tom.trull@utas.edu.au)

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