———. ETOPO2 gridded global database. http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html
Scientific Committee on Antarctic Research and General Bathymetric Chart of the Oceans. International Bathymetric Chart of the Southern Ocean, 2004. http://www.awi-bremerhaven.de/GEO/Bathymetry/ibcso/index.html
Smith, W. H. F., and D. T. Sandwell. "Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings." *Science* 277 (5334) (1997): 1956–1962.

SOUTHERN OCEAN: BIOGEOCHEMISTRY

Biogeochemistry as a scientific field recognizes the dominant influence of organisms and ecosystem processes on the cycling of elements in the planetary system. The Southern Ocean surrounding Antarctica is one of the largest contiguous biomes on the planet and exerts powerful controls on the ocean carbon and silicon cycles, and on the exchange of carbon dioxide (CO_2) between the ocean and atmosphere. The Southern Ocean below 50° S, with 10% of the total ocean area, is responsible for ~20% of the global ocean CO_2 uptake and 50% of sedimentary opal accumulation. Here the focus is on the roles played by the open Southern Ocean and the Antarctic marginal ice zone and coastal regions in these elemental cycles as well as on some of the ecological processes influencing the cycles.

CO_2 Exchange

The exchange of carbon dioxide across the air-water interface is influenced by the gradient in partial pressure of dissolved CO_2 gas (pCO_2) between the atmosphere and the ocean water, termed the ΔpCO_2. Atmospheric pCO_2 is about 380 ppm, and the pCO_2 in seawater varies between about 200 and 500 ppm although the range in some coastal areas can be larger. When seawater pCO_2 is below 380 ppm, CO_2 is driven into the water; when it is greater, CO_2 degasses from the ocean into the air. When the gradient is large, the gas flux is faster. The ocean in the past century became a net sink for atmospheric CO_2 because anthropogenic emissions have elevated the atmospheric pCO_2 by about 30% above its preindustrial level of 280 ppm. The ocean is now responding to this relatively rapid change in atmospheric chemistry, but the time to establish a new air-sea equilibrium (assuming anthropogenic emissions are eventually stabilized) is poorly known and will take centuries to millennia. Gas exchange is also directly proportional to turbulent mixing caused by wind shear. Faster winds increase the exchange rapidly as the cube of the wind velocity.

The Southern Ocean is responsible for ~20% of the global ocean CO_2 uptake (0.47 of 2.2 Pg C yr^{-1}; Takahashi et al. 2002; 1 petagram Pg = 10^{15} g). Polar continental shelves covered by seasonal sea ice have been hypothesized to act as rectified (one-way) CO_2 pumps, due to the phasing of sea ice cover and biological activity. In summer, when primary production is high and pCO_2 is low, Antarctic seas act as strong sinks for atmospheric CO_2. In winter, when respiration dominates over production and pCO_2 is high, gas exchange is prevented by the sea ice capping the ocean surface. Sea surface temperature is almost constant near Antarctica (relative to lower-latitude systems), and the CO_2 partial pressure excursion governing gas exchange is almost entirely due to biological drawdown and respiration. The Ross Sea polynya may function as a rectified sink for atmospheric CO_2 because it is strongly undersaturated in CO_2 in summer in response to the *Phaeocystis* bloom (Takahashi et al. 2002) and covered by ice during the rest of the year.

Whether the continental shelves of other areas such as the Antarctic Peninsula act as rectified or even unrectified net annual CO_2 sinks is not established. The Peninsular region is characterized by large spatial and temporal variability and by the co-occurrence of various biological (e.g., respiration and photosynthesis) and physical (e.g., heating, cooling, ice formation and ablation, freshening, and dilution) processes, all of which makes understanding and budgeting the carbon cycle very challenging. In summer (January), different regions of the Peninsula showed different patterns of CO_2 and O_2 (dissolved oxygen) over- and undersaturation, resulting from spatial variation in dominance of various physical or biological processes. Dissolved CO_2 was near atmospheric equilibrium in some regions, particularly offshore and toward the north. Net primary production is the dominant process in the inshore areas and especially in Marguerite Bay, leading to strong drawdown of DIC (dissolved inorganic carbon) and undersaturation of dissolved CO_2 ($pCO_2 < 200$ ppm). Other areas had excess CO_2 as a result of strong respiration.

The interior shelves and coastal regions of the Antarctic are small, however, and their influence on the global CO_2 exchange is slight. The regional fluxes are dominated by the larger areas of the Southern Ocean surface further away from the continent. The outer areas of the marginal ice zones 60°–70° S seem to exhibit low net CO_2 uptake from the air. In the permanently open areas of the Southern Ocean beyond the northern extent of the annual sea ice, CO_2

exchange occurs year-round but the pCO_2 excursions are less dramatic than in the coastal areas. The region between 50°–60° S is a net sink for CO_2 with fluxes of 1–2 moles CO_2 m^{-2} y^{-1}. These are moderate to low fluxes, but the area is vast, and the region serves as an important zone of CO_2 storage on the global scale.

Carbon Cycle

Air-sea gas exchange itself is strictly a physical-chemical process governed by gas solubility as it is influenced by temperature, salinity, alkalinity, partial gas pressure, and wind. However the amount of CO_2 dissolved in the water is also influenced profoundly by biological processes that produce and consume this important biogenic gas. Biological, chemical, and physical processes are linked through the action of the Solubility Pump and Biological Carbon Pumps (Volk and Hoffert 1985; Ducklow et al. 2001). CO_2 solubility is a function of temperature: more CO_2 dissolves in cold water than warm. The Solubility Pump transports dissolved inorganic carbon (DIC or TCO_2) against the vertical concentration gradient toward long-term storage in the deep ocean as cold waters with high CO_2 concentrations sink to depth (Feely et al. 2001).

The Biological Pump is responsible for vertical sedimentation of particulate and dissolved organic matter from the illuminated (euphotic) zone in the upper 100–200 m. The components of the biological pump are plankton organisms: autotrophic phytoplankton, bacteria, protozoans and larger zooplankton, and the trophic (feeding) interactions linking these groups in the foodweb. Phytoplankton fix inorganic nutrients into organic matter, a fraction of which is exported passively through gravitational sedimentation of organic matter and actively by zooplankton migration. The biological pump operates most efficiently when blooms of larger phytoplankton like diatoms sink without being grazed upon. Zooplankton like krill and salps repackage phytoplankton and other small particles into larger, rapidly sinking fecal pellets and marine snow. Primary production in the Southern Ocean, especially in the marginal ice zone is dominated by diatom blooms, and as a consequence particles sink rapidly in conspicuous pulses. The zooplankton community alternates over interannual scales between dominance by krill and salps which influence export in contrasting ways. Krill may decrease flux, even while producing rapidly sinking particles, by reingesting them as they sink. Salps vacuum the water column of a wide range of particle sizes and produce very rapidly sinking aggregates which themselves scavenge particles and grow as they sink. Krill versus salp dominance seems to be related to watermass variations and ENSO (El Nino Southern Oscillation); thus climate change may affect the biological pump (Loeb et al. 1997).

Sedimentation has been monitored throughout the annual cycle and over several years using sediment traps deployed in the Ross and Weddell Seas and off the Antarctic Peninsula. Sedimentation on the mid-continental shelf of the Antarctic Peninsula near 64° S ranges between 1%–10% of the annual primary production (1%–10% efficiency) with an annual flux of 0.5–4 gC m^{-2} y^{-1} and peak short term rates of 40–80 mgC m^{-2} d^{-1}. Particle flux exhibits extreme seasonality with a strong peak in the summer following the ice retreat and phytoplankton bloom when more than half the total flux may occur. In the Austral winter flux is generally negligible. The summertime peak includes both the remnant sea ice community, mostly pennate diatoms, as well as water column forms. The timing of the annual sedimentation episode is remarkably consistent, but the duration, amplitude, and total size (integrated flux) all exhibit significant interannual variability. In particular the annual sedimentation varied by nearly an order of magnitude over an 11-year observation period. In the Ross Sea sedimentation ranged from 2–14 gC m^{-2} y^{-1} with a strong north-south gradient from 73°–76° S (Collier et al. 2000). The peak flux occurs later than in the Peninsula with highest fluxes in March–April. Export efficiency as measured by sediment traps is quite low in both regions, indicating that much of the production is consumed and recycled in the upper 200 m.

Export efficiency is likely low because primary production is limited by iron availability over most of the Southern Ocean which is generally remote from continental sources of windborne dust. Iron limitation is seasonal in coastal regions and marginal ice zones and more persistent over the open sea.

Biogenic production can be in dissolved as well as particulate forms. A major difference between lower latitude and Antarctic polar ecosystems is the partitioning of organic carbon production and export between these two forms. In the subtropics dissolved organic carbon (DOC) may constitute up to half the export, with strong seasonal variation. However, the net production and subsequent export of DOC in higher southern latitudes appears to be negligible. In the Sargasso Sea, about 70% of the annual production flows through the dissolved phase, whereas in the Ross Sea about 70%–80% of the production remains in particulate form and sinks or is respired back to CO_2. The reasons for this global-scale contrast are not clearly understood, but they have important consequences for carbon storage in the deep sea.

Rapidly sinking particles are transported to greater depth before they are respired back to CO_2 than dissolved organic carbon, which depends on the slow mixing and sinking of water for downward transport. Thus organic carbon transport and storage is generally deeper in the Southern Ocean than in the subtropics.

Silicon Cycle

Diatoms are large phytoplankton (c. 20–200 μm long). They are the dominant primary producers in Antarctic waters and require silicon for growth. They have dense, ornamented opal plates or frustules covering their cells that serve as a deterrent to predation and, after the cell dies or loses buoyancy, enhance sinking rates. Thus besides their role as primary producers, diatoms are important vectors for export from the upper ocean. Silicon exists in seawater in dissolved form as silicate, Si(OH)4. The highest surface concentrations in the world ocean, 30–70 μM, are found in the Southern Ocean below the Antarctic Polar Front Zone (~60° S). These high concentrations, resulting from deep mixing, support the high diatom productivity. As a consequence of high production and rapid sinking rates, the sediments underlying the Southern Ocean are highly siliceous (>5% opal by weight) and account for about 50% of opal accumulation in the world ocean.

Silicate deposition (silicification) by diatoms is an active physiological process closely tied to cell wall synthesis and regulated by ambient nitrogen to iron concentration ratios in addition to silicate concentrations. When diatoms are iron-replete, cellular Si:N ratios are about 1 but can be much greater (~10) when iron is limiting, as it usually is in the Southern Ocean. This effect further enhances silica deposition in Antarctic waters. The opal cell wall is not a simple mineral covering, which would dissolve readily, but is instead deposited within an organic proteinaceous matrix maintained by the cell. Healthy active diatoms maintain neutral buoyancy by producing lipids, but buoyancy is lost when the cells die. As they sink, the protein matrix protecting the opal cell wall is attacked by bacteria through extracellular proteases (Bidle et al. 2002), exposing the opal to physical dissolution. The rates of proteolysis are a function of temperature, and are about three times faster at 20°C than at 2°C. In low latitude waters where surface temperatures are 10°C–30°C in the upper 500 m, diatoms rapidly lose their organic matrices, and opal dissolves before they sink into colder deep water. In the cold Southern Ocean the bacteria-enhanced decomposition and dissolution of the opal is inhibited, and the opal is preserved. Diatom dissolution and silicate remineralization was once believed to be a strictly chemical process but is now understood to be under strong biological as well as temperature control. This effect may explain the vast siliceous plains of sediment below the Southern Ocean.

Like other nutrients such as N and P, Si is stripped from surface ocean waters by biological uptake and sedimentation. If the organically bound silica were not remineralized back to silicate and returned to the surface by mixing and upwelling, diatom production would cease as the silica was depleted. Some fraction of the bound silica is regenerated *in situ* by bacteria and zooplankton, but most occurs in the midwater column between 100–500 m. The silica in this layer is returned to the surface, but not necessarily in the same geographic locations where it was originally fixed by diatoms and sank to depth. Diatom silicate produced in the Southern Ocean and regenerated in deeper water is transported horizontally in Subantarctic Mode Water (SAMW) far from its origin. SAMW sinks in the Subantarctic Zone and Antarctic Polar Front region and then flows north, spreading throughout the world ocean, returning to the surface in the upwelling regions of the eastern Pacific off South America and in the North Atlantic. In this way silica originally fixed by diatoms in the Antarctic is returned to surface waters to support diatom production globally. Computer simulation experiments suggest that silica in SAMW may support 75% of the diatom production north of 30° S latitude throughout the world ocean (Sarmiento et al. 2004).

Climate Change

The critical involvement of biological processes controlling geochemical cycles suggest that Southern Ocean element cycling may change greatly—though in still unexpected ways as climate warms in the next decades and centuries. Primary production, organic matter sedimentation, and silica cycling and deposition are all active biological processes under control by temperature and associated with the cycle and extent and duration of sea ice cover. As the Southern Ocean warms and sea ice declines, these processes will be altered, but it is not certain if they will increase or decrease. Primary production and sedimentation may decline if sea ice extent is the dominant control but could increase as more ocean area is exposed to solar irradiance. Ocean warming may enhance silica dissolution and retard the large-scale transport of Antarctic silica to remote regions, inhibiting primary production globally but increasing it locally. Biogeochemistry illustrates the important interplay of physical, chemical, physiological, and ecological processes governing the current, past and future state of the Earth System.

HUGH DUCKLOW

See also **Biodiversity, Marine; Carbon Cycle; Chemical Oceanography of the Southern Ocean; Climate Change Biology; Earth System, Antarctica as Part of; Ecosystem Functioning; Food Web, Marine; Mineralization; Phytoplankton; Polar Front; Productivity and Biomass; Zooplankton and Krill**

References and Further Reading

Bidle, K. D., M. Manganelli, and F. Azam. "Regulation of Oceanic Silicon and Carbon Preservation by Temperature Control on Bacteria." *Science* 298 (2002): 1980–1984.

Collier, R., J. Dymond, S. Honjo, S. Manganini, R. Francois, and R. Dunbar. "The Vertical Flux of Biogenic and Lithogenic Material in the Ross Sea: Moored Sediment Trap Observations 1996–1998." *Deep-Sea Research II* 47 (2000): 3491–3520.

Ducklow, H. W., D. K. Steinberg, and K. O. Buesseler. "Upper Ocean Carbon Export and the Biological Pump." *Oceanography* 14 (2001): 50–58.

Feely, R. A., C. L. Sabine, T. Takahashi, and R. Wanninkhof. "Uptake and Storage of Carbon Dioxide in the Ocean." *Oceanography* 14 (2001): 18–32.

Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. R. Fraser, W. Z. Trivelpiece, and S. G. Trivelpiece. "Effects of Sea-Ice Extent and Krill or Salp Dominance on the Antarctic Food Web." *Nature* 387 (1997): 897–900.

Sarmiento, J. L., N. Gruber, M. A. Brzezinski, and J. P. Dunne. "High-Latitude Controls of Thermocline Nutrients and Low Latitude Biological Productivity." *Nature* 427 (2004): 56–60.

Takahashi, T., S. C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R. A. Feely, C. Sabine, J. Olafsson, and Y. Nojiri. "Global Sea-Air CO_2 Flux Based on Climatological Surface Ocean pCO_2, and Seasonal Biological and Temperature Effects." *Deep-Sea Research II* 49 (2002): 1601–1622.

Volk, T., and M. I. Hoffert. "Ocean Carbon Pumps: Analysis of Relative Strengths and Efficiencies in Ocean-Driven Atmospheric CO_2 Changes." In *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present,* edited by E. T. Sundquist and W. S. Broecker. Washington, DC: American Geophysical Union, 1985, pp. 99–110.

SOUTHERN OCEAN CIRCULATION: MODELING

A fundamental problem in physical oceanography is determining the evolution of the state of the ocean over time. To do so, we have to solve equations for the ocean's momentum (mass times velocity) and its equation of state (essentially its density, a function of temperature, salinity, and pressure), and account for the constraint imposed by mass conservation. Those equations are complex, but numerical models with suitable boundary conditions have been widely used to simulate the circulation of the Southern Ocean. These models solve the pertinent equations on a discrete grid across time and space. For coarse resolution models, the horizontal grid spacing is typically 100–500 km, while high-resolution models have a grid spacing of 10–50 km or less. High-resolution models provide a more detailed description of the processes, but require much more computer time to perform a simulation. It is thus difficult to model the circulation at high resolution over long periods or large areas or to test hypotheses requiring a large number of simulations. Coarse and high-resolution models are thus complementary tools, the choice between them depending on the problem studied.

Models may cover domains ranging from a particular basin or region, in which case they can be at a relatively high resolution, to the entire Southern Ocean. In addition, the Southern Ocean provides the only deep connection between the Atlantic, Pacific, and Indian oceans; indeed, some of the Earth's major water masses acquire their characteristics in the Antarctic region before invading the other oceanic basins. It is therefore crucial to correctly reproduce the characteristics of this region in global models, which are widely used to analyze the Southern Ocean circulation, its global influence, and its response to remote changes.

Models must also take into account the influence of processes that occur at small scales, such as the turbulence that is responsible for vertical mixing near the sea surface. This usually involves parameterization of those processes (representation of physical effects in a model by simplified parameters), based on the dynamic equations and empirical evidence. High resolution models are able to simulate or permit the development and evolution of mesoscale eddies, swirling horizontal structures that are generally smaller than 100 km, whereas the influence of such eddies must be parameterized in coarse resolution models. This is particularly important for the Southern Ocean, where eddies play a large role in meridional (north–south) exchanges and in maintaining the vertical structure. Another difficulty of Southern Ocean modeling is the intrinsic coupling between ocean circulation and the sea-ice cover, which has a paramount influence at high latitudes on heat, salt and freshwater fluxes, as well as on stress exerted at the ocean surface. As a consequence, Southern Ocean models are generally coupled to a sea ice model and driven by atmospheric conditions derived from observations or