Remote Sensing of the Southern Ocean – Strategic Roadmap White Paper

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Polar regions are believed to be among the most sensitive to global change. They are also among the most difficult to study. Harsh conditions combined with their geographic isolation make it costly, difficult and dangerous to conduct research in polar regions using human expeditions. Consequently, satellite remote sensing offers unique advantages for polar research by providing observations of key parameters at spatial and temporal resolution not attainable by any other means. This information can and should be used to assess dynamics of these systems, the long-term changes in environmental conditions, and the consequences for the fragile ecosystems that struggle to survive at the ends of the Earth. This white paper addresses priorities for research on the Southern Ocean over the next decade, with particular application to Strategic Roadman Focus Area Number 8.

The Southern Ocean plays a critical role in regulating the partitioning of CO_2 between the ocean and atmosphere. Wind-driven upwelling in the Southern Ocean exposes deep waters to the atmosphere, where gases may be exchanged. It also supplies the euphotic zone with an abundance of nutrients, providing the potential for high levels of biological productivity. However, phytoplankton biomass and primary production in the Southern Ocean are low relative to levels that could be supported by available nutrients, a situation that has been termed the "Antarctic Paradox". The efficiency of the Southern Ocean's "biological pump", expressed as the fraction of available nutrients that is utilized by phytoplankton and exported to the deep sea as organic matter, is today only about half of its potential capacity. Consequently, the CO_2 content of the atmosphere is much greater than it would be if nutrients were utilized completely in the Southern Ocean.

Perturbing the Southern Ocean's biological pump may have a profound impact on the global carbon cycle. Recent models suggest that changes in biological productivity and nutrient utilization in the Southern Ocean could have been a major factor responsible for variability in the CO_2 content of the atmosphere over the past 400,000 years, as revealed by analysis of air bubbles trapped in Antarctic ice cores. Other models suggest that future changes in nutrient utilization efficiency of the Southern Ocean may play a key role in determining the amount of anthropogenic CO_2 that will ultimately be taken up by the ocean.

Several factors have been invoked to account for the low biomass and nutrient utilization in the Southern Ocean. These include light conditions that are unfavorable for phytoplankton growth (e.g., due to sea ice cover and deep mixed layers), grazing by zooplankton, low concentrations of iron (an essential micronutrient) and, in some regions, low concentrations of dissolved silicic acid (used by diatoms). Results from the U.S. Joint Global Ocean Flux Study (JGOFS) Antarctic Environment and Southern Ocean Process Study (AESOPS) indicate that each of these serves as a proximal factor limiting phytoplankton growth and nutrient utilization at certain times and in certain places within the Southern Ocean.

Recent process studies (e.g., JGOFS) and purposeful manipulations (e.g., iron enrichment experiments) have revealed new insights into phytoplankton growth and food web dynamics in the Southern Ocean. However, factors regulating year to year variability of

primary production, and the sensitivity of the Southern Ocean's biological pump to perturbation by climate change, remain largely unexplored. It is precisely these factors that may have induced the climate-related changes in atmospheric CO_2 levels recorded in ice cores, and these same factors may influence the rate at which the ocean takes up anthropogenic CO_2 in the future. Consequently, future research on the biological pump of the Southern Ocean must build upon the knowledge gained from recent studies to determine the ultimate factors regulating primary production, nutrient utilization, and carbon uptake over longer time scales.

Toward that objective, data from sensors aboard existing and planned satellites should be used to determine the response of primary and export production in the Southern Ocean to interannual variability in environmental conditions. Remote sensing can be used to characterize spatial and temporal variability of phytoplankton biomass, primary production, and nutrient utilization. Spatial and temporal variability of environmental conditions thought to regulate phytoplankton growth (e.g., sea ice cover, sea surface temperature, mixed layer depth) can also be derived from a combination of remote sensing and data-assimilative modeling. Statistical analyses can be used to identify relationships between environmental forcing and biological response. In addition, results of *in situ* studies since the early 1990s can be placed into the context of natural spatial and interannual variability provided by the satellite time series. Virtual process studies, combining remote sensing data with modeled parameters, can also be used to identify factors regulating spatial and temporal variability of phytoplankton biomass and biological productivity in the Southern Ocean.

Recent studies have revealed substantial and regular interannual variability of environmental conditions within the Southern Ocean. In some cases, this is linked to low-latitude modes of variability, such as the El Nino-Southern Oscillation (ENSO). In principle, one should be able to use this variability as a "natural laboratory" in which to investigate the biological response to changes in environmental forcing, and thereby ascertain the factors regulating year to year changes in primary production and nutrient utilization of the Southern Ocean.

Polar regions are among the most dynamic components of the Earth system. Historical data informs us that significant changes have occurred there in recent decades. The consequences for the organisms that live in the Southern Ocean have virtually been unexplored. NASA is uniquely positioned to study the changing dynamics of these regions, as well as the implications for living resources. For these reasons, studies of the biological response to changing conditions in the Southern Ocean should be a high priority for future NASA research.

The author served as coordinator of the US Joint Global Ocean Flux Study - Southern Ocean Process Study. Opinions and recommendations stated in this white paper are based on his experiences and lessons learned during the course of that program.