A New U.S. Polar Research Vessel (PRV): Science Drivers and Vessel Requirements

Final Report of the UNOLS PRV SMR Refresh Committee

Summary

U.S. interests in both polar regions are significant and are also rapidly increasing, driven in part by the effects of climate change and emerging geopolitical issues. Yet U.S. polar research has failed to keep pace with new and challenging science questions as they arise. Polar research requires specialized infrastructure, including icebreakers that can support science missions in the ice covered waters of the high latitudes. The nation currently lacks an ice-capable research vessel with which scientists can penetrate the ice-covered polar seas during most months of the year in Antarctica. Such a vessel is only available for a portion of the year in the Arctic. A new research icebreaker will allow the U.S. to more effectively pursue its priority polar research initiatives and ensure that the U.S. reestablishes a leadership role in polar marine science. The lead-time for funding, design, and construction of a new research icebreaker is on the order of 5 to 8 years. The new asset will serve the research community for at least 30 years. The PRV committee recommends that all efforts be made to ensure a timely start of an acquisition process.

The most important science drivers that justify a national investment in a new polar research vessel are described in this report and include understanding 1) the rates and processes controlling the extent of sea ice and glacial ice; 2) the outsized role of the polar oceans in the global climate system as well as the global carbon cycle; and 3) changes in polar marine ecosystems. New technologies are fostering innovative and transformative research in all of these areas. Access to a greater portion of the polar seas and during more months of the year is also required. Such access combined with the need to deploy new technologies determines the specifications for a new research icebreaker.

A careful review of science drivers and mission requirements leads to the following fundamental ship specification. The U.S. requires a research icebreaker that can approach ice sheet grounding zones and penetrate much of the polar sea ice pack during winter. This translates to a capability of transiting 1.5 m of sea ice at a speed of 3 kts (ice class PC3). This specification alone leads to minimum ship dimensions and propulsion requirements that then permit the incorporation of nearly all other important design features. The PRV committee recommends that the vessel have an endurance of 90 days, a range of 25,000 km, and an operating speed of 12 kts. The vessel should support up to 45 scientists in addition to crew and technical staff, and be capable of supporting science in the heavy seas of the open polar ocean as well as within sea ice. The ship design should include a large moonpool and the ability to support geotechnical drilling. Helicopter capability should be built in as well as design features for the use of autonomous vehicles, both marine and airborne. It is imperative that initial design studies be conducted immediately to better understand the extent that cost drivers impact overall project costs so that more informed decisions can be made on what is and is not included in the final vessel design.

A New U.S. Polar Research Vessel (PRV): Science Drivers and Vessel Requirements

Polar research requires specialized logistics and infrastructure, including icebreakers that can support science safely, efficiently, and effectively in the ice covered waters and rough seas of both polar regions. For the past 21 years, the research vessel *Nathaniel B. Palmer* (*NBP*) has provided the research community with an excellent platform for operations in areas that are within its limited icebreaking capabilities. Scientific discoveries from over 100 *NBP* cruises have transformed our understanding of the high latitude oceans and seafloor. Yet the vessel's limited ice capability and layout hampers our ability to build on these successes. High priority research questions with important ramifications for understanding global environmental change and its impacts remain unanswered. Addressing these issues is becoming increasingly important with the accelerating pace of global climate change and the amplification of its impacts in the high latitudes. Simply put, better access to ice-covered regions with a more capable icebreaker is required to address the most pressing research challenges. The PRV should incorporate enhanced capabilities as articulated by the research community to provide increased year-round access to a greater portion of the ice-covered seas.

The U.S. National Science Foundation is building *Sikuliaq*, a new ice-capable research vessel, but it cannot fill this gap in polar research capability. *Sikuliaq* will be less ice-capable than the *NBP* and is intended primarily for science operations in open water or first year ice in the Arctic, not as an icebreaker with medium ice capability or for regular use in the Southern Ocean. For U.S. ship-based polar research, particularly in Antarctica, there is inadequate ice capability beyond what *Sikuliaq* and the *NBP* are able to provide. The USCG Polar Class icebreakers have long since exceeded their service life and the limited research they once supported is now left undone, passed to foreign partners, or accomplished using contracted foreign flag icebreakers. This leaves *Healy*, the USCG's only other polar icebreaker, as the nation's sole vessel capable of conducting shipboard research in medium ice conditions. *Healy* is a successful research icebreaker with comparable ice capabilities to what is needed for the PRV, but its operational model limits science support to only six months per year with a focus on the Arctic. With the recent reduction in U.S. icebreaker assets, a predictable result has been realized; the global polar research enterprise is now primarily carried out on non-U.S. vessels (see appendix 6 for a table of new and planned polar research vessels around the globe). It is no longer the case that the majority of logistically demanding science projects are accomplished using American vessels. Although U.S. scientists continue to engage in collaborative research programs that make use of foreign resources they are often disadvantaged when it comes to setting the agenda. A new research icebreaker will allow the U.S. to more effectively pursue its priority polar research initiatives. It will also enhance international collaboration through science and logistics exchanges with other nations on a more equal footing. A new research icebreaker will ensure that the U.S. reestablishes a leadership role in polar marine science.

The Human Angle – Why the Polar Seas are Important

The polar regions provide important services to global ecosystems and mankind, ranging from food and energy to fresh water and reservoirs of biodiversity. Yet these regions are experiencing changes at rates that far outpace the rest of the planet. The coastal Arctic is home to indigenous communities that depend on marine ecosystem resources for subsistence food as they have done for centuries. These communities are impacted by climate change through coastal erosion, sea level rise, ice loss, and altered marine food webs, threatening the future of their subsistence lifestyle. Climate change has dramatically increased the melt rate of ice sheets and glaciers in both polar regions and has potential to significantly raise sea level worldwide. Oil and gas drilling as well as product transport in the Arctic has reached all-time high levels, in part because of reduced sea ice cover. Tourism is a growing industry at both poles, bringing more than

20,000 tourists each year to the western Antarctic Peninsula alone. Reduced ice cover increases the potential for extensive commercial shipping through the Arctic. The collateral effects of human activities include the potential for pollution of the marine environment, particularly through spills of hydrocarbons. Our ability to understand the effects of such activities and mishaps is limited, particularly in ice covered areas during winter.

In this report, we document the science drivers that provide a compelling argument for America's investment in a new polar research vessel. The research questions and initiatives described herein are strongly science-based but invariably address issues of importance to mankind's relation to the environment.

The Polar Research Vessel Science Mission Requirements (PRV SMR) Refresh Process

In December 2010, The National Science Foundation (NSF) tasked and funded the University-National Oceanographic Laboratory System (UNOLS) program office to establish a committee to review and update a 2006 Antarctic Research Vessel Oversight Committee (ARVOC) report on needs and requirements for a new U.S. polar research vessel. A 12 member multidisciplinary committee was formed and began meeting on January 7, 2011. Committee members were:

Robert Dunbar, Chair (Stanford University)
Vernon Asper (University of Southern Mississippi)
Eugene Domack (Hamilton College)
Bruce Huber (LDEO)
Daniel Oliver (University of Alaska)
Craig Smith (University of Hawaii)
Carin Ashjian (WHOI)
Dale Chayes (LDEO)
Hugh Ducklow (MBL)
Larry Lawver (University of Texas)
Doug Russell (University of Washington)
Maria Vernet (SIO-UCSD)

Jon Alberts represented the UNOLS Office at meetings. Committee charges were to:

- Update the science questions and review/modify the vessel science mission requirements defined in an ARVOC study conducted between 2002and2006.
- Articulate and evaluate emerging new science drivers.
- Utilize the UNOLS model for developing science mission requirements based on inclusive science community input
- Submit a report to NSF in two stages, with an interim report due in August 2011 and a final report due in early 2012.

The UNOLS Office created a survey designed to capture the community's vision of future scientific questions and associated ship requirements. We received 163 responses from the polar scientific and vessel logistics community. Additional and more nuanced contributions came from a UNOLS PRV workshop held at NSF headquarters in Arlington, VA, on February 28 and March 1, 2011. Sixty-six participants discussed science drivers for both Arctic and Antarctic research. Participants were asked to think across disciplines and 30 years into the future, the approximate lifespan of a new icebreaker. Committee members captured materials and viewpoints at the workshop. The PRV committee met again May 5-6, 2011 at Stanford University for discussion and report writing. After substantial committee review, an interim report was released publicly and to NSF for comment in August 2011.The PRV SMR committee met a final time at NSF headquarters on December 1-2, 2011 to discuss and incorporate comments and ideas received in response to the interim report. An updated interim report was posted at the UNOLS website on December 5, 2011, along with a final request for public comments. Following further revision the final report was released to NSF on February 10, 2012. The report starts with a focus on *Science Questions and Grand Challenges* in recognition that a strong scientific justification is of paramount importance for funding a new vessel.

Science Questions and Grand Challenges

Polar marine research is increasingly interdisciplinary, with many important science questions requiring approaches that depend on the careful integration of ideas derived from biology, ecology, earth science, chemistry, and physics. We expect further weakening of disciplinary boundaries in the decades ahead. As new interdisciplinary fields evolve the design specifications for polar research vessel are changing as well. Polar scientists envision using icebreakers as research platforms in new and different ways as fresh approaches to difficult problems and new technologies emerge. In describing science drivers for polar research over the next several decades we begin with two overarching and interdisciplinary "grand challenge" science questions.

Challenge 1.The Loss of Polar Ice: Understanding Processes and Thresholds

As our planet responds to ongoing climate change the most important polar systems to understand are the dynamic boundaries between ice sheets and the ocean (Figs.1 and 2). It is at these boundaries that parameters such as ice flow, seabed topography, and ocean temperature and circulation come together to regulate the transfer of continental ice into the ocean and thereby influence global sea level change. This environment is characterized by strong feedbacks suggesting the possibility of rapid sea level rise in response to ocean warming. For example, the loss of sea ice caused by warming enhances heat input into the ocean, and this in turn can speed the collapse of ice shelves. Disintegrating ice shelves then lead to the acceleration of continental ice discharge (Rignot et al., 2004, 2011).

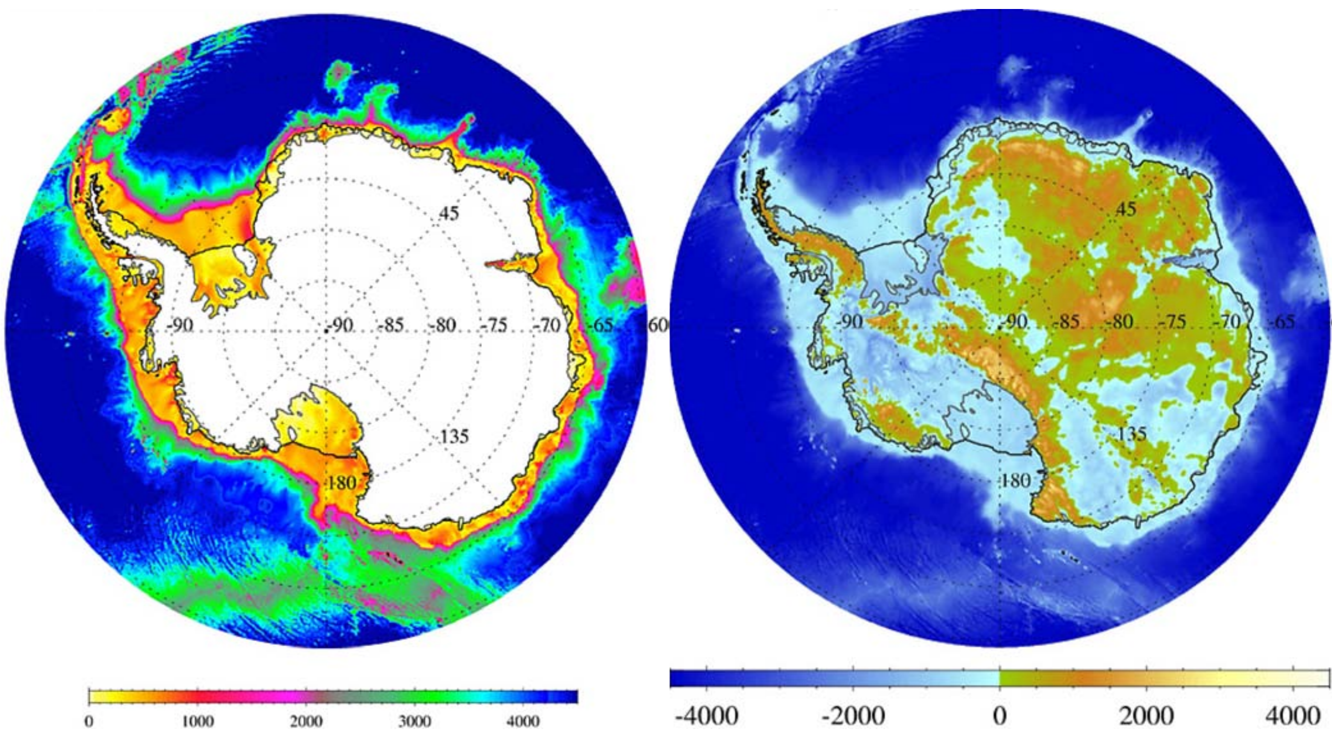


Figure 1. (a) Water depth (in meters) across the seafloor surrounding Antarctica and (b) elevation (in meters) of ice covered bedrock beneath the Antarctic ice sheet (from Timmerman et al., 2010). Note that depths >1000 meters are common on Antarctica's continental shelf. The areas in blue on the Antarctic continent in (b) are areas where the ice sheet is grounded below sea level. Ice grounded below sea level covers about 40% of Antarctica.

These processes at the interface between the continents and the ocean also have important biological and biogeochemical dimensions. Coastal polynyas in the vicinity of the great ice sheets are regions of enhanced biological productivity (Arrigo and van Dijken, 2003) and can act as strong sinks for atmospheric

CO_2 (Arrigo et al., 2008) as well as open water access areas for foraging and breeding mammals and seabirds. The input of trace metals required for phytoplankton growth, such as iron from glacier runoff and subglacial ice streams is an important subsidy fueling coastal blooms (Statham et al., 2008; Tremblay and Smith, 2007; Lin et al., 2011).As sea ice cover decreases and ice shelves collapse, new areas of ocean surface are exposed to sunlight for longer periods, increasing biological production (Peck et al. 2010; Montes-Hugo et al. 2009). Increased production of icebergs from ice shelf disintegration extends the influence of ice sheets into the open ocean by releasing freshwater and micronutrients and altering the pelagic ecosystem (Smith et al., 2007).

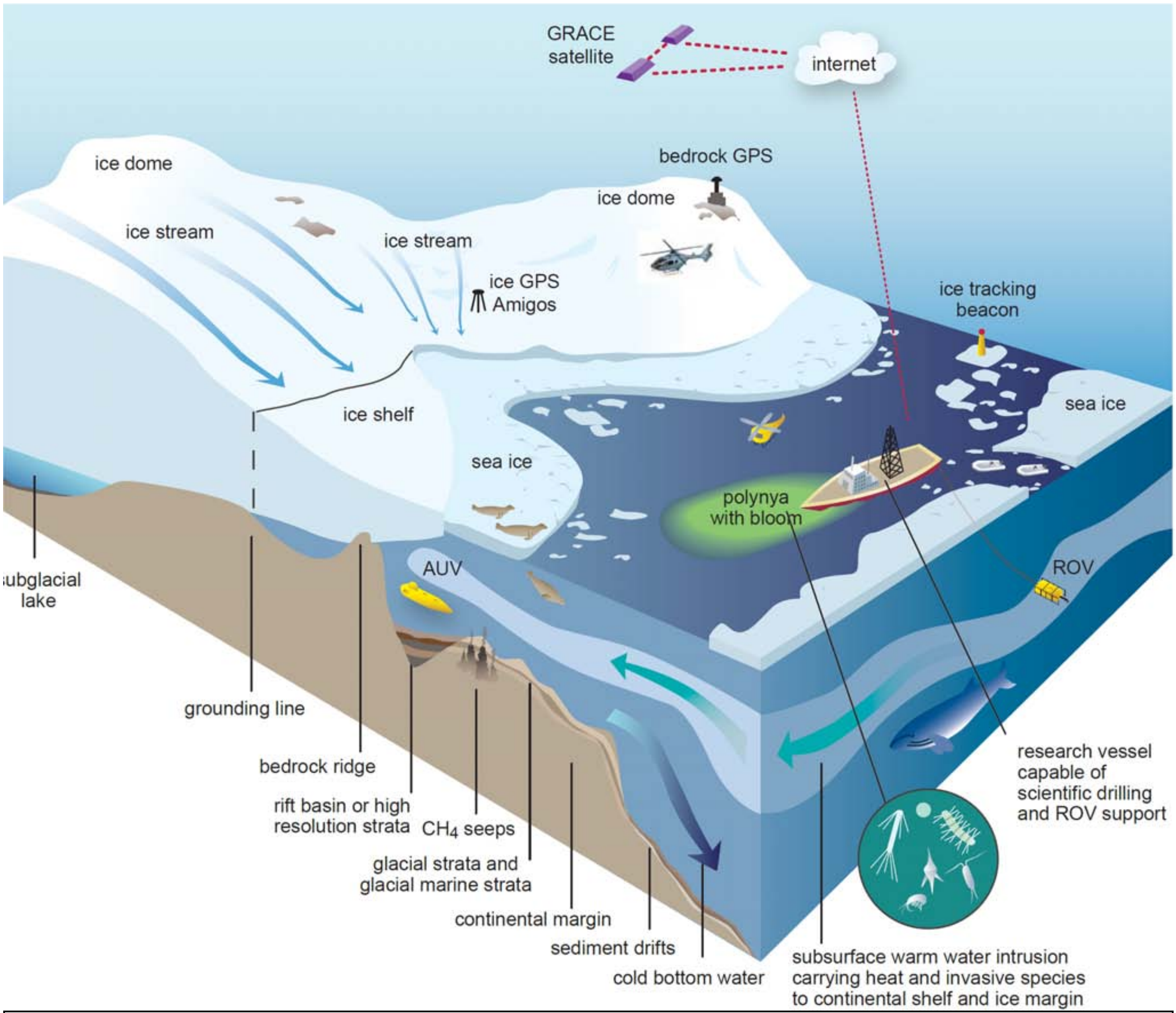


Figure 2.Schematic view of the operational and environmental settings in which a new US Polar Research Vessel and attendant instrumentation will be used.

While continental interior ice can be studied by airborne and on-ice geophysics, as well as via satellite remote sensing, analysis of key environmental conditions at the ice sheet-ocean boundary requires direct access and observation using marine research platforms. The area beneath Antarctic Ice Shelves (1.5 million km^2) is equal in size to the Sahara Desert or the Amazon basin, yet we have directly observed only a tiny fraction of this seascape. Even less well known are the grounding zones of outlet glaciers and ice streams that funnel continental ice into narrow channels along the submerged coast (Fig. 2). The importance of these two zones for understanding past and future sea level rise requires focused scientific efforts and evolving technologies. Such technologies include but are not limited to: Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), ship-to-air observation and deployment craft (unmanned sensor aircraft and helicopters), and an array of new bottom imaging sonar systems and sampling devices. Although some of these vehicles and moored systems operate unattended, they all require an icebreaker for deployment, servicing and recovery.

Challenge 2. What is the Role of the Polar Oceans in the Global Carbon Cycle?

The global ocean currently absorbs about 25% of the annual production of anthropogenic CO_2 (Friedlingstein et al. 2009). To predict the future course of global climate change, we need reliable models of oceanic uptake and storage of CO_2. The polar and subpolar seas figure prominently in such efforts because they are the primary conduits for CO_2 exchange between the ocean and atmosphere (Fig. 3). The Arctic Ocean comprises only 3% of the world ocean surface area yet accounts for 5 to 14% of the net global ocean C uptake each year (Cai et al., 2010). The southern high latitudes also exert an outsize influence on atmospheric greenhouse gas concentrations. Up to 30% of the net global atmosphere-to-ocean transfer of CO_2 occurs in the subpolar seas between 40°S and 55°S, facilitated by strong winds and deep mixing along density surfaces (Takahashi et al., 2002, 2009; Ho et al., 2006).

The processes that control high C uptake rates in polar and subpolar oceans are not yet well enough understood to permit credible forecasts for the future. The annual cycle of sea ice formation and melting, coupled with the high seasonal temperature range characteristic of the polar regions means that gas exchange between the ocean and the atmosphere exhibits strong signals with distinct annual cycles, especially in sea-ice zones. While all gasses are affected, carbon dioxide, oxygen, and other anthropogenic trace gasses such as chlorofluorocarbons are particularly dynamic in the cold polar seas. Uncertainty in estimates of oceanic CO_2 uptake (and the value of direct observations) is shown by Takahashi at al.'s (2009) recent downward revision of the total Southern Ocean share of global ocean CO_2uptake from 24 to 4%. In fact, the newest Takahashi et al. (2011) compilation suggests that a significant portion of Antarctica's seasonal sea ice zone may be a strong net source of CO_2 to the atmosphere. Little is known about the governing processes and this assessment is based primarily on summertime data. Recent observations suggest that in both the Arctic and Southern Ocean, the rate of CO_2 uptake is decreasing as sea ice extent declines and wind patterns change in response to a warming climate (Cai et al., 2010; Le Quéré, et al., 2007). It is clear that if Arctic or southern subpolar seas become less efficient C sinks or if polar Antarctic waters become stronger C sources, global atmospheric CO_2 levels will rise faster than currently predicted. Any reduction in the rate at which the ocean absorbs CO_2 has important consequences for the pace of global warming and our ability to predict it.

Accurate forecasting of the role of the polar oceans in the C cycle eludes us because C cycling in the water column is mediated by complex interactions between biological, chemical, and physical processes, including transformations within the food web. For example, food webs in polar seas are thought to be dominated by large plankton that produce large and fast-sinking fecal pellets, facilitating carbon export and thereby enhancing ocean uptake of atmospheric CO_2. Yet there are indications that smaller organisms may be replacing the classical food webs (Montes-Hugo et al., 2009), with uncertain consequences for future oceanic carbon uptake. Large seasonal and interannual variability, documented by atmospheric CO_2 measurements over the past 40 years, further complicates assessment of long-term oceanic CO_2 sequestration. Understanding this variability and determining whether or not the polar ocean carbon sink is declining (c.f., Le Quéré et al., 2007; Zickfeld et al., 2008) is of great importance for accurate forecasts of future climate change and ocean acidification. Major process studies in Antarctic and Arctic waters have elucidated controls on annual phytoplankton blooms and spring-summer variability in the annual cycle of C uptake, recycling, and flux to the deep sea (e.g., SO-JGOFS [Southern Ocean Joint Global Ocean Flux

Study; Smith et al., 2000], SBI[Western Arctic Shelf-Basin Interactions Project; Grebmeier et al., 2009], CORSACS [Controls on Ross Sea Algal Community Structure; Feng et al., 2010], IVARS [Interannual Variability in the Ross Sea; Smith et al., 2011], BEST/BSIERP [Bering Ecosystem Program; Sigler et al., 2010]). Autumn and winter, when deep water column overturn occurs and strong winds maximize air-sea gas exchange remain largely unstudied as existing research vessels have difficulty working during these seasons. Yet credible C budgets for the polar oceans will not be obtained until the full seasonal cycle of production, transport, and recycling is understood.

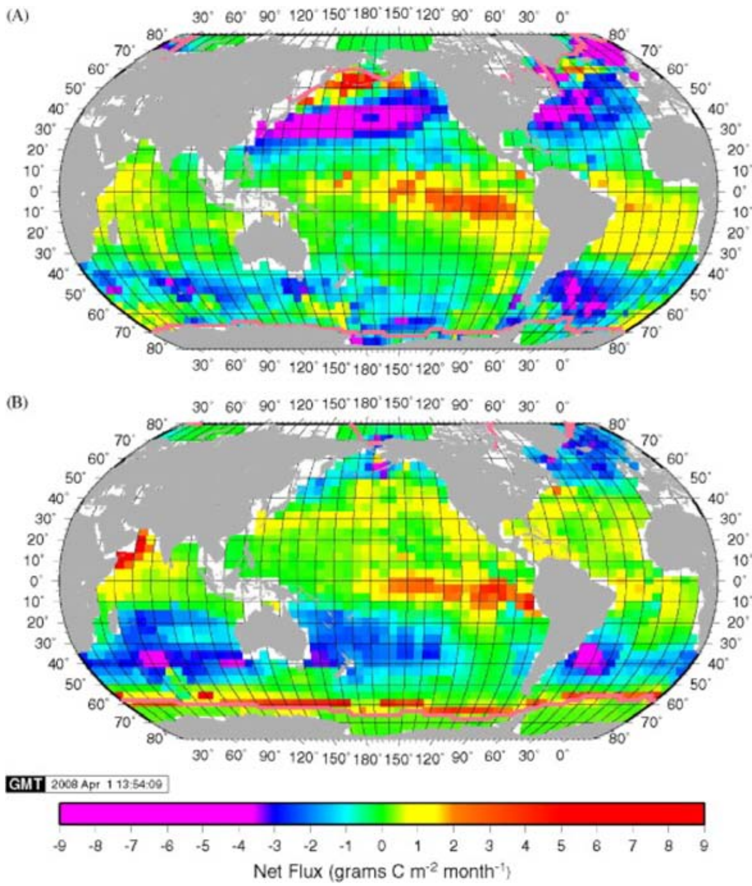


Figure 3.Mean sea–to-air CO_2 flux (g C m^{-2} $month^{-1}$) in February (A) and August (B) in the reference year 2000. Positive values (yellow–orange–red) indicate net sea-to-air fluxes, and negative values (blue–magenta) indicate net air-to-sea fluxes. Sea Ice boundaries shown as heavy pink lines are from NCEP/DOE 2 Reanalysis (2005). Figure and caption are from Takahashi et al. (2009). The polar and subpolar regions exhibit the highest fluxes across the air-sea boundary, both into and out of the ocean. These areas are also the least well-studied in terms of monitoring the magnitude and sign of CO_2 exchange as well as the processes that control air-sea gas transfer. The Antarctic sea ice edge and sea ice zone in winter (the pink band surrounding the continent in the lower panel) is a critical target for future research but is dependent on the acquisition of a more ice-capable research vessel.

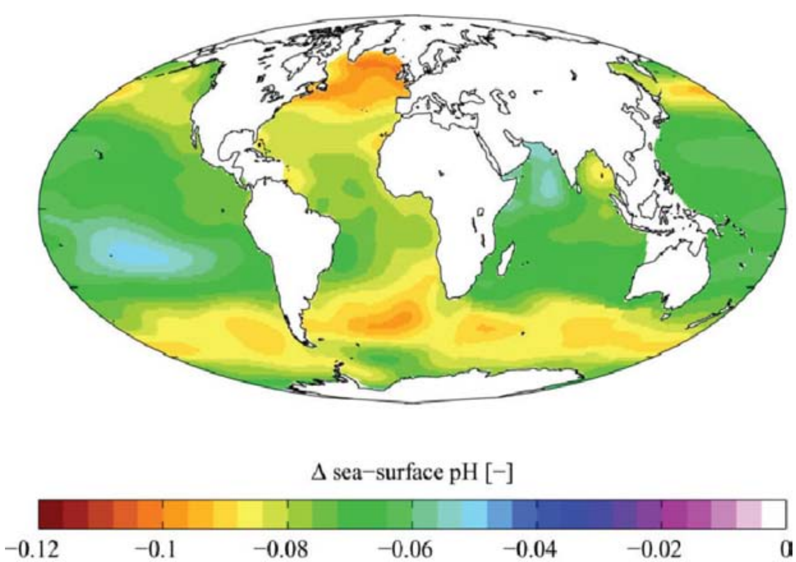


Figure 4. Estimated change in annual mean sea surface pH between the pre-industrial period (1700's and early 1800's) and the 1990's. Δ pH is in standard pH units and is calculated from fields of dissolved inorganic carbon and alkalinity from the Global Ocean Data Analysis Project (GLODAP) climatology (Sabine et al., 2005) and temperature and salinity from the World Ocean Atlas 2005 climatology (Locarnini et al., 2006; Antonov et al., 2006) using software created by Richard Zeebe. As excess CO_2 in the atmosphere is taken up by the ocean, pH declines. Lower temperatures in polar regions mean that larger pH reductions occur for any given CO_2 injection, relative to the warmer waters of the tropics and subtropics (Figure and caption modified from A. Yool, NOC UK).

Ocean acidification is an additional element of the polar ocean C cycle grand challenge. Because dissolved C speciation in seawater is temperature dependent, cold polar waters are experiencing the world's largest declines in pH as surface waters equilibrate with the rising CO_2 levels in the atmosphere (Fig. 4). Polar surface waters are projected to become under saturated this century with respect to several carbonate mineral phases, with as yet unknown consequences for shell-building polar organisms (e.g., Feely et al., 2004; Doney et al., 2009; Fabry et al., 2009). In fact, undersaturation has already been observed in regions of the Arctic well ahead of model predictions (Yamamoto-Kawai et al., 2009; Bates et al., 2009; Azetsu-Scott, et al., 2010). Thus it is clear that continued observations and process studies in ice-covered regions are urgently needed to test and improve the predictive capabilities of models. Ocean acidification also influences a wide variety of metabolic processes in non-carbonate producing organisms. Understanding the impact of ocean acidification on polar organisms is not only important for evaluating possible trophic cascade effects, it will also provide early insights into consequences for lower latitude seas where similar pH shifts are expected to be delayed by several decades.

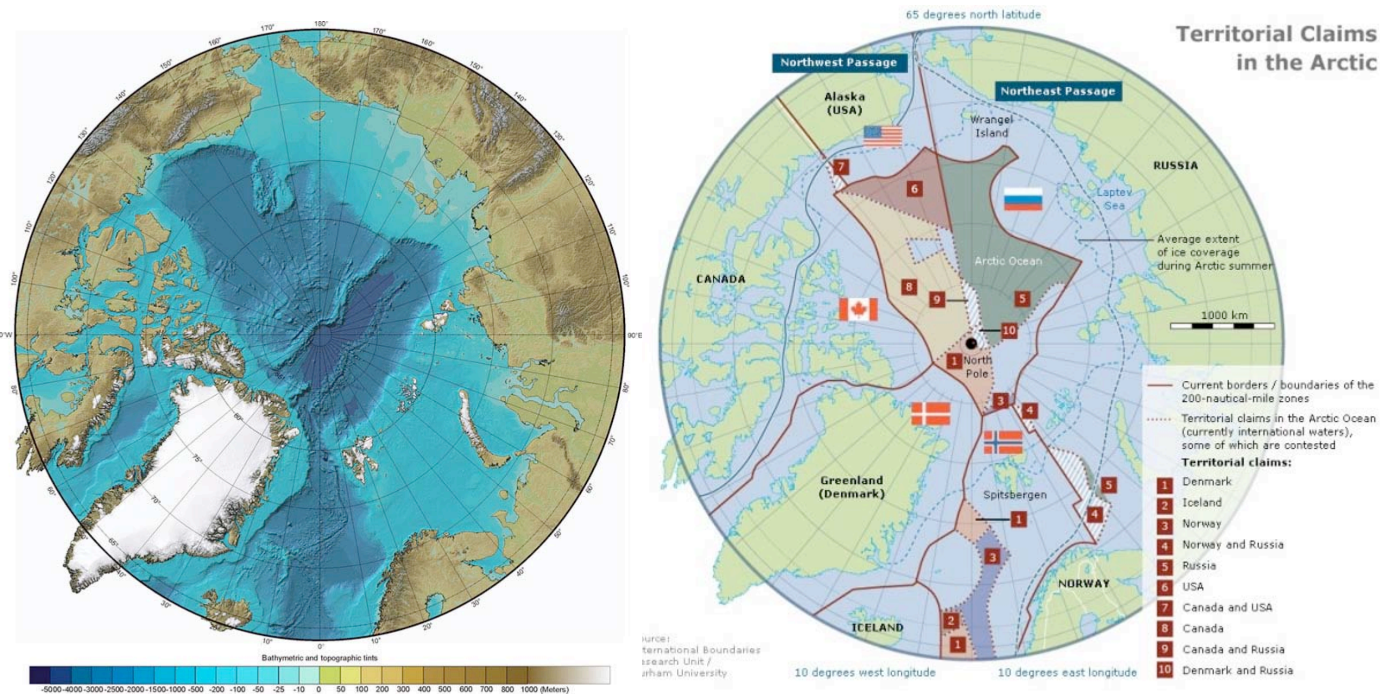


Figure 5.: (A) International Bathymetric Chart of the Arctic Ocean (produced by investigators representing the Intergovernmental Oceanographic Commission (IOC), the International Arctic Science Committee (IASC), the International Hydrographic Organization (IHO), the US Office of Naval Research (ONR), and the US National Geophysical Data Center (NGDC). (B) Territorial claims of 6 Arctic nations, current boundaries of the 200 nautical mile exclusive use zones, schematic northwest and northeast passage routes and average sea ice extent in summer (Graphic from Spiegel Online, 2011, using data from Durham University International Boundary Research Unit published in 2010). For updates to claim boundaries see: http://www.durham.ac.uk/ibru/resources/arctic.

Additional Science Questions Requiring an Increase in Polar Ocean Access

Here we describe additional important polar science questions articulated by the US science community.

What is the geologic nature and extent of the polar continental shelves and what natural resources do they contain?

The United States will benefit from a greater understanding of the geologic and tectonic structure of the Arctic and Antarctic regions for reasons of seabed sovereignty as well as natural resource assessment.

Geologic affinity is now part of the sovereignty criteria listed under the UN Convention on Law of the Sea (UNCLOS). Both Arctic and Southern Ocean nations are now conducting geophysical and geological surveys to advance territorial and sovereignty claims. This information is also directly relevant to understanding the role of the polar seas in the provision of future energy resources. Studies of one unconventional fossil C source, the widely dispersed clathrate deposits (methane and water "ice"), are urgently needed. Clathrates in the polar regions are viewed by some as large potential energy reserves; others view clathrates as dynamic C sources that could contribute dangerously to a warming climate. Both viewpoints require clarification of the characteristics of the marine geology of the polar regions.

How has life evolved in the polar regions in response to dramatic events in Earth history?

Here we address questions about how Earths past geologic and biotic systems have co-evolved in the polar regions under the unique conditions of extreme ice, temperature, tectonism, and oceanographic isolation. The recent National Research Council (2011) report, "Understanding Earth's Deep Past: Lessons for our Climate Future," describes how reconstructing environmental change during prior glaciated (icehouse) intervals and climatic transitions to deglaciated (hothouse) intervals can inform predictions of future climate change. Exploration of the interactions between geologic and oceanography history, adaptive radiations and paleocommunity structure will yield important new insights into the generation of evolutionary novelty and the ability of faunas to respond to rapid environmental change.

What is the temporal and spatial variability of glacial ice and water transfer to and from the oceans? How can polar marine research provide accurate assessments of the status of the Greenland and Antarctic Ice Sheets?

In its 4th assessment report, the Intergovernmental Panel on Climate Change (IPCC, 2007) concludes that the largest potential environmental and economic impacts from global warming will accrue from future sea level rise. The economic, social, and ecological costs of rising sea level are large for coastal regions of the U.S. and its territories, even under modest climate change scenarios (Leatherman, 2001; Lemkeet al., 2007; Vermeer and Rahmstorf, 2009). Given the paramount role of polar ice in driving future sea level rise, the past evolution of the earth's ice sheets and their current trajectories are critical avenues of investigation for the U.S. scientific community. While recent changes in sea level have been driven mostly by thermal expansion of the oceans and a cumulative reduction in alpine glaciers, ice caps, and ice sheets, the polar ice sheets alone are now believed to be, or will soon be, the dominant driver (Rignot et al. 2011).Rapid ice sheet-driven sea level change has occurred many 100's of times in the past and can be explored through marine geologic studies. Such research, particularly in ice sheet-proximal seas, provides valuable insights into rates of sea level rise as well as the dynamism of ice sheets (c.f., Naish et al., 2009).

Another significant development in our ability to measure ice mass change over short time intervals comes from the GRAvity and Climate Experiment (GRACE; Tapley et al., 2004). This NASA satellite platform estimates ice mass loss by measuring change in earth's gravity field over the relatively small scales spatial scales of individual ice drainage basins. These estimates are currently limited by the absence of information about isostatic adjustment of the earth's lithosphere to ice loading. This aspect of the earth system can be understood by measuring coastal uplift; either through studies of uplifted sediments and rocks or by establishing geophysical stations that measure crustal uplift directly (i.e., GPS systems). Both approaches are effectively implemented from research vessels with the capability to approach the Antarctic coastline and launch helicopters or a coastal workboat.

The polar marine geologic record is contained beneath the seafloor in water depths that range from 10's to 1000's of meters and in seas that are covered, sometimes year-round, in sea ice up to several meters thick. The broad continental shelves surrounding Antarctica and the Arctic Basin (Figs.1 and 5) have preserved a sedimentary record of past fluctuations of ice sheets in the form of buried strata as well as seafloor features that delineate the advance and retreat of ice sheets. Access to these regions and recovery of geologic records of past environmental change requires vessels with special characteristics and equipped with advanced instrumentation. While major strides have been made in the deployment of advanced technologies for coring in ice-covered seas (SHALDRIL[e.g., Michalchuk et al., 2009], ANDRILL [Naish et al., 2009], ACEX [Backman et al., 2005], MEBO [Freudenthal and Wefer, 2007], LPC [e.g., Curry et al., 2008; Mackintosh et al., 2011]),many remote regions that are key to understanding ice sheet volume change through time remain inaccessible because of current research vessel limitations. Improved access to ice-covered seas is the only way to answer questions regarding the evolution of the earth's ice sheets.

How are polar marine ecosystems and organisms adapted to extreme environmental conditions and how is this reflected in biodiversity and evolutionary novelty?

The adaptations of polar marine organisms to freezing temperatures, high salinities within sea ice brine channels (or low salinity when ice is melting), extreme boom-bust cycles in primary productivity, and long periods of darkness are unique. For example, anti-freeze proteins in fish blood, discovered 50 years ago in Antarctica, permit Antarctic and Arctic fishes to survive at -1.8^{o}C (~28^{o}F; Chen et al. 1997). Algae live within sea ice in spring and in ocean waters during summer, an adaptation that exposes them to sunlight early in spring as the polar night wanes. A polar marine ecosystem is a combination of species that are uniquely adapted to these extreme conditions and interact to create a system that often exhibits unanticipated properties. The timing of biological processes critical to the function of these ecosystems is tightly coupled to the march of the seasons. The temporal match (or mismatch) of key processes can affect an ecosystem as much as the appearance or disappearance of any of its component parts (e.g., Søreide et al., 2010; Leu et al. 2011). Marine ecosystems at both poles are isolated from surrounding seas, by the Polar Front/Antarctic Circumpolar Current in Antarctica and geography and, to a lesser extent by limited circulation in the Arctic. This geography serves to isolate genetic pools that store adaptations to extreme environmental conditions. Understanding the processes of adaptation at the molecular, cellular, organism, and system levels in the polar regions will increase our ever expanding view of life on Earth and also provide novel genetic and physiological information and for commercial applications.

How will unique polar marine ecosystems respond to climate change?

The potential effects of climate change on polar marine ecosystems are far-reaching and profound (e.g., ACIA, 2004; Ducklow et al., 2007; NAS, 2011). Even small changes in environmental conditions can have a significant impact on the structure and function of ecosystem components (Hsieh and Ohman, 2006; Li et al., 2009). The physical characteristics of the environment that structure polar ecosystems are varied, ranging from temperature and water circulation to precipitation and ice cover. For example, ongoing changes in the timing, extent, and quality of seasonal sea ice have a significant impact on ice-dependent organisms (Fig. 6) such as marine mammals and penguins that use sea ice as a substrate and larval krill that feed onepontic algae and micro-organisms (Ross et al., 2004; Bluhm and Gradinger, 2008). Changes in the distribution of water masses can result in the expansion or contraction of marine species ranges, including species invasions, as has been seen or predicted in the northern Bering Sea (e.g., Grebmeier et al., 2006) and along the Antarctic Peninsula (e.g., Ducklow et al., 2007; Nowacek et al., 2011; Smith et al., 2011). Alterations in the timing of ice and water column algal blooms relative to the timing of reproduction of plankton can result in a mismatch between the life cycles of grazers and prey and a failure of successful zooplankton reproduction (e.g., Søreide et al. 2010). Conversely, enhanced grazing opportunities in response to elevated primary production can lead to earlier reproduction and accelerated development of copepods (Ringuette et al. 2002). Prediction of impacts of climate change on polar marine ecosystems is compromised because our basic understanding of life cycles, trophic linkages, species distributions, winter ecology, and biological-physical interactions remains limited.

What is the role of polar marine ecosystems in the biogeochemical cycles of carbon and other elements?

Ocean carbon and nutrient storage is influenced by a complex array of interacting physical, chemical, and biological processes. Phytoplankton, zooplankton, and microbes in oceanic ecosystems fix CO_2 into organic matter, and package it into sinking particles that fall into the deep sea to join a long term C storage pool, where C is then isolated from the atmosphere for many 100's of years. This suite of biological interactions is called the Biological Pump, an ecological mechanism that pumps CO_2 from the ocean surface layer across a concentration gradient into the deep sea. Over geological time, variations in the Biological Pump are associated with large changes in the ocean carbon inventory and in atmospheric CO_2 that coincide with glacial-interglacial cycles (Sarmiento and Toggweiler, 1984). Our ability to predict the future of carbon storage in the polar oceans is strongly limited by the paucity of observations needed to define the magnitude and variability of the Biological Pump, especially in ice-covered waters during winter, in remote polynyas deep in the sea ice, and in coastal regions with high biological productivity.

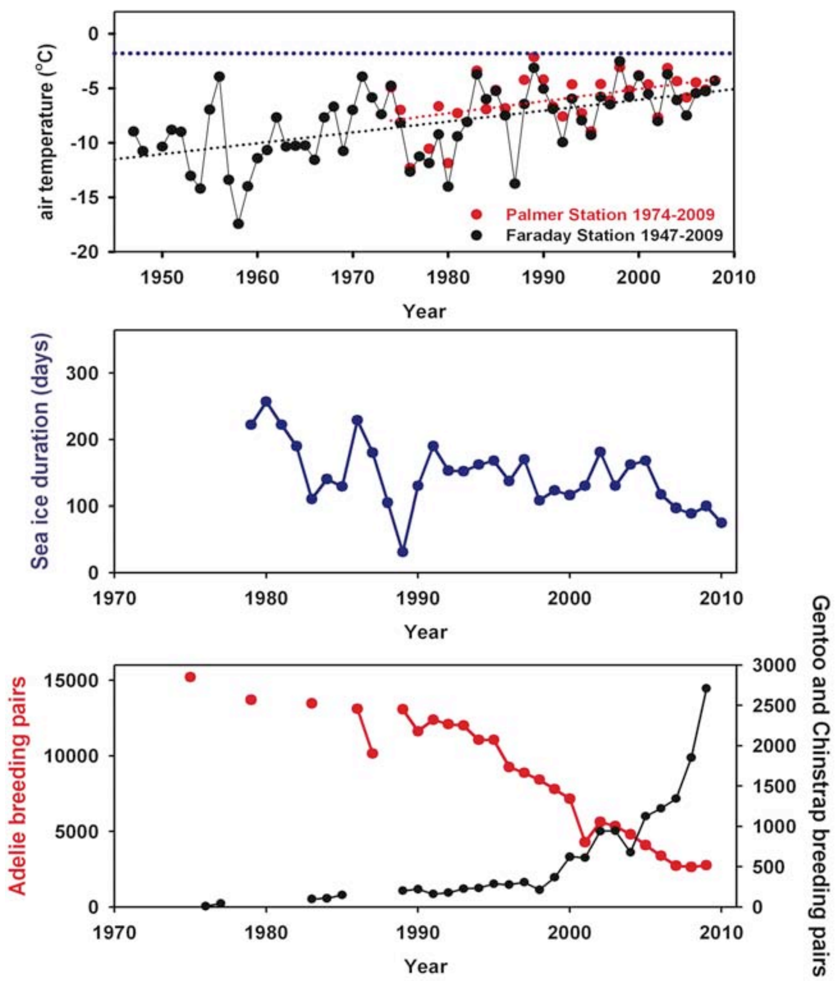


Figure 6.Climate variability and ecosystem response on the western Antarctic Peninsula. Top: surface air temperature at Vernadsky (previously Faraday) Station from 1947 to 2009 (black) and Palmer Station, from 1974 to 2009 (red). The blue dotted line is the surface freezing point of seawater (-1.8°C). Middle: duration of sea ice cover at Palmer Station from 1978 to 2010. Bottom: penguin population trends for declining ice-dependent Adélies (red) being replaced by Gentoos and Chinstraps (black) taking over the habitat, near Palmer Station from 1975 to 2010 (see Ducklow, 2007). Plots constructed using data from Palmer Long Term Ecological research project:http://oceaninformatics.ucsd.edu/datazoo/data/pallter/datasets.

How do changes in freshwater cycling in the polar regions affect earth system processes and biogeochemical cycles?

The salinity of polar surface waters is controlled by the balance between the formation and melting of sea ice, the input of fresh water from melting glaciers, evaporation, precipitation and runoff from continental areas. Surface ocean salinity influences the production rate and properties of deep and bottom waters formed in the polar oceans, a process with profound global impacts (Trevena at al., 2008a and 2008b). Variability in salt and fresh water fluxes in the polar regions impacts the global thermohaline circulation, influencing meridional ocean heat transport and global climate (Visbeck, 1995). Through its influence on the formation of deep and bottom waters, the polar surface water balance impacts important biogeochemical parameters, including the distribution of nutrients, coastal turbidity and sedimentation, oxygen levels in the sea, the isotopic composition of the ocean, and the pool of dissolved organic carbon (Sarmiento et al., 2004; Sarmiento et al., 2007). Substantial alterations to freshwater cycling in the marine context are occurring in the North Atlantic and these are tied to changes in sea ice and freshwater circulation within the Arctic in ways that have yet to be completely understood (Dickson et al., 2008). Similarly substantial changes are expected to occur in areas of persistent sea-ice cover along the Antarctic continental margin. A research vessel with ice-breaking capabilities is required to monitor and understand the mechanisms driving these changes that are tied to our global climate patterns.

What role do trace metals and similar compounds have on polar ecosystems and how can they be used to understand the complex processes taking place in these areas?

Many elements and compounds that are present in the ocean in trace amounts participate in fundamental ocean processes. By monitoring their concentration, distribution, and rates of change, polar scientists gain valuable new insights into these processes. Much of this material derives from the accumulation of dust on sea ice so that it is injected into the upper ocean as the ice melts each spring. In some cases, iron for example, this pulse represents a nutrient spike that can dramatically affect phytoplankton production. This process begins early in the growing season and has therefore been difficult to study due to ice concentrations and the limitations of existing vessels. Investigation of these processes requires the use of facilities that minimize the risk of contamination from the ship and sampling gear and these considerations require careful planning in ship design in order to be effective.

Understanding the ocean heat sink – where does the heat go as the climate warms and what is the impact on the Southern Ocean and Antarctica? How do we best predict trajectories of change in the polar regions as well uncertainties in the forecast?

The upper portion of the global ocean has absorbed the majority of the "extra" heat produced via atmospheric warming of the past century (Levitus et al., 2005, 2009; Barnett et al., 2005; Gouretski and Resghetti, 2010; Lyman et al., 2010) with the greatest penetration to depth occurring in the high latitudes (Gille, 2002; Purkey and Johnson, 2010). This heat content anomaly has mixed into the waters of the Antarctic Circumpolar Current (ACC) (Figs.7 and 8). The proximity of a warmer ACC to Antarctica's continental shelf and ice margin roughly correlates with regional ice sheet melt rates as estimated from satellite observations (Fig.7; Rignot et al., 2008). This heat also appears to be affecting the Greenland Ice Sheet (Holland et al., 2008; Straneo et al., 2010). Given the potential role of direct ocean transfer in the acceleration of continental ice loss and sea level rise, we see a critical need for observing and understanding processes by which heat exchange occurs within the Arctic and Southern Oceans and between the high and mid-latitudes.

The underlying processes that control the climate of the polar regions occupy time and spatial scales ranging from seconds and millimeters to weeks and kilometers. Small scale phenomena generally are associated with low density gradients while relatively large effects are caused by the earth's rotation at small horizontal scales. Yet air-sea-ice interactions at even the smallest scales can have profound impacts on regional oceanography, ice, and ecosystems. Recent advances in observing and understanding the role of eddies in deep mixing (Adams, et al., 2011) and the subtle interplay of wind and frontal dynamics in energy dissipation and mixing (D'Assaro, et al. 2011) highlight the need for future process studies aiming to achieve a broader understanding of how polar oceans and climates function. Such process studies require platforms with the flexibility to deploy new measurement technologies in a broad range of sea-ice condition as well as with the agility required to capture these often elusive processes.

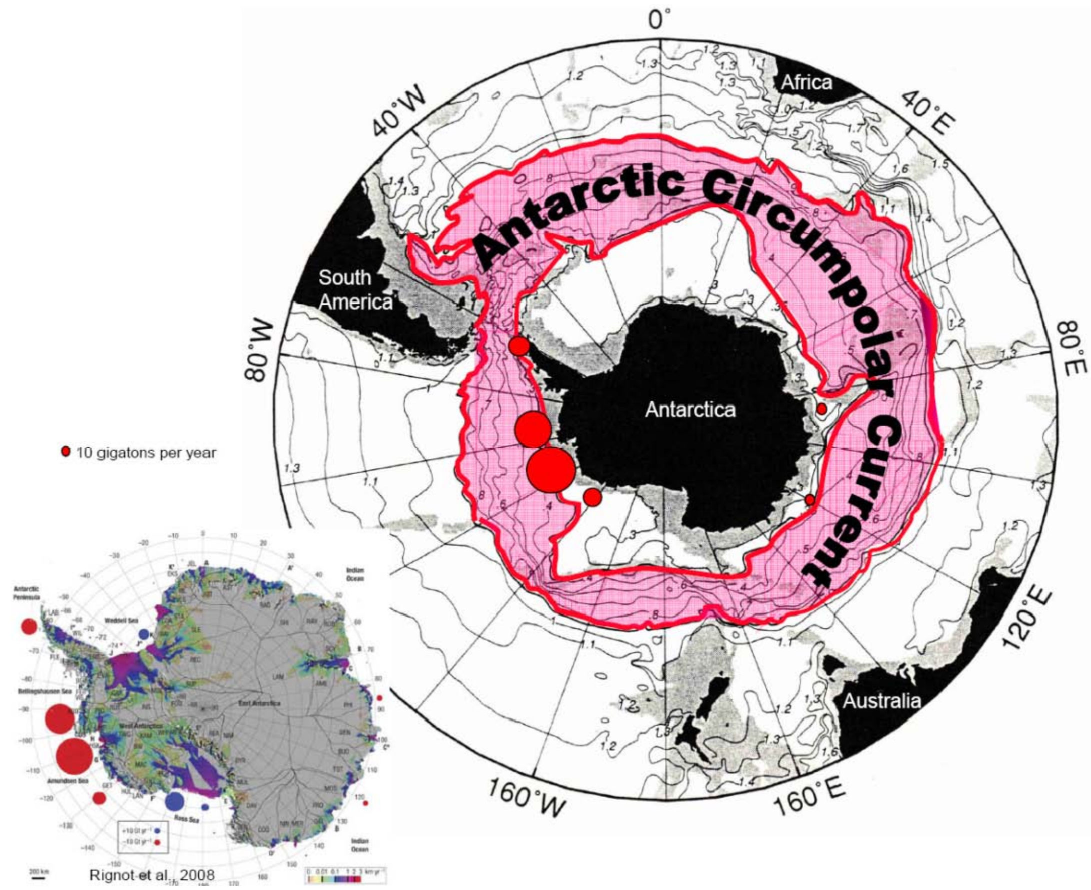


Figure 7. The Antarctic Circumpolar Current (ACC – pink area between red lines) circulates Upper Circumpolar Deep Water (UCDW) around the continent. This is the water mass that has been identified as a major (if not the primary) reason for the observed acceleration of glacial melt in the Amundsen Sea Embayment, a principle drainage region for the West Antarctic Ice Sheet. In this diagram, the red circles show areas of significant loss of ice to the oceans (from Rignot et al., 2008, where size of the circle correlates with amount of ice loss). The UCDW is effective in melting glacier ice in these areas as they correspond to locations where the ACC delivers warm water close to the coast (figure and caption from Doug Martinson, LDEO; location of ACC from Orsi et al., 1995). Insert: color patterns on Antarctica illustrate velocity of glacial flow and convergence of ice steaming (blue to white) into major outlet systems (after Bamber et al., 2000). Red circles relate to the magnitude of negative mass balance for adjacent outlet systems (Rignot et al., 2008).

How does the ocean interact with ice shelves?

Large or increasing melt rates of floating ice shelves have garnered much attention by the research community and the public. Most of Antarctica's ice shelves are in regions where relatively warm Circumpolar Deep Water (CDW) is in close proximity to the continental shelf break, potentially providing ready access to the underside of the ice shelves to enhance ice shelf melting rates or grounding line recession. However, there are vast ice shelves in regions that are not exposed to the direct influence of CDW – among these are the Ronne-Filchner, and Larsen B and C ice shelves of the Weddell Sea. The interaction of these ice shelves with the underlying near-freezing seawater is a crucial component of the suite of processes responsible for generating the water mass properties of Antarctic Bottom Water. We can infer some of the details of ice/ocean interactions by observing the water mass properties of the products of the interactions (Nicholls et al., 2009, Holland et al, 2008; Johnson et al., 2011). Yet we have only a handful of direct observations under the ice shelves that can lead us to a better understanding of the physics involved in the complex melting/refreezing/buoyancy exchange processes that occur when near-freezing sea water is proximal to an ice shelf (Jenkins et al., 2010). New technologies such as AUVs will eventually provide us with the tools necessary to make small scale observations under the floating ice sheets. But fully utilizing such tools will require deployment and recovery of AUVs and ROVS in zones of difficult ice conditions (such as the western Weddell in front of the Larsen C ice shelf).

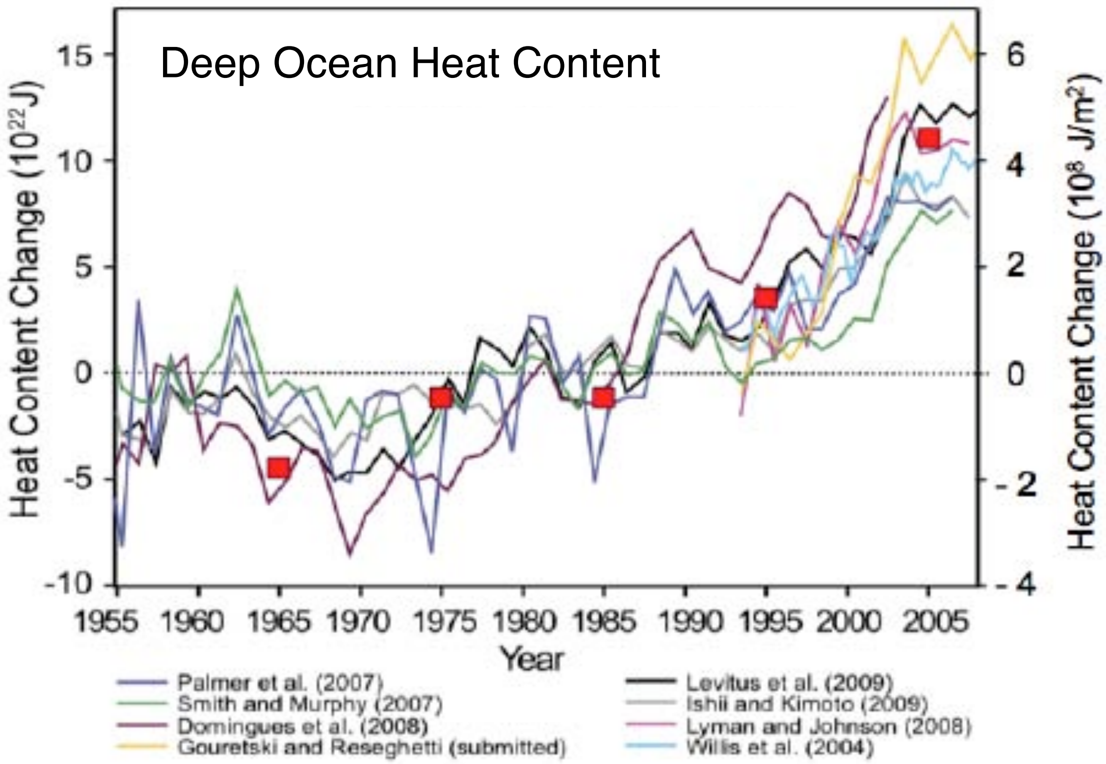


Figure 8.Solid lines show results from 8 independent studies confirming the transfer of heat from global warming into global deep waters. All ocean basins have southward-moving currents that must deliver this warm water to the ACC. Red squares show the measured increase in upper water column heat content of the UCDW (e.g., water that can impact the continental shelf) in the Palmer Long Term Ecological Research domain on the west side of the Antarctic Peninsula. This comparison shows that globally derived excess heat arrives at the coast of Western Antarctica (figure and caption from Doug Martinson, LDEO, Data sets from Palmer et al., 2007; Smith and Murphy, 2007; Domingues et al., 2008, Gouretski and Reseghetti, 2010; Levitus et al., 2009, Ishii and Kimoto, 2009; Lyman and Johnson, 2008; Willis et al.. 2004).

What are the dynamics and thermodynamics of polynyas and associated convective processes? How are ventilation rates of the deep ocean impacted by deep water formation at the poles?

Significant fluxes from surface waters to the deep ocean occur at both poles through the agency of polynyas and their attendant convective physics. These fluxes can be most significant in hard-to-reach ice covered regions during the early spring and winter, periods for which there are few direct observations. Little is known about the onset of large polynya formation in the Antarctic, especially in regions such as the southern Ross Sea. Satellite data notwithstanding, there are few direct observations of conditions attending the initial formation of large Antarctic polynyas. Direct winter observations of shore leads (or ice front polynyas) which ring the Antarctic continent are also rare. Convective processes in shore leads can induce local along-shore currents which can be baroclinically unstable, shedding eddies that contribute to the cross-shelf fluxes of water masses (Nicholls et al., 2009). Understanding these processes is critical to elucidating the processes of deep water formation and ventilation of the world's oceans. Access allowing the study of these polynyas year round requires a highly flexible, highly ice-capable research vessel.

Deep and bottom waters forming around Antarctica are the source of water masses that escape the Southern Ocean to fill the world oceans' abyssal depths. Since the processes by which these waters form include interactions with the polar atmosphere and Antarctic ice shelves, the properties of deep and bottom waters are imprinted with changes in the climate and ice regime of the Antarctic continent and margin. Limited long-term observations of the properties of newly-formed Antarctic deep waters have revealed surprising variability in temperature, which can be linked to large-scale climate variability (Gordon, et al. 2010; McKee, et al., 2011). As sensitive indicators of climate variability with a strong connection to the global thermohaline circulation (Johnson, et al. 2008; Purkey and Johnson, 2010), it is important to expand our ability to measure the properties and rates of deep ventilation at key sites around Antarctica, and to maintain those observations. Presently, such measurements are made by either repeatedly occupying oceanographic sections with profiling instruments (CTDs) or by installing and maintaining moored instruments. Both approaches are vessel-intensive and subject to limitations imposed by ice cover. Newer tools are becoming available, such as profiling floats, and long-range gliders, but these too require an ice-capable platform for launch and recovery.

Mission Statement and Science Mission Requirements- Polar Research Vessel

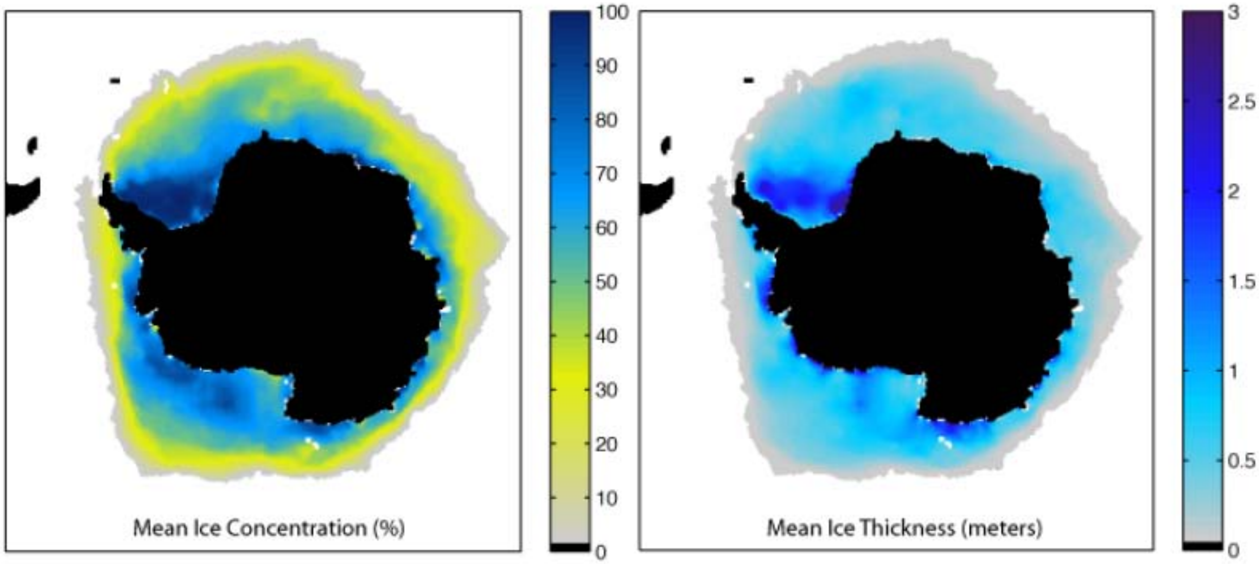
A new U.S. Polar Research Vessel (PRV) will provide improved access to the polar regions of the world. The ability to reach further into ice covered waters on a year round basis will significantly advance our understanding of global environmental change and the oceanographic processes that impact long term stability of polar ice sheets and ecosystems. The new ship will carry scientific teams to study the impacts of climate change on polar physical and biological systems. The ship will ensure that the US achieves and maintains a global leadership role in polar marine science as well as in setting the polar research agenda. Improved understanding of the polar regions will also affect political sovereignty.

The PRV SMR committee strongly recommends that the new vessel be designed using broad community input and planning for ever increasing interdisciplinary science demands. The ship will serve as a general purpose research vessel capable of operating safely in ice covered waters as well as the rough seas common in ice-free polar regions. Access to the sea ice zone in winter, to remote polynyas, and to nearshore coastal regions are essential elements for vessel design. The ship will provide increased access to areas we have not been able to reach with previous U.S. vessels. Laboratories should be designed to support interdisciplinary research teams. Significant advances in green technologies aimed at reducing operating costs as well protecting the environment will be incorporated. Compliance with new environmental regulations, such as emissions and discharges, is required. Vessel design should incorporate several new features aimed at promoting flexible use and reconfiguration for science missions.

Science Mission Requirements

The purpose of the science mission requirements (SMR) survey is to thoughtfully develop design features and parameters for use as guidelines during vessel design. A key concept is that ship systems are integrated with the science mission for the research platform. The SMR states with as much specificity as possible what attributes the ship must have to perform the science missions envisioned. The SMR provides a science capability framework for the steps between community input, vessel concept design, and final construction. Although mission requirements and technology change with time, the SMR represents broad community consensus of what the ship must have.

We utilized the University-National Oceanographic Laboratory System (UNOLS) SMR process. A summary view of ship requirements is given below. A more detailed tabulation and description of requirements and design elements is given in Appendices 1-3. Appendix 4 links specific design elements to science drivers.



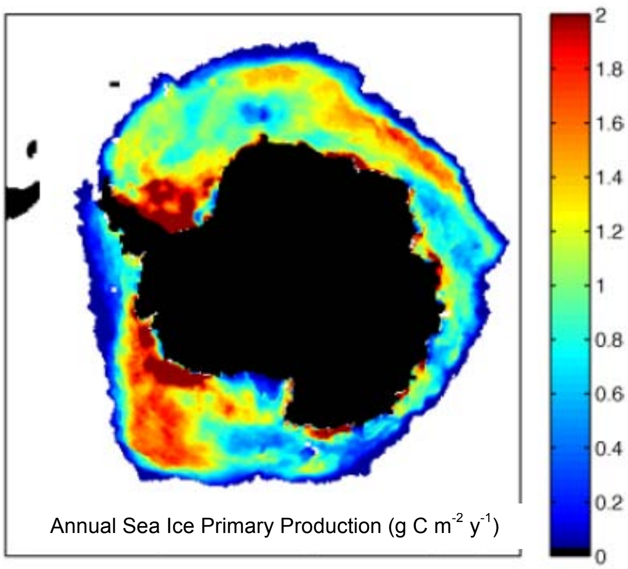


Figure 9. Mean sea ice concentration from satellite data (upper left). Ice thickness (upper right) is model-generated but validated via matching to ASPECT ice and snow thickness observations (Worby et al. 2008). Lower left panel shows modeled annual sea ice primary production from sea ice algae (Saenz, 2011). We are currently unable to reliably work in areas with ice cover >70% and ice thickness over 1 meter (the dark blue portions of the upper maps). Some of these areas are important biological hotspots about which we know little because of access difficulties. A new PRV with the specifications described in this PRV SMR report will allow scientists to reach all areas of the margin during at least part of the year and some of the sea ice thickness over 1 m throughout the year.

Translation of science drivers into sampling needs, technologies, locations

Most shipboard polar research has been conducted during the late spring through early autumn. In the Antarctic, research has mostly been limited to marginal ice zone areas that are accessible with the current icebreaking capability of the NBP. Field research has been more extensive in the Arctic because of the greater ice breaking capability of the Polar Class icebreakers and USCGC *Healy* relative to the NBP. However, little ship-based work has been done during the polar winter, early spring, or late autumn at either pole, or in areas of year-round heavy ice cover, particularly in the Antarctic. Fig. 9 shows data- and model-based estimates of mean sea ice cover and thickness, as well as annual sea ice primary production for the Antarctic margin. Areas that have proven difficult or impossible for the NBP to access are shown in dark blue in the upper left-hand figure (e.g., >70% ice cover and ice thickness exceeding 1 m). Yet many of these areas are important biologically (Fig. 9, bottom panel), biogeochemically, and in terms of ocean physics, and must be studied to provide a view of Antarctica's role in a variety of globally-significant processes. Moored or tethered autonomous sampling systems, while valuable for describing annual cycles, cannot yet quantify many key biological and biogeochemical processes (e.g., rates, population structure, community composition, trophic linkages, and species-specific standing stocks, C fluxes, air-sea exchange, nutrient dynamics). Nor can moorings provide information on spatial variability both within and between oceanic regions. ***Year-round access using a capable vessel from which to measure, observe, and describe and understand ecosystem structure and function, physical and biogeochemical linkages, and the impact of physical drivers is needed to adequately understand ongoing changes in polar ecosystems.***

Ice breaking performance should allow access to ice sheet and ice shelf marginal areas during most months of the year. Our current observational shortcomings can be alleviated to some extent by increased reliance on autonomous platforms such as AUVs, moorings, and satellites, but a new PRV with enhanced icebreaking capability is required to deploy these assets in areas currently inaccessible to U.S. oceanographers. In addition, experimentation with polar marine organisms is carried out almost exclusively on board ships and in their natural habitats since they are difficult to keep alive in the laboratory or during transport to shore facilities. A new vessel should accommodate a larger scientific and technical crew in well-quipped labs in order to perform the next generation of interdisciplinary experiments and observations.

Capabilities and costs of a new Polar Research Vessel

Considerable expertise was assembled during our March, 2011, workshop to assist the PRV SMR committee in translating science needs into vessel requirements. The following list of items includes essential characteristics. We have used examples of current instrumentation. These examples are not intended as an endorsement of a specific model or manufacturer, nor do we expect these specific instruments to actually be installed on the ship when it is eventually built. They are used as a way to briefly capture the capabilities we have in mind. We recommend that the operating institution, with active participation from the science community (scientists and technical personnel) perform a careful re-assessment of the available systems as close as practical to construction.

There are two fundamental factors that drive the size and consequently the cost of a new Polar Research Vessel. In order to pursue the scientific objectives of a new PRV, a class PC3 icebreaker (1.5m of ice at 3 kts) is required that has an endurance of 90 days in order to reach presently unexplored Polar regions. These two criteria dictate a vessel that will provide the berths, deck configurations, and lab space considered adequate for cutting-edge research. Additional features of any new research vessel in the 21st century that increase the basic cost include multibeam and bottom penetrating systems, workboat capability, a science mast for atmospheric measurements and dynamic positioning for station work. Cost items that will enhance research capabilities include the requirements for an acoustically quiet ship both concerning habitability and noise radiated into the environment, ability to operate in difficult sea states, helicopter operations to service shore experiments and on ice work distant from the ship, a moon pool that will facilitate ROV/AUV launch and recovery operations in ice covered regions, geotechnical drilling, and capability for seismic collection operations.

Essential PRV Capabilities

1) A new PRV must be able to approach modern ice sheet grounding zones, regardless of typical sea ice conditions, i.e., capable of navigating 50 km transects through moderately heavy sea ice (up to 1.5 m).

2) Similarly, a new PRV must be able to transit independently through winter pack ice to reach coastal polynyas (requiring longer transects through ice up to 1.5 m thick) and be able to operate in both polar regions year-round. The committee notes that solo winter access to the central Arctic area will require greater icebreaking capability than we envision for this PRV.

3) The vessel must have sea-keeping capabilities that permit work in the rough seas of the Southern Ocean and sufficient environmental control to allow year round work in polar seas.

4) A new PRV must be able to host and deploy/recover Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV), both with a wide variety of capabilities. Most likely, such operations will take place in ice covered seas and hence vehicles will be needed to be deployed through a moon pool or over the side after ice clearing.

5) A new PRV should be designed with labs and berthing to accommodate up to 45 scientists in addition to the on-board technical support and ship's crew.

6) Multiple large laboratories designed to support advanced biological and chemical analyses and experiments, including clean sites for genomics and trace organic and metals analysis and sample preparation, and to accommodate modern analytical instrumentation.

7) The vessel must be equipped to acquire long stratigraphic sections (50 m via a jumbo piston core or other long core system) and be capable of accommodating temporarily-installed geotechnical drilling to 100 m below sea floor, at water depths of up to 1200 m.

8) The vessel must be able to core sedimentary sections in ice-covered seas and should be able to support drilling operations as allowed by sea ice movement and available ice-clearing assistance.

9) A new PRV must be able to operate seismic gear, including towing long multi-channel streamers and a moderate source array, while underway at speeds of 3.5 to 4.5 kts in moderate (three to four tenths) sea ice cover.

10) The new vessel should be equipped with reliable, well-known multibeam swath mapping echo sounders installed behind ice protection windows. Given the expected range of water depths this will require both a deep-sea multibeam such as a Kongsberg EM122™ and a shallow water system such as an EM710™for high quality data collection on continental shelves and upper slopes. Supporting equipment for the multibeam systems will include primary and backup attitude, position, and heading reference providers, such as the Applanix POS/MV™.

11) The vessel should be equipped with a reliable, ice-protected, hull mounted sub-bottom profiler operating in the 3.5 kHz range. Typical systems are either FM-modulated (CHIRP) such as a Knudsen 3260™, parametric (narrow beam) system such as an Atlas Parasound™ or Kongsberg Topas™. The sub-bottom may be integrated with the multibeam, e.g. Kongsberg SBP120™.

12) Significant efforts should be directed towards making the ship as acoustically quiet as practical. Significant and detailed technical compromises are necessary to achieve a reasonable balance between the performance of ships' acoustic systems and the power and strength necessary to be an efficient icebreaker.

13) A new PRV should have the capability of supporting two helicopters. The minimum acceptable aircraft should be able to make 150 nm round trips with 3 passengers and 1200 lbs. of cargo. The PRV should be capable of landing a single medium-lift helicopter such as a Bell 412, Sikorsky S-70, or landing a (USCG) HH60.

14) The vessel should be capable of launching small drone aircraft for ice survey and reconnaissance (remotely or autonomously operated).

15) A new PRV should be equipped with high-speed data processing facilities capable of handling large data sets for rapid processing, display, evaluation, and archiving. Typical data sets might include: LiDAR elevation surveys from glaciologists, seismic imaging, and multibeam swath map output.

16) Built-in climate controlled workspaces.

17) Built-in reefer/freezers.

18) A flow-through science sea water system: ~10-20 liters/minute maximum, for instrumentation (TSG, fluorometers, nitrogen analyzer, flow-through mass spectrometers, DO, pCO_2 etc.) only, not for sampling. This system will be driven by a separate pump (and spare) from the sampling, incubator cooling water and washing water.

19) Incubator/washing water: 400 liters (~100 gallons) per-minute delivered to the location of the incubators. Also delivers water to science sinks, vans sites, science working deck areas.

20) Capability of storing instruments and sampling gear, washing nets, and processing benthic samples in a warm environment during winter operations.

21) Capable of supporting “UNOLS standard” lab vans.

22) Capable of high speed internet for shipboard scientists and crew.

23) Science winches: CTD (0.322” conductor), multipurpose (e.g., camera, nets, benthic grabs) (3/8” wire rope), trawl/core (9/16” wire rope), deep tow (0.681” FO/EM).

Table 1. Conceptual specifications based on the workshop and committee deliberations through December, 2011.

Characteristics	**Specification**
Icebreaking Capability	Continuous transit through 4.5 feet sea ice at 3 knots
Accommodations	Crew and marine technicians plus 45 scientists
Length Overall	~115m (380 ft)
Beam	~23m (75 ft)
Draft	~9m (30 ft)
Displacement	~ 11,000 LT (11,200 MT)
Propulsion Horsepower	~16.8 MW (22,400 HP)
Special features	Box keel, 4m x 4m interior moon pool, lab van capable (4 or 5), helicopter support, 24/7 internet, small boat operations, designed for flexible use of both starboard and port rails for instrument deployment

The June 2006 “Report from the Antarctic Research Vessel Oversight Committee (ARVOC)” presented the requirements seen <u>at that time</u> as needed for a future polar research vessel. The ARVOC report included a copy of a paper presented at ICETECH 2006 titled “Next Generation Polar Research Vessel” (Volker et al., 2008) that laid out a concept design for a vessel meeting those requirements. It is the judgment the current PRV SMR refresh committee that the principle characteristics and attributes of that design remain valid today with few changes. This finding is reflected in the specifications listed in Table 1.

The changes in requirements since the 2006 concept study include:

- Renewed emphasis on a moon pool that is at least 4m x 4m in size and that opens into an interior space to allow sheltered science operations during polar winter conditions. The 2006 report included a smaller moon pool.
- Extension of endurance from 80 days to 90 days.
- Addition of an instrumented foremast for atmospheric studies combined with a deckhouse design that further enhances the ability of the vessel atmospheric sensors to sample undisturbed air.
- Use of the latest in “green” technology for the vessel’s systems to ensure an environmentally clean and operationally cost effective vessel.
- Limited compliance with ADA guidance.

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Appendix 1: Details for several PRV requirements

Acoustic noise

We recommend using the following general guidelines. As acoustically quiet as is feasible considering the choice of all shipboard systems, their location, and installation. Special consideration should be given to machinery noise isolation, including heating and ventilation. Propeller(s) are to be designed for minimal cavitation, and hull form should minimize bubble sweep down without compromising ice-breaking capability. Airborne noise levels during normal operations at sustained speed or during over-the-side operations using dynamic positioning shall conform to standards in USCG NVIC No. 12-82 and IMO Resolution A.468(XII), "Code On Noise Levels On Board Ships."

With regard to sonar systems, the design should strive to achieve less than 45 dB re 1µPascal at 1 meter in the frequency band from 3 kHz to 200 kHz to avoid compromising the performance of permanent and visiting sonar systems. The design effort to accomplish this goal should be developed using an experienced shipboard noise consultant. The actual levels should be measured and documented as part of the acceptance and/or science trials. The ship should be equipped with a system to measure and record broadband (2-200kHz) noise and the measurements should be compared to historical data as part of the normal science operation.

Moon pool

The PRV should have a single moon pool. The moon pool shall meet the following requirements:

1. 4 meters X 4 meters in size, with sufficient overhead clearance to allow temporary installation of drilling rigs. The moon pool must be closed to the sea when not in use.
2. Capable of being pumped down free of water and ice when the bottom door(s) for the pool are closed.
3. Accessible from an environmentally controlled compartment with sufficient space and support systems to enable the deployment of scientific gear including CTDs, ROVs, VPRs, nets, drilling systems, portable ADCPs, etc.
4. Shall be supported by the same oceanographic winches that support over the side operations.
5. Located as close to the center of motion of the ship as is practicable so as to minimize the impact of ship's motions

Flight Deck and Hangar

Ship operations in remote areas of both polar regions necessitates helicopter capability to support transfer of personnel, vessel logistics, ice recon, expanded scientific reach with the vessel as a mobile science base, and emergency medical evacuations. The ship shall be capable of landing and supporting two small helicopters of the 3 to 4 person size. The flight deck shall be structurally capable of landing a larger single rotor helicopter. The hangar shall be sized to house the two smaller helicopters with the rotors folded and the necessary storage/shop capability. On board aviation fuel capacity shall be adequate to support two helicopters for up to the endurance of the ship, based on flying one helo for four hours for 1/3 of the underway days. At least one of the ship's cranes shall be capable of reaching the flight deck to move cargo. Accommodations for the helicopter crew and technicians would come out of the science berths.

Science Foremast and Science Antenna Farm

The ship shall have a permanently mounted foremast that is equipped with an instrument platform for permanently mounted atmospheric and meteorological sensors. The instrument platform shall also be capable of temporarily mounting additional sensors with preinstalled cableways for routing power and data cables. Access to the instrument platform shall be built into the foremast to allow at sea servicing and installation of sensors.

Globally Corrected Differential Global Navigation Satellite System (GNSS) navigation and GNSS-aided inertial navigation systems will provide navigation and dynamic vessel attitude in support of everything from the multibeam systems to dynamic positioning for drilling. Over the lifetime of the vessel the systems of choice will change often and many temporary installations will be necessary for specialized equipment. The ship design will incorporate a location with good to excellent full-sky visibility for mounting navigation and attitude antennas. In addition to good sky view, the location should be easy and safe to access to mount antennas with easy cable runs to the labs.

Satellite antenna pedestals

For the foreseeable future, at latitudes less than about 83º primary high speed Internet access will be provided by a Very Small Aperture Satellite (VSAT) system. A location for installing a 2 to 3 meter VSAT or similar actively stabilized antenna will be provided in the design with a full-sky view. Above 80º degrees Internet connectivity will be provided by ganged (load equalized) systems via Low Earth Orbit (LEO) satellite systems such as Iridium Openport™. The operating area and schedule of the ship will probably require it to be outside of VSAT footprints often and therefore a location for an Inmarsat™ antenna such as a Fleet Broad Band™ will also be required.

Direct weather satellite antenna pedestal

Ships operating at high latitude and in ice are generally outside the foot print of high quality weather, sea, and ice predictions and are largely “on their own” with limited shore support. Critical synthetic aperture satellite (SAR) data for ice coverage and type is only available (over the Internet connection) after it has been down linked and processed by specialized systems (e.g. Radarsat, Envisat, etc.) At best, the processing of SAR data can add hours of delay degrading the utility of the data for tactical decision-making when working in ice. Ship-based weather satellite receivers (e.g. Terascan™ and Dartcom) provide real-time visual and infrared imagery from NOAA HRPT and US DOD DMSP satellites with no delay. The PRV design will have a suitable mounting location for a 1.5m dynamic antenna to support direct satellite reception.

Appendix 2.Polar Research Vessel Science Capabilities

Major Cost driver: Icebreaking Capability, Endurance, Science Capacity

Fundamental requirements
Ice Breaking Capability: 4.5 ft.(1.5m) Rating: PC-3,
Endurance: 90 days
Speed: Operating at up to 12 kts.

Major requirements
Range: continuous operations over a distance of up to 25,000 km.
Science berths: 45 science berths – not including crew or technicians.
Sea-keeping capability/motion criteria: Ability to operate in heavy seas in polar regions.

Additional costs dependent on exact specifications
Acoustically quiet ship with minimal underwater radiated noise
Habitability
Geotechnical drilling
Moon pool operations
Helicopter ops
Seismic capability

"Must-have" outfitting requirements
Workboats
Science Mast
Dynamic Positioning
Multibeam, deep water
Multibeam, Shallow water
Echosounder
Sub-bottom profiler
Communication, internal, external
Winches
Cranes
ROV/AUV Operations
Data Processing

Standard ship features with variable costs
Green ship design features
ADA compliance
Net tows and trawls
Unmanned Aerial Systems, (UAS) operations
Portable Labs
Laboratory Spaces
Scientific Seawater System
De-ionized water
General Specifications (8 foot corridors and elevators)
Frozen Science Storage space
Science Storage
Science Navigation Systems
Onboard incubators
Freezers, Refrigerated spaces

Temperature-Controlled Chambers

Appendix 3.PRV Conceptual Design Objectives and Targets from SMR Process

Objective	Capability	Target Objective
1	Icebreaking	Icebreaking Capability 4.5ft at 3knots, International Association of Classification Societies (IACS) PC-3). Capable of 50km transects through moderately heavy sea-ice (up to 4.5m thick) to include operations in both polar regions year-round. It is noted that this will not include the central Arctic area.
2	Endurance	90 day endurance with full complement
3	Speed	12kt in open water
4	Range	25,000 nm (assumes 90 days @12 kts)
5	Berths	45 Scientists, above the crew and technician complement
6	Sea-keeping ability	Must have sea-keeping capabilities that permit work in rough seas of the polar regions and sufficient environmental control to allow year round work in the polar seas.
7	Underwater radiated noise	Significant efforts should be directed towards making the ship as acoustically quiet as practical. Significant and detailed technical compromises are necessary to achieve a reasonable balance between the performance of ships' acoustic systems and the power and strength necessary to be an efficient icebreaker. Special consideration should be given to machinery noise isolation, including heating and ventilation. Propeller(s) are to be designed for minimal cavitation, and hull form should attempt to minimize bubble sweep down. Airborne noise levels during normal operations at sustained speed or during over-the-side operations using dynamic positioning shall conform to standards in USCG NVIC No. 12-82 and IMO Resolution A.468(XII), "Code On Noise Levels On Board Ships." Sonar self noise should meet or exceed manufacturer's requirements. Underwater radiated noise and airborne noise specifications should be developed using an experienced shipboard noise consultant.
8	Habitability	Accommodations and personnel spaces shall be designed to maximize comfort and reduce fatigue and to meet and/or exceed industry standards for acceptable noise and vibrations levels.
9	Geotechnical Drilling	Capable of accommodating temporarily-installed geotechnical drilling to 100 m below sea floor, at water depths of up to 1200 m in ice covered areas.
10	Moon Pool Operations	The moon pool shall meet the following requirements: 4 meters X 4 meters in size, with sufficient internal overhead clearance

		for Jason, Ropos, Mebo, to allow temporary installation of drilling rigs (see Geotechnical Drilling above). The moon pool must be closed to the sea when not in use. Capable of being pumped down free of water and ice when the bottom door(s) for the pool are closed. Accessible from an environmentally controlled compartment with sufficient space and support systems to enable the deployment of scientific gear including CTDs, ROVs, VPRs, nets, drilling systems, portable ADCPs, etc. Shall be supported by the same oceanographic winches that support over the side operations. Located as close to the center of motion of the ship as is practicable so as to minimize the impact of the ship's motion.
11	Helicopter	Ship operations in remote areas of both polar regions necessitates helicopter capability to support transfer of personnel, vessel logistics, ice reconnaissance, expanded scientific reach with the vessel as a mobile science base, and emergency medical evacuations. The ship shall be capable of landing and supporting two helicopters and to be able to make 150 nm round trip with 3 passengers and 1200 lbs. of cargo (eg Bell 214, Sikorsky S-70, or landing a (USCG) HH60). The flight deck shall be structurally capable of landing a larger single rotor helicopter. The hangar shall be sized to house the two smaller helicopters with the rotors folded and the necessary storage/shop capability. On board aviation fuel capacity shall be adequate to support two helicopters for up to the endurance of the ship, based on flying one helicopter for four hours for 1/3 of the underway days. Accommodations for the helicopter crew and technicians would come out of the science berths.
12	Seismics	The science objectives require periodic use of a broad range of marine seismic sources for reflection and/or refraction studies require substantial infrastructure including large volume (100 SCFM to 1,000 SCFM), high pressure (3,000 PSI) air compressors. At a minimum the vessel should be designed to accommodate operating a range of compressor sizes in protected space near the fantail. A careful technical and cost analysis of the total cost of ownership (TCO) over 20 or 30 years may lead to a decision that the optimum solution would be to build the compressors into the ship and carry their maintenance as part of normal operation.
13	Workboats	The vessel shall be equipped with sea-worthy boats for scientific sampling
14	Instrumented Science Mast	The main mast shall be provided with yardarms capable of supporting five scientific packages each weighing 100 pounds and measuring 2 feet wide by 2 feet long by 3 feet high.

		The ship design will incorporate a location with good to excellent full-sky visibility for mounting navigation and attitude antennas. Additionally, the area should be easy and safe to access to mount antennas with easy cable runs to the labs. A second lightweight and removable mast shall be provided on the foredeck. The secondary mast shall be located as far forward on the bow as possible in a region where airflow is as little disturbed as possible by the ship's structure. The secondary mast shall be designed for easy servicing of installed scientific packages and instruments. The secondary mast shall be provided with yardarms capable of supporting 5 scientific packages weighing 25 lbs. each and measuring 1 foot wide by 1 foot long by 2 feet high. The secondary mast shall be of adequate height and stiffness to properly support the scientific packages in a region of undisturbed airflow. The secondary mast shall be provided with means (ex. hand-winch) for raising and lowering to allow servicing of installed sensors in one hour or less. The cranes or oceanographic winches shall not be used for raising or lowering.
15	Dynamic Positioning	Dynamic Positioning capability to meet the requirements of over-the-side sampling is required.
16	Multibeam- Deep	Reliable, well-known deep water multibeam swath mapping echo sounders with a 1° x 2° array or 1° x 1° array installed behind ice protection windows (eg Kongsberg EM122 add trademark). Supporting equipment for the multibeam systems will include primary and backup attitude, position, and heading reference providers, such as the Applanix POS/MV™.
17	Multibeam- Shallow	Reliable, well-known deep water multibeam swath mapping echo sounders installed behind ice protection windows (eg EM710™) for high quality data collection on continental shelves and upper slopes. Supporting equipment for the multibeam systems will include primary and backup attitude, position, and heading reference providers, such as the Applanix POS/MV™.
18	Echosounder	Reliable, ice-protected, hull mounted sub-bottom profiler operating in the 3.5 kHz range. Typical systems are either FM-modulated (CHIRP) such as a Knudsen 3260, parametric (narrow beam) system such as the Atlas Parasound or Kongsberg Topas. The sub- bottom may be integrated with the multibeam, e.g. Kongsberg SBP120™.
19	Sub-bottom Profiler	A number of science objectives require routine operation of a sub-bottom profiler. The vessel should be equipped with a reliable, ice-protected, hull mounted sub-bottom profiler operating in the 3.5 kHz range. Typical systems are either FM-modulated (CHIRP) such as a Knudsen 3260™, parametric (narrow beam) system such as an Atlas

		Parasound(TM) or Kongsberg Topas(TM). The sub- bottom may be integrated with the multibeam, e.g. Kongsberg SBP120™.
20	Acoustic-Doppler Current Profiler (ADCP)	Acoustic-Doppler Current Profilers to meet low and high frequency surveys is required. Typical systems are the Ocean-Surveyor 38 and the Ocean Surveyor 150 kHz systems.
21	Communications	Primary high speed Internet access will be provided by a Very Small Aperture Satellite (VSAT) system. A location for installing a 2 to 3 meter VSAT or similar actively stabilized antenna will be provided in the design with a full-sky view. Above 80 degrees Internet connectivity will be provided by ganged (load equalized) systems via Low Earth Orbit (LEO) satellite systems such as Iridium Openport™. The operating area and schedule of the ship will probably require it to be outside of VSAT footprints often and therefore a location for an Inmarsat™ antenna such as a Fleet Broad Band™ will also be required. Ship-based weather satellite receivers (e.g. Terascan™ and Dartcom) provide real- time visual and infrared imagery from NOAA HRPT and DMSP satellites with no delay. The PRV design will have a suitable mounting location for a 1.5m dynamic antenna to support direct satellite reception.
22	Winches	Hydrographic winches, (2) capable of 10,000m of 0.322 E-M and/or 3/8" wire rope. Trawling/coring winch, (1) capable of handling 10,000m of 9/16" wire rope and 1 deep-tow winch capable of handling 10,000m of 0.681 F-O cable.
23	Cranes	Cranes capable of reaching all areas of the working deck including the flight deck to move cargo, science equipment, including vans.
24	Remotely Operated Vehicle (ROV) Autonomous Underwater Vehicle (AUV)	A new PRV must be able to host and deploy/recover Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV), both with a wide variety of capabilities. Most likely, such operations will take place in ice covered seas and hence vehicles will be needed to be deployed through a moon pool or over the side after ice clearing with a capable handling system.
25	Data Processing	High-speed data processing facilities capable of handling large data sets for rapid processing, display, evaluation, and archiving. Typical data sets might include: LiDAR elevation surveys from glaciologists, seismic imaging, and multibeam swath map output.

26	Green Ship	Environmental, sustainable ship design features must be incorporated in vessel design. Every effort should be made to incorporate recycled materials, non-polluting equipment and instrumentation and fuel efficient or alternative fuel technologies to make these vessels as environmentally friendly and cost effective as possible.
27	ADA Compliant	Implement as many of the ADA Guidelines as possible within the budget and size constraints for the vessel. ADA Guidelines for UNOLS Vessels_Final_Feb08.pdf
28	Net Tows/Trawls/Ice Clearing stern	Ability to tow nets and instruments from the stern during ice-breaking.
29	Unmanned Aerial Systems	The vessel should be capable of launching small unmanned aircraft for multiple science surveys, ice survey and reconnaissance (remotely or autonomously operated).
30	Portable labs	Space to carry 5-6, science vans- ISO standard 8 foot x 20 foot portable deck vans ("UNOLS Standard" lab vans).
31	Laboratory Spaces	Labs to accommodate up to 45 scientists. To include: Main Lab Wet-Lab Computer Lab with separation of computing facilities with climate control and limited vibration Dry Lab Hydrolab Refrigerated Lab (2ea.) Microscope Lab (2ea.) Gimbaled platform Electrophoresis equipment Trace Metal Clean lab Core Processing Facilities Built-in climate controlled workspaces. Built-in refrigerators/freezers. Aquariums- with flowing seawater Electronic Technician Shop Marine Technician Shop Conference room Exercise Room
32	Ship and Winch Control	Vessel shall have an aft conning and aft winch control station to facilitate over-the-operations and vessel maneuvering.

Appendix 4. Science Questions Linked to PRV Requirements

Science Questions	**Required Capabilities (unique to PRV)**
Ice Sheet to Marine Transitions: Understanding Processes and Thresholds	Icebreaking - 4.5 ft. (PC-3) Maximum Endurance Long Coring- 50 meters Sonars/Sub-bottom profiler Moon Pool Seismic Helicopters/Flight Deck Baltic Room Dynamic Positioning
What is the role of the polar oceans in the global carbon cycle?	Icebreaking- 4.5 ft. (PC-3) Year Round Access Maximum Endurance Heavy Seas Capability Moon pool Baltic Room Forward Science Sensor Mast Trace Metal-Clean laboratories Aquariums/ On-Deck Incubation
What is the geologic nature and extent of the polar continental shelves and what natural resources do they contain?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Long Coring Sonars/Sub-bottom Profiler Seismic Geotechnical Drilling Helicopter/Flight Deck Gravity/Magnetics Dynamic Positioning
How has life evolved in the polar regions in response to dramatic events in Earth history?	Icebreaking- 4.5 ft (PC-3 Maximum Endurance Moon Pool Long Coring Stern ice clearing Dynamic Positioning Capable Science Workboat
What is the temporal and spatial variability of glacial ice and water transfer to and from the oceans? How can polar marine research provide accurate assessments of the status of the Greenland and Antarctic Ice Sheets?	Icebreaking- 4.5 ft, (PC-3 Maximum Endurance Sonars/Sub-bottom Profiler Long Coring Moon Pool Helicopters / Flight Deck Capable Science workboats Personnel Access to Ice floes

How are polar marine ecosystems and organisms adapted to extreme environmental conditions and how is this reflected in biodiversity and evolutionary novelty?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Moon Pool Small Boats Major Aquarium/ On Deck Incubator Temperature Controlled Science Chambers
How will unique polar marine ecosystems respond to climate change?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Instrumented Forward Science Mast Moon Pool Helicopters Science Capable workboats Major Aquarium/On Deck Incubator
How do changes in freshwater cycling in the polar regions affect earth system processes and biogeochemical cycles?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Moon Pool Long Coring Clean Laboratories Science Seawater / Incubator
What role do trace metals and similar compounds have on polar ecosystems and how can they be used to understand the complex processes taking place in these areas?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Moon Pool Clean Laboratories On Deck Incubator
How does the ocean interact with ice shelves?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Long Coring Helicopters / Flight Deck Unmanned Aircraft Instrumented Forward Science Mast Moon Pool Dynamic Positioning
What are the dynamics and thermodynamics of polynyas and associated convective processes? How are ventilation rates of the deep ocean impacted by deep water formation at the poles?	Icebreaking- 4.5 ft. (PC-3) Maximum Endurance Instrumented Forward Science Mast Dynamic Positioning Science Capable Workboat Helicopter/Flight Deck

Appendix 5. Glossary

Term	Explanation
ACC	Antarctic Circumpolar Current, a large ocean current that flows from west to east around Antarctica.
ACIA	Arctic Climate Impact Assessment, n international project of the Arctic Council and the International Arctic Science Committee (IASC), http://www.acia.uaf.edu/
ADA	Americans for Disability Act, a US federal law that addresses accessibility for disabled persons, http://www.ada.gov/
ANDRILL	Antarctic Geological Drilling, an International Science Program, http://www.andrill.org/
ARVOC	Antarctic Research Vessel Operators Committee, a committee of the US Antarctic support contractor, http://www.usap.gov/USAPgov/conferencesCommitteesAndWorkshops/userCommittees
AUV	Autonomous Underwater Vehicle
BEST	Bering Ecosystem Study, an NSF-sponsored Arctic science project, http://www.arcus.org/bering/reports/
CDW	Circumpolar Deep Water
CO_2	Carbon Dioxide
CORSACS	Controls on Ross Sea Algal Community Structure, and NSF-sponsored Ross Sea science project, www.whoi.edu/sites/Corsacs/
CTD	Conductivity Temperature Depth - typically refers to a deployable logging instrument that measures these properties in water column depth profiles
DOC	Dissolved organic carbon, see also particulate organic carbon (POC)
GNSS	Global Navigation Satellite System, a satellite based global navigation system using satellites operated by a number of different countries, http://en.wikipedia.org/wiki/Satellite_navigation
GPS	Global Positioning System, a US Department of Defense satellite-based navigation system, http://en.wikipedia.org/wiki/Global_Positioning_System
GRACE	GRAvity and Climate Experiment
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Study, a late 1980s to 1990s project to study the ocean carbon cycle, http://www1.whoi.edu/
LIDAR	Light Detection And Ranging, an optical mapping method, http://en.wikipedia.org/wiki/LIDAR

MEBO	Seafloor Drill Rig designed in Germany, http://www.marum.de/en/Sea_floor_drill_rig_MeBo.html
NBP	Nathaniel B Palmer, a US light icebreaker dedicated to science operations, mostly in the Antarctic, http://www.nsf.gov/od/opp/support/nathpalm.jsp
NCEP/DOE Reanalysis	A joint National Centers for Environmental Prediction (NCEP) and Department of Energy project to provide updated, gridded data products ion the state of Earth's atmosphere.
NSF	US National Science Foundation, an independent US federal agency that funds basic science, http://nsf.gov
POC	Particulate organic carbon
POLENET	Polar Earth Observing Network, http://www.polenet.org
PRV	Polar Research Vessel
ROV	Remotely Operated Vehicle
SBI	Shelf Basin Interaction
SHALDRIL	Shallow (Antarctic) Drilling, http://www.arf.fsu.edu/projects/shaldril.php
SMR	Science Mission Requirements
UCDW	Upper Circumpolar Deep Water
UNCLOS	United Nations Convention on Law of the Sea
UNOLS	University National Oceanographic Laboratory System, an organization of (mostly) US academic oceanographic labs, http://www.unols.org/
USCG	United States Coast Guard, a US federal agency, part of the Department of Homeland Security
USCGC	United States Coast Guard Cutter, a ship operated by the US Coast Guard (USCG)
WAIS	West Antarctic Ice Sheet

Appendix 6. Global Polar Research Vessel Fleet, New and Expected Vessels, 2005-2017

Global Polar Research Vessel Fleet - New and Expected Vessels 2005 - 2017

Delivery Year	Vessel	Nation	Ice Class*	Ice Capability	Build Type	Status
2005	*ARTIGAS*	Uruguay			Conversion	Operational
2006	*MARIA S. MERIAN*	Germany	PC7		New Build	Operational
2009	*ALM. MAXIMIANO*	Brazil			Conversion	Operational
2009	*ARAON*	Korea	PC5	1m @ 3 kts	New Build	Operational
2009	*SHIRASE*	Japan		1.5m @ 3 kts	New Build	Operational
2012	*SA AGULHAS II*	South Africa	PC5	1m @ 5 kts	New Build	Launched
2012	*AK.TRYOSHNIKOV*	Russia	PC4-PC5	1.1m @ 2 kts	New Build	Operational
2013	*INVESTIGATOR*	Australia	Ice IC		New Build	In Build
2013	"Polar Research Vessel"	China		1.5m @ 3 kts	New Build	In Build
2013	"Polar Research Vessel"	India	PC5	1m @ 3 kts	New Build	In Design
2014	*SIKULIAQ*	United States	PC5	0.9m @ 2 kts	New Build	In Build
2014	*AURORA BOREALIS*	Europe	PC1	2.5m @ 3 kts	New Build	On Hold
2015	*NVC 395*	Norway	PC2	1m @ 3 kts	New Build	In Design
2016	*POLARSTERN II*	Germany		1m @ 3 kts	New Build	Development
2017	*JOHN G. DIEFENBAKER*	Canada	PC1	2.5m @ 3 kts	New Build	Development
2017?	**"Polar Research Vessel"**	**United States**	**PC3**	**1.5m @ 3 kts**	**New Build**	**Under Consideration**

*IACS (International Association of Classification Societies) Ice Classifications:
PC1: Year-round operation in all Polar waters
PC2: Year-round operation in moderate multi-year ice conditions
PC3: Year-round operation in second-year ice which may include multi-year ice inclusions
PC4: Year-round operation in thick first-year ice which may include old ice inclusions
PC5: Year-round operation in medium first-year ice which may include old ice inclusions
PC6: Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC7: Summer/autumn operation in thin first-year ice which may include old ice inclusions