CLIMATE CHANGE AT HIGH LATITUDES: AN ILLUMINATING EXAMPLE

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Abstract: A striking example is presented of a newly observed phenomenon in the ice-covered Arctic Ocean that appears to be a consequence of changes in the physical forcing. In summer 2011 a massive phytoplankton bloom was observed north of the Bering Strait, between Russia and the US, underneath pack-ice that was a meter thick – in conditions previously thought to be inconducive for harboring such blooms. It is demonstrated that the changing ice cover, in concert with the resulting heat exchange between the atmosphere and ocean, likely led to this paradigm shift at the base of the food chain by altering the supply of nutrients and sunlight. Such early-season under-ice blooms have the potential to profoundly alter the Arctic food web.

Key Words: Climate change; Arctic Ocean; Chukchi Sea; under-ice blooms; Arctic ice cover.

"The Arctic is screaming." This is how the head of the US National Snow and Ice center, Mark Serreze, reacted after the most recent ice minimum occurred in September 2012. At the time, the ice cover was estimated to be roughly 3 million square kilometers – less than half the amount present in September of 1979 when satellite ice records began. This drastic loss of summertime pack-ice is just one of the myriad of changes that have taken place in the Arctic as a result of our warming climate. It is commonly believed that climate change will be felt first – and to a greater extent – at high latitudes versus temperate regions. However, it remains unclear what the effects will be on the delicate Arctic ecosystem and how these changes will ultimately impact the rest of the planet.

Scientists studying high latitude climate change are faced with number of unique challenges. One of them is to distinguish the warming-induced trends from the background state. This is especially difficult in the Arctic because of the harsh conditions in which measurements are collected. Icebreakers are only able to operate from late-spring to early-fall; plus, the US only has one icebreaker dedicated for science – the US Coast Guard Cutter (USCGC) *Healy*. Hence we are limited in our ability to collect ship-borne measurements. (Contrast this to lower latitudes where the University National Oceanographic Laboratory System (UNOLS) operates more than 20 research vessels over the course of the year.) Furthermore, much of the newer technology being employed by researchers at lower latitudes is difficult or impossible to implement in the presence of pack-ice. For instance, unmanned autonomous vehicles are increasingly being deployed from ships or from shore, which pilot themselves and gather various types of measurements. However, these vehicles need to surface at regular intervals in order to communicate with satellites, both to transmit their data back to land and to receive instructions for carrying out their missions. This dearth of high-latitude measurements means that, in certain respects, we don’t understand some of the basic functioning of the Arctic ice-ocean-atmosphere system; therefore, how can we confidently identify what is changing due to human activity?

Another complicating factor in deciphering the impacts of high-latitude climate change is that the different components of the ecosystem are tightly coupled, so it is often difficult to flesh out cause and effect when a given change is firmly documented. For example, it has been demonstrated that gray whales are now present during the winter months north of Alaska (Stafford and Moore 2005), which was not the case in previous decades. Is this related to the declining ice cover or due to a change in the availability of their prey? If the latter, what caused the shift in number of prey in the water and/or the bottom sediments? At the most basic level, we need to be able to document the changes in the physical drivers – for instance the atmospheric forcing (e.g. winds), the ice concentration and thickness, changes in the characteristics of the water and how it circulates – and then relate this to the biological responses.

In this paper we present a striking example of a newly observed phenomenon in the ice-covered Arctic Ocean and how this appears to be a consequence of changes in the external forcing. Our example applies to the base of the food chain – the growth of phytoplankton – which impacts the different trophic levels right up to marine mammals (including gray whales). We relate this new aspect of phytoplankton blooms to changes in the supply of nutrients and sunlight, the most basic building blocks of plant growth, and how these have been influenced by ice cover and atmospheric forcing. It is hoped that this case study will provide insights to the interconnectedness of the Arctic system and how sensitive it is to changes in our climate.

The study area is the Chukchi Sea, north of the Bering Strait, which connects the Arctic and Pacific Oceans (Figure 1). We begin with a short summary of the changing physical drivers in the Pacific sector of the Arctic Ocean. We then present a surprising discovery that occurred on USCGC *Healy* in the spring of 2011: the observation of a massive phytoplankton bloom underneath pack-ice that was a meter thick, in conditions previously thought to be inconducive for harboring such blooms. Finally, we discuss how the changing ice cover, in concert with the resulting heat exchange between the atmosphere and ocean, likely led to this paradigm shift at the base of the Arctic food chain.

CHANGING PHYSICAL DRIVERS IN THE PACIFIC SECTOR OF THE ARCTIC OCEAN

Nearly everyone is aware that the Arctic ice cover is shrinking at an alarming rate. Some studies estimate that the summertime ice cover in the Arctic Ocean could completely vanish in only a few decades (e.g. Holland et al. 2006; Wang and Overland 2009). The biggest losses to date have occurred in the Pacific sector of the Arctic, including the shallow Chukchi Sea and the deep area to the north known as the Canada Basin (Frey et al. 2015; Figure 1). A lesser-known fact is that the volume of ice is also decreasing: in the past, much of the Arctic Ocean contained multi-year ice (which grew up to 10 meters thick through successive winters), while most of the Arctic is now characterized by thin, first-year ice (typically 1-2 meters thick). Different factors are contributing to this loss of pack-ice, including heating from above and heating from below. Last year the air temperature in the Arctic was the warmest in the instrumental record dating back more than 100 years. For the region north of 60^{o}N, the mean temperature was 2^{o}C, compared to -1^{o}C at the turn of the 20th century (“Arctic Report Card” 2016). The rate of atmospheric warming in these northern climes exceeds that of the global mean. Since 1960 the global mean temperature has increased by 1.5^{o}C, while the mean temperature north of 60^{o}N has increased by 2.5^{o}C. This is one aspect of the phenomenon known as “Arctic amplification”.

Along with the warming air temperatures, the atmospheric circulation has been changing as well. In particular, there are now more frequent and more powerful storms. There are two types of storm systems that impact the Chukchi Sea: Arctic-born storms and Pacific-born storms.

The former are spawned in the high-Arctic and tend to travel from west to east as they pass by the Chukchi Sea. The westerly winds associated with these low pressure systems result in a storm surge along the northern coast of Alaska. In the past, the ice along the coast was fast, i.e. anchored to the coast and hence immobile. However, in recent times the ice is often freely moving or absent altogether, which results in severe coastal erosion due to the storm surges. Since the mid-1900s, the number of Arctic-born storms in the summer months has increased from less than 5 per year to more than 20 per year (J. Walsh, pers. comm. 2006).

The Pacific-born storms are referred to as “Aleutian Lows.” These storms originate off the coast of Asia and tend to follow a well-defined track as they progress to the east. When they reach the vicinity of the Aleutian Island chain they tend to intensify (hence their name). Even though the centers of the storms are often located hundreds of kilometers to the south of the Arctic Ocean, they are so powerful that the winds in the Chukchi Sea and in the neighboring Beaufort Sea (north of Alaska) can exceed 30 knots. In this case the winds are out of the east and the sea level drops near the coast. Associated with this, a process known as upwelling occurs along the north slope of Alaska whereby deep water from offshore is drawn onto the continental shelf, bringing nutrients and zooplankton with it (Williams et al. 2006; Pickart et al. 2013a). Since the 1980s, the number of such upwelling events has doubled, and the wind speed during these events has increased as well (Pickart et al. 2013b). Furthermore, the ocean response is greater when the ice cover is reduced.

As noted above, the melting of the pack ice is not only the result of warmer air temperatures, but is due to warmer ocean temperatures as well. For the past 25 years there have been sub-surface moorings positioned in the Bering Strait to monitor the flow of Pacific water entering the Chukchi Sea. Over the last decade these data have revealed that the volume transport of Pacific water into the Arctic has increased by more than 35%. The yearly mean value is now 1.1 million cubic meters per second (more than 50 times greater than the flow rate of the Mississippi River). Perhaps more importantly, the amount of heat transported by the water has significantly increased as well (Woodgate et al. 2012). Among other things, this means that there is more heat available to melt the underside of the ice in late-spring and summer, and also delay the onset of freezing in the fall. Some of the water flowing through Bering Strait is now reaching previously unthinkable high temperatures, at times exceeding 10^{o}C, which is flooding the Chukchi Sea with warm water during the summer. Woodgate et al. (2012) estimated that the amount of heat transported through the Bering Strait in such a warm year can melt 1,500,000 km^2 of first-year pack ice, an area more than twice the size of the Chukchi Sea.

There are also marked changes occurring to the hydrological cycle of the Pacific Arctic. More moisture is being transported to high latitudes (Moore 2016). Furthermore, the precipitation is falling increasingly in the form of rain rather than snow. North of Alaska the ratio of snow to rain has been declining by more than 5% per decade (K. Moore, pers. comm. 2017). Since snow has a high reflectivity (greater than that of ice), this impacts the surface albedo (the fraction of incoming sunlight that is reflected back to space rather than absorbed), which has huge consequences for the stability of the pack ice. Not surprisingly, the increased moisture has also resulted in an increase in river discharge into the Arctic Ocean ("Arctic Report Card" 2015). This is true of both Siberian rivers and American rivers. Notably, the Arctic Ocean receives more river discharge than any other ocean in the world. Together, these various sources of fresh water impact different parts of the Arctic system, and over the past couple of decades there has been a pronounced increase in the fresh water content of the Canada Basin (Proshutinsky et al. 2009; Figure 1). It is thought that if/when this fresh water is released, it could flood parts of the surface North Atlantic Ocean and possibly disrupt the circulation there – with consequences for the maintenance of our global climate.

With this backdrop of changing physical drivers in the Pacific Arctic Ocean, we now describe the recent discovery of a massive phytoplankton bloom under the pack ice north of Bering Strait in the Chukchi Sea, and explore the possible reasons for the occurrence of the bloom as well as the ramifications for the regional ecosystem.

AN UNDER-ICE BLOOM IN THE CHUKCHI SEA

Discovery of the Bloom. In the summers of 2010 and 2011, the National Aeronautics and Space Association (NASA) conducted a biophysical field program in the Chukchi Sea aboard the USCGC *Healy*. The name of the program was “Impacts of Climate on Ecosystems and Chemistry of the Arctic Pacific Environment,” or ICESCAPE. It was the first time that NASA funded a dedicated oceanographic expedition, and, not surprisingly, this generated a fair amount of press. The main goal of the project was to collect in-situ data that would ultimately lead to a more quantitative interpretation of the various satellite products provided by NASA in this remote part of the planet. Nearly fifty scientists sailed on the two cruises, representing a variety of disciplines ranging from biology to optics to physical oceanography and ice processes. In July 2011, near the end of the second cruise, the science team serendipitously discovered a massive phytoplankton bloom in the northern Chukchi Sea (Arrigo et al., 2012). The discovery was extraordinary for two reasons: (1) the bloom was occurring underneath fully consolidated pack ice that was 1 meter thick; and (2) it was one of the largest blooms ever recorded in the World Ocean.

The long-standing paradigm for phytoplankton blooms in the Arctic Ocean is that they form in the open water near the edge of the pack ice as it retreats northwards during spring. The idea is that not enough light can penetrate fully consolidated ice to trigger significant bloom activity, and it is not until the ice melts that the plant cells can utilize the nutrients in the surface water in the presence of the enhanced light levels. So when the ICESCAPE team announced its discovery, it was met with some degree of skepticism. One thought was that the measurements must have reflected a remnant open water bloom that had subsequently flowed northward underneath the ice. If that were the case, however, the phytoplankton cells would be near the end of their life stage, but the ICESCAPE data revealed that the cells were completely healthy. Another thought was that the bloom was likely comprised of ice algae that had sloughed off the underside of the pack ice prior to the measurements. This was also shown not to be the case; these were without doubt phytoplankton that grew in the water. Once it was verified that this was in fact a healthy under-ice bloom, the next question was, what factors conspired to make this happen? To answer this, let's go back to the fundamentals of plant growth: nutrients and sunlight.

Nutrients. Over the course of the year different types of water flow from the Pacific to the Arctic through the Bering Strait. During winter and spring, very cold water (near the freezing point of seawater in the vicinity of -1.8^{o}C) enters the Chukchi Sea, followed later in the year by different varieties of summer water. One of the characteristics of the winter water is that it is very high in nutrients, which makes it critically important for the regional ecosystem. The phytoplankton utilize these nutrients in springtime – when there is enough light – and, once the nutrients are drawn down, the bloom ceases. After passing through Bering Strait the winter water splits into different flow branches and progresses northwards across the shallow Chukchi Sea.

As such, it was thought that the dominant source of nutrients was from the northern Pacific Ocean, and, furthermore, that the nutrients were only present within the flow pathways on the Chukchi shelf (Figure 1). At least this was the thinking at the time of the ICESCAPE program.

A follow-up study in 2014 called "The Study of Under Ice Blooms in the Chukchi Ecosystem," or SUBICE, revealed that this was not the case. The purpose of SUBICE was to document the conditions before, during, and after under-ice blooms. Recall that the discovery of the massive bloom in the Chukchi Sea in July 2011 was serendipitous, and we were ill equipped at the time to collect the necessary measurements to fully quantify the different processes at work. One of the unique aspects of SUBICE was that it began early in the season, before the onset of any bloom activity. The aim was to capture the "initial conditions" leading up to under-ice blooms. As such, the *Healy* passed through the Bering Strait in early May, and we subsequently carried out the first dedicated survey of the Chukchi Sea this early in the season.

One of the surprises of SUBICE was that the high-nutrient winter water was found throughout the Chukchi Sea, i.e. not just in the flow pathways. Furthermore, the cold water was nearly uniform in properties from the surface to the bottom. Using the SUBICE measurements, in conjunction with atmospheric data and a simple numerical simulation, we devised a new conceptual framework regarding the supply of winter water and nutrients to the Chukchi Sea (Pacini et al., submitted). The idea is as follows.

Despite the fact that the ice cover was essentially 100% during SUBICE, there were small leads (openings) and polynyas in the ice everywhere we went. This is a reflection of the fact that the ice pack is dynamic: it constantly moves around, largely due to the variable winds, creating lots of small holes. Notably, the air was still cold enough during the first part of the cruise that these leads were re-freezing. When sea-ice forms it is very low in salt content, which means that the surface water underneath the newly forming ice is especially salty and hence very dense. If it becomes dense enough it will sink and mix the cold, salty water down into the water column. This in turn forms (or renews) winter water locally, including outside of the flow pathways.

This explains why winter water was observed throughout the Chukchi Sea. But why was this locally formed winter water high in nutrients? To understand this let's review the seasonal cycle of phytoplankton in the Chukchi Sea. As phytoplankton grows in the spring and summer, some of it is consumed by zooplankton, and the remaining amount dies and sinks to the bottom. During the fall and winter this carbon is broken down by bacteria, resulting in large amounts of nutrients in the sediments. Therefore, when the locally formed winter water reaches the bottom, it stirs up these nutrients into the water column, making them available for phytoplankton to grow the following spring. Our SUBICE measurements were consistent with this notion: we observed numerous instances of completely well-mixed profiles of winter water and nitrate within re-freezing leads – and most of the other profiles were also nearly homogenized, indicating recent top-to-bottom mixing. Note that there are two critical aspects that make this local formation of high-nutrient winter water possible. The first is that the sinking winter water must reach the bottom. If the Chukchi Sea were not shallow (i.e. less than 50 m deep) then this might not happen, in which case the winter water would not have a high nutrient content. The second is that there must be lots of leads present throughout the Chukchi shelf. In past decades this may not have been the case, since the pack ice was thicker (in some years containing multi-year ice) and hence less mobile. Therefore, the warming climate, with its less stable ice cover, has apparently led to greater nutrient availability in the Chukchi Sea.

Sunlight. Despite this enhanced supply of nutrients in springtime, if there is not enough available sunlight then there will be no associated phytoplankton bloom beneath the pack ice. The thicker ice cover of the past most certainly didn't allow enough light for this. In fact, even relatively thin first-year ice scatters/absorbs most of the incident sunlight. So what enabled the massive bloom to occur that was measured during the ICESCAPE expedition? The answer is melt ponds. As air temperatures continue to warm during the spring, the layer of snow atop the ice melts, and then the ice itself starts to melt. As part of this process, thin ponds of water develop on the surface of the ice which can populate large expanses of the Chukchi Sea. It turns out these ponds act as skylights, allowing more sunlight to penetrate into the water. This was quantified during the ICESCAPE expedition using optical instruments above and below the ice (Arrigo et al 2014). We found that more than three times the amount of sunlight can enter the water column beneath the melt ponds. Furthermore, due to scattering, this illuminates the areas surrounding the melt ponds as well. The end result is that this allowed the phytoplankton to utilize the nutrients in the winter water, resulting in the under-ice bloom.

However, this does not fully explain why the bloom observed in 2011 was so massive. We believe the reason for this was that the bloom developed at the northern edge of the Chukchi Sea, i.e. near the shelfbreak (the shelfbreak is the boundary between the continental shelf and the continental slope). To understand why this is important, let's go back to the circulation of the winter water on the Chukchi shelf. We now know that, in late spring, much of the shelf is filled with this cold water. However, the water continually drains from the shelf into the deep Canada Basin, predominantly through two canyons – Barrow Canyon in the east and Harold Canyon in the west (see Figure 1). Once off the shelf, the water sinks to a deeper level and occupies a subsurface layer in the basin. Importantly, the exiting winter water is not completely devoid of its nutrient content, which means that there is a source of nutrients just seaward of the Chukchi shelf, but at a deeper depth.

Recall that the Pacific-born storms result in easterly winds which drive upwelling of deep water from the basin onto the shelf. It turns out that, at the time of the massive bloom in 2011, this process was occurring (Spall et al., 2014). Furthermore, the largest concentrations of phytoplankton in the bloom were found precisely where the upwelled winter water was first reaching the shelf. This leads us to conclude that, while the bloom first originated because the melt ponds allowed enough sunlight for the phytoplankton to tap the nutrients in the winter water beneath the ice, the bloom grew to massive levels because additional winter water was transported to the outer shelf via the upwelling process. That is, once the nutrients were expended from the shelf winter water, the basin winter water provided an additional source of nutrients, one that was quite vast.

RAMIFICATIONS FOR THE ECOSYSTEM

Several aspects of climate change in the Pacific sector of the Arctic Ocean resulted in the development of the massive phytoplankton bloom observed during the 2011 ICESCAPE expedition, and will likely lead to more such occurrences in the future. Looser pack ice means more leads, which in turn means more winter water formation during the cold season and stirring up of nutrients from the sediments. Thinner first-year ice that is more prone to ponding because warmer air temperatures will provide greater amounts of sunlight to the water, allowing the phytoplankton to utilize these nutrients in the spring. Finally, increased storminess means more upwelling which recoups nutrients that were lost to the basin and reintroduces them onto the shelf.

Recent measurements suggest that by August most of the winter water has drained from the Chukchi shelf (Pickart et al., submitted). Hence, in the past when the pack ice was thicker and retreated later in the summer, this limited phytoplankton growth for two reasons. First, the thicker ice reduced the amount of sunlight penetrating the water. Second, by the time the pack ice melted, much of the winter water had already vacated the shelf, meaning less available nutrients for an open water bloom. Consequently, blooms that can form while the ice is still present will not only lead to greater primary production overall, it will shift the timing of the spring bloom to earlier in the season.

Both of these changes are apt to have large consequences for the ecosystem, although it is difficult to know at this point exactly what these will be. As noted by Arrigo et al. (2014), the seasonal timing of the peak in primary production is tightly coupled to the migration and life cycles of many Arctic organisms. A change in this timing could disrupt a balance that has been in place for thousands of years. For instance, if the bloom ends before the Pacific-origin zooplankton arrive in the Chukchi Sea, this means less prey for the zooplankton which could reverberate up the food chain to the higher tropics, including marine mammals and seabirds. For example, different species of fish consume zooplankton, while certain cetaceans consume fish. On the other hand, if there is less grazing by the zooplankton, this means that more of the phytoplankton will sink to the sediments. This will enrich the various fauna that live in and above the sea floor such as clams, crabs, and sponges. This illustrates the complex manner in which climate change can influence the Arctic system, with consequences that in many cases are hard to predict. It underscores the need to continue scientific research in this remote part of the world.

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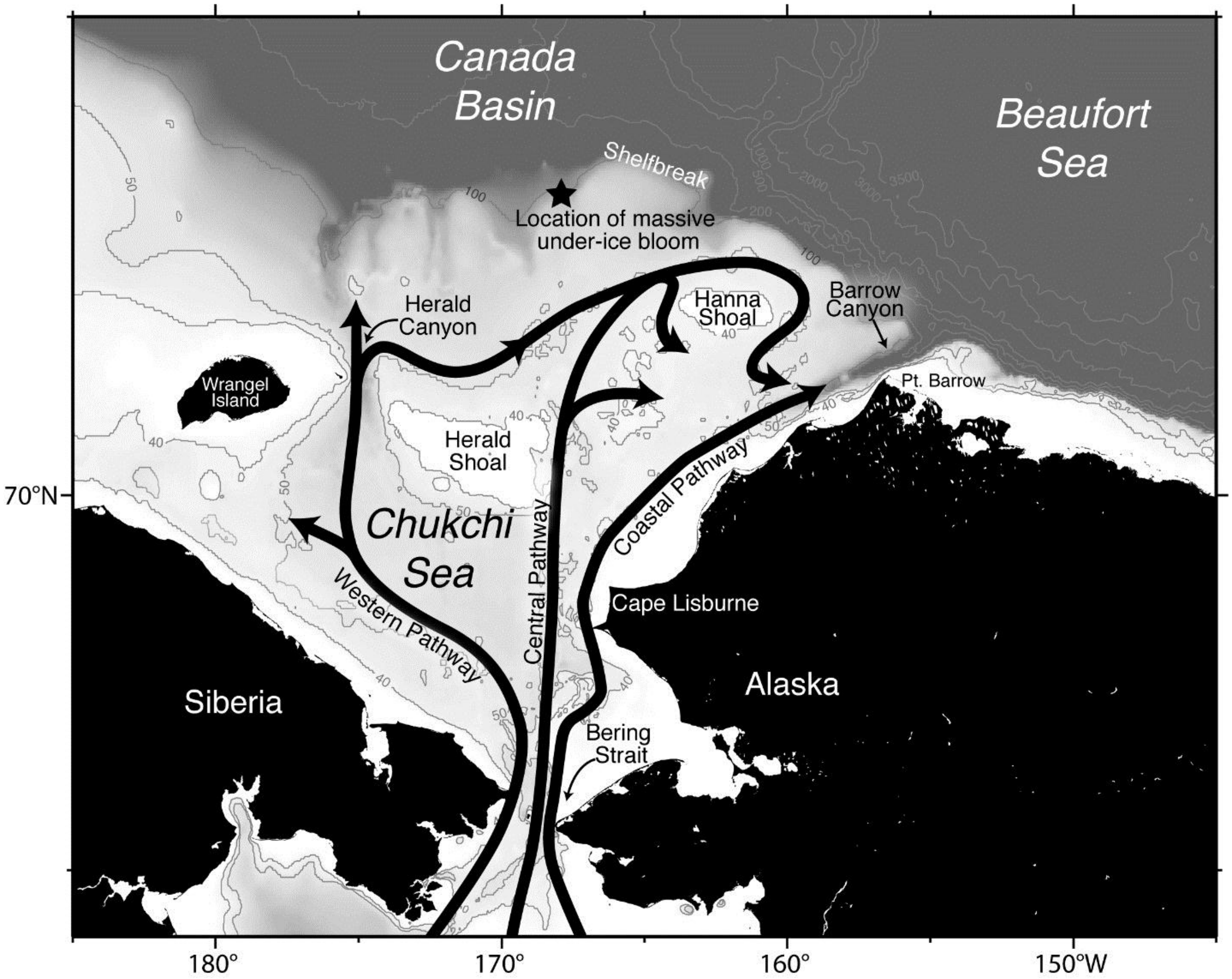

Figure 1: Map of the Study region. Immediately north of the Bering Strait is the Chukchi Sea, a wide and shallow continental shelf sea, with bottom depths generally less than 50 m. Two canyons cut into the northern part of the Chukchi Sea: Herald Canyon in the west and Barrow Canyon in the east. The shelfbreak corresponds to the boundary between the continental shelf and the continental slope. North of the Chukchi Sea is the Canada Basin, and north of Alaska and Canada is the Beaufort Sea. The lines/arrows schematically represent the three main Pacific water flow branches emanating from the Bering Strait: the western, central, and coastal pathways. The star denotes the location where the massive phytoplankton bloom was observed in summer 2011. The thin contours indicate the depth of the seafloor in meters.