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GLOBAL WARNING
The Arctic Meltdown

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Why the Disappearance of Arctic Sea Ice Matters

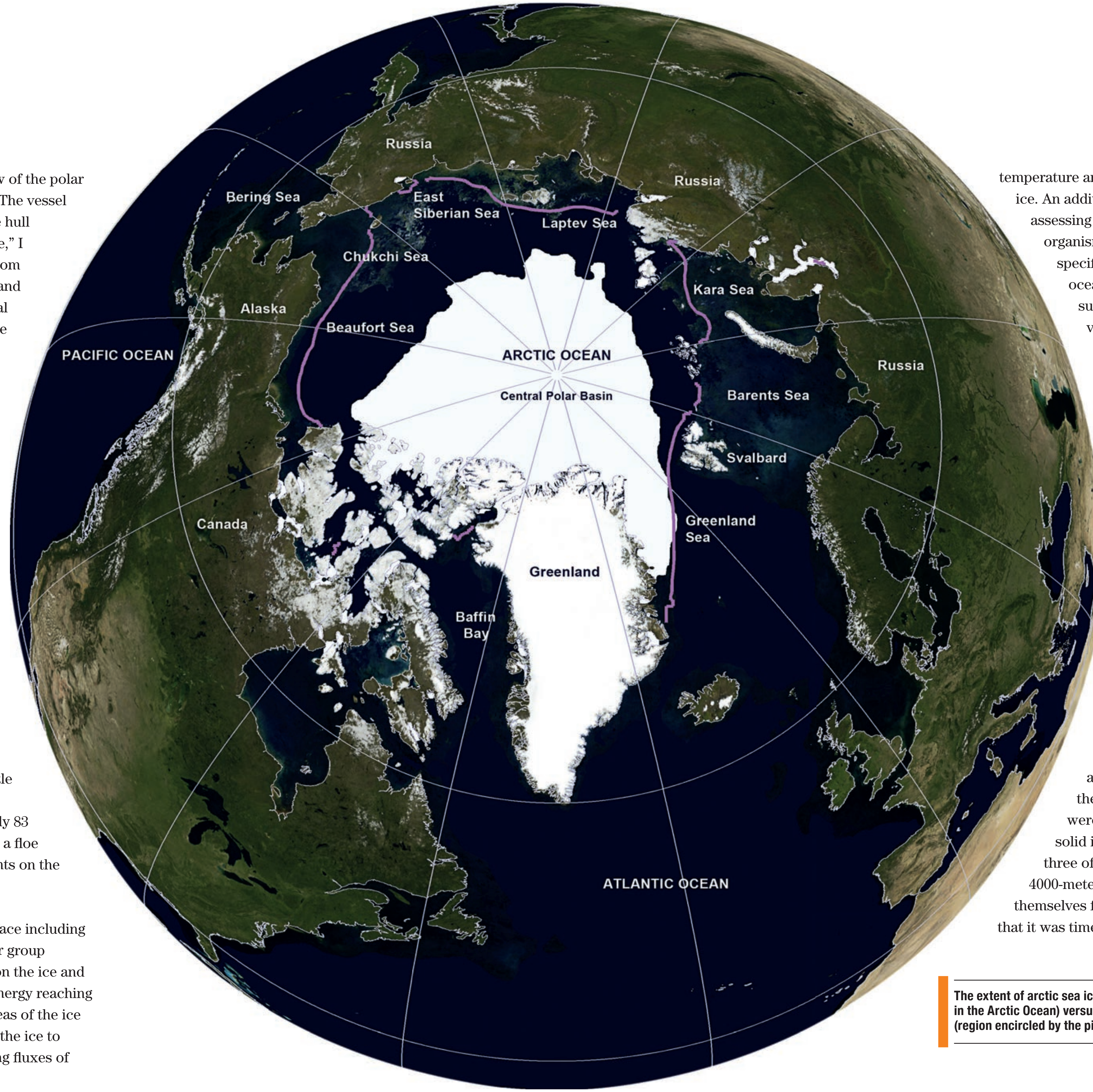
Asleep on my bunk in the bow of the polar research ship RV Lance, I awoke suddenly to a jarring crash. The vessel shuddered with the impact, and its metal skin shrieked as the hull scraped past an obstacle seemingly inches from my head. "Ice," I thought. "Finally." After sailing nearly 350 kilometers north from the arctic port of Longyearbyen in the Svalbard archipelago, and traveling through open water in the Greenland Sea and central Arctic Ocean for almost three days, we had finally reached the rapidly-receding edge of the melting sea ice.

I was accompanying an international team of scientists participating in the Norwegian Polar Institute's 2012 Ice, Climate and Ecosystems ("ICE") expedition, a voyage focused on investigating the causes and effects of arctic sea-ice loss, encompassing issues ranging from geophysics to ecology. The next morning, as we sailed among chunks of bright ice scattered across the dark ocean surface as far as the eye could see, the scientists searched for an appropriate floe on which to conduct their research activities. "We were looking for a floe that was representative of the majority of the ice in the area in terms of its surface characteristics and thickness, but that was also large enough so we could spread out to do the many experiments we'd planned," explains Stephen Hudson, a sea-ice geophysicist affiliated with the Norwegian Polar Institute (NPI). "The ice in the area was mostly pretty similar, so finding representative ice wasn't a big problem, but it was more difficult to find a large enough floe." We pressed forward hour after hour past inadequate little patches of ice that were quickly disintegrating. Finally, after traveling more than 150 kilometers farther and reaching nearly 83 degrees north, the researchers were able to tether the ship to a floe in the central polar basin that met their needs, and experiments on the ice began.

One team of scientists mapped the topography of the ice surface including areas covered with melt ponds of various sizes, while another group analysed ice thickness using devices deployed both directly on the ice and via helicopter. A third team quantified the amounts of solar energy reaching the ice surface, being reflected back into space by various areas of the ice with different characteristics, and being transmitted through the ice to the seawater below. Other scientists collected data concerning fluxes of temperature and salinity in the ocean at varying depths beneath the melting ice. An additional group focused on ice-associated flora and fauna, assessing such subjects as species composition and growth rates of organisms in different ice conditions. A few researchers evaluated specific biochemical processes occurring in the ice-covered ocean. And a team of scientific divers spent long hours each day submerged beneath the ice assisting the other researchers with various underwater aspects of their experiments. Working with intense focus, the scientists toiled from early morning to late evening, amassing voluminous collections of data to be analyzed fully following the voyage.

There was a subtle sense of urgency in the researchers' activities during the ICE expedition, stemming in part from the need to accomplish as much work as possible before the melting summer sea ice literally disintegrated beneath them. But the work was urgent as well because of a larger issue. Scientists are scrambling to understand the specific processes causing extraordinarily rapid loss of arctic sea ice due to climate change, to develop better means of predicting how the arctic transformation will unfold in the future, and to determine the nature and severity of the ramifications of ice loss for both the Arctic and the rest of the planet. But the sea ice is melting so quickly that it's difficult for scientific studies even to keep pace.

By the time the ICE scientists had completed their research activities in the Arctic's central polar basin, the floe on which they were working had deteriorated dangerously. Melt ponds were widely proliferating on the sea-ice surface and previously solid ice had become disconcertingly slushy. In the final days, three of the researchers fell through thin ice, plunging into the frigid 4000-meter-deep ocean below. Thankfully they were able to extract themselves from the water quickly and safely. But it was palpably clear that it was time to leave.



The extent of arctic sea ice remaining at the end of the melt season in September 2012 (white region in the Arctic Ocean) versus the average September sea ice extent documented from 1979 to 2000 (region encircled by the pink line). (National Snow and Ice Data Center / NASA Earth Observatory)

The Arctic Ocean's vast cap of floating sea ice is shrinking at an alarming rate as a result of human-caused climate change. Arctic sea ice naturally expands and contracts on a seasonal basis as the North Pole points away from the sun in winter and toward it in summer due to Earth's tilted axis. The sea ice achieves its largest surface extent each year at the end of winter sometime in March, and reaches its minimum annual extent at the end of the summer melt season in approximately mid-September. But in recent years, as the concentrations of carbon dioxide and other greenhouse gases in our atmosphere have increased significantly, temperatures have been rising dramatically and sea ice has been declining precipitously in both surface extent and thickness.

In September 2012, the National Snow and Ice Data Center (NSIDC) at the University of Colorado announced that arctic sea ice extent had shriveled to 3.41 million square kilometers, the smallest ice cover in the Arctic Ocean ever documented by scientists, and only 51% of the average sea ice extent existing at the end of the melt season during the period 1979 to 2000. The ice had dwindled shockingly in thickness as well. In September 2012 the total volume of arctic sea ice calculated by scientists plummeted to a stunning new record low that was a mere 20% of the ice volume existing in 1979.

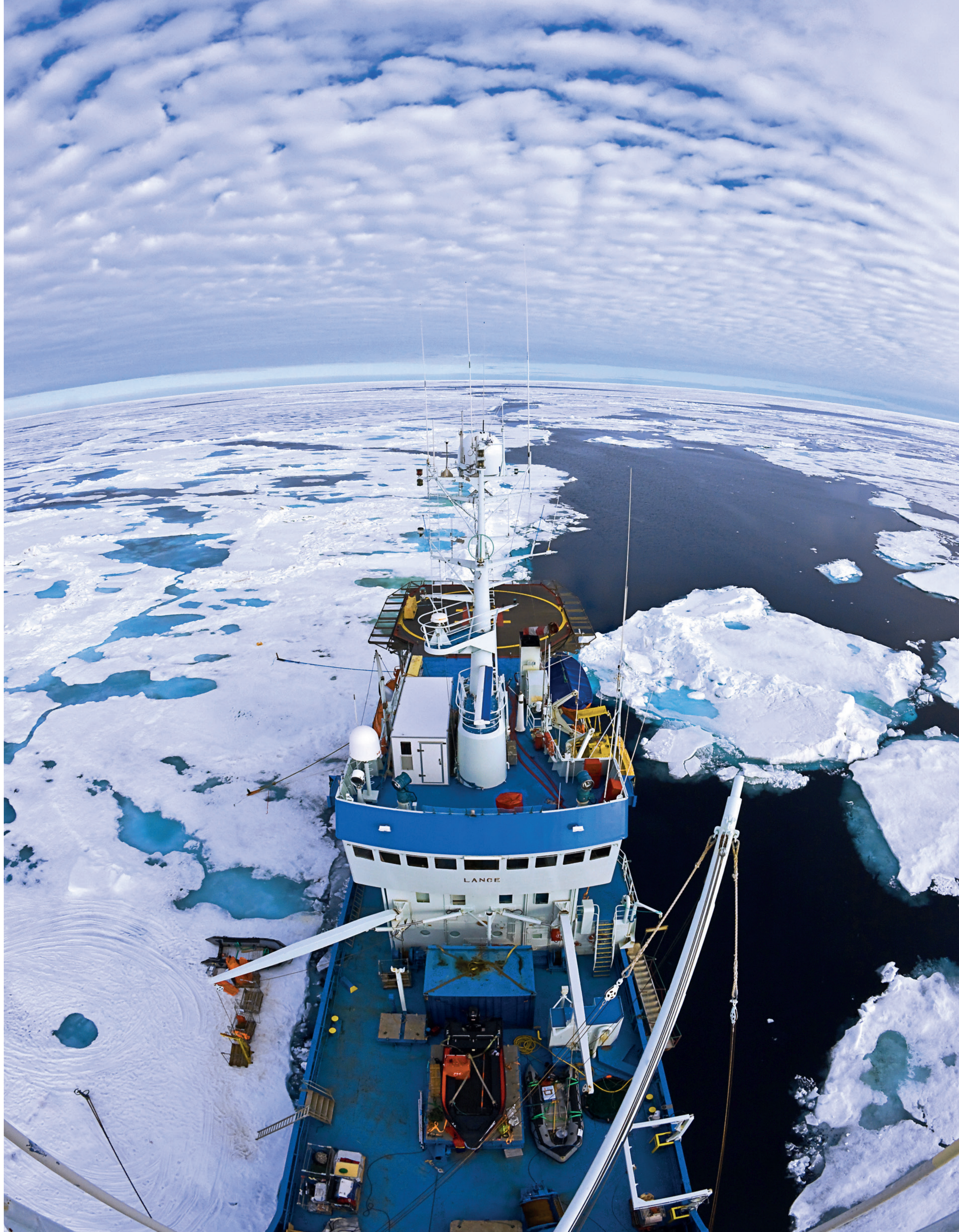
Although the ice loss during the summer of 2013 did not match the extreme melt that occurred in 2012 – most likely due to natural variability in weather conditions that consistently favoured retention of thin ice cover despite its overall fragility – the long-term declining trend nonetheless continued. In September 2013, sea ice extent at the end of the melt season fell to 5.10 million square kilometers, the sixth lowest extent ever documented and 1.12 million square kilometers lower than the 1981-2010 average – a reduction in area roughly the size of Texas and California combined. In the last seven years, 2007 to 2013, arctic sea ice has reached the seven lowest minimum extents since satellite observations began in 1979.*

Research concerning climate conditions in Earth's geologic past indicates that sea ice has covered at least a portion of the Arctic Ocean for a minimum of 13 to 14 million years. Although there were occasional episodes of reduced ice during that time, scientific studies have shown that those fluctuations were tied to variations in Earth's orbit and our planet's position in relation to the sun, as well as other natural occurrences such as massive and widespread volcanic eruptions and large-scale movements of Earth's tectonic plates. Now, however, the process forcing Earth's climate to change and arctic sea ice to vanish is originating from a different source. Through extensive, painstaking, and repeatedly-confirmed research of various kinds, scientists have determined that the current source of climate warming and the dominant factor responsible for the associated melting of arctic sea ice is a human cause: our emissions of greenhouse gases, primarily carbon dioxide from the burning of fossil fuels. Natural variability plays a role in the status of arctic sea ice from year to year, but the driving force now causing the long-term declining trend is man-made climate change.

Rapid decline of arctic sea ice is one of the most obvious indicators that anthropogenic climate change is real and is already causing major impacts. Furthermore, melting of the sea ice is also one of the most ominous effects of global warming, because disappearance of the ice will contribute to causing a torrential cascade of additional grave consequences that will ultimately affect every living thing on the planet, including humans, either directly or indirectly.

The Norwegian Polar Institute's research ship RV Lance is tethered to a large floe of arctic sea ice in the central polar basin, enabling an international team of scientists to conduct a variety of experiments on the ice during the record-setting melt season in summer 2012.

** Editor's Note: This article went to press during the 2014 melt season. Therefore, data relating to the September 2014 sea ice minimum are not discussed.*



Using an airborne instrument called the EM-Bird, a large torpedo-shaped device that hangs from a helicopter, scientists assess the thickness of arctic sea ice. As the helicopter flies transects back and forth above the ice, electromagnetic and laser sensors in the EM-Bird continuously and synchronously collect data that can then be used to calculate the thickness of the ice.

Sea-ice geophysicists Stephen Hudson and Mats Granskog assemble an automatic weather station on the ice near 83 degrees north during the 2012 ICE expedition, to collect a variety of data continuously while other research activities are conducted.

TURNING OFF EARTH'S AIR-CONDITIONER

Arctic sea ice has played an important role in regulating Earth's climate for millions of years, and has been crucial for that purpose throughout the entire period in which human civilization has flourished. Without the ice, our planet would be a very different and far less hospitable place for both ourselves and countless other species, many of which we depend upon for sustenance.

The most vital function performed by arctic sea ice is its role as a planetary air-conditioning system. Primarily due to the vast expanse of bright white ice floating on the surface of the Arctic Ocean, most of the incoming solar energy reaching the far-northern portion of our planet is reflected back out into space, and therefore does not affect our climate. This high reflectivity of the arctic sea ice, known as high albedo, is crucial for maintaining global temperatures within the relatively narrow range that is required for life on Earth as we know it. On the other hand, if arctic sea ice were absent, most of the incoming solar energy in the Far North would instead be absorbed by the dark ocean, which has low albedo, and that immense amount of additional heat would significantly raise temperatures of the sea, air, and land both in the Arctic and far beyond.

Due to the major shrinkage of arctic sea ice that has occurred during the past few decades, and the associated increase in absorption of solar energy by ice-free areas of the Arctic Ocean, an important process known as the ice-albedo feedback mechanism has begun to accelerate disappearance of the ice. As the bright ice melts and is progressively replaced by dark ocean, more solar energy is absorbed in the water, the temperatures of the ocean and air in that region consequently rise, more ice therefore melts, more dark water is then exposed, and further heating of the ocean and air occurs as a result. This self-reinforcing process, referred to as a positive feedback effect, is expected ultimately to be a key factor causing the summer arctic sea ice to disappear entirely.

Rapidly-melting arctic sea ice in the central polar basin, August 2012. As a result of human-caused climate change, arctic sea ice is quickly deteriorating and shrinking. In September 2012, the Arctic Ocean's floating cap of ice shriveled to the lowest extent and volume ever documented by scientists.

To gain a better understanding of sea-ice loss and heat-transfer processes in the Arctic Ocean as Earth's atmosphere warms, geophysicists Stephen Hudson and Mats Granskog use several scientific instruments mounted on a sledge to collect data relating to the reflection, absorption, and transmission of solar energy by different types of arctic sea ice and by melt ponds of varying depth on the surface of the ice.

The nearly-impenetrable thick cap of floating ice that covered an enormous expanse of the Arctic Ocean in the past and previously survived year after year – so-called multiyear ice – has already been replaced in many regions by thin first-year ice that forms in the winter and readily disintegrates by the end of the summer. According to an April 2013 report by NSIDC, "While multiyear ice used to cover 60% of the Arctic Ocean, it now covers only 30%." The oldest ice – the subset of multiyear ice that has survived more than four years – comprised only 5 percent of the ice at the end of the winter in 2013, NSIDC concluded.

The shift from mostly multiyear ice to mostly first-year ice is important not only because the ice pack is therefore more fragile, but also because during summer the younger ice has a lower albedo than the older ice and therefore reflects much less solar energy. Research by sea-ice geophysicist Marcel Nicolaus and colleagues from the Alfred Wegner Institute, published in the scientific journal *Geophysical Research Letters* in 2012, analyzed the first-year ice that is now widespread throughout much of the Arctic Ocean, and compared certain key characteristics of this young ice to those of multiyear ice. In particular, the research focused on the fact that there is extensive melt water ponded on the surface of the first-year ice during the summer. The study concluded that young, thin ice with many melt ponds reflects much less solar energy than older, thicker ice with fewer melt ponds. "Its reflection rate is just 37 percent," says Nicolaus, compared for example to a reflection rate of 62 percent for thicker ice in the same regions in 1980. In addition, explains Nicolaus, young ice with many melt ponds "also absorbs 50 percent more solar radiation, which causes more melt."

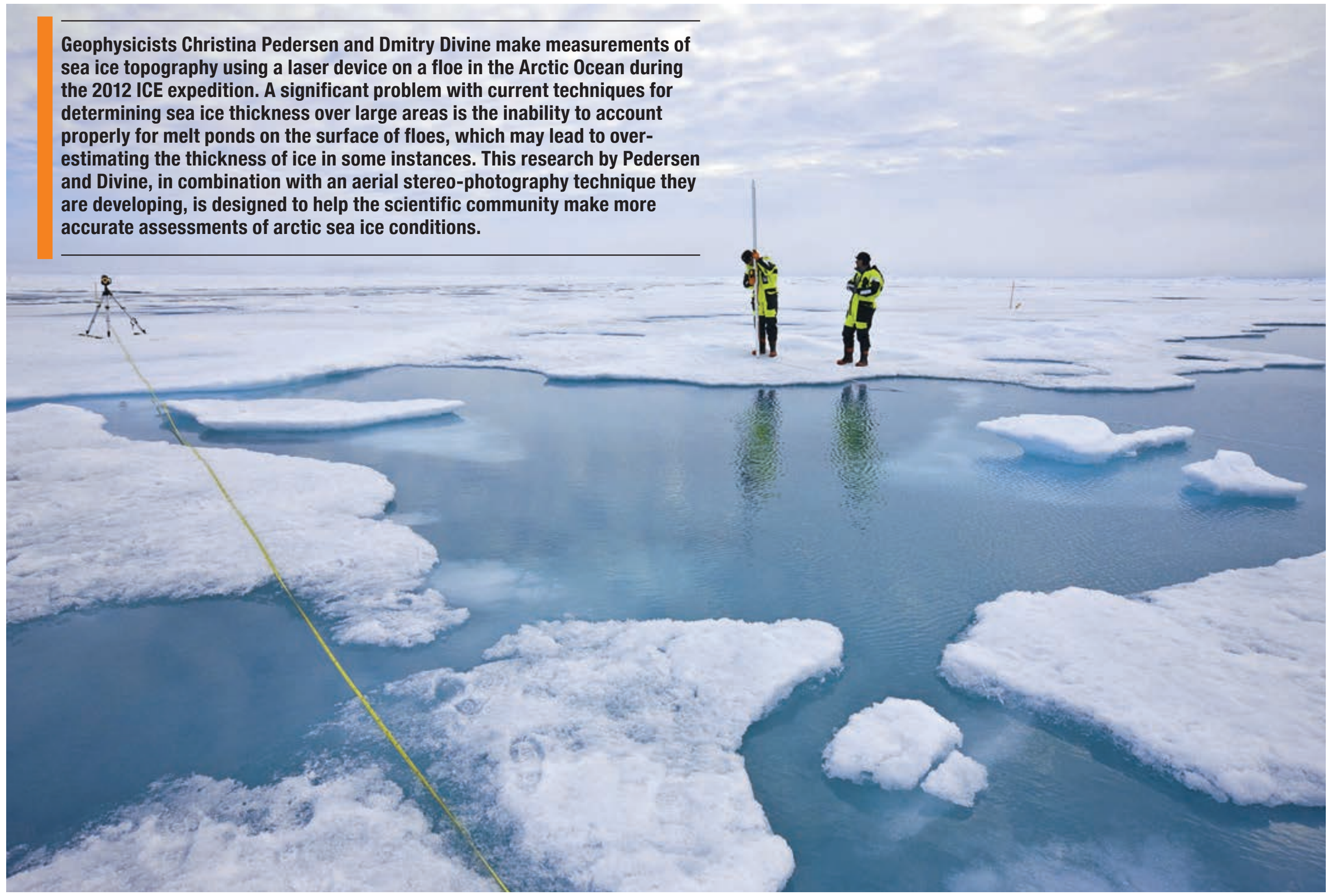
Research conducted by Norwegian Polar Institute scientists in the central Arctic Ocean during the 2012 ICE expedition further explored the ways in which thin first-year ice responds to incoming heat not only from the sun, but also from the atmosphere and ocean. By fully evaluating and quantifying the role that all sources of energy input play in causing sea ice to melt, the scientists were able to shed additional light on the interlinked processes resulting in the drastic decrease of arctic sea ice that has occurred recently. In their study, published in *Geophysical Research Letters* in 2013, the researchers concluded that absorption of solar energy plays the largest role in causing sea ice to melt, and absorption of heat from the ocean below is also important. In addition, they quantified the portion of solar energy that is transmitted through the sea ice to the ocean below, where it contributes to additional melting of ice from underneath. Importantly, the scientists found that thinner and less-reflective first-year ice with many melt ponds not only absorbs more solar energy than multiyear ice, it also transmits more of the absorbed energy to the underlying ocean. "We now see that the Arctic Ocean absorbs more solar energy than in the past," explains Stephen Hudson, lead author of the study, "simply because thinner first-year ice is more transparent than thicker multiyear ice. We also see that some of the energy melts the ice rather quickly, while some is stored as heat in the ocean, where it can delay the formation of new ice in autumn." In a self-reinforcing cycle, the late-forming new ice then has less time to accumulate thickness over the winter, and is therefore more easily melted during the following spring and summer.

Because the declining condition and shrinking extent of sea ice are enabling increasing amounts of solar energy to reach surface waters in the Arctic Ocean, water temperatures are rising significantly. Whereas in the past arctic sea-surface temperatures hovered around freezing all year in all areas, now many of the Arctic Ocean's marginal seas are heating up dramatically as the ice disappears. For example, the 2012 Arctic Report Card issued by the U.S. National Oceanic & Atmospheric Administration (NOAA) determined that sea-surface temperatures in ice-free portions of the Beaufort, Barents, Kara, and Laptev Seas during August 2012 were as much as 3°C higher than the average August temperatures were in those regions from 1982 to 2006. And in some areas of the ice-free ocean north of Siberia where the sea ice vanished early in the record-breaking 2012 melt season, the sea-surface temperatures rose as much as 4-6°C higher than they were in recent decades.

The extent to which arctic sea ice has already dwindled and been replaced by energy-absorbing dark ocean during the summer is not only causing additional melting of the ice and heating of ocean surface waters; it is also contributing considerably to overall warming of the Arctic region. A 2008 study published in *Geophysical Research Letters* by David Lawrence of the U.S. National Centre for Atmospheric Research (NCAR) and colleagues determined that "extensive and rapid sea-ice loss results in strong and spatially extensive warming of Arctic land." Specifically, the researchers concluded that during periods of sustained and speedy sea-ice loss such as the Arctic has experienced in recent years, the rate of increase in arctic surface air temperatures over land is three and a half times greater than global warming would otherwise cause it to be if the sea ice were not disappearing. The scientists found that this enhanced warming is apparent throughout most of the year, but reaches its maximum levels in the autumn after the summer melt season, when the ice-free portions of the Arctic Ocean release their accumulated heat to the atmosphere. The greatest warming of air over land occurs in proximity to the regions of the ocean where loss of sea ice is most extensive. However, importantly, the researchers also determined that significant increases in land and surface air temperatures directly attributable to sea-ice loss extend very far inland — up to 1500 kilometers from the arctic coast. These results were subsequently confirmed in a related NCAR-led study in 2010.

In addition, largely as the result of the ice-albedo feedback effect and associated warming, it is clear that surface air temperatures are increasing in the Arctic much more rapidly than elsewhere across the globe – more than twice as fast as the planet's overall average temperature is rising, a phenomenon known as "arctic amplification" of climate change. For example, according to NOAA data, average surface air temperatures in the Arctic from 2001 through 2012 were 2–3°C higher than they were during the period 1979-2000, whereas average mid-latitude temperatures had a smaller increase of 0.5–1°C.

Melt ponds on the surface of arctic sea ice, such as this one near 81 degrees north, are both a symptom and a cause of sea-ice deterioration during the melt season. As temperatures rise, melt ponds increase in number and size. As they do so, the albedo (reflectivity) of the ice decreases, more solar energy is absorbed, and more melting occurs. Research published in April 2014 found that the fraction of the sea ice surface covered by melt ponds in spring can be used to estimate the total extent of sea ice that will remain at the end of the melt season in autumn. More pond coverage early in the melt season in May is strongly correlated with smaller sea ice extent in September.



Geophysicists Christina Pedersen and Dmitry Divine make measurements of sea ice topography using a laser device on a floe in the Arctic Ocean during the 2012 ICE expedition. A significant problem with current techniques for determining sea ice thickness over large areas is the inability to account properly for melt ponds on the surface of floes, which may lead to over-estimating the thickness of ice in some instances. This research by Pedersen and Divine, in combination with an aerial stereo-photography technique they are developing, is designed to help the scientific community make more accurate assessments of arctic sea ice conditions.

Research published in 2013, conducted by James Screen and Ian Simmonds at The University of Melbourne in collaboration with colleagues at NCAR, focused on quantifying the specific impact of sea-ice loss on terrestrial surface warming in the Arctic. The scientists concluded that 50–75% of the annual average change in surface temperatures of arctic land regions can be explained by the decrease in sea ice and the associated increase in ocean temperatures. The influence of sea-ice loss is apparent year-round but is most pronounced in the later part of the melt season, when the largest areas of ocean are ice-free and sea-surface temperatures have warmed the most, and continuing through the winter. In spring, increasingly early melting of snow cover due to rising arctic temperatures also contributes to enhancing warming through a self-reinforcing mechanism similar to the ice-albedo feedback effect. Like ice, snow cover has a high albedo and reflects most of the sunlight that hits it, but bare tundra has a low albedo and absorbs much of the incoming solar energy. As loss of sea ice increases arctic temperatures, snow cover on the tundra melts more quickly, more of the darker ground underneath is exposed to the sun, more solar energy is absorbed in land areas, and temperatures rise even more.

Overall, "sea ice acts as a very strong control on near-surface warming of the terrestrial Arctic," explains geophysicist Frans-Jan Parmentier in another recent study. Although other factors such as the snow-albedo feedback in spring contribute to arctic amplification, "the most important control on circumpolar surface temperatures seems to be sea-ice extent."

Moreover, new research by geophysicist Clara Deser of NCAR and collaborators indicates how important the loss of arctic sea ice may ultimately prove to be for Earth's climate throughout the Northern Hemisphere and globally. The study, completed but not yet published, reveals that by the time arctic sea ice is absent throughout the summer – toward the end of this century or sooner – the loss of the ice in itself may be responsible for causing up to 35% of warming in the Northern Hemisphere (defined for the study as the hemispheric region above 40 degrees north), and 14% of total global warming. Stated another way, the scientists have determined that by the end of the 21st century, average annual air temperatures in the Northern Hemisphere will be about 35% higher, and average annual air temperatures globally will be about 14% higher, than they otherwise would have been if the summer sea ice had not disappeared.

Physical oceanographer Arild Sundfjord deploys a scientific device through a hole in the arctic sea ice during the record-setting 2012 melt season. The device is a tethered, free-falling, turbulence drop-sonde containing several scientific instruments which collect a variety of data at different ocean depths as the sonde moves down through the water column in a particular location. The ultimate goal of this research is to gain a better understanding of the physical and thermodynamic processes in the ocean affecting the integrity of sea ice.

SHREDDING THE ARCTIC OCEAN WEB OF LIFE

As arctic sea ice shrinks significantly, many species are already being affected by both the loss of the ice itself and by the resulting increases in ocean, air, and land temperatures. If the ice ultimately disappears throughout much of the summer, arctic ecosystems in the ocean and on land will be transformed. Many species will suffer substantial negative effects, and some are likely to vanish entirely. It is becoming increasingly clear that loss of sea ice will shred the intricate and delicately balanced web of life in the Arctic.

Far from being the barren wasteland that many people assume it to be, the Arctic Ocean and its marginal seas are ecologically rich, and some areas are literally teeming with life. Profuse populations of flora, invertebrates, fish, birds, and marine mammals utilize and depend on this icy region. For example, the arctic coastal realm sustains an estimated 500 million seabirds alone.

Contrary to popular belief, arctic sea ice is not comparable to an ice cube floating in a glass of water; rather, it is an essential component of a thriving ecosystem. Arctic wildlife ecologist Ian Stirling of the Department of Biological Sciences at the University of Alberta draws a concise analogy: "Sea ice is as central to life in the Arctic Ocean as soil is to life in a forest." In fact, there is a large and growing body of research revealing that sea ice is such an integral element of the Arctic Ocean biome that every ice-associated and cold-adapted marine species there – ranging from ice algae, phytoplankton, crustaceans and fish, to seabirds, seals, walruses, whales and polar bears – will be affected by the loss of sea ice, and some will be irreparably harmed. Furthermore, in a 2013 paper published in the journal *Science*, Pennsylvania State University Polar Center biologist Eric Post and colleagues, including Stirling, emphasize that "[a]s one of Earth's major biomes, sea ice not only comprises unique ecosystems in, on, and under the ice itself but also strongly influences patterns and processes in adjacent terrestrial ecosystems." Scientists are just beginning to explore in detail the potential ecological domino effects of sea-ice loss in the Far North, but it is already clear they are significant.

An adult female harp seal surfaces in a breathing hole she has maintained in the arctic sea ice to monitor her young pup resting on the floe nearby. The disappearance of sea ice will transform arctic ecosystems, and will have dire consequences for ice-associated marine species ranging from algae and crustaceans to seals, walruses, and polar bears.

> “Sea ice is as central to life in the Arctic Ocean as soil is to life in a forest.”

Forming the foundation of the Arctic Ocean food web are so-called primary producers, photosynthesizing organisms on which all higher-level marine life depends. They transform solar energy into fats, carbohydrates and proteins that ultimately fuel the entire ecosystem. Primary producers are eaten by herbivorous zooplankton — tiny marine invertebrates that float in the water column, such as lipid-rich copepods and amphipods – as well as some small fish. Those creatures in turn become prey for larger zooplankton and fish, seabirds, and some marine mammals. At the arctic marine food web's highest levels are carnivorous mammals such as seals, some whales, and polar bears that eat the lower-level predators.

Ice algae are primary producers that live on the underside of arctic sea ice, as well as within the ice itself. They may be attached to individual ice crystals inside the pack ice or live in the tiny brine channels crisscrossing the interior structure of floes, or they may grow and thrive affixed to the bottom surface of the floating ice. There are more than 1000 species of ice algae in the Arctic. Amazingly, in one study scientists counted 237 species in just a single core of sea ice. Ice algae are a crucial high-quality food resource directly sustaining innumerable ice-associated creatures including herbivorous single-celled organisms, zooplankton, and fish, and indirectly supporting much of the arctic food web. But the reliance of ice algae on sea ice for at least part of their life cycle strongly indicates that they are likely to fare increasingly poorly as the sea ice melts and disappears because of climate warming.

Some arctic phytoplankton — other photosynthesizing organisms that float freely in the ocean under the ice and between floes — will initially thrive as deterioration of sea ice provides more sunlight for their growth. However, phytoplankton require more than light in order to flourish; they also need dissolved nutrients such as nitrates, phosphates, and iron that are in low supply in the ocean surface waters where these tiny organisms live. Mixing of the ocean, which brings nutrients from lower to upper water levels where they can be utilized by phytoplankton, is naturally limited due to the tendency of seawater to divide itself into discrete layers. Moreover, nutrient upwelling in the Arctic Ocean from mixing is becoming even more restricted as melting sea ice causes greater stratification of the water. When sea ice forms, salt is gradually expelled into deeper water as the surface water freezes. The older the ice, the less salty it becomes. So when sea ice melts, it creates a thick layer of fresh water on the ocean surface that warms quickly in the sun and floats on top of the more saline, colder, and denser seawater underneath. Like oil and water, these layers do not mix well. All of this means that although phytoplankton will receive more sunlight as the sea ice disappears, without more nutrients the extra solar energy may be of limited use to them. Theoretically, in some shallow continental shelf regions there might be increased wind-driven upwelling of nutrients caused by greater ocean turbulence as the protective cover of sea ice vanishes. However, it remains to be seen whether or not this will indeed be the case. And, even if this mixing occurs in shallow shelf areas, deeper stratified waters are likely to be unaffected.

Furthermore, although extra sunlight may be beneficial to some extent for certain species of primary producers even in the absence of additional nutrients, other species may undergo detrimental physiological changes with exposure to more solar radiation and higher temperatures. For example, ice algae are exquisitely adapted to thrive in limited light conditions beneath and within the arctic sea ice. They are therefore able to provide essential high-quality food for herbivorous marine animals that graze on them in the arctic spring and early summer before there is sufficient light for phytoplankton to bloom. But as the arctic sea ice thins,

In the central basin of the Arctic Ocean, biological oceanographer Philipp Assmy (in red, kneeling on the ice) works with scientific divers Haakon Hop (standing), Peter Leopold (kneeling), and Rupert Krapp (in the water) on an experiment designed to assess the growth rate of algae beneath different ice types and in varying light conditions. Ice algae live on the underside of arctic sea ice, as well as within the ice, and are a crucial food resource directly sustaining many ice-associated creatures and indirectly supporting much of the arctic food web. They are threatened by loss of sea ice as the climate changes and temperatures rise.

Numerous ice algae aggregates float in melt water as sea ice in the Arctic Ocean rapidly disintegrates. During the 2012 ICE expedition when sea ice was shrinking toward a record low extent, scientists discovered widespread occurrences of these free-floating lumps of ice algae. The researchers investigated possible causes of this unusual phenomenon, and evaluated the potential ecological role that formation of such aggregates may play during the arctic melt season.

fractures, and melts due to climate warming, ice algae are being subjected to significantly greater amounts of solar radiation. There is scientific evidence that at least some of these organisms, when exposed to such sunnier and warmer conditions, undergo a biochemical transformation that renders them much less nutritious for animals higher in the food web dependent on them for sustenance. These basic changes could undermine the health of the arctic marine ecosystem in important ways.

In addition, as the sea ice vanishes and ocean conditions change, it appears the larger phytoplankton that are most vital for supporting the marine food web will have greater difficulties coping compared to smaller phytoplankton. Research recently conducted in the Canada Basin of the Arctic Ocean determined that the tiniest phytoplankton, so-called picoplankton that are less than 2 microns in diameter, are likely to become more common in regions where the sea ice has disappeared. This is because their high surface-area-to-volume ratio augments acquisition of scarce nutrients from the surrounding sea, and their structure makes them resistant to sinking in freshening surface waters. On the other hand, scientists anticipate a decline of larger phytoplankton — the most crucial free-floating food resources for herbivorous creatures — because their physical characteristics will cause them to be less able to obtain necessary nutrients and more likely to sink to the seafloor in the altered ocean conditions associated with loss of sea ice. Replacement of larger phytoplankton by miniscule picoplankton could have major negative effects on higher levels of the food web.

Fundamentally, as emphasized by Eric Post and his collaborators in their 2013 study, the dramatic decline of arctic sea ice as the result of climate warming "represents a stunning loss of habitat for sea-ice algae and sub-ice phytoplankton, which together account for 57% of the total annual primary production in the Arctic Ocean." With sea-ice loss undermining such vital foundational components of the ecosystem, it is clear there will be momentous ramifications for many other organisms throughout the arctic marine web of life.

Arctic zooplankton species that are very specialized for living in association with the sea ice are likely to have serious problems coping as the ice disappears. For example, the shrimp-like amphipod *Gammarus wilkitzkii* is uniquely well-adapted physiologically, anatomically, and ecologically to live on the underside of the floating sea ice and graze on ice algae, even sporting some pairs of legs that face upward and others that are oriented downward. But this creature is poorly suited for functioning exclusively in open water, and is expected to have increasing difficulty surviving as sea ice continues to diminish.

The zooplankton *Calanus hyperboreus* and *Calanus glacialis*, small herbivorous copepod crustaceans, are also closely associated with sea ice, and are among the most important of all organisms in the Arctic Ocean's food web. Higher-level animals ranging from polar cod to arctic seabirds and bowhead whales all rely heavily on these little crustaceans for vital high-energy food, preying largely on *C. hyperboreus* in deep-water areas of the Arctic Ocean, and primarily on *C. glacialis* in shallower continental shelf regions. Grazing on ice algae and phytoplankton, *C. hyperboreus* and *C. glacialis* consume large quantities of crucial omega-3 fatty acids, substances that are necessary for successful reproduction and development of all marine organisms, and are produced exclusively by photosynthesizing algae and plankton. The copepod crustaceans then transform the omega-3 fatty acids into huge lipid reserves that are stored in internal sacs comprising nearly the entire volume of their bodies. Those fat reserves, needed for basic life-cycle activities of *C. hyperboreus* and *C. glacialis*, are then also available to provide essential top-quality nutrition for higher-level animals that eat the copepods.

But because these lipid-rich copepod species live in close association with arctic sea ice, they are likely to decline as the ice disappears and temperatures rise. For example, scientific studies indicate that *C. glacialis* – the most important copepod species throughout the Arctic's continental shelf areas for supporting higher levels of the food web — will indeed be negatively affected by both the loss of sea ice and by associated rising ocean temperatures. Ice algae are an essential source of nutrition for *C. glacialis* at times of year when other foods are not available. The annual bloom of ice algae occurs as much as two months prior to the bloom of free-floating phytoplankton, and is crucial for key life functions of *C. glacialis* in spring and early summer, including reproduction. Rapid melting of increasingly-thin sea ice during that time will decrease the availability of ice algae as a food resource, and will therefore cause grave consequences for *C. glacialis*. Decline of *C. glacialis* will in turn cause major negative effects to cascade through the food web.

Creatures that feed on ice-associated zooplankton are expected to suffer problems as populations of their prey shrink because of dwindling sea ice. One example is the little auk (*Alle alle*), currently a common arctic seabird. Scientists are concerned that the little auk will confront serious challenges as melting ice and rising temperatures increasingly affect its key food resources. The small chubby bird feeds almost exclusively on calanoid copepods (*Calanus spp.*), and relies on the largest and most lipid-rich species of those invertebrates, *C. hyperboreus* and *C. glacialis*, which occur in cold arctic waters. But as arctic sea ice disappears and Arctic Ocean temperatures rise, a much smaller and less nutritious copepod, *C. finmarchicus*, which prefers temperate waters, is moving north and becoming more prevalent in the little auk's habitat. If current climate trends continue, scientists anticipate that the larger and fattier arctic copepods will decline, and little auks will be forced to rely increasingly on *C. finmarchicus* instead. However, in that case the birds, which hunt by sight, will need to expend far more energy in order to obtain the same amount of nutrition. Tiny *C. finmarchicus* is much harder to see and catch than the larger copepods; moreover, its lipid sac holds 25 times less energy than *C. hyperboreus* and 10 times less energy than *C. glacialis*. As the little auks are obliged to fly farther and work harder to feed themselves, they may ultimately burn more calories than they consume, and their long-term survival could be in jeopardy. Furthermore, the little auk is not alone in feeding almost exclusively on the fatty calanoid copepods, and in facing a significant threat from the potential climate-related demise of *C. hyperboreus* and *C. glacialis*. Many other arctic species, including the magnificent bowhead whale, depend on those lipid-rich crustaceans for nourishment.

The ivory gull (*Pagophila eburnea*), a rare and beautiful high-arctic bird, is confronted by similar challenges. Ivory gulls are dependent on sea-ice habitat and feed exclusively in icy waters, munching on nutrient-rich arctic invertebrates including the ice-dependent zooplankton *Gammarus wilkitzkii*, as well as small ice-associated fish such as juvenile polar cod. The birds also follow polar bears on the sea ice and scavenge on bits of seal carcasses left atop floes by the huge arctic predators. Ivory gulls nest on steep and inaccessible cliffs at the edges of remote arctic islands near the pack-ice edge where they forage for food, and during the non-breeding seasons they are wholly associated with arctic sea ice. The pure-white birds strongly prefer areas of ocean with 70–90 percent ice coverage. As arctic sea ice progressively melts and disappears, these polar seabirds are declining ominously. The species is designated as Near Threatened throughout its range by the International Union for the Conservation of Nature (IUCN), and is separately listed as Endangered in Canada and Threatened in Greenland. Scientists believe that loss of sea-ice habitat due to climate change, and related effects on the ivory gull's prey, are primary factors imperiling the species.

Significant effects on arctic fish populations are also anticipated to occur as the sea ice diminishes and ocean temperatures rise. Major changes in species composition, abundance, and distribution in various arctic regions appear inevitable, and have indeed already begun. Some arctic fish graze on ice algae and ice-associated phytoplankton, and others eat cold-water zooplankton. Loss of sea ice, increasing water temperatures, and other related alterations in ocean conditions that affect these important lower-level arctic food resources will unavoidably have indirect impacts on the fish that eat them. Moreover, arctic fish that are particularly cold-adapted, and those that are closely associated with sea ice for at least a portion of their life cycle, will also be directly affected by disappearance of the ice and rising ocean temperatures. These fish are likely to shift their ranges northward toward the central polar basin as the ice shrinks, at least during summer. In fact, such range adjustments are already starting to occur. But availability of food for these fish, as well as specialized habitats they require for different stages of their life cycles, will likely decrease as they move northward away from the biologically-productive and shallower continental shelf regions. Furthermore, as sea ice continues to shrink and ocean temperatures keep rising, the specific environmental conditions necessary for some cold-adapted fish may eventually disappear entirely. Ultimately, the ice will be absent for much of the summer throughout the central Arctic Ocean and at the North Pole, and the ocean temperatures may become too warm for them even in that area. And then there will be nowhere farther north for them to go.

On the other hand, temperate fish are expected to expand their ranges into warming and increasingly ice-free arctic waters, and some of those warmth-tolerant species may benefit at the expense of polar fish. The southern invaders are likely to compete increasingly with arctic resident species for food and desirable habitats, and may also predate on the arctic fish, their young, or their eggs. The precise nature of these new interactions is not yet clear, but there is little doubt that major changes will occur, and there will be ecological winners and losers.

One high-arctic fish likely to be affected by the rapid transformation of the Arctic Ocean is polar cod (*Boreogadus saida*, known as arctic cod in North America), a currently-abundant species that plays a central role in arctic marine ecosystems. It is a primary food for many seabirds and marine mammals including arctic seals and some whales, as well as for other fish species such as arctic char that are consumed by people and are commercially valuable. Polar cod, which feed on lipid-rich arctic zooplankton such as *C. glacialis*, spend much of their time in ice-covered areas of polar seas rather than in open water.

To evaluate which species of ice-reliant zooplankton are present at this location in the Arctic's central polar basin, scientific divers Haakon Hop, Michael Tessman, and Peter Leopold prepare to collect samples of the invertebrates living beneath a large floe of ice using a suction pump.

In particular, young polar cod are often observed hiding within small sea-ice cracks and brine channels, which is likely a predator-avoidance behaviour. The specific effects that increasing temperatures and vanishing sea ice will have on polar cod are not yet certain, but potential impacts are numerous and significant. Possibilities include harmful physiological consequences and reproductive decline because of rising temperatures, diminishing food resources as their prey are affected by sea-ice loss and warming of the ocean, displacement by invading competitors, and increased mortality from new predation. Within the past decade, several species of temperate fish have begun encroaching substantially into polar cod habitat. Scientists are just beginning to study the species interactions and consequences in this newly-evolving situation. But it is apparent that the stakes are potentially high not only for the polar cod but for arctic birds, marine mammals, and commercially important fisheries that are all reliant to one degree or another on the fate of the polar cod.

Shrinking sea ice and rising temperatures also pose a variety of major challenges for arctic marine mammals. Species that depend on the sea ice itself for some or all essential aspects of their lives are already beginning to face substantial problems in some regions. Polar bears are the most well-known example. Fundamentally reliant on sea ice for vital life functions, polar bears are unquestionably confronting a dire threat from arctic warming and loss of the ice. Most crucially, in the absence of sea ice the iconic predators cannot hunt seals, their primary prey. If current climate trends continue, scientists anticipate that two-thirds of the world's polar bears will vanish by 2050 as their sea-ice habitat disappears, and all remaining polar bears throughout the Arctic will be endangered by the end of this century. Less well-known is the fact that other arctic marine mammals also face serious threats from deteriorating ice conditions as the result of increasing temperatures.

Recent research indicates that ramifications of vanishing sea ice are starting to affect the whale species that live year-round exclusively in arctic and sub-arctic waters – bowhead whales, narwhals, and belugas. In a number of areas, some of these iconic creatures are beginning to face problems such as negative effects on their food resources from rising ocean temperatures associated with ice loss, entrapments in ice because of unpredictable melting and re-freezing conditions, and increased predation by killer whales that are invading the Arctic from more temperate areas as the sea ice melts. But the news so far is not all bad. For example, populations of bowhead whales currently appear to be faring well overall in most locations where they are closely monitored. So it remains to be seen whether the Arctic's unique whale species can adapt successfully over the long term to the major challenges they will face as the sea ice shrivels.

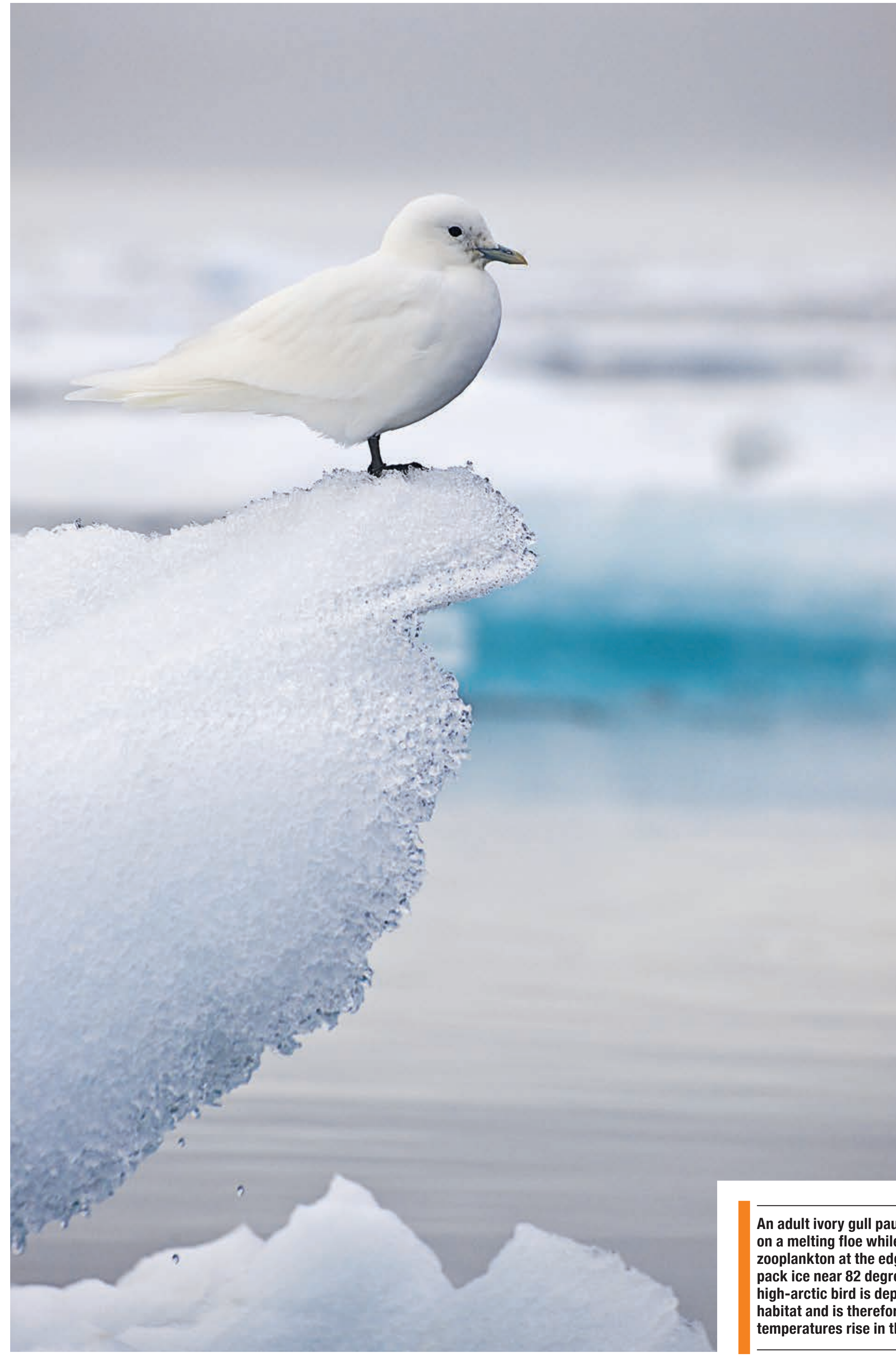
There are already serious concerns that arctic pinnipeds (seals and walruses) may not be able to adapt to ice-free conditions. Their reliance on sea ice for various crucial aspects of their lives renders them likely to have increasingly severe difficulties and to suffer major declines as the arctic meltdown continues.

The ringed seal (*Pusa hispida*) is uniquely specialized for life in ice-covered seas, and its range extends farther north, and into areas of thicker ice, than any arctic marine mammal other than the polar bear. Using strong, sharp claws on their front flippers, ringed seals are able to maintain holes in extensive areas of pack ice for breathing and for access to the sea-ice surface where they rest and molt. They also construct cave-like lairs in the snow above some of their holes, which they use for giving birth and nursing. These snow lairs provide crucial shelter and thermal insulation for young seal pups, as well as concealment from predators.

Sea ice stability is essential for ringed seal reproduction and survival of young. The ice must provide a solid surface to support mothers and pups during the entire spring birthing and nursing period that typically lasts from mid-March through May. Ringed seal pups are very small at birth – only about 4.5 to 5 kilograms, the smallest of any polar seal neonate — and they initially have no insulating layer of blubber. Pups nurse for 5 to 7 weeks before being weaned, and they grow more slowly than any other ice-associated pinniped. If a ringed seal pup is forced to spend a lot of time in the water prior to weaning — for example, if the ice beneath its snow lair disintegrates prematurely in the spring — the vulnerable young seal will face severe challenges. It will be at high risk of succumbing to hypothermia as well as to becoming separated from its mother. If a young pup is obliged to remain in the water or is weaned too soon, it will not survive. Moreover, even after normal weaning, all pups require secure access to sea ice for frequent resting because being submerged in arctic waters is very energetically costly for a small warm-blooded animal.

Snow cover on the sea ice is also a crucial factor affecting ringed seal breeding success. Without sufficient snow supported by the ice, a ringed seal mother cannot construct a proper birth lair; and without the thermal insulation provided by a chamber with a thick roof of snow, a pup may die of hypothermia. But even if a lair has initially been well-constructed, rising arctic temperatures and melting ice and snow can cause serious problems. A seal pup inside a lair will face great difficulty surviving if spring precipitation falls as rain instead of snow and causes the protective chamber to disintegrate, or if the underlying ice deteriorates and the entire structure collapses.

Unquestionably, without adequate sea ice and associated snow cover, the ringed seal's breeding success and



An adult ivory gull pauses to rest on a melting floe while foraging for zooplankton at the edge of the receding pack ice near 82 degrees north. This rare high-arctic bird is dependent on sea ice habitat and is therefore in jeopardy as temperatures rise in the Far North.

overall survival will be in jeopardy. In fact, research has determined that early break-up and melting of sea ice, as well as deteriorating spring snow conditions, have already caused some populations of ringed seals to begin suffering from declining body condition, reproductive failure, and high pup mortality.

All other species of arctic seals including bearded, harp, hooded, ribbon, and spotted seals, also require sea ice for giving birth and nursing their young pups. In addition, like the ringed seal, they need the frozen platform to rest for extended periods during their annual molt after the breeding season. Thus, as is the case for ringed seals, there are significant reasons for concern regarding the future survival of all these ice-dependent animals. For example, a 2012 study found a clear link between thin, sparse sea ice in breeding areas and high mortality of harp seal pups. With poor ice conditions, pups may be born in the water rather than on ice, they may be dumped into the ocean when thin ice deteriorates beneath them before they can survive in the frigid sea, or they may be crushed by collisions of highly mobile floes when the ice fails to form extensive solid sheets or breaks apart prematurely. In recent years when poor ice conditions have occurred in the important harp seal breeding area within Canada's Gulf of St. Lawrence, mortality of pups has been extremely high, approaching 100 percent.

During the record-setting melt season in summer 2012, an adult female polar bear and her young twin cubs travel on rapidly-deteriorating sea ice in the Arctic Ocean's central basin. Adult polar bears are capable of swimming long distances between floes as they travel and search for prey. But young cubs such as these have little body fat for insulation and buoyancy, and are at risk of drowning or succumbing to hypothermia if obliged to swim far in frigid water.

Like arctic seals, walruses (*Odobenus rosmarus*) use sea ice during the spring and summer for giving birth and nursing calves, and as a platform for undergoing their annual molt following the breeding season. In addition, although they are excellent swimmers with tremendous endurance, walruses must haul out on sea ice or land to rest on a regular basis. Sea ice tends to be preferable for this purpose because it provides a place for walruses to rest close to where they feed on the seafloor, minimizing the need for energetically-costly travel between land-based haul-outs and off-shore foraging locations. Furthermore, using floating sea ice instead of land for resting enables walruses to move passively from one region of the ocean to another, minimizing expenditure of energy for swimming while maximizing feeding range and avoiding over-utilization of limited food resources in one area.

Walruses are bottom-feeders in shallow continental shelf regions of the Arctic Ocean's marginal seas. Although adults are physically capable of relatively deep dives down to 250 meters or more, the animals are normally shallow divers. They forage at depths less than 100 meters, where their prey are most abundant and easier to obtain. The diet of walruses consists mostly of invertebrates living on or near the seafloor or in the sediments, primarily

A sub-adult male polar bear climbs precariously on the face of a cliff above the ocean at Novaya Zemlya in the Russian High Arctic, attempting unsuccessfully to eat eggs in the nests of Brünnich's guillemots. The bear was marooned ashore, unable to feed on seals – his normal prey – because the sea ice had melted throughout the region and receded far to the north. A blubber-rich diet of marine mammal prey is crucial for polar bears. The iconic predators occasionally snack on eggs, vegetation, and even human garbage when they're trapped on land without the ability to hunt seals; however, such alternate foods cannot sustain them.

clams, snails, and worms, as well as crabs, amphipods, shrimp, and sea cucumbers. An enormous quantity of such creatures may be consumed by a walrus in a short time. Research has shown that in a single feeding session of 16 to 17 hours, consisting of repeated dives and foraging forays on the bottom of the ocean, an individual adult walrus may locate, excavate, and consume 6000 clams. Depending on the location, walruses typically forage intensively on the seafloor for a few days, and then haul out on sea ice or land to rest for a day or two. If sea ice is readily available, walruses will often have brief rest periods daily on the ice during bouts of feeding nearby on the ocean bottom.

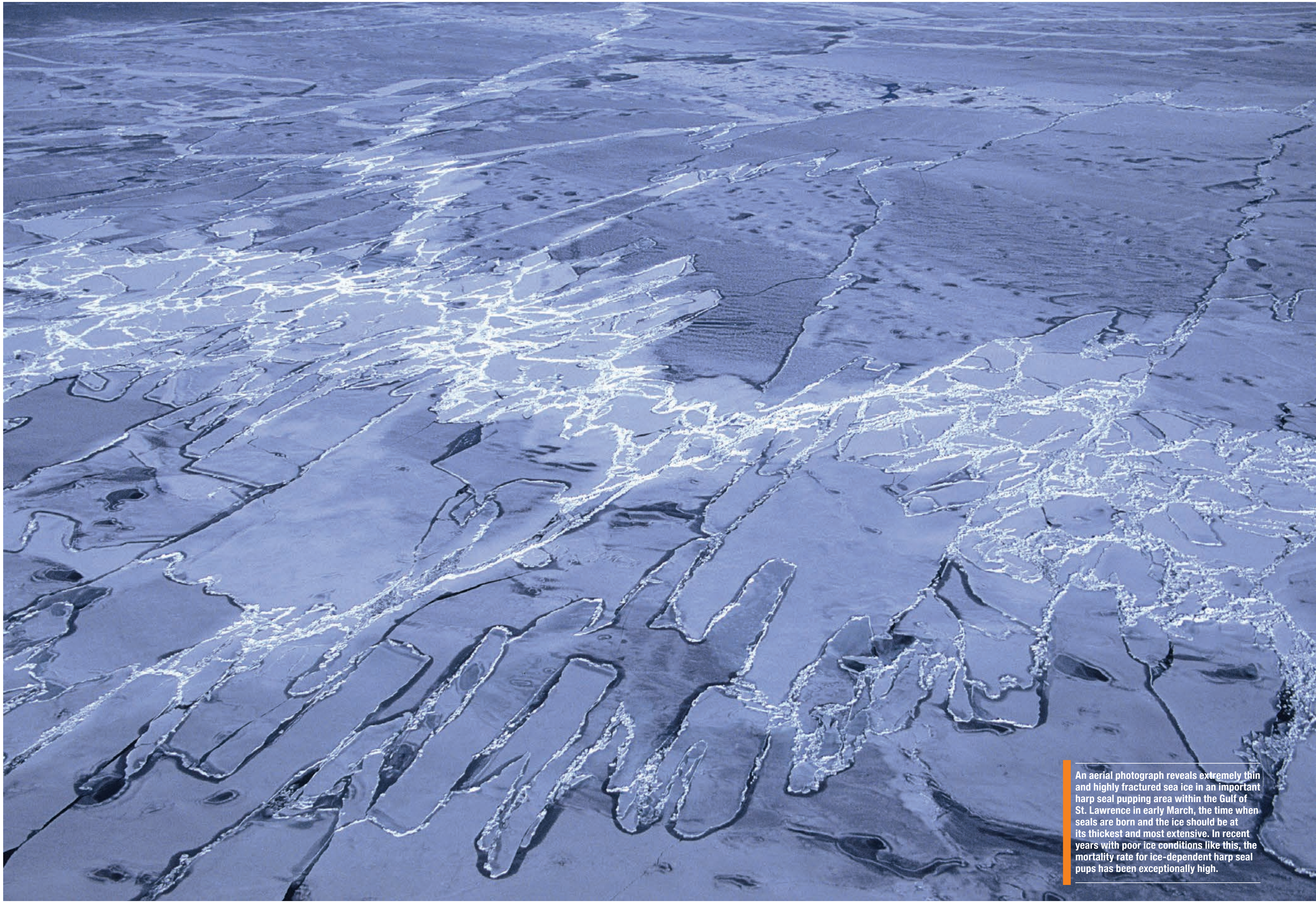
The ability to haul out safely on sea ice and rest in close proximity to feeding areas is particularly important for walrus mothers with calves. Young walruses are dependent on their mothers and rely on nursing for up to two years. An adult female with a calf can more readily meet her own nutritional needs while nursing her offspring frequently if she can forage on the seafloor near the sea ice where her calf is resting. In addition, sea ice helps to shelter the animals from storms and protect them from predators.

But the shrinking summer sea ice is receding northward into the very deep central Arctic Ocean, far from the biologically-productive continental shelf regions walruses depend on for feeding. There is no benefit for walruses to gain by remaining with the sea ice as it retreats into the central polar basin; on the contrary, the water in that region is 3000–4000 meters deep, and feeding on the seafloor there is impossible for them. So, during periods in the summer and autumn when the

A harp seal mother and her young pup – less than 2 weeks old – rest together on the sea ice where the pup was born. All species of arctic seals require sea ice for giving birth, rearing young, and molting. Climate change therefore poses a serious threat to their continued survival.

continental shelf region in many areas is now ice-free, walruses are obliged to go ashore for resting. This situation restricts their ocean-foraging range and may result in depletion of heavily-used feeding areas near terrestrial haul-out sites — a situation which in turn obliges the animals to travel farther seeking food, and then to swim back longer distances to haul out and rest again. These challenges may cause the balance between caloric intake and caloric expenditure to become increasingly tenuous for walruses as the sea ice disappears, particularly in the Pacific portion of their range.

In addition, the inability to use sea ice for resting also often causes walruses to become dangerously over-crowded at haul-outs on land. In recent years when the ice they need has vanished, tens of thousands of walruses have been amassing on thin slivers of beach. Along a single one-kilometre stretch of Alaskan shoreline in 2011, scientists doing an aerial survey estimated 30,000 walruses were jammed together. In such situations, young calves and juveniles are at great risk of being trampled, squashed and suffocated by massive adults if the herd is disturbed. In some coastal areas of Russia and Alaska adjacent to the Chukchi Sea, many young walruses have in fact been crushed to death at haul-outs during ice-free periods when sea ice has receded hundreds of kilometers north of continental shelf regions.



An aerial photograph reveals extremely thin and highly fractured sea ice in an important harp seal pupping area within the Gulf of St. Lawrence in early March, the time when seals are born and the ice should be at its thickest and most extensive. In recent years with poor ice conditions like this, the mortality rate for ice-dependent harp seal pups has been exceptionally high.

According to a scientific assessment recently conducted by the IUCN Species Survival Commission, although the overall walrus population throughout the Arctic is still currently large, there is evidence that the animals are suffering declines in some regions — likely related to the challenges described above. And as summer arctic sea ice continues to shrink, scientists are concerned there may be increasing negative consequences for walruses, and particularly severe impacts on the Pacific subspecies. James MacCracken, a Supervisory Biologist with the U.S. Fish & Wildlife Service in Alaska whose work focuses on Pacific walruses, explains, "In the short term, the most plausible hypotheses predict a continuing northward shift in walrus distribution, increasing use of coastal haul-outs in summer and fall, and a smaller population due to reduced access to prey and subsistence hunting. Alternatively, under worst-case conditions, the population will decline to a level where the probability of extinction is high." MacCracken says management efforts should focus on ensuring subsistence hunting of walruses by indigenous people is sustainable, and on reducing walrus mortalities at crowded terrestrial haul-outs by minimizing disturbance of the animals — a strategy that has had some success recently. However, he emphasizes, "ultimately, reductions in greenhouse gas emissions are needed to reduce sea-ice habitat losses."

An adult Atlantic walrus surfaces to breathe while swimming in the Arctic Ocean north of the Svalbard archipelago. Walruses are strong swimmers, but they must haul out to rest on sea ice or land in between bouts of foraging for food on the seafloor.

A Pacific walrus herd, including individuals of all ages and both sexes, is hauled out on a tiny strip of beach at the base of towering cliffs on Russia's Herald Island in the Chukchi Sea. The receding edge of the melting summer sea ice was hundreds of kilometers to the north, and the walruses were therefore obliged to rest on land. In situations such as this, young walruses are vulnerable to being crushed and suffocated by enormous adults if the herd is suddenly disturbed and there is a stampede toward the water.

THREATENING AN ANCIENT CULTURE

Loss of arctic sea ice, rising temperatures, ecological transformation of the Far North, and associated changes in ocean and land conditions are profoundly affecting indigenous arctic people, and endangering their traditional culture.

Humans have lived in arctic coastal regions for thousands of years, subsisting on harvests of marine mammals, fish, and shellfish, and managing to thrive in one of the harshest places on Earth. In some remote areas of the Arctic even today, traditional subsistence lifestyles persist and are central both to sustaining indigenous communities and to maintaining their cultural identities. In those isolated regions, food from the sea remains one of the only readily available sources of high-quality nutrition.

But the ancient way of life that is reliant on the Arctic Ocean for sustenance is being jeopardized by loss of sea ice and warming arctic temperatures. Even in the most remote northern areas of Greenland where indigenous people still live, the sea ice is now absent for an increasingly lengthy portion of the year. The Inuit there must use boats when sea ice is insufficient to hunt more traditionally by dogsled. However, the conditions are often perilous for hunting in a small vessel, because the weather has become extremely erratic, and the severity of storms and turbulence of the ocean are increasing dangerously. Moreover, unpredictably-forming new ice can suddenly trap or fatally damage a little boat. In addition, as arctic sea ice shrinks, the long-term survival of many animals hunted by indigenous people, including walruses and seals, is at risk. Currently well-controlled subsistence harvests may become unsustainable eventually as disappearance of sea ice takes an increasing toll on arctic wildlife populations.

A sub-adult female Atlantic walrus, killed by Inuit subsistence hunters, is towed through thin sea ice in Northwest Greenland. Hunting of walruses has been an integral part of the ancient Inuit culture for millennia, and is still important for sustaining indigenous people in isolated regions of the Arctic where the meat of these animals remains a key source of food.

ACIDIFYING THE ARCTIC OCEAN

Since the Industrial Revolution, as human emissions of greenhouse gases from the burning of fossil fuels have increased greatly, concentrations of carbon dioxide in the atmosphere have risen from approximately 280 parts per million to about 400 parts per million. But they have not risen as much as they would have if the oceans had not been absorbing an enormous amount of the excess CO_2 from the air on an ongoing basis. According to the comprehensive scientific report "State of the Climate in 2012," a Special Supplement of the *Bulletin of the American Meteorological Society* published in August 2013, the world's oceans have absorbed about 155 billion metric tons of carbon dioxide during the past two and a half centuries. At first blush, that seems highly beneficial — by absorbing nearly 30% of anthropogenic carbon dioxide, the oceans have been considerably slowing the rate at which CO_2 accumulates in the atmosphere and heats Earth's climate system. Unfortunately, however, there's a substantial and growing price to be paid for absorption of carbon dioxide in the oceans.

When dissolved in water, carbon dioxide forms carbonic acid. Consequently, absorption of CO_2 from the atmosphere has caused ocean surface waters to increase in acidity by about 30% since the start of the Industrial Revolution.

This issue is cause for tremendous concern because ocean acidification has the potential to cause long-lasting detrimental effects in every marine ecosystem worldwide, by literally dissolving many organisms at the foundation of the food web, depriving many more ocean creatures of their food resources, and potentially rendering others unable to function normally and therefore possibly unable to survive. In addition, ultimately billions of people worldwide are likely to be seriously affected by loss of food from the oceans, as well as by economic harm from damage to commercially-important fisheries.

Scientists have determined that the Arctic Ocean may be especially vulnerable to acidification. Indeed, as explained in the first-ever comprehensive assessment of Arctic Ocean acidification published in 2013 by the Arctic Monitoring and Assessment Program (AMAP) of the Arctic Council, a high-level intergovernmental forum in which representatives of eight arctic countries and indigenous peoples participate, for a number of reasons the Arctic Ocean is already undergoing rapid acidification as the atmospheric concentration of CO_2 quickly rises. First, naturally low temperatures in the Arctic Ocean accelerate the acidification process, because carbon dioxide dissolves more readily in cold water. Second, the relative freshness of the Arctic Ocean compared to more saline seas in temperate regions causes arctic surface waters to be less effective at chemically neutralizing the carbonic acid formed when CO_2 is absorbed from the atmosphere into the water. The Arctic Ocean's freshwater surface layer originates from the input of numerous rivers and melting glaciers along the arctic coast, as well as from increasingly large expanses of rapidly-melting arctic sea ice. In addition, the arctic meltdown is playing another major role in the acidification process. The vast cap of thick sea ice that previously protected the Arctic Ocean from exposure to atmospheric carbon dioxide, acting essentially as a lid that minimized absorption of CO_2 by the water, no longer serves that function as effectively because the ice is shrinking. Consequently, as the sea ice melts and the surface of the Arctic Ocean is progressively in greater contact with the air, the water increasingly absorbs more CO_2 from the atmosphere, and therefore is becoming quickly acidified. As the AMAP report explains, "Arctic waters are among the world's most sensitive in terms of their acidification response to increasing levels of carbon dioxide. The recent and projected dramatic decreases in arctic summer sea-ice cover mean that the amount of open water is increasing every year, allowing for greater transfer

This sample of zooplankton collected by scientific divers beneath arctic sea ice in the central polar basin contains five ice-reliant amphipod species. These creatures, vital for supporting higher levels of the arctic food web, are among the many organisms at risk of suffering severe consequences from ocean acidification. Scientists anticipate that as sea ice vanishes and the Arctic Ocean becomes increasingly acidic due to absorption of carbon dioxide from the atmosphere, these animals will eventually be unable to build and maintain their calcium carbonate exoskeletons, and will literally begin dissolving.

of carbon dioxide from the atmosphere into the ocean."

Many marine creatures living in shallow, biologically productive ocean ecosystems — including various species of plankton, crustaceans, bivalve mollusks, snails, crabs, and coral — build protective shells, exoskeletons, and other crucial structural components made of calcium carbonate minerals. But as atmospheric carbon dioxide is absorbed by the ocean and seawater becomes more acidic, the availability of carbonate ions is reduced, and the ability of those calcifying organisms to build and maintain their essential physical structures from calcium carbonate becomes impaired. "At today's concentrations, the additional carbon dioxide is making it more difficult for many marine organisms to survive," explains Ken Caldeira, a climate scientist with the Carnegie Institution Department of Global Ecology who specializes in ocean acidification. "If we do not greatly reduce carbon dioxide emissions soon," he says, "sometime around mid-century, the oceans will reach higher concentrations that will actually start dissolving the calcium carbonate shells and skeletons of many marine organisms."

In fact, a study led by scientists from NOAA and published in *Proceedings of the Royal Society B* in June 2014 determined that acidity of cold Pacific Ocean waters off the U.S. West Coast is already beginning to dissolve the shells of tiny snails called pteropods. Free-swimming pteropods are found in oceans around the world, and are a vital food resource for many other marine creatures, including commercially important fish such as salmon. In the new study, fifty-three percent of pteropods sampled by scientists in continental shelf waters stretching from northern Washington to central California had severely dissolved shells. Decline of these and other calcifying organisms is expected to have major repercussions throughout the marine food web, because creatures that feed on them are also likely to decline as their prey species disappear.

Rising carbon dioxide in seawater may cause other serious problems as well. Recent research on fish has documented the occurrence of potentially debilitating neurological harm caused by exposure to elevated CO_2. For example, studies have concluded that the ability of some larval fish to detect predators by smell becomes impaired when they are exposed to ocean water with high levels of carbon dioxide, and some may even become strongly attracted to the odour of predators. An additional study determined that elevated CO_2 can impair key auditory functions in fish, and another found that high CO_2 levels decreased the ability of fish to distinguish between favourable and unfavourable habitats. Other research indicates that exposure to elevated concentrations of CO_2 in seawater can significantly alter the cognitive abilities of juvenile fish, rendering them unable to learn how to avoid predators. In all these studies, the fish were exposed to levels of carbon dioxide projected by scientists to be present in the world's oceans within the 21st century.

"CO_2 concentrations predicted to occur in the oceans by the end of this century will interfere with fishes' ability to hear, smell, orient and evade predators," says Göran Nilsson from the Department of Molecular Biosciences at the University of Oslo. In a 2012 study published in the journal *Nature Climate Change*, Nilsson and colleagues sought to determine the underlying cause for these diverse and significant detrimental effects of elevated carbon dioxide on fish. The scientists discovered that the impairments could all be explained by the same mechanism: interference with a vital neurotransmitter receptor in the brain called the GABA-A receptor. Importantly, because GABA-A receptors play a crucial ubiquitous role in neurological function for both vertebrates and invertebrates, the implications of this research are substantial. Increasing absorption of carbon dioxide by the oceans could ultimately cause extremely harmful sensory and behavioral impairments in a wide range of marine species, leading to their decline as well as disruption in the functioning of entire ecosystems.

Numerous studies indicate that rising CO_2 and a level of seawater acidity harmful to marine ecosystems could be widespread in a number of regions in the Arctic within decades. In fact, as arctic sea ice rapidly declines, seasonally corrosive conditions have already been observed by scientists in some Arctic Ocean surface waters and shallow subsurface waters. A study published in 2013 found an unprecedented rate and scale of ocean acidification is currently occurring in the western Arctic Ocean, and identified "recent melting of multiyear sea ice and the associated seawater freshening and uptake of atmospheric CO_2" as the primary cause. The research focused on the Canada Basin, a region of the Arctic Ocean at the juncture of the Chukchi and Beaufort Seas north of Alaska, where melting of arctic sea ice has been particularly extensive during the past decade. Lisa Robbins, U.S. Geological Survey oceanographer, chief of the agency's ocean acidification project and lead author of the study notes, "A remarkable 20 percent of the Canada Basin – an area nearly as large as the entire state of Montana – has become corrosive to carbonate minerals in an unprecedented short period of time. Nowhere on Earth have we documented such large scale, rapid ocean acidification."

Ocean acidification will have major socio-economic and cultural ramifications in the Far North. Commercially important cold-water fisheries, including cod, pollock, salmon, and crab could be seriously affected by ocean acidification this century. One needs only to consider the possible consequences for Alaska alone to get a sense of scale regarding the potential losses involved. According to the 2013 McDowell Group report "Economic Value of the Alaska Seafood Industry," the 2011 wholesale economic value of commercial fisheries in Alaska was $4.6 billion U.S. dollars. And that figure does not include the difficult-to-quantify but substantial annual value of fish and shellfish harvested by individuals – indigenous peoples, non-indigenous Alaskans, and visitors to Alaska – for subsistence and personal consumption. Loss of the ability to rely on subsistence harvest of fish and other marine life would have particular significance for large numbers of Native Alaskans. For many indigenous communities, such harvests not only have tremendous cultural importance, but also provide crucial protein that is otherwise unavailable in remote regions.

Richard Bellerby, report chairman for AMAP's Arctic Ocean Acidification Assessment and a Research Scientist at the Norwegian Institute for Water Research, emphasizes that continued rapid change in Arctic Ocean conditions is a certainty at this point. Furthermore, he cautions, "We have already passed critical thresholds. Even if we stop emissions now, acidification will last tens of thousands of years. It is a very big experiment." Ken Caldeira echoes his concerns: "We don't know with certainty what the consequences of ocean acidification ultimately might be or how quickly they will occur. But we know that we are toying with the chemistry of the ocean in a profound way."

In the absence of sea ice, a bearded seal rests on a small iceberg near the front of Hamilton Glacier in Svalbard. Like other species of arctic seals, bearded seals are threatened by climate change because they rely on sea ice for giving birth, rearing young, resting, and molting. In addition, bearded seals are in jeopardy from ocean acidification, because they feed primarily on calcifying organisms such as clams, crabs, and shrimp that will ultimately be unable to build their shells, exoskeletons, and other crucial physical structures as the ocean becomes increasingly corrosive.

Altering Atmospheric Chemistry & Increasing Mercury Contamination

Scientists have recently discovered another way in which the decline of sea ice is having deleterious effects on the arctic environment and posing threats to wildlife and people in the Far North. There is growing evidence that warming-induced changes in the characteristics of arctic sea ice are playing a major role in causing alterations of atmospheric chemistry that could increase the amount of toxic mercury in arctic ecosystems.

Mercury is an extremely hazardous and persistent pollutant that accumulates in the environment and magnifies in concentration and toxic potency as it moves from lower to higher organisms in food webs, particularly in marine ecosystems. Both wildlife and humans can be seriously harmed by mercury contamination. Mercury enters Earth's atmosphere primarily as the result of human activities including coal burning, waste incineration, and mining. In addition, some natural processes, such as volcanic eruptions, also emit mercury. Once airborne, mercury can travel long distances over extended periods of time. The pollutant is transported all around the globe in air currents, and large amounts of gaseous mercury make their way from lower latitudes to the Arctic on an ongoing basis. Ultimately, airborne mercury is chemically transformed in a manner that causes it to fall from the air and enter ecosystems.

It has long been known that people who are chronically exposed to elevated levels of mercury by regularly consuming foods containing substantial amounts of that toxic substance, such as certain marine mammals and fish, are at risk of suffering very serious harm to their health. Significant adverse effects on reproductive, immune, and cardiovascular systems have been documented, and it is well-established that mercury is a potent neurotoxin that can cause irreparable damage to the central nervous system. Therefore, any environmental process that increases the amount of mercury entering ecosystems is clearly of tremendous concern.

As arctic temperatures rise, thick multiyear sea ice is increasingly being replaced by thin first-year ice that is much more salty. First-year sea ice, also known as annual ice or seasonal ice, contains a much higher concentration of salt than multiyear ice because it has had less time to undergo the natural processes that gradually expel salt from frozen seawater. In addition, the surface of annual ice is often adorned with so-called frost flowers — clusters of ice crystals in flower-like shapes that are up to four times saltier than the ocean.

Research has determined that when the sun rises above the arctic horizon in March after the dark polar winter, the increasing solar energy triggers a chemical reaction involving the salty first-year sea ice that ultimately releases large amounts of bromine, a chemical element, into the atmosphere. This process, known as a bromine explosion, is initiated on the saline surface of young sea ice and is propagated in the lower level of the atmosphere above the ice surface known as the boundary layer. The bromine explosion then initiates a cascading series of additional chemical reactions in the air. Particularly worrisome is the fact that bromine reacts with gaseous mercury in the atmosphere, transforming it to oxidized mercury – a form of the chemical that is of much greater concern for living things. Oxidized mercury readily precipitates out of the air, either on its own or attached to water droplets or dust particles, and falls to Earth's surface. There it accumulates as a toxic pollutant in ice, snow, soil, and water, and enters ecosystems.

In addition, recently scientists have found that the high concentration of salt at the surface of young sea ice also appears to interact with sunlight in the early spring in a manner that causes the release of very large amounts of chlorine into the arctic atmosphere in some areas. Like bromine, the chlorine then reacts readily with gaseous mercury in the atmospheric boundary layer, producing more dangerous oxidized mercury that can make its way into the food web.

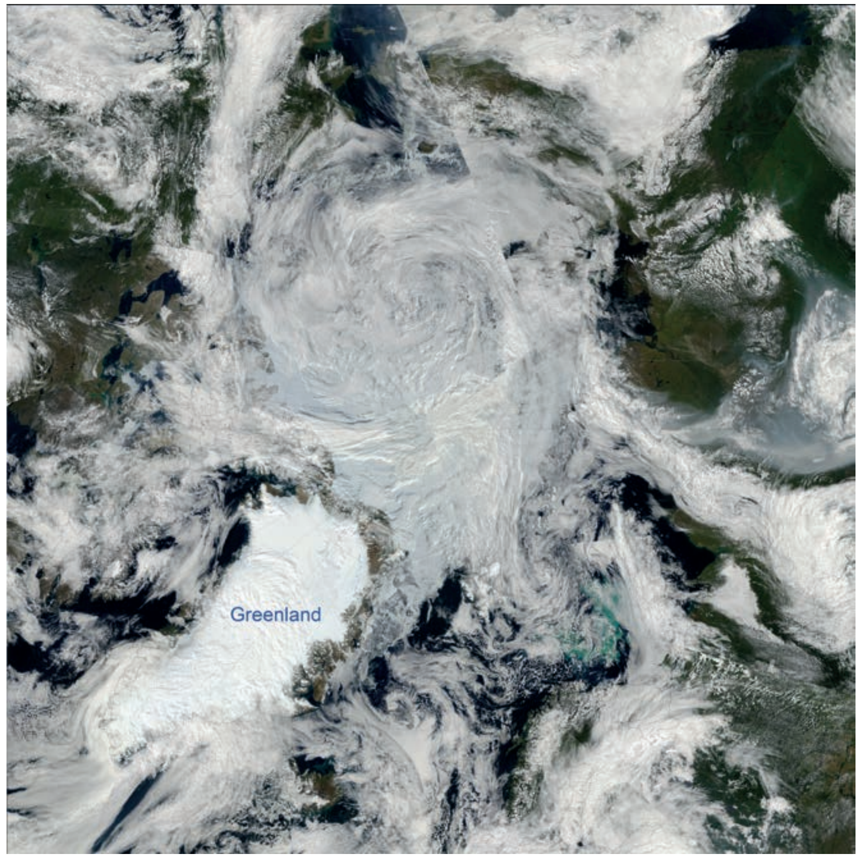
Atop a small floe of sea ice in the remote Smith Sound region of Northwest Greenland, Inuit hunters butcher two walruses they have just killed. The meat will provide food for the men, their families, and their sled dogs. Walruses and other marine mammals are central to the traditional subsistence diet of arctic indigenous peoples, but frequent consumption of those foods entails exposure to high levels of mercury. A recent study of mercury contamination in the marine mammals of West Greenland indicated that Inuit consumers of such animals ingest dangerously elevated amounts of mercury that exceed the European Food Safety Authority's Tolerable Daily Intake level.

Another key characteristic of thin, seasonal sea ice is its fragility, which causes it to fracture and separate into discrete floes on the ocean surface far more readily and frequently than thick perennial ice. Sea-ice leads — large open channels of water separating floes of ice — are therefore much more prevalent in first-year ice than in multiyear ice. New research by environmental scientist Christopher Moore of the Desert Research Institute in Nevada and colleagues, published in the journal *Nature* in February 2014, discovered that these widespread open leads in young sea ice appear to play a central role in atmospheric processes that increase the production of oxidized mercury, and therefore may increase the likelihood that this dangerous pollutant will enter the arctic food web in large amounts.

Moore and his colleagues observed that air masses in the atmospheric boundary layer above intact first-year sea ice contained low concentrations of gaseous mercury. This situation was consistent with gaseous mercury having been transformed into oxidized mercury through chemical reaction with bromine or chlorine above the salty young ice. But the scientists determined that when the air masses depleted in gaseous mercury subsequently moved over open leads in the sea ice, the concentrations of gaseous mercury rose again very quickly. Through extensive investigation of possible causes for this phenomenon, the researchers ultimately determined that vigorous churning of the air above large open cracks in the sea ice is functioning essentially as an atmospheric conveyor belt for gaseous mercury. When an air mass that is depleted in gaseous mercury travels over an open lead in the ice, powerful turbulent mixing of the air above the gaping crack — a convection process caused by the relatively warm surface water in the open lead coming into contact with the colder air – pulls a new supply of gaseous mercury from higher levels of the atmosphere down to the surface boundary layer. Once in the boundary layer, the additional supply of gaseous mercury can then react with bromine or chlorine to produce additional oxidized mercury. Ultimately this process is expected to result in higher levels of that toxic contaminant entering the food web.

Scientists have not yet quantified the specific consequences of these newly-discovered processes involving atmospheric mercury that are linked to the decline of arctic sea ice. But in light of the ongoing warming-induced transformation of the sea-ice cover from thicker multiyear ice to thinner, more fragile and saltier seasonal ice, there is great concern that mercury pollution in the Far North will rise. “The atmospheric mercury depletion and replenishment cycle in the Arctic might be responsible for adding hundreds of tons more mercury to arctic ecosystems annually,” explains Moore. Clearly the ramifications for arctic wildlife and people of such a major increase in toxic contamination are potentially dire.

On the coast of Greenland at Siorapaluk, the northernmost inhabited indigenous settlement in the world, an Inuit man carries ashore the meat of seals and walruses he obtained during a multi-day hunting expedition with other members of the community. In many isolated regions of the Arctic such as this, the meat of ice-associated marine mammals is one of the only readily-available sources of high-quality protein.



A massive cyclone dubbed "The Great Arctic Cyclone" churned the Arctic Ocean for nearly 13 days in summer 2012 – very atypical longevity for an arctic storm. The tempest formed over Siberia on August 2, moved into the central arctic basin, and ultimately dissipated above the Canadian Arctic Archipelago on August 14. Based on an analysis of all the storm's characteristics, scientists subsequently classified it as the most extreme August cyclone ever recorded in the Arctic during the satellite era, and the 13th most extreme arctic storm documented at any time of year. This NASA satellite image reveals that the extraordinary cyclone nearly filled the arctic basin. Although scientists believe the arctic sea ice would have reached a record low amount by the end of the melt season in 2012 even if the storm had not occurred, the powerful cyclone battered the ice and likely contributed to its shocking reduction in extent.

FUELING ARCTIC CYCLONES

Research has determined that arctic surface air temperatures have recently been warming significantly at all times of year, with diminishing sea ice playing a leading role in this process. Moreover, because warmer air can hold more water vapor, the arctic atmosphere has become increasingly moist as temperatures have risen. And, since increased heat and moisture in the air provide more fuel for storms, the atmospheric conditions in the Far North appear to be primed for enhanced storm development. In fact, scientists project that major storms in the Arctic Ocean — hurricane-like tempests referred to as arctic cyclones — are likely to increase in frequency and severity as sea ice continues to disappear, arctic amplification persistently raises temperatures, and the arctic atmosphere becomes increasingly warm and moist.

Climate scientist Ian Simmonds of The University of Melbourne, whose work focuses on atmospheric processes in the Arctic, explains that there have already been noteworthy changes in cyclone activity originating in the Eurasian sector of the Arctic, and those changes are expected to intensify. Rising land and surface air temperatures in northern Siberia are being exacerbated by major loss of sea ice in the Arctic Ocean's marginal seas adjacent to that portion of the continent. Steep atmospheric temperature gradients there between land and sea regions especially during summer, as well as the release of considerable storm-fueling heat and moisture into the air from large ice-free areas of the Arctic Ocean particularly during autumn and early winter, are conditions that scientists believe are linked to the development of more storms and more intense storms.

In addition to threatening northern communities, arctic coastal ecosystems, commercial shipping, and offshore infrastructure, more frequent and severe Arctic Ocean cyclones are likely to accelerate disintegration of sea ice and may also help to drive ice out of the Arctic entirely. As storms churn the increasingly ice-free ocean, the remaining ice is subjected to extreme turbulence that can cause it to break up and melt more quickly. Furthermore, storm-related atmospheric conditions can create powerful winds that tend to push sea ice away from Eurasia, across the Central Arctic Basin, and out of the Arctic Ocean through the Fram Strait between Greenland and Svalbard. This transported ice then moves into the North Atlantic, where it quickly melts and disappears.

TRANSFORMING WEATHER IN NORTHERN HEMISPHERE MID-LATITUDES

There is also a growing body of evidence indicating that the arctic meltdown is already playing an important atmospheric role far beyond the Arctic and affecting weather in the northern hemisphere mid-latitudes. "There is no question regarding *whether* the loss of arctic sea ice and arctic amplification are affecting large-scale atmospheric circulation and therefore weather patterns; the question is *how* are these processes affecting the atmospheric circulation and our weather," explains Jennifer Francis, a climate scientist at the Institute of Marine and Coastal Sciences at Rutgers University who has focused on this issue in her research. Studies by Francis and others have found that loss of arctic sea ice may be linked to atmospheric changes that in turn affect regional temperatures, storm characteristics, and precipitation in the middle latitudes of the Northern Hemisphere. In particular, this research indicates that recent extreme weather events in North America, Europe, and Eurasia – such as persistent heat waves and droughts, atypically heavy and prolonged precipitation events, and unusual outbreaks of intense cold – may be caused by significant alterations in atmospheric circulation resulting from the loss of arctic sea ice and associated rising temperatures in the Far North.

The northern hemisphere jet stream, which generates weather systems and steers them from west to east around the globe, is essentially a river of wind in the upper atmosphere that flows in a meandering manner, typically between latitudes of 30 degrees and 60 degrees north. The jet stream is pushed along its wavy path by forces related to gradients in air temperature and pressure, as well as by effects of Earth's rotation. A crucial factor strongly influencing the speed and route of the jet stream is the temperature difference between the Arctic and northern hemisphere mid-latitude regions. When the temperature difference is very large — when the Arctic is very cold, and the mid-latitude regions are warm — there is a steep gradient that causes the jet stream to be strong, similar to a river flowing down a steep mountain. In that situation, when the west-to-east flow of the jet stream is fast and powerful, the north-south meanders of the path tend to be relatively slight. Conversely, if the temperature difference between the Arctic and mid-latitudes is small, the shallow gradient between the two regions causes the jet stream to move like a river flowing across a barely-sloping plain. The west-to-east flow is slow and weak, and the north-south meanders of the path tend to be very wavy, forming large loops.

Heating of the Arctic, enhanced by loss of sea ice, is decreasing the temperature difference between the Far North and the mid-latitudes. Research by Francis and colleagues shows that this weakened temperature gradient may be causing the jet stream to slow down as it travels from west to east, and to form more substantial north-south meanders in its route. Studies indicate that the slower and wavier jet stream is increasing the likelihood of extreme weather phenomena in the middle latitudes by creating so-called blocking patterns that cause weather conditions to become stuck in particular regions. Extended bouts of hot and dry conditions or prolonged heavy precipitation resulting from these blocking patterns can lead to very serious problems. "If you're in a nice dry pattern with sunny skies, it's great if it lasts for a few days. But if it lasts for a few weeks, well then you're starting to talk about a drought," says Francis. "If you're in a rainy pattern and it hangs around for a long time, then that becomes a situation that could lead to flooding." Many recent extreme weather events in the northern hemisphere mid-latitudes such as severe drought affecting California and other regions of the western and south-western United States, dangerous heat waves in Europe and Russia, and record deluges and flooding in Britain and portions of the U.S., are examples of havoc caused by blocking patterns in the jet stream that appear to be linked with loss of sea ice and arctic amplification. "These are the types of weather phenomena that are expected to occur more frequently as the world continues to warm and the Arctic continues to lose its ice," says Francis.

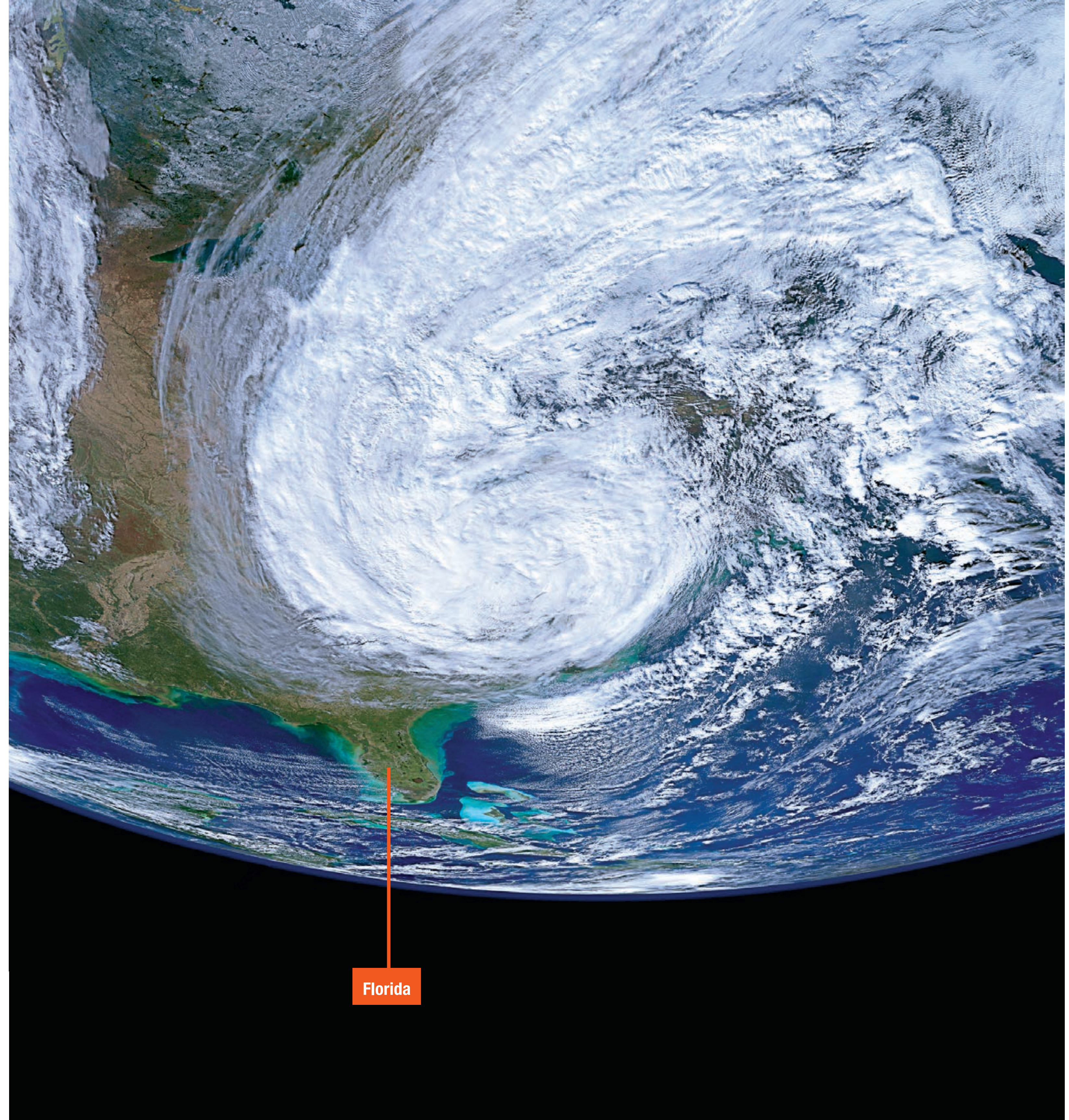
Furthermore, the very large north-south loops in the slowly meandering path of the jet stream are also substantially increasing the likelihood of arctic air masses spilling down into the middle latitudes, where they cause unusual and prolonged outbreaks of frigid and snowy weather. It seems paradoxical that warming of the Arctic might be instigating episodes of extreme cold temperatures and heavy snow in portions of Europe, the United States, Russia and Asia, but scientific research increasingly indicates that may be what is happening.

“We think the recent snowy winters could be caused by the retreating arctic ice altering atmospheric circulation patterns by weakening westerly winds, increasing the amplitude of the jet stream and increasing the amount of moisture in the atmosphere,” explains Jiping Liu, a senior research scientist in the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology, and the lead author of a study concerning these issues published in 2012. “These changes enhance blocking patterns that favor more frequent movement of cold air masses to middle and lower latitudes, leading to increased heavy snowfall in Europe and the Northeast and Midwest regions of the United States,” he says. Liu and colleagues analyzed both model simulations and observational data, and found consistent results. They determined that the rapid loss of sea ice in summer, the resulting heating of the Arctic Ocean in ice-free regions, and the release of considerable heat and moisture from the ocean to the atmosphere in autumn, collectively modulate snow cover, winter temperatures, and the frequency of cold air outbreaks in mid-latitudes. The researchers concluded that diminishing arctic sea ice appears to induce significant episodes of atypical cooling over parts of Europe, North America, Russia and Asia, and may be causing unusually heavy winter snowfall events in some areas.

In late October 2012, just six weeks after the arctic sea ice shrivelled to a shocking new record low amount, and during the period when the overheated ice-free regions of the Arctic Ocean would have been releasing substantial extra warmth and moisture into the atmosphere, a massive hybrid storm system dubbed Superstorm Sandy devastated the northeast coast of the United States. The hurricane killed 147 people, and caused approximately $70 billion dollars in damage all along its path. Was the record loss of arctic sea ice related to this extremely unusual and dangerous storm?

Sandy began in the Caribbean as an Atlantic hurricane. If it had followed a typical route, the storm would have moved north-eastward out to sea and died in the North Atlantic. Instead, however, Sandy took a dramatically different route, making a sharp left turn and heading directly toward the most heavily-populated region of the U.S. east coast. In a blog post at the time, Weather Channel hurricane expert Bryan Norcross marvelled, “This is a beyond-strange situation. It's unprecedented and bizarre... No October tropical systems in the record book have turned left into the northeast coast.”

Why did Sandy take such an extraordinary and destructive path? An unusual and strong atmospheric ridge of high pressure that was parked over Greenland and the North Atlantic played an important role. This so-called blocking high was created, sustained, and locked in position by the very sort of wavy and slow-moving jet stream conditions many scientists now believe are connected to sea-ice loss and arctic amplification. This major ridge of high pressure blocked the typical storm track and instead steered Sandy directly toward New York and New Jersey. Meanwhile, another significant storm was on a collision course with Sandy, moving over land from the west and heading toward the same region of the U.S. east coast. With their intersecting paths dictated by the troughs and ridges of the wavy jet stream, the two storms collided and merged, forming a massive, powerful hybrid “superstorm” that battered the eastern seaboard relentlessly. And then, rather than quickly weakening after it made landfall as hurricanes ordinarily do, Superstorm Sandy continued to wreak sustained havoc as it advanced far inland. Fundamentally, this devastating scenario would not have occurred if the crucial blocking high-pressure ridge stuck over Greenland had not been there. “While we can’t say definitively that the record ice loss during summer 2012 caused or increased the block in the North Atlantic that played a key role in Sandy’s evolution,” says Francis, “this wavy jet-stream pattern is exactly the type of situation we expect to occur more often as greenhouse-gas emissions continue to increase and the Arctic warms faster than mid-latitudes.”



The immense size of Hurricane Sandy is apparent in this satellite image showing the storm shortly after it made landfall on the northeast coast of the United States in October 2012. Sandy’s winds reached a diameter spanning nearly 1800 kilometers, making it the largest Atlantic hurricane on record. *(NOAA/ NASA GOES-13 satellite)*

ACCELERATING DISINTEGRATION OF THE GREENLAND ICE SHEET

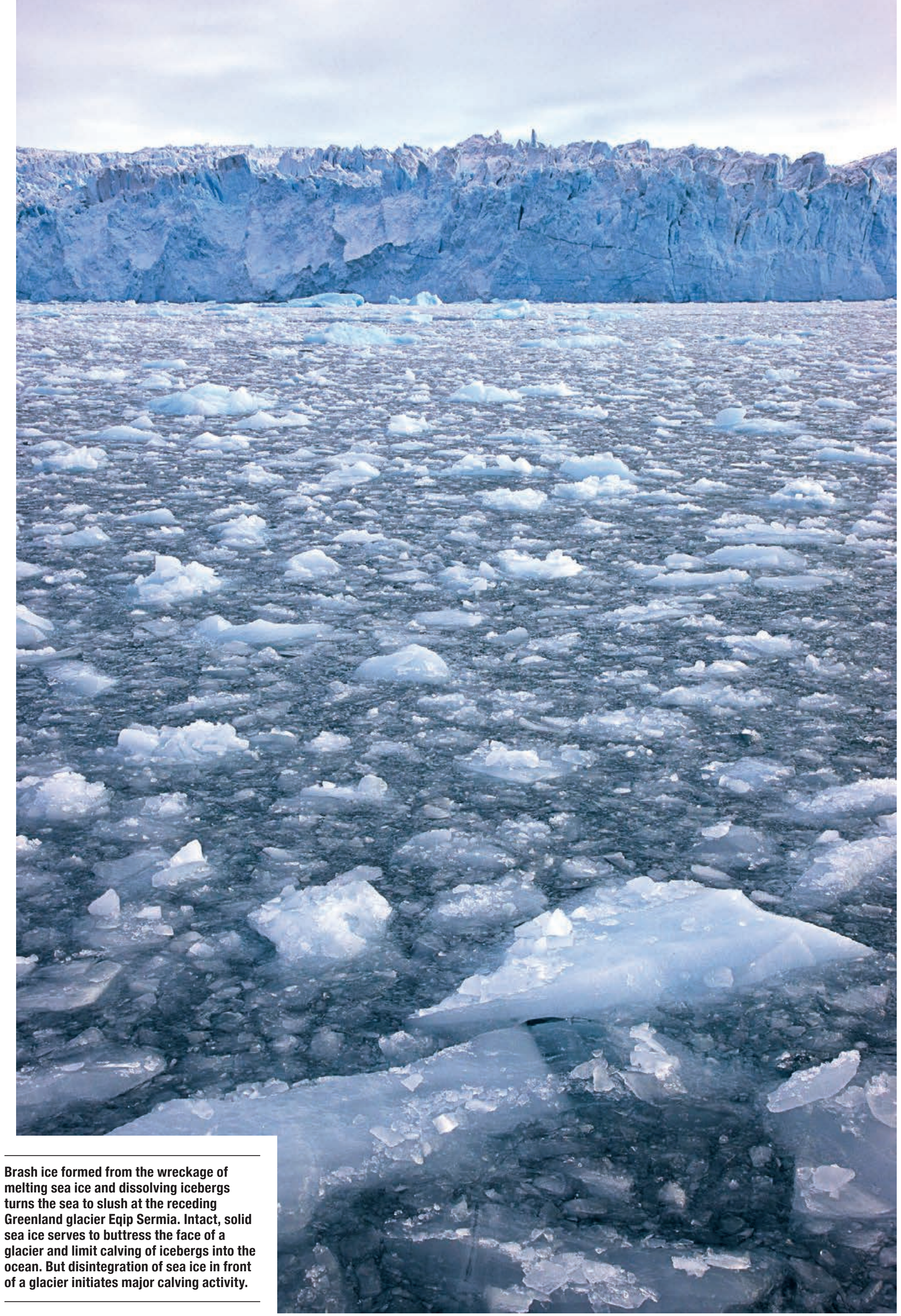
In recent years, glaciers and ice caps in the Arctic have been shrinking at a rapid rate, and the enormous body of ice enveloping about 80% of Greenland has been losing mass at an accelerating pace. The vast Greenland Ice Sheet is of particular concern due to its gargantuan size and the potential for major sea-level rise to occur if it continues to disintegrate. The ice sheet covers approximately 1.71 million square kilometers, has an average thickness of about two kilometers, and contains a massive amount of ice – a total of about 2.85 million cubic kilometers. If the ice sheet were to melt completely, global sea level would rise about 7.2 meters, enough to inundate many coastal regions and major cities around the globe and submerge some low-lying countries entirely.

The Greenland Ice Sheet gains mass by accumulation of snow, which is gradually transformed to ice, and it loses mass in part by melting at the surface and base. Melt water eventually flows into the ocean or evaporates. In addition, Greenland loses ice through marine-terminating glaciers that move from upper elevations of the ice sheet down to the coast. The glaciers discharge ice into an attached floating ice shelf or glacier tongue, and ice is lost there through basal melting and calving of icebergs into the sea. The mass of the ice sheet is stable, and is said to be in "mass balance," if the amount of ice lost through melting and calving is fully offset by ice gained through snow accumulation. Between 1961 and 1990, the Greenland Ice Sheet was in relative mass balance. But during the past two decades as the result of climate change, loss of ice has exceeded accumulation, and the ice sheet has been shrinking at an accelerating rate.

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in September 2013, the average rate of ice loss from the Greenland Ice Sheet substantially increased from roughly 34 gigatonnes (34 billion metric tons) per year over the period 1992-2001 to an average of approximately 215 gigatonnes per year from 2002 through 2011 – a 600% increase. Greenland's melt water and dissolving icebergs are already measurably contributing to rising seas, and experts anticipate that will continue as atmospheric concentrations of greenhouse gases keep increasing and temperatures inexorably climb. Consequently, there is growing apprehension about the ultimate fate of the Greenland Ice Sheet. The recent acceleration of mass loss has fuelled fears that the gargantuan body of ice may be approaching a crucial threshold, a tipping point beyond which the complete disintegration of the ice sheet will become inevitable and massive sea-level rise will become unavoidable.

In July 2012, as the rapidly-dwindling arctic sea ice was well on its way to setting shocking new records for the lowest ice extent and volume ever documented, another ominous record-setting melt event was occurring on the Greenland Ice Sheet. Temperatures there were anomalously high in spring 2012, and summer melting of the ice sheet's surface began much earlier than in the past – about two weeks earlier than average, and a full month earlier than it did three decades ago when satellite monitoring first became possible. For nearly the entire summer – during 79 out of 92 days – the ice sheet experienced above-normal melt rates. In addition, the total surface area covered by melting during 2012 was larger than ever previously documented. Moreover, in most locations the melting lasted significantly longer than usual – up to 30 days longer than the 1981–2010 average for large regions of the ice sheet on the west side of Greenland, and up to two months longer than average in portions of northwest Greenland. And most disconcertingly, in mid-July multiple independent satellite sensors collectively detected melting on 98.6% of the ice-sheet surface. During this astonishing event on July 11-12, even locations at

Giant icebergs calved from Greenland's massive glacier Jakobshavn Isbrae are stranded temporarily on a submerged ridge – the glacier's ancient terminal moraine – until they melt sufficiently to clear the obstacle. They will ultimately float onward into the Atlantic Ocean. Jakobshavn Isbrae is one of the fastest flowing streams of ice in the world. In summer 2012 it reached an unprecedented speed of more than 46 meters per day, the most rapid flow rate ever recorded for any glacier or ice stream in Greenland or Antarctica. The faster Jakobshavn flows, the more quickly it moves massive amounts of ice from the Greenland Ice Sheet into the ocean, raising sea level. Between 2000 and 2010, icebergs and melt water originating only from Jakobshavn Isbrae raised global sea level by 1 millimeter. Approximately 30 percent of the ice lost from Greenland since 2000 has come from Jakobshavn and four other glaciers.



Brash ice formed from the wreckage of melting sea ice and dissolving icebergs turns the sea to slush at the receding Greenland glacier Eqip Sermia. Intact, solid sea ice serves to buttress the face of a glacier and limit calving of icebergs into the ocean. But disintegration of sea ice in front of a glacier initiates major calving activity.

the summit of the ice sheet, about 3200 meters above sea level, underwent melt. Researchers subsequently confirmed the satellite data using both field verification and modelling. Ultimately, the ice sheet lost a total of approximately 628 gigatonnes of ice during summer 2012, a stunning new record.

Is the decline of arctic sea ice playing a role in the recent acceleration of ice loss from the Greenland Ice Sheet? And was the extraordinary melting of Greenland's ice in 2012 related to the record-breaking loss of arctic sea ice that occurred simultaneously? There are several clear reasons to be concerned that diminishing sea ice and associated changes in ocean and atmospheric conditions are indeed enhancing loss of ice from Greenland.

On a local basis, vanishing sea ice may increase ice loss from individual glaciers that flow from the Greenland Ice Sheet to the sea. Marine-terminating glaciers are the outlets through which the largest amounts of ice can be funneled most quickly into the ocean, and the disappearance of sea ice may initiate or accelerate that process. Studies indicate that the stability of a floating glacier margin may actually depend on the presence of intact sea ice in front of the glacier. Research has shown that in periods with solid, permanent sea-ice cover buttressing a glacier front, no calving of icebergs occurs; however, if that protective sea ice disintegrates, the glacier responds with major calving activity, during which immense quantities of accumulated glacier ice suddenly break away and enter the ocean. In addition, when sea ice near a marine-terminating glacier disappears and ocean surface temperatures rise, warm waters can increase melting at the glacier front, causing undercutting and higher calving rates, as well as thinning and retreat of the glacier.

Moreover, a 2009 study by geophysicist Åsa Rennermalm of Rutgers University and colleagues determined that sea-ice loss may also enhance surface melting on the Greenland Ice Sheet. The researchers investigated possible links between patterns in the timing and location of surface melting on the ice sheet and patterns of sea-ice decline and resulting open water extent in nearby ocean areas. They found a significant correlation between the extent of open water from sea-ice loss and the extent of melting on the surface of the ice sheet, "particularly in the latter part of the sea-ice melt season in August, and especially in south-western Greenland regions adjacent to Baffin Bay." Importantly, there was a slight lag between the development of open water due to loss of sea ice and the subsequent intensification of surface melting on nearby areas of the ice sheet, implying a causal connection. The scientists noted that there are several reasons the link between sea-ice loss and ice-sheet melt is strongest in late summer and on the west side of Greenland, including the fact that ocean temperatures in locations devoid of sea ice have warmed most substantially by late summer, and westerly winds typically arriving in the region at that time help to push ocean heat from areas of ice-free water onto the adjacent ice sheet.

The rapid loss of summer sea ice throughout the Arctic is also exacerbating overall melting of the Greenland Ice Sheet simply by playing a major role in forcing arctic temperatures rapidly upward. Vanishing sea ice is already a primary cause of arctic amplification, and it will increase heating of the Far North even more as it continues to disappear. The warmer it gets in the Arctic during the coming decades, the more quickly Greenland's ice will melt.

In addition, shrivelling sea ice may enhance loss of land ice from Greenland indirectly by affecting large-scale atmospheric circulation patterns and altering the behaviour of the jet stream. Just as the atmospheric blocking patterns that have been linked to sea-ice loss and arctic amplification have caused some extreme weather events in the northern hemisphere mid-latitudes, those blocking patterns have also created the persistent warm, dry, clear-sky weather conditions in Greenland that have contributed significantly to mass loss from the ice sheet.

Scientists have determined that a jet-stream blocking pattern over Greenland in summer 2012 was a crucial overarching cause of the extraordinary melting of the ice sheet and the voluminous ice loss that occurred then. Notably, this happened just a few months before another Greenland blocking pattern played a major role in steering Superstorm Sandy toward its path of destruction on the U.S. northeast coast. In a study published in 2013, Edward Hanna of the University of Sheffield and an international team of climate and glaciology experts concluded that an exceptionally strong blocking high-pressure ridge was parked above Greenland for most of the summer in 2012, and "this circulation pattern pulled relatively warm southerly winds over the western flank of the ice sheet, forming a 'heat dome' over Greenland that led to the widespread surface melting." Similar circulation anomalies developed over Greenland every summer from 2007 through 2011, causing warm, dry conditions that amplified melting and sustained the recent acceleration of mass loss from the ice sheet during the past decade. But the anomalous blocking pattern that was stuck above Greenland in summer 2012 — concurrently with record-setting loss of arctic sea ice — was by far the strongest. In fact, it had the highest atmospheric pressure ever documented by the U.S. National Centre for Atmospheric Research in records dating back to 1948. The resulting dome of heat over the ice sheet caused extreme warmth to prevail both in coastal regions and inland, with unusually elevated temperatures extending all the way to the summit. Extensive, intense melting and enormous loss of ice ensued.

Was the extreme melt on Greenland in 2012 a one-off event, or was it a prelude to a massive meltdown of the ice sheet? The answer to that crucial question may not be absolutely clear for another five to ten years. However, the scientific evidence to date indicates the ultimate demise of the ice sheet is now foreseeable.

Research focused on understanding climate issues in Earth's past shows that humans have set in motion approximately 20 meters of sea-level rise because of the huge quantities of greenhouse gases we have already pumped into the air. A 2012 study by geophysicist Kenneth Miller of Rutgers University and colleagues evaluated how much sea-level rise occurred in ancient prehistoric times when the quantity of carbon dioxide in the atmosphere naturally reached approximately the same concentration as it is now. The scientists determined that during the Pliocene Epoch, 2.7 to 3.2 million years ago, an atmospheric level of CO_2 comparable to the current amount caused sufficient heating of the planet to melt enormous amounts of ice on both Greenland and Antarctica, and initiated about 20 meters of sea-level rise. This research indicates that even if we were to cease our greenhouse gas emissions now and stabilize the atmospheric concentration of CO_2 at the current level of approximately 400 parts per million, temperatures would continue to increase for a long time due in part to feedback effects that have already been triggered, huge amounts of land ice would ultimately melt, and sea level would consequently rise about 20 meters before the entire climate system reached a new equilibrium.

"The natural state of the Earth with present carbon dioxide levels is one with sea levels about 20 meters higher than they are now," explains Miller. "Such a rise of the modern oceans would swamp the world's coasts and affect a large percentage of the world's population," he says. But thankfully, due to inertia inherent in the climate system, this process will not occur overnight. So the key questions at this point are: how quickly will temperatures increase, how fast will Earth's land ice melt, and how rapidly will sea levels rise? These timing issues are extremely difficult for scientists to estimate, due to the complexity of the geophysical processes involved – many aspects of which are not yet fully understood – as well as the fact that the rapid rate at which we are emitting greenhouse gases is unprecedented. There is no precise paleoclimate analogue that can be used as a guide for predicting exactly how the modern meltdown will unfold. But experts are gradually moving toward consensus regarding the future of Greenland's ice and associated sea-level rise, in part by using paleoclimate data along with sophisticated computer models to make projections.

A 2013 study led by Anders Levermann of the Potsdam Institute for Climate Impact Research utilized that approach. The research makes clear that greenhouse gases emitted during the past century and those we continue to emit today will fundamentally undermine the integrity of the Greenland Ice Sheet and cause increasing sea levels for centuries to come. In fact, like Miller's research, this new study indicates the fate of the Greenland Ice Sheet may already be sealed. Levermann and his collaborators conclude that the status of the ice sheet will cross a crucial threshold when the global average temperature reaches 1.5 to 2 degrees Celsius above 19th century pre-industrial temperatures. At that tipping point, a dramatic process of colossal ice-loss will be initiated, a huge portion of the Greenland Ice Sheet will inexorably melt, and the melt water will ultimately contribute at least 6 meters to sea-level rise. And if the global average temperature increases just a bit more, to a total of 2.5 to 3 degrees C above the pre-industrial level, that additional heat will trigger complete loss of all Greenland's ice over time.

Because the global average temperature has already risen by about 0.85°C since the 19th century due to our soaring carbon dioxide emissions (with most of the increase occurring during the past several decades), this study makes clear that an additional escalation of only 0.65 to 1.15 degrees will commit us to melting most of Greenland's ice and causing an eventual rise in sea level of at least 6 meters. Further increasing the temperature by just 0.5 to 1.0°C more will probably then commit us ultimately to losing the entire the Greenland Ice Sheet.

Once the crucial initial threshold of a 1.5 to 2°C temperature increase is reached, which scientists project will occur within mere decades based on a business-as-usual carbon emissions scenario, how long will it take for the ice to melt and the seas to rise? There is one bit of relatively good news regarding timing: the full meltdown of Greenland's massive ice sheet will not happen quickly. Scientists agree it is likely to transpire over the course of many centuries, or perhaps even millennia. Nonetheless, there will be significant melting of ice on Greenland between now and the end of this century, and that melt water will contribute substantially to ongoing sea-level rise during the coming decades. But it is challenging to predict precisely how the process will develop. Estimates of how much the world's oceans will rise by 2100 therefore vary widely, and predictions continue to change as scientists learn more about the relevant geophysical processes. Worryingly though, the recent assessment of this issue by the international climate-science community in the September 2013 IPCC report indicated that global average sea level may increase as much as 1.5 meters this century due to melting of land ice in both the Arctic and Antarctic. And a study published in December 2013 by paleo climatologist Eelco Rohling of The Australian National University and colleagues concluded that, when considering the need for long-term planning in defence of the world's coasts, projected sea-level rise of approximately 2 meters by 2100 "represents a useful upper limit" that is consistent with current scientific understanding of the processes involved.

Experts believe that, overall, the pace of ice loss from Greenland will be linked to the speed at which the threshold temperature increase of 1.5 to 2°C is reached and then exceeded. Any factors that accelerate temperature rise will hasten the arrival of that tipping point and accelerate melting of the ice sheet, whereas any factors that slow down the temperature rise will help to decrease the pace of ice loss and delay passing the point of no return. Since a large increase in sea level will ultimately be unavoidable based on our emissions trajectory and the resulting elevated concentration of CO_2 in the atmosphere, slowing down the process in every way possible will be key to maximizing the amount of time human beings and other species have to adapt to the enormous global changes underway.

But it is clear that diminishing sea ice is already playing a major role in forcing arctic temperatures rapidly upward, and will persist in doing so. Greenland's meltdown will inevitably be hastened as a result.

HEATING ARCTIC LAND & THAWING THE PERMAFROST

Heating of arctic land caused by dwindling sea ice and related arctic amplification will have a variety of extremely serious consequences, some of which are already beginning to occur. The numerous important effects of the magnified terrestrial warming are anticipated to include transformation of ecosystems, decline and potentially extinction of some species, thawing of vast permafrost regions, major socio-economic impacts from both ecosystem changes and damage to infrastructure as permafrost thaws, and the ominous potential for previously-frozen ground to release huge amounts of carbon into the atmosphere that have been safely sequestered for millennia until now.

Significantly warming arctic land temperatures have begun to cause substantial increases in quantity and variety of plant growth, referred to as greening of the Arctic, during the past few decades. The growing season is lengthening, shrubby plants are invading the tundra, and the tree line is moving north. Entire terrestrial ecosystems in the Arctic are undergoing rapid change, and many arctic wildlife species, as well as migratory ones that spend a portion of the year in the Far North, will face major challenges as a result.

Dramatic light from an approaching storm illuminates small hummocks covering the sub-arctic tundra in an area of Russia underlain by permafrost. These features are in a layer of soil above the permafrost called the "active layer" that freezes and thaws annually. In many permafrost regions, the seasonal cycle of soil dynamics in the active layer causes a variety of distinctive patterns on the ground surface such as this. Due to rising arctic temperatures, the active layer in some areas is progressively thickening as the underlying permafrost begins to thaw. Consequently, an increasing amount of previously-frozen organic material is decomposing, and emissions of carbon dioxide and methane from the ground – byproducts of decomposition – are also increasing.

“Arctic sea ice is such an important component of the climate system and arctic biome that its disappearance is bound to have major ramifications reaching beyond the Arctic Ocean into terrestrial ecosystems.”

For example, in a 2013 study published in the journal *Nature Communications*, Pennsylvania State University biologists Jeffrey Kerby and Eric Post determined that the timing of calving by caribou in West Greenland has gotten out of synchronization with the growth of vegetation they rely on for nutrition in their breeding area, because the plants are now emerging much earlier in the spring as the result of rising temperatures associated with loss of arctic sea ice. The migration and reproductive cycles of the caribou are based on seasonal changes in daylight length and are not responsive to shifts in timing of climate conditions such as temperature. So when the caribou arrive to give birth in their ancestral calving grounds in the late spring, there is far less nourishment available for them than they need. “Since plants are emerging earlier in the year, they tend to be older and past their peak nutritional value by the time the hungry caribou arrive to eat them,” Kerby explains. “The animals show up expecting a food bonanza, but they find that the cafeteria already has closed.” Kerby and Post determined that the consequences of this so-called trophic mismatch are decidedly negative for the caribou: fewer calves are being born, and calf mortality has been increasing. The scientists were able to connect the trophic mismatch and its adverse effects with rising arctic temperatures related to vanishing sea ice. Post emphasizes that arctic sea ice is such an important component of the climate system and arctic biome that its disappearance is bound to have major ramifications reaching beyond the Arctic Ocean into terrestrial ecosystems. "Sea ice is part of a broader climate system that clearly has important effects on both plants and animals,” he says. “Exactly how sea-ice decline might affect species interactions in this and other types of food webs on land in the Arctic is a question that deserves greater attention."

Moreover, the greening of the Arctic is itself expected to cause further warming of the Far North through a self-reinforcing feedback process. Heating of arctic land accelerates plant growth; lush green vegetation is generally darker and less reflective than typical arctic tundra, so it increases absorption of the sun’s energy by arctic land regions; and the additional solar radiation absorbed by expanding areas of green vegetation causes arctic temperatures to rise even more, which in turn causes more shrubby plants and trees to grow, more solar energy to be absorbed, and more heating of the Arctic to occur.

In addition, vast areas of permafrost (permanently frozen ground) are beginning to thaw as arctic temperatures climb. Permafrost covers nearly one-fourth of the Northern Hemisphere, and it extends to depths of more than 700 meters in some locations. When permafrost thaws, the ice within the soil melts, and because liquid water takes up less space than frozen water does, the soil often sinks substantially to fill the voids left by the melting ice. All structures in northern permafrost regions — essentially anything attached to the ground, from cabins in small villages to large buildings in cities, and from roads, power lines, and pipelines to major industrial facilities and bridges – will be affected by collapsing ground. Damage to infrastructure, which is already starting to occur as permafrost begins to degrade, will ultimately be severe and immensely costly, and will have very significant economic ramifications. Some entire communities will have to be relocated. A recent evaluation in Alaska, cited in the U.S. National Climate Assessment published in May 2014, estimated that sinking of ground in response to permafrost thaw will add $3.6 to $6.1 billion to the cost of maintaining buildings, roads, pipelines, airports, and other public infrastructure just during the next 20 years in that state alone.

Furthermore, thawing of permafrost, elevated sea-surface temperatures, and rising ferocity of the increasingly warm ocean due to lack of sea-ice cover are collectively causing arctic coastal regions to become much more vulnerable to erosion. Shorelines in the Arctic that were previously protected from strong waves and storm surge by a thick layer of ice capping the ocean are now increasingly subjected to the erosive power of raging seas as the ice disappears. In the past, extensive and heavy ice cover on the ocean served to suppress wave action, even during storms. But now, lacking ice, the surface of the sea is able to churn without restriction, and waves increasingly batter the coast. In addition, vast expanses of ice-free ocean provide longer fetch lengths – longer distances for the wind to blow uninterrupted across the sea and push the water – creating larger and more powerful waves and higher storm surge that pummel the shore. Warmer ocean temperatures augment the effectiveness of this wave action in dissolving shoreline permafrost. And where permafrost has already thawed as the air and land temperatures have increased, the previously-frozen coastline is even more vulnerable to being thrashed by the ice-free ocean, and the shore is eroding away even more quickly.

Along a 75-kilometer section of the Arctic Ocean coast in the Beaufort Sea of northern Alaska, the rate of shoreline permafrost erosion has more than doubled during the past decade as sea ice has diminished. Researchers determined that from the mid-1950s through the 1970s the pace of erosion was about 7 meters per year, but it accelerated to approximately 14 meters annually between 2002 and 2007. Additional study of a 7-kilometer portion of the coastline found erosion rates had risen further to 15 meters per year during 2008-2011 and then to 19 meters per year in 2011-2012. At some locations scientists documented stunningly rapid erosion rates as high as 30 meters annually. The research established that this dramatic acceleration in the amount of coastal permafrost dissolving into the ocean is attributable to the increasingly lengthy period in summer when there is no sea ice. Scientists determined that the shoreline permafrost bluffs in the region have very high mechanical strength when frozen because they contain about 64% ice. Their rock-hard structure makes them very resistant to erosion by abrasion, as long as they don’t thaw. However, after the sea ice has disappeared in mid-summer, when relatively warm ocean water is able to come into contact with the base of a permafrost bluff, the ice within the soil melts at the point of contact, and a large section of the bluff face then ultimately disintegrates in a chain reaction.

As part of their analysis, the researchers used time-lapse photography to monitor segments of the rapidly-eroding Alaska coast. They found that the position of the bluff face remained relatively stable prior to the disappearance of sea ice from the region in early July. But once the sea ice was gone and the temperature of the ice-free ocean rose near shore, warm seawater began cutting into the bluff at the waterline by dissolving the permafrost. Eventually, as the gouge at the waterline became sufficiently deep, massive blocks of destabilized ground crumbled off the cliff and fell into the water, where they quickly disintegrated.

The Alaskan village of Shishmaref located on Sarichef Island in the Chukchi Sea, where the Inupiat indigenous people have lived for thousands of years, is one of many locations where rising air and ocean temperatures, thawing permafrost, increasing fetch lengths and storm intensity have all conspired to escalate coastal erosion dramatically as sea ice has shriveled. Shishmaref is literally disappearing into the ocean. In the absence of protective sea-ice cover during increasingly lengthy portions of the year, rapidly-thawing permafrost along the coast is exposed to incessant pounding by waves with a fetch that may extend hundreds of kilometers across ice-free ocean. The problem is especially severe during storms. Houses and other structures have been collapsing into the sea as the land beneath them disintegrates. The people of Shishmaref have moved buildings away from the shore, and have attempted to reinforce the coastline with rocks and sandbags, but they are fighting a losing battle. Eventually the villagers will have no choice but to abandon their traditional homeland and relocate permanently. But the price tag for doing so will be staggering. In a 2006 report, the U.S. Army Corps of Engineers estimated the cost to relocate Shishmaref will be $100-200 million U.S. dollars. Other northern communities are confronting the same challenges.

RELEASING THE ARCTIC'S SEQUESTERED CARBON

"Global climates only slightly warmer than today are sufficient to thaw significant regions of permafrost."

Beyond the structural consequences of collapsing land, and the associated safety and economic issues, looms an even more portentous problem linked to disintegration of permafrost: the potential for enormous quantities of greenhouse gases to be released into the atmosphere as rising arctic temperatures cause organic matter in the frozen ground to thaw and decay.

The permafrost region in the Northern Hemisphere encompasses about 19 million square kilometers of land. Comprising massive amounts of ancient plant material and animal remains accumulated in soils over millennia, the vast expanses of permafrost in this area constitute immense reservoirs of sequestered carbon. Overall, near-surface soils in the permafrost region are estimated to contain at least 1700 gigatonnes of carbon, which is twice the amount currently in the atmosphere. For comparison regarding how much weight 1700 gigatonnes (Gt) actually represents, consider the fact that all of the billions of adult human beings currently on Earth collectively weigh only about 0.287 Gt.

As long as permafrost remains frozen, the carbon it contains will remain safely stored in the ground. But as arctic temperatures continue to rise and permafrost thaws, the sequestered carbon is at risk of being released into the atmosphere in the form of potentially huge quantities of planet-heating carbon dioxide and methane.

When frozen organic matter thaws, it decomposes through consumption by microorganisms. This is true whether the organic material at issue is last week's vegetable stew removed from your freezer and discarded into the garbage or the defrosting limb of an extinct woolly mammoth suddenly protruding from an eroding hillside of thawing permafrost along the coast of the Arctic Ocean where the sea ice has disappeared. If decomposition occurs in an environment where oxygen is available, microbial breakdown of the defrosting organic matter will produce carbon dioxide. On the other hand, if the process occurs in an oxygen-limited context, such as in saturated soil beneath a lake or under one of the countless wetlands that can be seen scattered across much of the soggy arctic tundra in summer, the microbes breaking down the waterlogged organic material will produce methane instead. The methane will then bubble up to the surface and be released into the atmosphere.

Scientists believe that most of the carbon emitted from thawing permafrost will be in the form of carbon dioxide, but it is quite clear that some portion will be vented to the atmosphere as methane. Both greenhouse gases are of great concern from the standpoint of their possible contribution to future climate warming. However, based on new data presented in the September 2013 IPCC report, methane is 34 times more powerful than CO_2 in its heat-trapping capacity over a period of 100 years. This means that even if the amount of methane released from thawing permafrost is relatively small in relation to the amount of CO_2 released, its share of responsibility for causing additional climate warming could be comparatively large.

Release of carbon into the atmosphere from thawing permafrost in the form of carbon dioxide and methane is a one-way process and "is a classic tipping point," explains Kevin Schaefer, a permafrost expert at NSIDC. "Once the organic matter that's currently frozen thaws out and decays away, there's no way to put the carbon back into the permafrost. Once the permafrost thaws and the emissions start, you can't turn it off."

Ongoing decline of arctic sea ice will continue to exacerbate heating of land in the Far North and therefore will negatively affect the integrity of permafrost. But until recently, there were no studies specifically assessing whether diminishing sea ice is directly connected to increasing greenhouse gas emissions from arctic tundra. Research by Frans-Jan Parmentier of Lund University and colleagues, published in the journal *Nature Climate Change* in 2013, evaluated that issue. The scientists found, "In autumn, substantial methane emissions from tundra have been reported at the same time that sea-ice retreat has the largest warming effect." In addition, they determined that "a lower sea-ice extent clearly occurs in the same years as higher methane emissions" from arctic land regions. The researchers concluded, "Consequently, a direct relation between sea-ice decline and increasing methane emissions seems probable." However, due to a shortage of data on methane released from arctic tundra in recent years when sea-ice loss has been most significant, the scientists were only able to analyze the period from 1979 to 2006. But further investigation of this issue for subsequent years is now underway.

New paleoclimate research in Siberia indicates that global warming of only 1.5°C above pre-industrial temperatures could thaw vast regions of permafrost across northern lands, potentially releasing immense amounts of carbon from defrosting ground into the atmosphere. Since the global average temperature has already risen by approximately 0.85°C above pre-industrial temperatures and will unquestionably continue to rise rapidly as the result of our ongoing greenhouse gas emissions, this recent study provides the basis for very serious concern.

The research, conducted by Anton Vaks of Oxford University and an international team of colleagues, was published in the journal Science in 2013. The scientists analyzed ancient speleothems — stalactites and stalagmites — deep within Siberian caves, using radiometric dating techniques to determine when growth of the formations last occurred. Speleothems are mineral deposits created when water containing dissolved inorganic substances seeps through cracks in a cave's surrounding rock and drips inside the cavern over a long period of time. Because speleothems initially form and subsequently increase in size only if liquid water can leak into the cave, the formations cannot grow in a cavern surrounded by solid, intact permafrost. But if temperatures rise and the permafrost thaws, speleothems can then develop. Therefore, the presence of ancient stalactites and stalagmites inside a cave located within rock-hard permafrost is clear evidence the climate at that location was much warmer at some time in the past.

By dating stalactites in Siberia's Ledyanaya Lenskaya Cave located within a region of continuous permafrost, and comparing their ages to existing climate records, the researchers were able to identify the degree of warming that previously caused the permafrost surrounding the cave to thaw and resulted in the formation of the speleothems. The data revealed that the most recent episode of speleothem growth in the cave occurred approximately 400,000 years ago, during a period when global temperatures are believed to have been about 1.5°C above 19th century levels – "showing," says Vaks, "that this degree of warming is a tipping point for continuous permafrost to start thawing." Thus the study ominously concludes, "Global climates only slightly warmer than today are sufficient to thaw significant regions of permafrost." And the eventual result of that process would be "substantial release of carbon" from the permafrost into the atmosphere.

If human emissions of greenhouses gases continue on a business-as-usual trajectory, experts project that the global average temperature is very likely to exceed 1.5°C above pre-industrial temperatures within just a few decades. And, due to sea-ice loss and arctic amplification, temperatures in the Far North will increase much faster than that. How much permafrost is therefore likely to thaw? How much carbon might be released into the atmosphere from deteriorating permafrost in the form of CO_2 and methane as a result, and during what period of time?

There is already reason to be worried about the integrity of permafrost as temperatures continue to rise in the Arctic, explains NSIDC's Kevin Schaefer. "Recent observations indicate widespread permafrost degradation," he says. But it is difficult to predict in detail precisely what the future holds. Research into the potential rate and magnitude of permafrost deterioration and related carbon emissions for the rest of the 21st century and beyond is at an early stage, and the studies that have been done so far have been hampered by a shortage of data and limitations in the capabilities of available computer models. Nonetheless, a lack of precision regarding specific numbers should not be misinterpreted to mean there is overall uncertainty concerning whether or not the permafrost will actually thaw and release its carbon to the atmosphere if humans continue to emit tens of millions of tons of greenhouse gases each day and arctic temperatures continue to surge upward.

Stone circles adorn the ground along the coast of Nordaustlandet, a high-arctic island in the Svalbard archipelago. The intriguing features result from natural sorting of stones and soil particles during repeated frost-heave and thaw-subsidence cycles in the active layer of ground above permafrost.

There is clear scientific consensus that if anthropogenic emissions persist at the current high rate, there will certainly be increasing permafrost disintegration driven by rising land and air temperatures, and there will be very large amounts of carbon released from the thawing ground into the atmosphere. Moreover, scientists warn that emissions of greenhouse gases from degrading permafrost will initiate a self-reinforcing process called the permafrost-carbon feedback: the release of carbon dioxide and methane from thawing permafrost will result in amplified surface warming, which will in turn cause more deterioration of permafrost and more release of greenhouse gases, which will then cause further amplification of surface warming, additional permafrost thawing, more emissions of CO_2 and methane, and so on.

There is also expert agreement that the speed and intensity of arctic warming are, and will continue to be, so significant that widespread permafrost thawing will cause arctic land to become a net emitter of carbon rather than a net absorber of carbon within only a couple of decades. That will occur despite the recent "greening" phenomenon which is somewhat enhancing uptake of CO_2 from the air as the biomass of shrubby plants and trees increases. Soon carbon emissions from thawing arctic ground will completely overtake carbon absorption by plants throughout the Far North. In fact, research by Schaefer and colleagues indicates that ultimately the huge amount of carbon emitted from disintegrating permafrost will be 42–88% of the total quantity of carbon absorbed by vegetated lands all around the planet, canceling out much of the benefit we currently gain from such global terrestrial carbon sinks.

The most recent attempt by scientists to articulate a numerical ballpark regarding how much permafrost may thaw and how much carbon may be emitted from it during the foreseeable future, the September 2013 IPCC report, conveys a general sense of where we may be headed if the current high rate of man-made greenhouse gas emissions persists this century and arctic temperatures continue to climb upward. The report concludes that as much as 81% of near-surface permafrost (defined as frozen ground extending to a depth of 3.5 meters) could be completely thawed by the year 2100.

Moreover, the IPCC states that this stunning meltdown is likely to begin in earnest very soon, and projects a reduction of approximately 20% in near-surface permafrost area just during the next two decades. Regarding the carbon emissions associated with this thawing of frozen ground, the IPCC projects that between now and the end of the century sustained arctic warming could cause degrading permafrost to release up to approximately 200 petagrams (Pg) of carbon in the form of carbon dioxide and up to an additional 5 petagrams of carbon in the form of methane. (One petagram is equal to one gigatonne.) Furthermore, with regard to the 5 petagrams of carbon projected to be emitted as methane this century, the IPCC states, "Given methane's stronger greenhouse warming potential, that corresponds to a further 100 Pg C [carbon] of equivalent carbon dioxide released until the year 2100."

So, essentially, if human beings persist with business-as-usual greenhouse gas emissions as sea ice vanishes and arctic temperatures continue to rise, permafrost will increasingly thaw across vast regions, and millions of square kilometers of no-longer-frozen ground may emit as much as 300 gigatonnes of heat-trapping carbon pollution into the atmosphere during the next 85 years. To get a sense of scale regarding the massive amount of carbon involved and its potential to cause substantial additional climate warming, consider that during the entire period from 1750 to 2011 human beings all around the globe emitted a grand total of about 545 gigatonnes of carbon, primarily through the burning of fossil fuels and secondarily through land-use changes including deforestation. But just between now and the end of this century, disintegrating permafrost by itself is projected to emit more than half that amount of carbon into the atmosphere. The future climate consequences of unrelenting anthropogenic greenhouse gas emissions alone would be horrific, but they will be made even worse, and will occur even more quickly, with this major added boost of planet-heating carbon coming from thawing permafrost.

The carbon emitted from defrosting frozen ground will affect global policy-making strategies to mitigate climate change in addition to affecting the climate itself. If the world hopes to avoid exceeding specific targets for maximum atmospheric carbon concentration and maximum global temperature increase, we must account for emissions of greenhouse gases from thawing permafrost in our planning, emphasizes NSIDC's Schaefer. But he explains that even the most sophisticated current climate models – including the ones used to frame international discussions of climate policy – do not yet account for any releases of greenhouse gases from thawing permafrost. For that reason, current modelling-based projections under-estimate the amount of future warming that will occur, and over-estimate the remaining amount of carbon it is "safe" for humans to emit into the atmosphere. Therefore, any policies implemented in reliance on those projections could cause us to overshoot climate goals. "If we want to hit a target carbon concentration, then we have to reduce fossil fuel emissions that much lower than previously calculated to account for this additional carbon from the permafrost," Schaefer says. "Otherwise we will end up with a warmer Earth than we want."

The estimate of 1700 gigatonnes for the total amount of carbon currently sequestered in soil within the northern hemisphere permafrost region does not include any of the carbon known to exist within submarine permafrost on the shallow continental shelves beneath the marginal seas of the Arctic Ocean. The precise quantity of carbon sequestered in seabed permafrost is uncertain, but it is likely very large. According to some estimates, about 1400 gigatonnes of carbon may be stored just within the East Siberian Arctic Shelf (ESAS), which is the world's largest continental shelf, encompassing more than two million square kilometers of Arctic Ocean seafloor. In addition, some scientists think the permafrost in continental shelf regions may be especially vulnerable to widespread thawing because of recent rapid sea-ice loss and associated increases in ocean temperatures, particularly where the permafrost lies beneath very shallow seas, as it does throughout the ESAS where the average depth is only 45 meters.

Carbon is stored within the arctic seabed on continental shelves primarily in three forms. First, as is the case with permafrost on land, the carbon is sequestered in frozen organic material that will release methane if it thaws and decomposes in the oxygen-deprived underwater environment. Second, some carbon is also present as free methane gas trapped in pockets within the otherwise solid structure of subsea permafrost, ready to be released as soon as the surrounding impermeable frozen ground thaws and disintegrates. And finally, a significant amount of carbon is also stored in the form of an ice-like crystalline substance called methane hydrate, the building block of which consists of a methane molecule surrounded by a cage of interlocking water molecules. Large quantities of methane hydrate are located within subsea permafrost. Methane hydrate is stable at low temperatures and high pressures, but becomes unstable as temperatures rise. Therefore deposits of methane hydrate are at risk of dissociating and liberating methane gas if temperatures increase sufficiently to thaw and degrade the permafrost in which the methane hydrates are currently encased.

Methane originating within seabed sediments and bubbling up from the bottom of the ocean does not ordinarily reach the atmosphere, because it typically dissolves in the water or is broken down by other processes before it arrives at the ocean surface. But when the seabed is only tens of meters deep as is the case throughout the very shallow East Siberian Arctic Shelf, bubbles rising from the bottom do not have far to travel before they quickly reach the air above the water's surface. So the potential exists there for bubbles of methane gas to ascend directly and rapidly from the seafloor into the atmosphere.

In fact, that is precisely what scientists have recently documented. During numerous scientific expeditions throughout the ESAS region, a team of scientists led by Natalia Shakhova and Igor Semiletov of the International Arctic Research Centre at the University of Alaska discovered vast areas of the Arctic Ocean where seawater and air above the very shallow continental shelf were super-saturated with methane. In the ocean, concentrations of dissolved methane were often hundreds of times higher — or even thousands of times higher — than normal background levels. In some places the researchers observed the ocean surface actively effervescing as methane bubbles disgorged gas into the atmosphere. Comprehensive investigation of this phenomenon over the course of several years led the scientists to conclude that the methane is originating from subsea sediments, and that the permafrost covering the ESAS – which was previously believed to constitute an impermeable barrier preventing release of the huge amounts of carbon sequestered there – is no longer fully intact.

In a 2010 paper published in the journal *Science*, Shakhova and colleagues presented findings establishing that the total amount of methane (CH_4) out-gassing annually from the subsea sediments of the ESAS "is of the same magnitude as existing estimates of total CH_4 emissions from the entire world ocean." Furthermore, in a paper published in *Nature Geoscience* in January 2014, the researchers revised this estimate upward based on new data from extensive additional research. Using a conservative calculation method that assumed methane is bubbling up from the seafloor and being vented to the air only 50% of the time, the scientists concluded that the total annual flux of methane from the ESAS to the atmosphere is currently about 17 teragrams (17 billion kilograms, or 0.017 gigatonnes), an amount that is more than double their previous estimate. In addition, by collecting data at great personal risk during violent, life-threatening storms in the ESAS region of the Arctic Ocean, the scientists were able to determine that such storms — which are projected to increase as the result of climate warming and loss of sea ice — facilitate the emission of methane into the atmosphere as they powerfully churn the sea.

Despite these sobering conclusions, the researchers note that the quantity of methane currently being released from the ESAS is not in itself large enough to warrant alarm concerning potential effects on global climate. However, they emphasize that additional investigation and monitoring are urgently needed in light of the very large size of the carbon reservoir within the ESAS, their own findings that "the permafrost 'lid' is clearly perforated, and sedimentary CH_4 is escaping to the atmosphere," and the fact that if a rapid release of even a relatively small percentage of the ESAS methane reservoir were to occur in the future it could cause abrupt climate catastrophe.

A number of scientists who did not participate in the ESAS research have cautioned that there is currently no specific evidence a large and abrupt release of subsea methane from that continental shelf region is even realistically within the realm of possibility, and they stress that the documented out-gassing process there is a slow and steady one involving a comparatively small amount of methane. Other climate scientists emphasize, however, that the possibility of a major, rapid methane release from the ESAS cannot simply be dismissed out of hand even if it is unlikely. They underscore the immense magnitude of the potential climate calamity that would result from such an event, and maintain that the scale of the possible global harm justifies doing everything feasible to investigate fully the geophysical processes involved and understand all the risks.

Shakhova and colleagues indicate that currently-available data are not sufficient to determine whether the methane out-gassing from the seafloor on the ESAS represents a new or newly intensified phenomenon attributable to recent arctic warming, or whether it is simply a newly-discovered but ongoing process that began gradually when the frozen exposed land in Siberia that ultimately became the submerged continental shelf was first inundated with ocean water following the last ice age. Either way, however, the methane now being emitted constitutes an influx of carbon into the atmosphere in a powerfully heat-trapping form, and it represents an incremental addition to the atmospheric burden of greenhouse gases – albeit one that is not in itself large enough currently to affect the climate.

Even assuming that the release of methane from the ESAS seabed is not a new process and has been ongoing to some extent for a very long time, the lack of sea ice on the ocean surface above the degrading permafrost is indeed a new phenomenon and it has altered the context in which the release of subsea methane is occurring. In the past, methane bubbles reaching the ocean surface would have been blocked by ice, and emission of the heat-trapping gas into the atmosphere would therefore have been limited. Now, however, the ice is absent throughout most of the ESAS region for much of the summer, and any methane reaching the water's surface is therefore immediately vented into the atmosphere. Moreover, as Shakhova and her collaborators determined in their most recent study, this situation will be exacerbated by increasing storm-driven turbulence of the ocean as arctic sea ice continues to disappear.

There is no doubt that the ESAS region is one of the areas in the Arctic Ocean where sea ice has diminished most rapidly and ocean temperatures have risen most dramatically during the summer in recent years. On the surface of the shallow ocean above the ESAS permafrost, the sea-ice melt season has lengthened by nearly 30 days during the past few decades. Because vast areas of vulnerable permafrost are now located beneath increasingly ice-free and rapidly-warming ocean waters, even if the current out-gassing of methane is attributable to a pre-existing long-term process, there is reasonable basis for some concern about future permafrost integrity and ongoing stability of the immense carbon stores in the region. As sea ice continues to shrink and arctic temperatures continue to rise, there will be growing justification for unease about the status of subsea permafrost and the potential insecurity of major submarine carbon stores in the coming years.

Disintegrating sea ice in the central polar basin near 83 degrees north is illuminated by the warm glow of the midnight sun in August 2012. Previously locked in solid ice year-round, this region will likely be ice-free throughout the summer within a few decades as carbon dioxide in the atmosphere continues to increase and temperatures keep rising.

THE FUTURE OF ARCTIC SEA ICE & EARTH'S CLIMATE

It is not possible to predict precisely when we will first see largely ice-free conditions in the Arctic Ocean at the end of the annual melt season, nor is it feasible to forecast exactly how long it will be before there is essentially no sea ice for most of the summer. But at this point the only question is when, not if, those scenarios will occur. "We are definitely headed to ice-free conditions seasonally," emphasizes Mark Serreze, Director of NSIDC. "The Arctic will be ice-free in the summer in a few decades," he says. "All we'll have is winter ice." An Arctic Ocean that is ice-free during the summer will result from the high concentration of greenhouse gases already in the atmosphere, the significant amount of heat already in the climate system as a consequence, the rapid decline of arctic sea ice that has already occurred, feedback processes related to that ice loss, the immense and increasing amount of carbon that human beings are continuing to emit, and the additional temperature rise that will necessarily ensue.

The fact that we are headed toward an essentially ice-free Arctic Ocean during the summer by mid-century is a conclusion reached in a variety of ways by scientists who specialize in studying arctic sea ice and related climate issues. In a 2013 study published in the journal *Geophysical Research Letters*, James Overland of NOAA and Muyin Wang of the University of Washington evaluated three categories of scientific methods for analyzing whether and when the Arctic Ocean will be nearly ice-free in summer, and they assessed the extent to which consensus exists despite differing modes of analysis. Overland and Wang determined that all scientific methods yield the conclusion that the summer arctic sea ice will indeed be lost, and that it is likely to be lost within a few decades. Some analytical techniques indicate that major sea-ice loss could occur even more rapidly, possibly in just a decade or two. One method suggests it is even possible that catastrophic ice loss may abruptly happen by 2020, because much of the ice cover has already become very thin and vulnerable to disintegration.

Vanishing summer sea ice is a clear and portentous warning that we are being confronted by a rapidly-developing planetary crisis requiring urgent action if even more dire consequences are to be averted. Like a smoke detector's alarm notifying everyone to exit a building immediately because something is already burning, the melting arctic sea ice is loudly signifying that damage is already occurring and we must act now to fight climate change before even worse, potentially irreparable, harm occurs in the Arctic and globally.

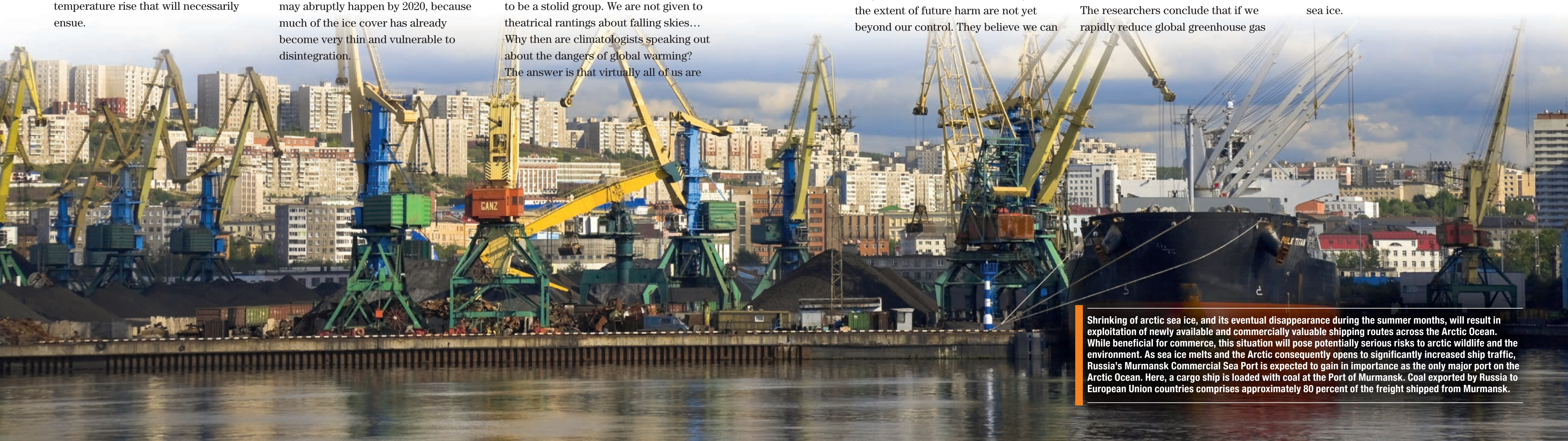
This is not hyperbole. In contemplating the prospect of catastrophic climate impacts, many scientists have begun to warn the public and policymakers about the dangers of failing to reduce our carbon emissions. In a 2010 article, paleoclimatologist Lonnie Thompson of the Byrd Polar Research Center at The Ohio State University wrote, "Climatologists, like other scientists, tend to be a stolid group. We are not given to theatrical rantings about falling skies… Why then are climatologists speaking out about the dangers of global warming? The answer is that virtually all of us are now convinced that global warming poses a clear and present danger to civilization."

Due to our lack of mitigation action so far, it is clear climate change has already developed to the point that a certain amount of harm is unavoidable. In fact, there is no reasonable doubt we have begun to experience some of that harm, for example, in the form of ecosystem changes and related negative effects on a variety of species, dangerous heat waves, severe droughts and fires, and deadly flooding. More global warming and more resulting harm are certainly already in the pipeline based on the quantity of greenhouse gases we've emitted so far and are continuing to pump into the atmosphere.

Does this mean it's already "too late"? We now know it is indeed already too late to prevent the loss of the summer arctic sea ice. But is there any action we can still take that will make any real difference in fighting climate change and averting other devastating impacts? Scientists whose work focuses specifically on this issue think the magnitude of future climate change and the extent of future harm are not yet beyond our control. They believe we can still affect to some degree how much the climate will ultimately change and how much resulting harm will occur, by acting in concert on a global basis to reduce our emissions of greenhouse gases very quickly, very significantly, and permanently. But we are rapidly running out of time to make a difference.

Research led by NOAA's James Overland and published in December 2013 by the American Geophysical Union in the journal *Earth's Future* concludes that prompt implementation of major reductions in carbon emissions worldwide could cut in half the increase in arctic and northern hemisphere temperatures that will otherwise occur by the end of this century without such mitigation action. Using computer modelling, the study projects that average arctic temperatures from late autumn through January will undergo an astonishing increase of 13°C between now and 2100 if global greenhouse gas emissions continue on a business-as-usual upward trajectory. But the scientists also determined that we can still mitigate this shocking and dangerous consequence of our current do-little-or-nothing approach to climate change. The researchers conclude that if we rapidly reduce global greenhouse gas emissions and stabilize atmospheric carbon concentrations by mid-century, average temperatures in the Arctic from autumn through January will rise by half as much as they would in the absence of such emissions control. The study reaches similar conclusions regarding increases in northern hemisphere temperatures this century: a business-as-usual emissions scenario is projected to cause an increase of 6°C in average autumn-through-January temperatures, but a smaller temperature increase of 3°C is possible based on a scenario in which global emissions are reduced quickly and significantly.

The science makes clear that the longer we wait to address the underlying causes of climate change, the worse the problem and the resulting harm will be. Unquestionably, the costs involved in solving the problem are immense, but they are a tiny fraction of the costs involved in failing to do so. The gravest peril — the truly existential peril for both human beings and countless other species — will result from continued inaction. Our narrow window of opportunity to avert unimaginable harm is rapidly shrinking along with the arctic sea ice.



Shrinking of arctic sea ice, and its eventual disappearance during the summer months, will result in exploitation of newly available and commercially valuable shipping routes across the Arctic Ocean. While beneficial for commerce, this situation will pose potentially serious risks to arctic wildlife and the environment. As sea ice melts and the Arctic consequently opens to significantly increased ship traffic, Russia's Murmansk Commercial Sea Port is expected to gain in importance as the only major port on the Arctic Ocean. Here, a cargo ship is loaded with coal at the Port of Murmansk. Coal exported by Russia to European Union countries comprises approximately 80 percent of the freight shipped from Murmansk.

ABOUT

Jenny E. Ross is an award-winning photographer and journalist specializing in wildlife natural history and conservation, ecosystems, earth systems, environmental issues, scientific research, and related policy topics, with particular emphasis on the Arctic and climate change. Her previous feature article for Ocean Geographic, in January 2012, focused on polar bears.

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