Climate Change and Sustainability: Connecting Atmospheric, Ocean and Climate Science with Public Literacy

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Abstract

Climate has changed throughout Earth's history, sometimes slowly, sometimes abruptly. Organisms have either adapted to the changes or have ceased to exist. From a human perspective, climate change may profoundly influence civilization. To make responsible decisions about adaptations to climate change including sustainability, the public must understand climate change. The trouble with gaining this understanding is two-fold. From a scientific perspective, the dynamics of coupled atmosphere, ocean and climate processes responsible for climate change are complex and are still being systematically investigated. From a public perspective, one needs to learn enough about the complex climate change processes to ensure human life remains sustainable.

Here we focus on some of the processes related to the ocean's role in modulating and regulating climate and environmental changes, using the Arctic Ocean as a key example. We then present the public's perception of climate change from press articles, including one stating that the Arctic Ocean could soon be ice-free during summertime. Finally we show attempts to bridge the gap between science and the press through atmospheric, ocean and climate literacy programs to help the public make scientifically informed, responsible decisions about climate change and to advance understanding of the impacts of climate change and sustainability.

Introduction

Climate has changed throughout Earth's history, sometimes slowly, sometimes abruptly. An example of a slow change is a movement of tectonic plates, while an example of an abrupt change is a volcanic eruption. Organisms have either adapted to the changes or have ceased to exist. From a human perspective, climate change can profoundly influence civilization. In particular, climate can play a key factor in whether societies thrive or perish. To make responsible decisions about adaptations to climate change including sustainability, the public must understand the operation of climate and causes and effects of its change. This understanding can result in building sustainable communities and societies that are resilient to both natural and human-caused climate changes

The trouble with gaining this understanding is two-fold involving a scientific and a public perspective. Let us address the scientific perspective first.

From a scientific perspective, the dynamics of coupled atmosphere, ocean and climate processes responsible for climate change are complex and are still being systematically investigated. Besides the complexity of coupled interactions between the atmosphere, ocean, ice and land, which can lead to climate change, there is the complexity of understanding the dynamic role of each of the above climate components. For example, the role of the ocean in climate change has become recognized as an increasingly important element of climate research since at least the 1980s (e.g., Batteen, 1984). What gives the oceans the potential for exerting a strong influence on climate and its variations is the large heat capacity, coupled with the global redistribution of heat and other properties by ocean currents acting over time scales much longer (i.e., years or decades compared to days or weeks) than atmospheric processes. An added complexity is that ocean eddies (e.g., Gulf Stream rings) could be important mechanisms for transporting heat. As a result, the role of ocean eddies in climate is also becoming an increasingly important element of climate research.

To allow the systematic exploration of the contribution by eddies to the ocean heat transport and also the effect of eddies on the ocean general circulation, eddy resolving ocean numerical models have been suggested as appropriate tools for the investigation of the ocean's role in climate since the late1970s (e.g., Holland, 1978; Batteen, 1984). Due to computational limitations, however, eddy-resolving three-dimensional ocean models have usually been restricted to regional scales while global ocean models have usually been coarse, non-eddy-resolving models. Note that eddy-resolving, near-global models have become more common since the 1990s (e.g., Semtner and Chervin, 1992). Furthermore, the global ocean models may or may not include the polar regions such as the Arctic Ocean.

As a result, global ocean models either are not eddy-resolving or do not include the two polar regions. Due to the vast expanse of the ocean, there also remain limited direct field observations so that complex processes such as air-sea interaction remain poorly understood. Analysis and subsequent understanding of field observations play a big role contributing to significant improvements in climate models. As a result, the dynamics of ocean processes as well as coupled atmosphere, ocean and ice processes responsible for climate change remain challenging for models and continue to be systematically investigated with both numerical models and field observations.

Besides the scientific perspective on climate change, there is the public perspective. In particular, one needs to learn enough about climate change and processes driving its change to ensure human life remains sustainable. As a result atmospheric, ocean and climate literacy programs that can connect the science with the public are necessary to help close the gap between science and the general population.

This paper addresses both the scientific and public perspectives by using the Arctic Ocean as a key illustration for understanding the ocean's role in climate. Highlights from both modeling and field observations in the Arctic Ocean are used. We then present the public perception of Arctic climate change from press articles.

The Arctic Ocean as a Key Illustration for the Ocean's Role in Climate

Here we present one of the processes, the ocean, in modulating and regulating climate and environmental changes, using the Arctic Ocean as a key illustration for the ocean's role in climate. We will use highlights of recent results from a high-resolution regional Arctic Ocean model (Maslowski et al., 2007) and then key results from a recent direct field experiment in the Arctic (Shaw et al., 2008; Stanton et al., 2008). These will illustrate the scientific challenges of understanding the role of the ocean in Arctic climate change.

Highlights from a Typical Arctic Ocean Climate Model. One of the basic scales of ocean dynamics is the Rossby radius of deformation, which is defined as the length scale at which effects due to the earth rotation become as important as buoyancy effects in the evolution of the flow about a disturbance. This scale decreases with increasing latitude and decreasing stratification and is of order of 10 km or less in the Arctic Ocean. Like global models, recent regional models such as the Arctic Ocean models are not yet eddy-resolving (their horizontal resolution is not sufficient to resolve the Rossby radius of deformation of order 10 km); instead they are eddy-permitting (allowing larger eddies than 20 km in diameter). This means that the horizontal resolution of Arctic Ocean models covers a rather large area for each grid cell, so that direct model-observation comparisons are qualitative rather than quantitative. To date high resolution remains one of the top requirements for advanced modeling of the Arctic climate (Maslowski et al., 2008).

Nonetheless great strides in increasingly higher resolution modeling have made significant advancements in simulating the Arctic Ocean, its sea ice cover and climate. Here we present highlights of recent modeling work (Naval Postgraduate School Arctic Modeling Effort (NAME); Maslowski et al., 2007) that is subsequently being cited in popular press articles as saying that the Arctic may be ice-free by 2013. The public perception of the Arctic being ice-free will be addressed in the next section.

In Fig. 1, sea ice extent and thickness for September (a) 1982 (b) 1992, and (c) 2002 from the NAME model is shown as an example of dramatic reduction in both sea ice cover and thickness in the 2000s (Maslowski et al., 2007). The sea ice extent data from the U.S. National Snow and Ice Data Center (NSIDC) before and after the late1990s show similar changes. Satellite estimates of September ice extent were 7.5 million km^2 both in 1982 and 1992 and 6 million km^2 in 2002, which represent a 1.5 million km^2 or ~20% reduction. The most notable declines occurred in the Western Arctic and Greenland Sea.

Model results are in agreement with satellite data, as they show largely similar sea ice cover before the late 1990s and a significantly reduced (by ~23%) ice extent in 2002 compared to 1992. As in observations, most sea ice is lost over the Greenland shelf and in the western Arctic. However, model results also demonstrate a dramatic decrease in ice thickness, the information which is not readily available from satellites. The mean September ice thickness in 1982 was 2.47 m. It increased slightly to 2.60 m in 1992, and then decreased to 1.50 m in 2002. Relative to the mean September sea ice thickness of 2.37 m for 1979-2004, the mean ice thickness in 2002 represents a thinning of 0.87 m or ~37%. The relative reduction of modeled sea ice thickness during that time period was much greater than the decline of sea ice cover. Limited measurements of ice thickness in the Transpolar Drift (moving ice across the basing toward Fram Strait) using electromagnetic soundings from a helicopter (Haas et al., 2008) indicate a thinning of 0.8 m (from 3.1 m to 2.3 m) between late summer of 1991 and 2001 with an additional reduction of 1.0 m (from 2.3 m to 1.3 m) in 2007. In order to fully understand the rate of change in the Arctic sea ice cover one needs to consider a change of total volume of ice, not just areal changes. The modeled trend in the ice volume since the late 1990s, when extended into the future, projects an ice-free summer in the Arctic Ocean by 2013.

In order to understand the oceanic forcing of sea ice we focus on the Greenland Sea (Fig. 2a), where some of the recent declines of sea ice cover have been both observed from satellites and modeled (Stroeve and Maslowski, 2007). Model results are analyzed over the Greenland shelf to determine a correlation between time series of monthly mean net ice melt/growth anomalies (within the yellow rectangle) and oceanic heat flux anomalies (into the dashed grey box in Fig. 2a). The correlation coefficient during the summer months (July, August, September) is -0.8 (Fig. 2b), which means that 64% of sea ice extent variability over the Greenland shelf can be explained by the oceanic heat advection of warm recirculating Atlantic Water onto the shelf (Stroeve and Maslowski, 2007). Oceanic thermodynamic forcing of ice melt in this region appears to be of primary significance, especially since atmospheric forcing (e.g., winds, surface air temperatures) cannot account for much of the remaining portion of sea ice extent variance. Similarly, other regions of significant ice loss, i.e. the western Arctic Ocean, are argued to be under a significant oceanic thermodynamic control as well (Maslowski and Clement-Kinney, 2008). Those findings imply that the under-ice ablation of sea ice due to the excess of oceanic heat accumulated during the summer and redistributed near the ocean's surface through the following spring has been recently increasingly contributing to a long-term climate change in the Arctic.

Highlights from a Direct Field Experiment in the Arctic. The Arctic ocean-ice-atmosphere feedbacks are not yet represented realistically in Arctic climate models because the turbulent physics is not yet fully understood, even in direct field observations. However large-scale field programs such as the autonomous ocean flux buoys in the Arctic observing system, a component of the International Polar Year, have made great strides towards these goals. Here we describe this field work which is making ocean-ice interaction measurements using recently developed ocean flux buoys in the Arctic observing network (AON).

The science tells us that the ocean acts as a thermal fly-wheel to more rapid atmospheric forcing changes acting across the coupled ocean-ice-atmosphere system. As a result, it is important to determine the vertical fluxes of heat, salt, and momentum across the ocean mixed layer (defined by Moran, 2008, as the surface layer of the ocean that is mixed by the action of waves and tides; underlain by a pycnocline) to understand the relative influences of heat coming from the warm, stratified (not very diffusive) Atlantic and Pacific Ocean waters, compared with the strong and variable surface forcing.

Autonomous ocean turbulent flux buoys (Fig. 3) have been developed at the Naval Postgraduate School (NPS) by Tim Stanton and have been deployed since 2002 with co-located ice thermal flux and atmospheric flux observation systems on ice flows near the North Pole, and more recently in the Beaufort Gyre north of Alaska (Fig. 4).

The autonomous ocean flux buoy is a very high technological instrument. For sensors, it has co-located, high frequency three-dimensional velocity, temperature, and conductivity sensors which give direct eddy-correlation measurements of heat, salt and momentum flux. It has a downward looking 300 kHz Doppler current profiler that measures the upper ocean current structure every 2 m through the ocean mixed layer into the stratified layer that defines the pycnocline (defined by Moran, 2008, as the layer of ocean water in which density decreases rapidly with depth due to vertical changes in temperature and/or salinity). The density gradients in the pycnoline below the well mixed layer greatly inhibit transport of momentum and heat from / to the ocean interior. For data communications, the buoys have two-way, twice per day Iridium communications which allows sampling to be adapted to forcing conditions and available buoy power, and has sufficient bandwidth to send back spectral flux quantities. For power, it uses lithium battery packs and, as an optional feature, can use wind turbine and/or solar panels. For endurance, it can last 1 to 3 years and can survive periods of open water.

The objectives of the buoy program are three-fold: 1) monitor the upper ocean heat content and ocean-to-ice fluxes; 2) quantify entrainment rates of heat that result from temporal and spatial variability in both the structure of the Arctic halocline and the strength of turbulent mixing mechanisms; and 3) test and improve parameterizations of ocean-to-ice fluxes for use in Pan-Arctic scale modeling efforts. Note that the latter objective illustrates the ultimate goal of improving the model physics in the Arctic models.

To date, 10 flux buoys have been deployed on Arctic Ocean pack ice (Fig. 4). The data have been displayed and made available in near real-time (Stanton, 2008).

An example of summer-averaged fluxes derived from the NPS flux buoys for the summertime central Arctic from 2002 through 2007 in a convergent region of the transpolar drift is shown in Fig. 5. It is important to note that these operations were made between the North Pole and Greenland, an area of consistently thicker ice than the more rapidly changing Beaufort

Sea, consistent with Fig. 1. In this region, the ocean mixed layer fluxes are dominated by variations in ice coverage modulating the amount of solar radiation entering the upper water column during the summer. Since, as stated earlier the flux analysis shown in Fig. 5 is for the summertime central Arctic in a convergent region of the transpolar drift, it comes as no surprise that changes in summertime, solar radiation-dominated heat fluxes into the upper ocean are dominated by small changes in ice coverage or divergence over the 6-year study period.

As a result, the buoy observations show that this central Arctic region has not seen the 40% ice cover changes observed during the summer of 2007 in the Western Beaufort Sea. The ocean flux buoys have only been deployed in the Beaufort Sea for 3 years, but they have been deployed during a time of great change in summer ice extent and volume seen in 2007. The buoys, along with the co-located ice mass balance and atmospheric flux systems are allowing the processes acting in the rapid positive feedbacks of the ice-ocean albedo (defined by Moran, 2008,as the ratio of the amount of solar radiation reflected by a body to the amount incident on it) feedback to be evaluated.

The Public Perception of Arctic Climate Change

Here we present the public's perception of climate change from press articles using a recent press article stating that the Arctic Ocean could soon be ice-free during summertime. In particular, an article on 27 June, 2008 on abcnews.go.com by Bill Blakemore and Tuan C. Nyugen had the double headline:"Arctic's First Ice-Free Summer Possible Even This Year; Experts Worry about a Disturbing Trend at the North Pole". Pictured in the article is a polar bear standing on ice next to open water with the caption: "A polar bear by water's edge, Arctic National Wildlife Refuge, Alaska. An increase in thin, young ice raises the possibilities that the polar bear's Arctic home may one day be ice free." Other photos with no captions show from left to right : a large area of ice split from one end to the other by a river of open water; a polar bear and cubs frolicking on the ice; and a large region of open water with ice in the distance.

With the attention getter of polar bears, the authors talk about the North Pole being free of sea ice as a distinct possibility this summer and say this is a common subject of discussion among the world's climate experts. The authors cite satellite data from the NSIDC showing young sea ice, which is no more than 60 inches deep and much more susceptible to melting away, as presently making up 72 % of the Arctic ice sheet. Using this estimate they say that scientists at the University of Colorado's NSIDC like Andy Mahoney see a 50% chance that ice at the "highest point in the Arctic will melt by summer's end." The authors then cite Maslowski who they say told ABC news last summer that there was a chance that the Arctic's entire ice sheet could vanish for the first time in just 4 or 5 years. This was noted to be in contrast with other climate prediction models that say it would take 40 to 50 years before such a scenario is likely to occur. Maslowski is cited as stating that 'whether the Arctic sea ice disappears for the first time this summer or 4 to 8 summers from now may be beside the point. The point is that we may well be passing through the sea-ice tipping point now…Losing the ice sheet means losing an important way of cooling down. As a result, global warming would accelerate as the ice retreats."

Connecting Atmospheric, Ocean and Climate Science with Public Literacy

When press articles such as the one in the previous section are presented to the public, there can be a sense of human emotion and perhaps of fear that overwhelms the public's desire for being scientifically informed. For example, even though the article never mentions polar bears, there are pictures of polar bears near large open water areas, suggesting to the public a possible extinction of the bears, which is alarming, should the Arctic ice melt. The public also knows that the polar bears depend on sea ice floes, travel across sea ice to reach their families, and may lose their food sources.

With such human reactions, the public is likely to be less interested in the quantitative science results presented earlier. Recall that we saw that the modeling efforts of Arctic climate models can take ice thickness as well as ice coverage into account. In contrast satellite observations can take only surface area into account. The projection of ice thickness in time suggests that the Arctic Ocean could become ice-free during summertime as early as 2013. Recall also that the observational results showed that the ice near the North Pole in the summertime is still quite thick and not prone to be ice-free by this summer (Fig. 5e, for example).

This shows a serious gap between the science and the press coverage. This gap needs to be narrowed so that the public can make scientifically informed, responsible decisions about climate change and to alleviate fears of climate change and sustainability. This involves science literacy as well as atmospheric, oceanic and climate literacy. Let us discuss current efforts towards closing this gap.

Programs on science literacy have laid the groundwork for atmospheric, ocean and climate literacy. In 1985 Project 2061 began, which is an initiative began by the American Association for the Advancement of Science (AAAS). This project was named during the year that Halley's comet was seen and for the year when Halley's comet will be visible from the Earth again. Its goal is to help all Americans become literate in science, mathematics and technology.

Most notably in 1989 AAAS produced an online book called *Science for All Americans: Education for a Changing Future* (AAAS, 1989), which is about science literacy. The book is a set of recommendations on what understandings and ways of thinking about science are needed for citizens in a world shaped by science and technology. The book presents recommendations in four categories: 1) the nature of science, mathematics and technology as human enterprises; 2) basic knowledge about the world as seen from a science and mathematics perspective and shaped by technology; 3) presenting what people should understand about some key advances in science and cross-cutting themes that can serve as tools for thinking about how the world works; and 4) the habits of mind essential for science literacy. These recommendations are presented as learning goals rather than as a curriculum document or a textbook. The book states that the recommendations are intended to convey levels of understanding appropriate for all people. Building on resources that have come to AAAS through Project 2061 are *Benchmarks for Science Literacy*, which is an online access to Project 2061 Benchmarks; and an *Atlas of Science Literacy: Mapping K-12 Science Learning*.

The atmospheric, ocean and climate literacy programs have been built on the notion that teaching weather, currents and climate can be a rewarding challenge that crosses many disciplines. In 2006 the first of these literacy programs was published by the National Geographic Society: *Ocean Literacy – The Essential Principles of Ocean Sciences K-12*. It defines ocean literacy as an understanding of the ocean's influence on you, and your influence on the ocean. The seven key points of ocean literacy are: 1) the Earth has one big ocean with many features; 2) The ocean and life in the ocean shape the features of the Earth; 3) The ocean is a major influence on weather and climate; 4) The ocean makes life habitable; 5) The ocean supports a great diversity of life and ecosystems; 6) The ocean and humans are inextricably connected; and 7) The ocean is largely unexplored. Under each of the key points is a list of fundamental concepts that should also be taught. For example, one of the fundamental concepts listed under key point number 1 is that sea level changes as ice caps on land melt or grow; it also changes as sea water expands and contracts when ocean water warms and cools.

In 2007 an abbreviated guide for teaching climate change, from Project 2061 at the American Association for the Advancement of Science, was published. This publication is called *Communicating and Learning about Global Climate Change.* The guide is intended to map out what K-12 students should learn as well as describe what a science literate adult should know and be able to do after understanding the science of climate change. It includes a list of recommended books for a general audience wishing to learn about the science of climate change with links to the online book *Science for All Americans.*

Lastly *Climate Literacy–Essential Principles and Fundamental Concepts* was just published in time for the 2008 National Science Teachers Association meeting. It defines a climate literate person as one who understands the influence of the climate on you and society, and your influence on climate. The 7 key points of climate literacy are: 1) Life on earth has been shaped by, depends on, and affects climate; 2) We understand the climate system through observation and modeling; 3) The sun is the primary source of Earth's energy; 4) Earth's weather and climate system are the result of complex interactions between land, ocean, ice and atmosphere; 5) Earth's weather and climate vary over time and place; 6) Recent climate change is primarily caused by human activities; and 7) Earth's climate system is influenced by human decisions, which are complex and involve economic costs and social values. One of the fundamental concepts under key point number 4 is that the ocean circulation serves as a thermostat for Earth; changes in the ocean's circulation have produced large, abrupt changes in climate in the past.

These programs have laid the groundwork for helping the public ultimately become science literate as well as literate in the earth sciences such as ocean and climate science. The guides list what is takes to be considered literate in the science covered. For example, to be an ocean-literate person, the ocean literacy guide states that 1) you need to understand the essential principles and fundamental concepts about the functioning of the ocean; 2) you need to communicate about the ocean in a meaningful way; and 3) you need to be able to make informed and responsible decisions regarding the ocean and its resources. As another example, to be a climate literate person, the climate literacy guide states that you 1) need to understand the essential principles and fundamental concepts about the functioning of weather and climate and how they relate to variations in the air, water, land, life and human activities in both time and space; 2) you need to be able to communicate about the climate and climate change in a meaningful way; and 3) you need to be able to make scientifically informed and responsible decisions regarding the climate.

It is important to realize that becoming science literate does not carry with it an expectation that the public will readily understand the complex interactions of the atmosphere, ocean and climate. Rather the public should be able to understand enough science so that they understand the issues, understand their implications, and can subsequently make responsible decisions concerning climate change. In short they should learn enough about climate change and these processes affecting it to understand the potential impacts on human life and sustainability.

5. Conclusions

Climate has changed through Earth's history. Organisms have adapted to the changes or have ceased to exist. From a human perspective, climate change may profoundly affect civilization. To make responsible decisions about adaptations to climate change including sustainability, we stated that the public must understand climate change. The trouble with gaining this understanding is two-fold: From a scientific perspective, the dynamics of coupled atmosphere, ocean and climate processes responsible for climate change are complex and are still being systematically investigated. From a public perspective, one needs to learn enough about climate change and these processes to ensure human life remains sustainable.

To illustrate the scientific perspective, we focused on some of the processes related to the ocean's role in modulating and regulating climate and environmental changes, using the Arctic Ocean as a key example. The modeling efforts of Arctic climate models were shown to take ice thickness as well as ice coverage into account. In contrast satellite observations were shown to take only surface area into account. The model projection of ice thickness in time suggested that the Arctic Ocean could become ice-free during summertime as early as 2013.

To illustrate the public perspective, we presented the public's perception of climate change from press articles, including one stating that the Arctic Ocean could soon be ice-free during summertime, as early as this year. The authors of the press article also cited Maslowski who they say told ABC news last summer that there was a chance that the Arctic's entire ice sheet could vanish for the first time in just 4 or 5 years. We noted that, even though the article never mentions polar bears, in the article are pictures of polar bears near large open water areas, suggesting to the public a possible extinction of the bears, which is alarming, should the Arctic ice melt.

We pointed out that when press articles such as the one discussed in this paper are presented to the public, there can be a sense of human emotion and perhaps of fear that overwhelms the public's desire for being scientifically informed. With such human reactions, the public is likely to be less interested in observational quantitative science such as the statement we made in this paper that the Arctic ocean-ice-atmosphere feedbacks are not yet represented realistically in Arctic climate models because the turbulent physics is not yet fully understood even in direct field observations. The observational results showed that the ice near the North Pole in the summertime is still quite thick and not prone to be ice-free by this summer (Fig. 5e, for example). If the public understood enough about science, these results could help calm fears about the North Pole becoming ice-free this summer.

Finally we showed attempts to bridge the gap between science and the press through atmospheric, ocean and climate literacy programs to help the public make scientifically informed, responsible decisions about climate change and to alleviate fears of climate change and sustainability. With such a proliferation of effort into science literacy programs, the public has the opportunity and should have the responsibility to learn enough about climate change to ensure human life remains sustainable.

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Figures

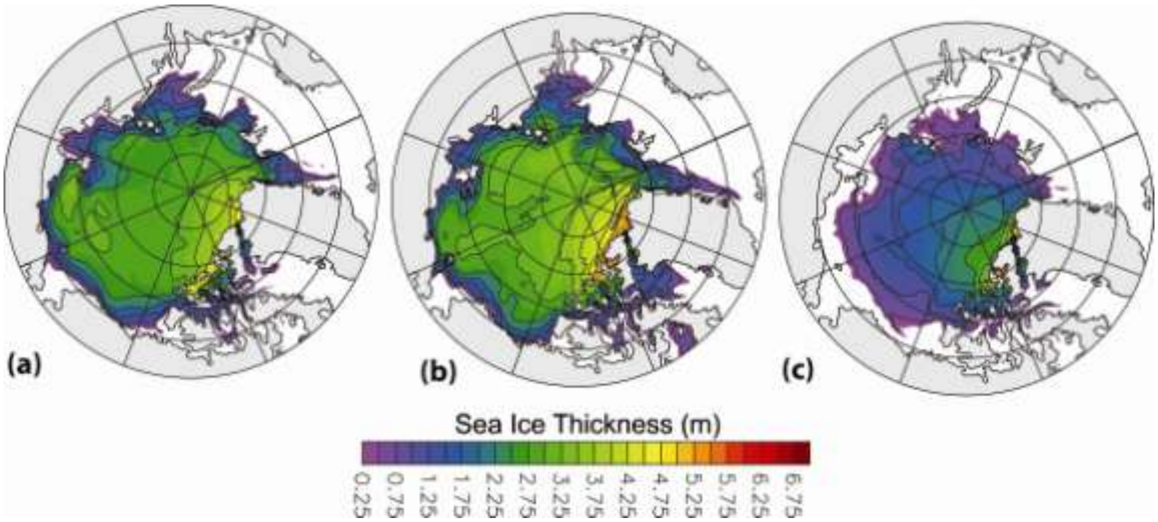

Figure 1. Modeled September sea ice thickness distribution [in meters] in (a) 1982, (b) 1992, and (c) 2002 from the Naval Postgraduate School Arctic Modeling Effort (NAME) model (after Maslowski et al., 2007).

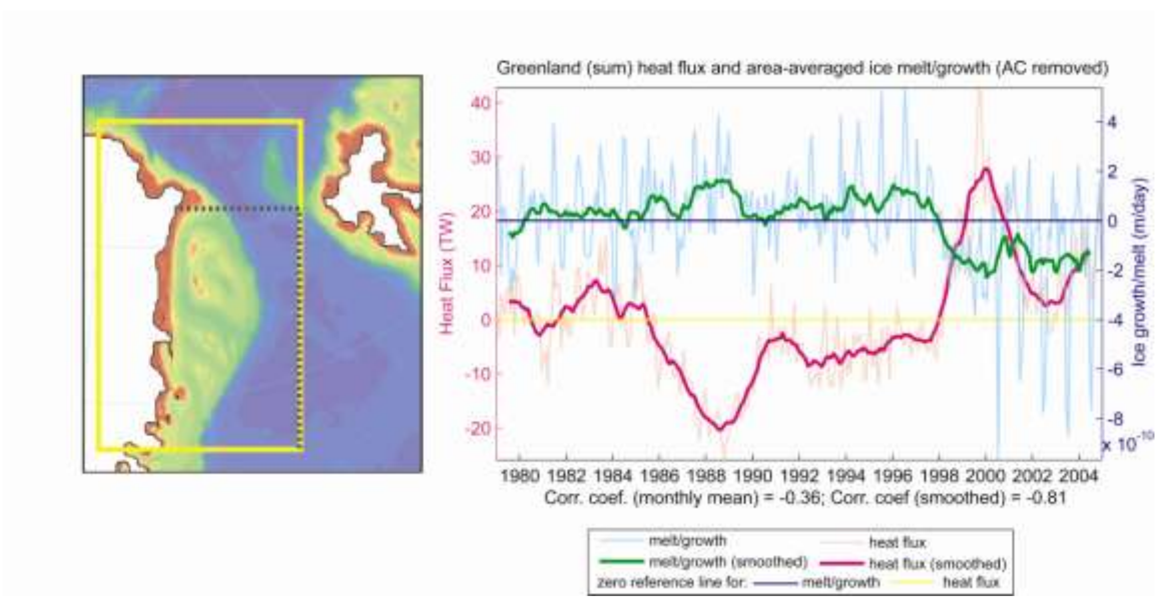

Figure 2. Monthly mean time series of net ice melt/growth anomalies [within the yellow rectangle shown on the left ; in m/day] and of the total ocenic heat flux anomalies [into the dashed grey box ; in TW] (after Stroeve and Maslowski, 2007).

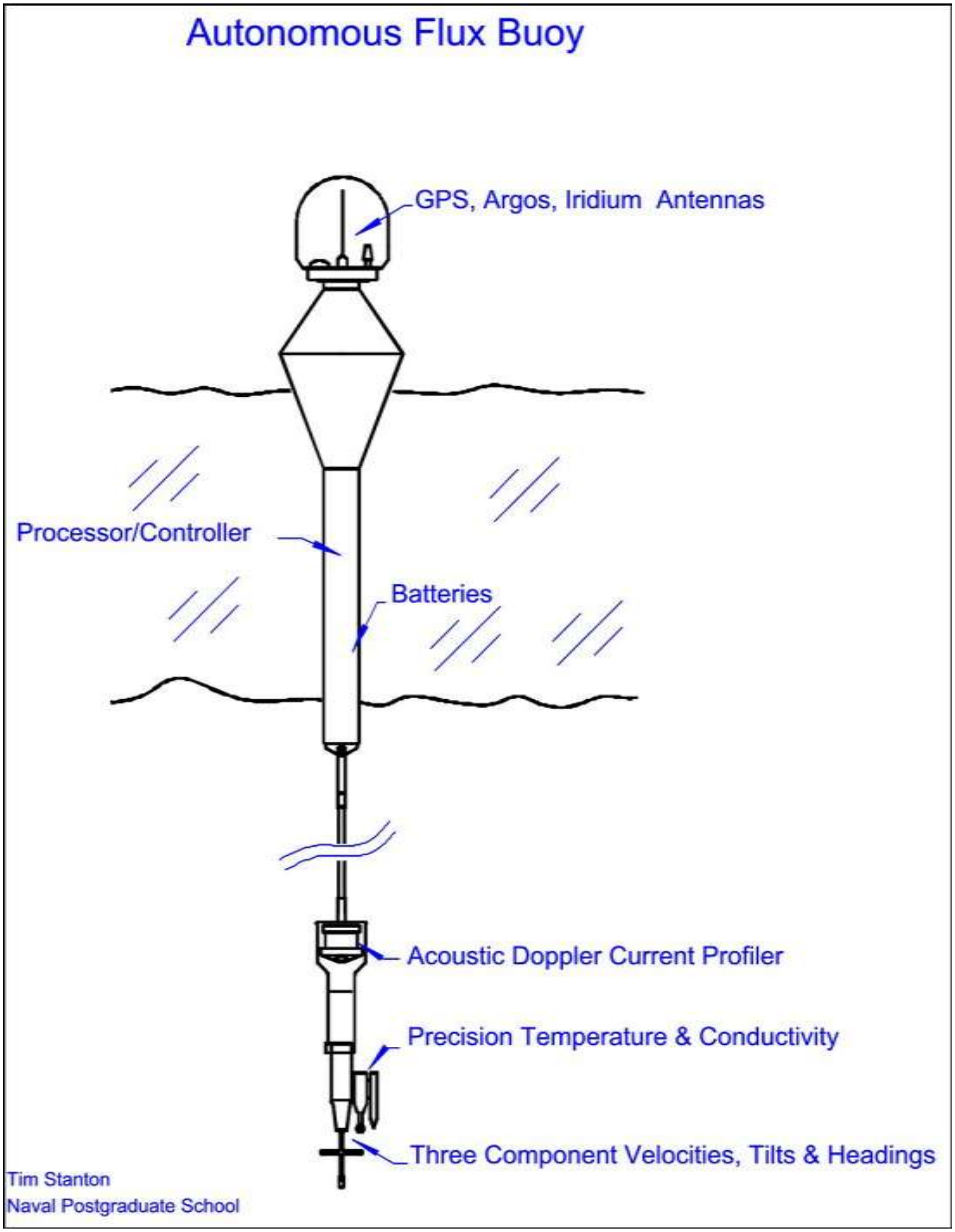

Figure 3. The Autonomous Ocean Flux Buoys (AOFBs) developed at NPS have an instrument cage suspended 5m below the ice and a surface support buoy that processes data from the ocean instruments and transmits these data every day back to NPS using iridium satellite cell phone technology. The instruments directly measure vertical turbulent fluxes using eddy correlation techniques.

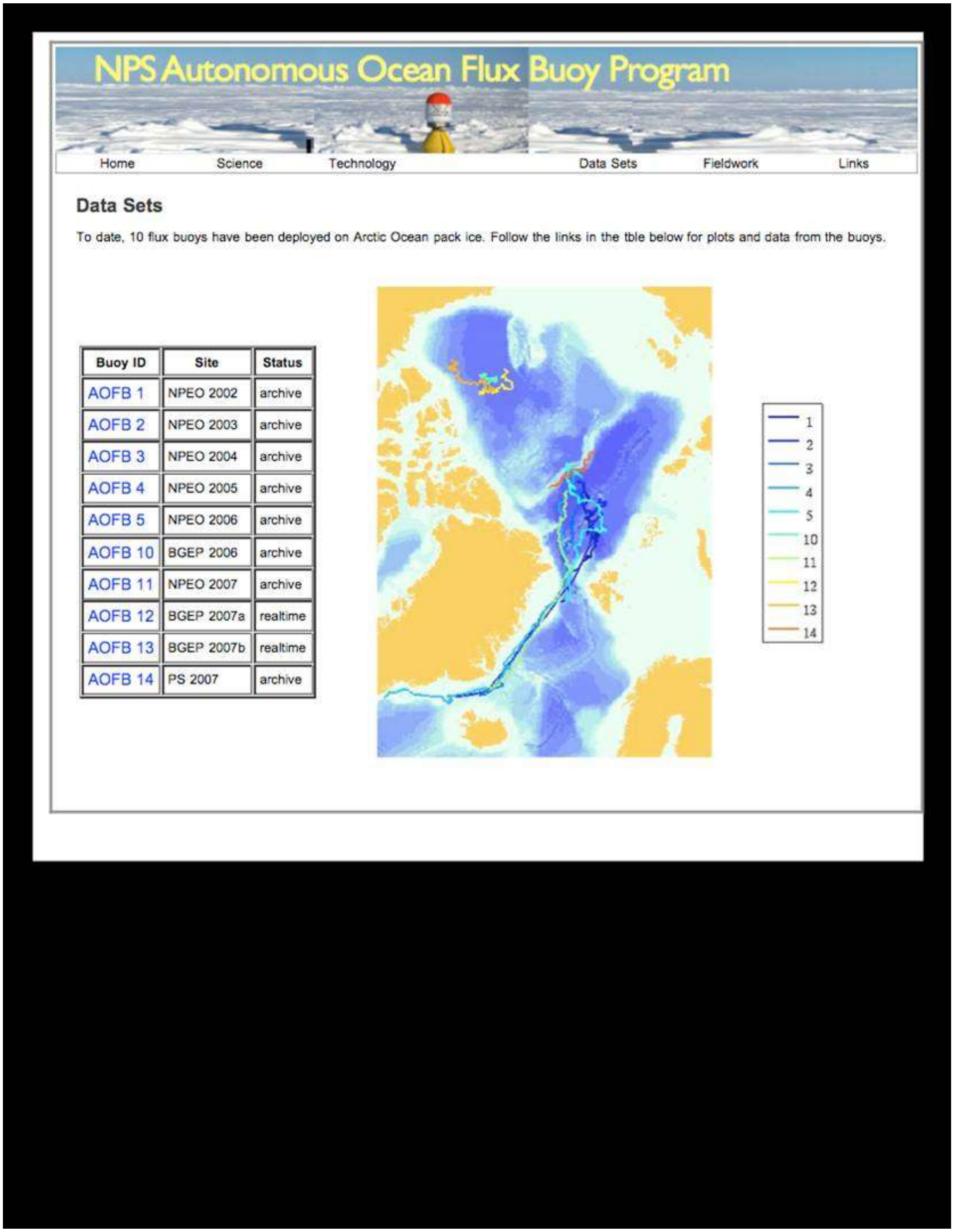

Figure 4. Data from the Arctic AOFBs are made available in near real-time on a web page which shows the buoy drift tracks and timeseries plots of data from each buoy.

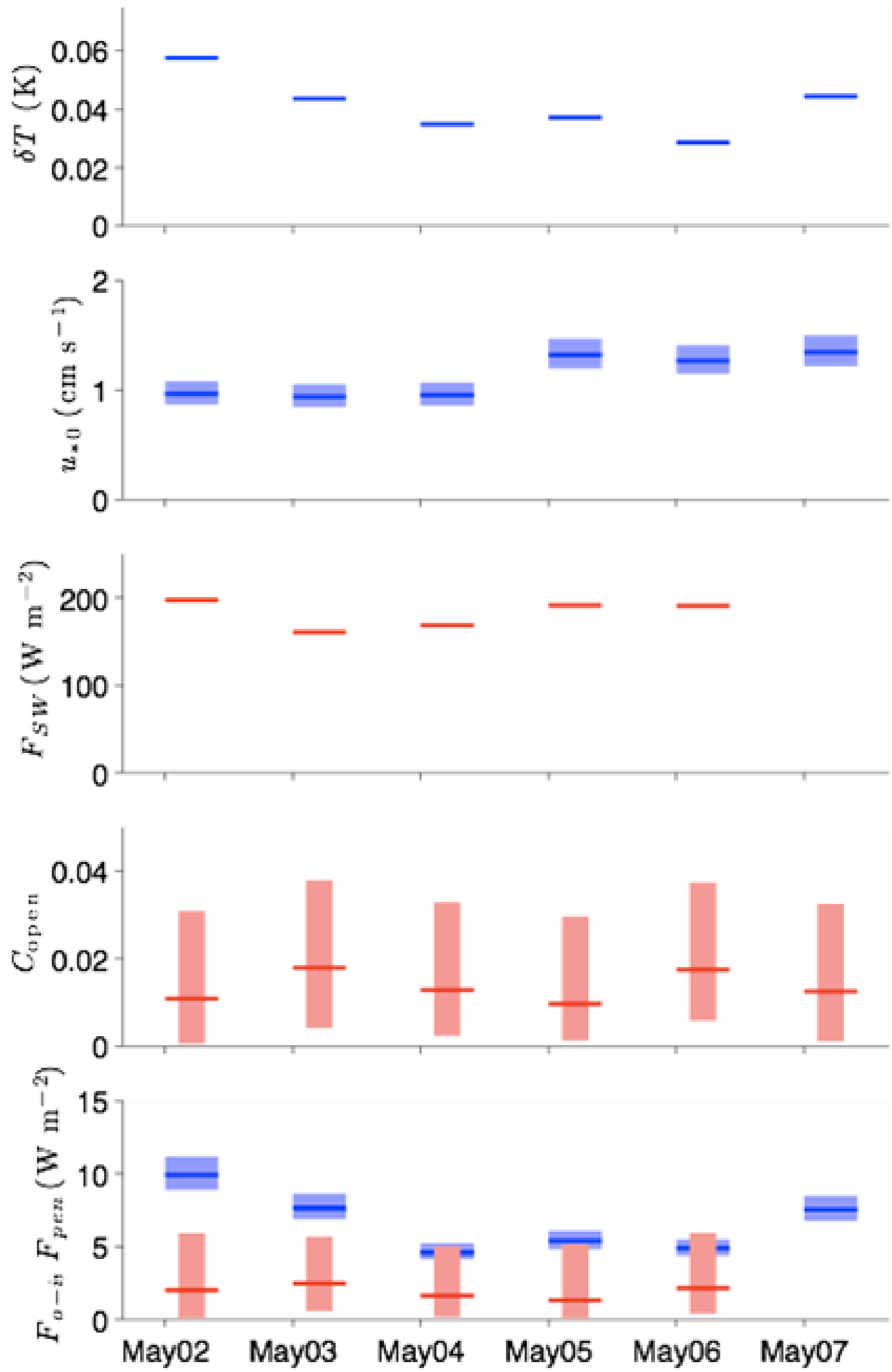

Figure 5. Summer time averages of properties measured by or near the AOFB's as they drift south from the North Pole for years spanning 2002 to 2007 (adapted from Stanton, Shaw, Rogor 2008, submitted). The departure from freezing is shown in Fig. 5a, the turbulent friction velocity in Fig. 5b, the shortwave incident solar heating in Fig. 5c, and the fraction of open water within 50 km in Fig. 5d. Fig. 5e shows the vertical ocean heat flux plotted in blue, while estimated solar fluxes based on the per cent of open water are plotted in red in the same figure.