

# The Critical Role of the North Atlantic and Arctic Oceans in Abrupt Climate Change

*A Scientific Strategy*



Developed by the  
Ocean and Climate Change Institute





*COVER: In February of 1997, Woods Hole Oceanographic Institution's 278-foot research vessel Knorr undertook a risky and dangerous expedition north to the Labrador Sea to study wintertime oceanic processes that help drive global ocean circulation and affect Earth's climate system. Ship's crew and scientists, including Captain A.D. Colburn, right, worked side by side in grueling shifts to keep decks and bulwarks free of ice to allow repeated, round-the-clock deployment and recovery of heavy oceanographic instrumentation during the 47-day cruise. In a typical shift, the crew cleared roughly 15 tons of ice—10 inches thick in places—that formed continually during much of the voyage.*

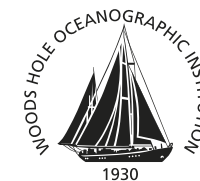
Photo by George Tupper, WHOI.



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WOODS HOLE OCEANOGRAPHIC INSTITUTION



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## As most of the world gradually warms in the future...

Over the past decade, a steadily accumulating body of evidence has led scientists to the following conclusions:

### **Earth's climate can change abruptly and dramatically.**

The changes can cause widespread regions to become much colder, warmer, wetter, or drier—in time spans as short as 3 to 10 years.

### **Earth's climate system may have sensitive thresholds.**

Pushed past a threshold, the system can abruptly switch the way it operates—establishing different climate patterns that persist for decades or centuries.

### **The oceans can trigger or amplify abrupt climate changes.**

The global ocean circulation system (often called the Ocean Conveyor) can also shift rapidly and change the ways that heat and rainfall are distributed around the planet.

### **The North Atlantic Ocean is a potential Achilles' heel.**

The sinking of dense, salty North Atlantic waters drives the Ocean Conveyor, making this ocean a critical linchpin in the climate system.

### **The delicately balanced Arctic Ocean is also vulnerable.**

Global warming and ocean circulation changes threaten the Arctic's sea ice cover—whose melting would have catastrophic consequences.

### **Large, rapid changes are now being detected in the Atlantic.**

Since the 1960s, North Atlantic subpolar waters have become steadily fresher, while the tropical Atlantic has become saltier. These may signal disruptive changes in global ocean circulation and climate.

### **Society should prepare for possible abrupt climate change.**

Rapid advances in our ability to understand and predict ocean-related climate changes can help to mitigate their impacts.

## ...will some regions turn abruptly colder?

To stimulate creative scientific thinking on these issues and to devise a research strategy to address them, the Ocean and Climate Change Institute (OCCI) at Woods Hole Oceanographic Institution (WHOI) convened an Ocean Forum on Abrupt Climate Change in the summer and fall of 2002.

With generous support from The Comer Science and Education Foundation, the OCCI invited four leading scientists in the field of abrupt climate change to Woods Hole as Visiting Summer Scholars. Their broad range of expertise and perspectives complemented those of WHOI scientists. The Ocean Forum Scholars were: Richard Alley (Pennsylvania State University), David Battisti (University of Washington), Mark Cane (Columbia University), and Robert Dickson (Centre for Environment, Fisheries and Aquaculture Science, UK). The scientists reconvened on Nov. 11–12 in Woods Hole to summarize their work.

### **The goals of the Forum were to:**

- assess what we know and need to know about the issues,
- devise strategies to catalyze advances in knowledge, and
- foster dialogue between the public and science communities.

### **The Forum scientists summarized their work, including:**

- 1) evidence and theories for abrupt climate change (pages 6–7),
- 2) an assessment of the role of the oceans, particularly the North Atlantic, in climate change (pages 8–9),
- 3) evidence for recent, dramatic oceanographic changes in the North Atlantic (pages 10–11), and
- 4) identification of strategic locations for promising research (pages 12–13).

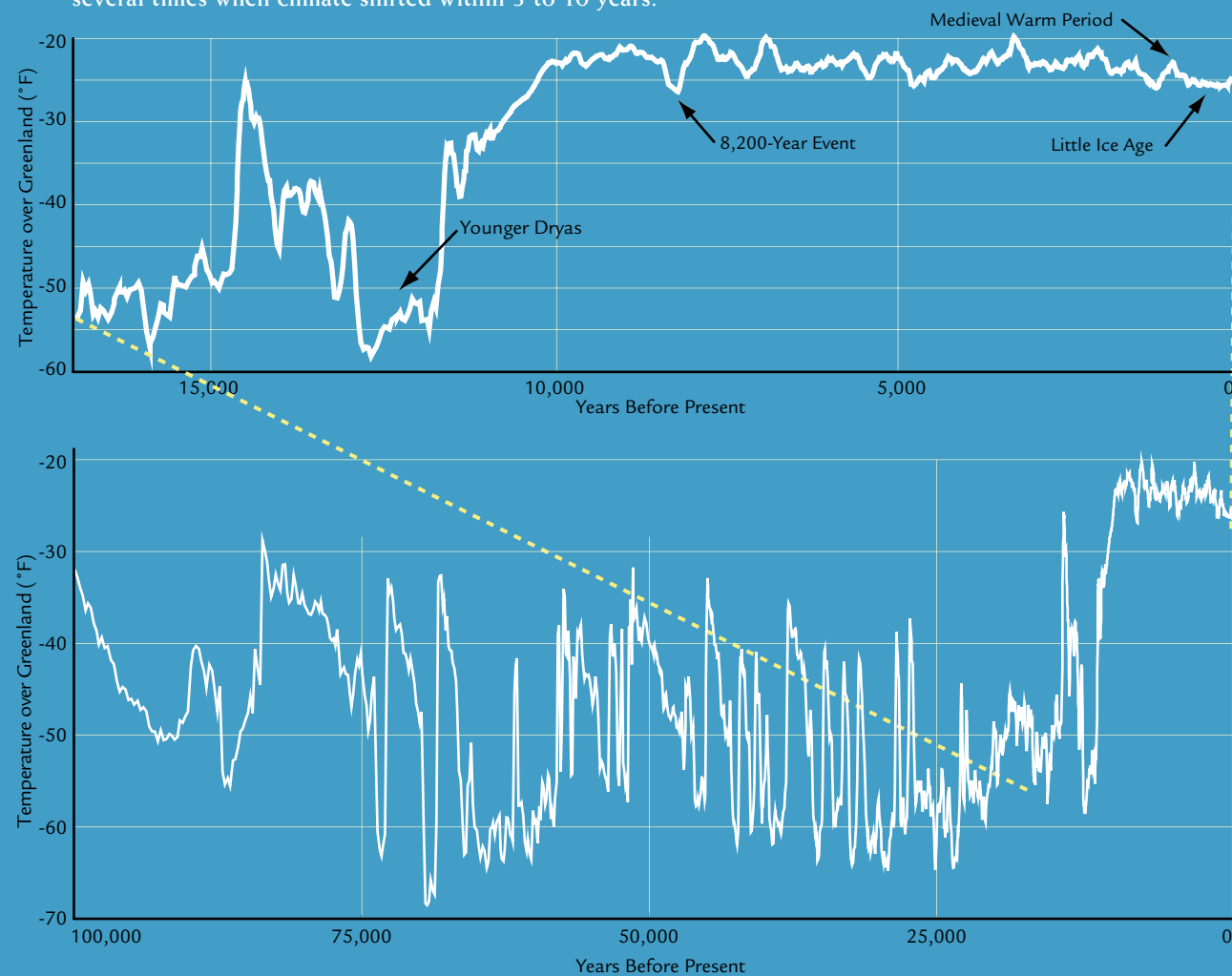
### **Given this evidence, the Forum scientists recommended:**

- 5) overall strategies to accelerate advances in abrupt climate change research (page 14), and
- 6) specific initiatives WHOI can launch to contribute most effectively to this overall effort (page 15).

## Earth history is filled with abrupt climate changes

### Dramatic temperature swings—in time spans as short as a decade

Ice cores extracted from the two-mile-thick Greenland ice sheet preserve records of ancient air temperatures. The records show several times when climate shifted within 3 to 10 years.



**The Younger Dryas**—About 12,700 years ago, average temperatures in the North Atlantic region abruptly plummeted nearly 10° F and remained that way for 1,300 years before rapidly warming again.

**The 8,200-Year Event**—A similar abrupt cooling occurred 8,200 years ago. It was not as severe and lasted only about a century. But if a similar cooling event occurred today, it would have dire impacts.

**The Medieval Warm Period**—An abrupt warming took place about 1,000 years ago. It was not nearly so dramatic as past events, but it nevertheless allowed the Norse to establish settlements in Greenland.

**The Little Ice Age**—The Norse abandoned their Greenland settlements when the climate turned abruptly colder. Between 1300 and 1850 A.D., severe winters had profound agricultural, economic, and political impacts in Europe.

### Large, rapid climate shifts occur repeatedly on Earth

The surprising realization that Earth's climate fluctuates fast and furiously was confirmed in the early 1990s when scientists analyzed cores drilled through the two-mile-thick ice sheet atop Greenland. The ice contained a climate record ranging back about 110,000 years. Scientists discovered that past air temperatures over Greenland (left) repeatedly swung up and down by 10° to 20° F—within 3 to 10 years. Additional evidence has reinforced these conclusions:

- Abrupt climate shifts have affected widespread regions, causing large-scale cooling, warming, and drought.<sup>1</sup>
- Earth's climate system has sensitive thresholds. Crossing a threshold can trigger further and faster climate changes.<sup>1</sup>
- The relative stability of Earth's climate since the last ice age ended is no guarantee of continuing stability.<sup>2</sup>
- Greenhouse warming and other anthropogenic changes may be destabilizing factors that increase the likelihood of rapid climate change.<sup>3</sup>
- Past North Atlantic climate changes have been linked with shifts in the Southwest Asian monsoon, whose rains sustain broad populations spanning Africa, India, and China.<sup>4,5</sup>
- Recent evidence has linked ocean-related climate shifts with widespread "megadroughts" and abrupt civilization collapses: the Akkadian empire in Mesopotamia 4,200 years ago, the Mayan empire in central America 1,100 years ago, and the Anasazi in the US Southwest in the late 13th century.<sup>6,7</sup>
- Many of these abrupt climate changes have been linked to rapid shifts in ocean circulation—particularly in the North Atlantic.<sup>3,8</sup>

## The oceans—an under-explored key to our climate

### The ocean and atmosphere are partners in creating our climate

By circulating heat and water around the planet and transferring it to the atmosphere, the oceans play a critical role in Earth's climate system. A large portion of this heat transport occurs in the North Atlantic Ocean. In the past, changes in the North Atlantic have led to climate changes, but scientists do not fully understand what caused them. The changes may have been triggered in the North Atlantic, or they may have originated in the tropical Pacific.

Either way, the Atlantic clearly amplifies and extends climate changes, with significant impacts in Europe and the US East Coast.

### The North Atlantic is a critical component of our climate system

The northern North Atlantic is one of the few places on Earth where relatively cold, salty waters are dense enough to sink to the abyss. The plunge of this great mass of cold, salty water propels a system of global ocean circulation called the Ocean Conveyor. The Conveyor also draws warm, salty tropical waters northward into the North Atlantic. This pumps heat into the region (which significantly raises average winter temperatures), as well as salt (which makes North Atlantic waters denser and increases sinking that drives the Conveyor). Changes in this strategic region can lead to widespread abrupt climate changes.<sup>8</sup>

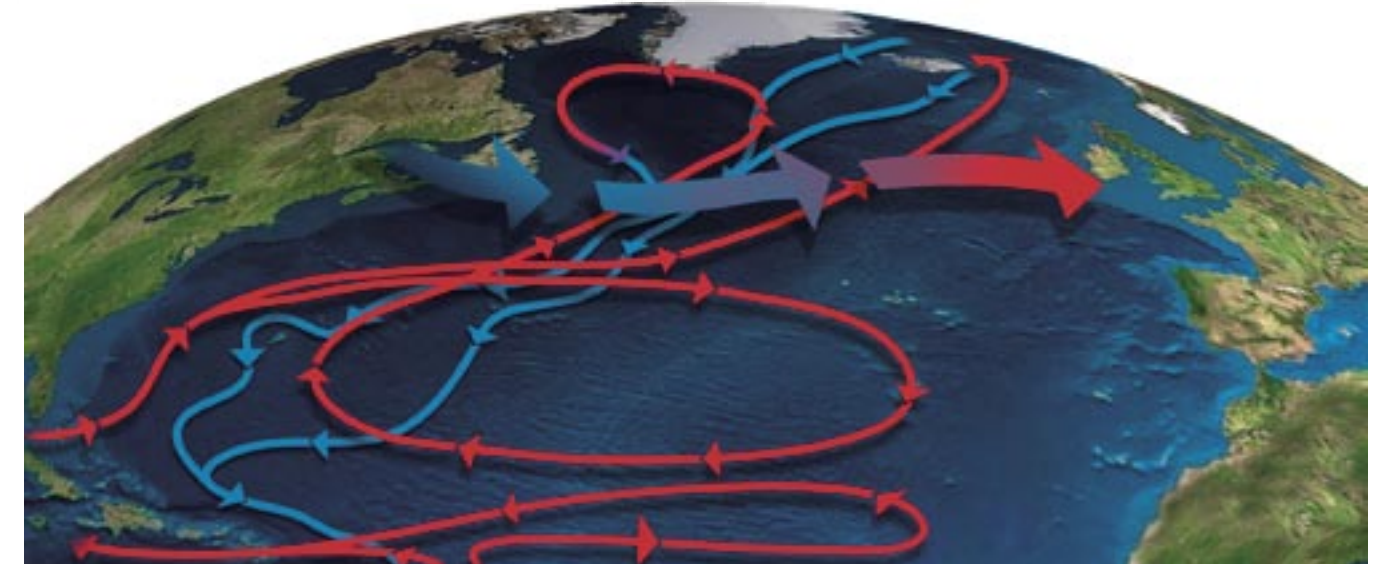
- Deep-sea sediments have revealed that the Ocean Conveyor has rapidly slowed down or stopped several times in the past.
- These disruptions in ocean circulation are linked to dramatic cooling in the North Atlantic region and drought in other areas of the Northern Hemisphere.
- Computer models simulating ocean-atmosphere dynamics predict that greenhouse warming can cause a Conveyor slowdown in the future.
- A Conveyor slowdown would rapidly cool the North Atlantic region, while the earth as a whole continues to warm.



The global ocean circulation system, often called the Ocean Conveyor, transports heat worldwide. White sections represent warm surface currents. Purple sections represent cold, deep currents.

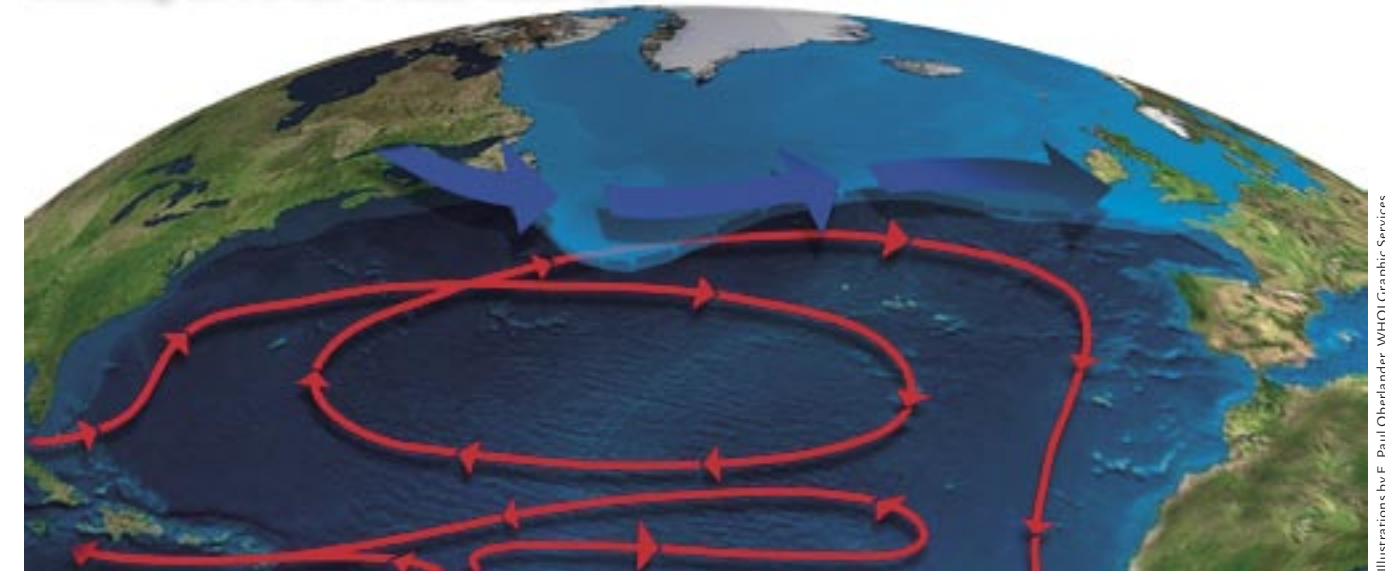
Jayne Doucette, WHOI Graphic Services

### The North Atlantic ocean-atmosphere system today



The Ocean Conveyor is driven by the sinking of cold, salty, and therefore denser, waters in the North Atlantic Ocean (thin blue lines). This draws warm, salty surface waters northward (thin red lines). The ocean gives up heat to the atmosphere above the North Atlantic Ocean, and prevailing winds (large arrows) carry the heat eastward to warm Europe.

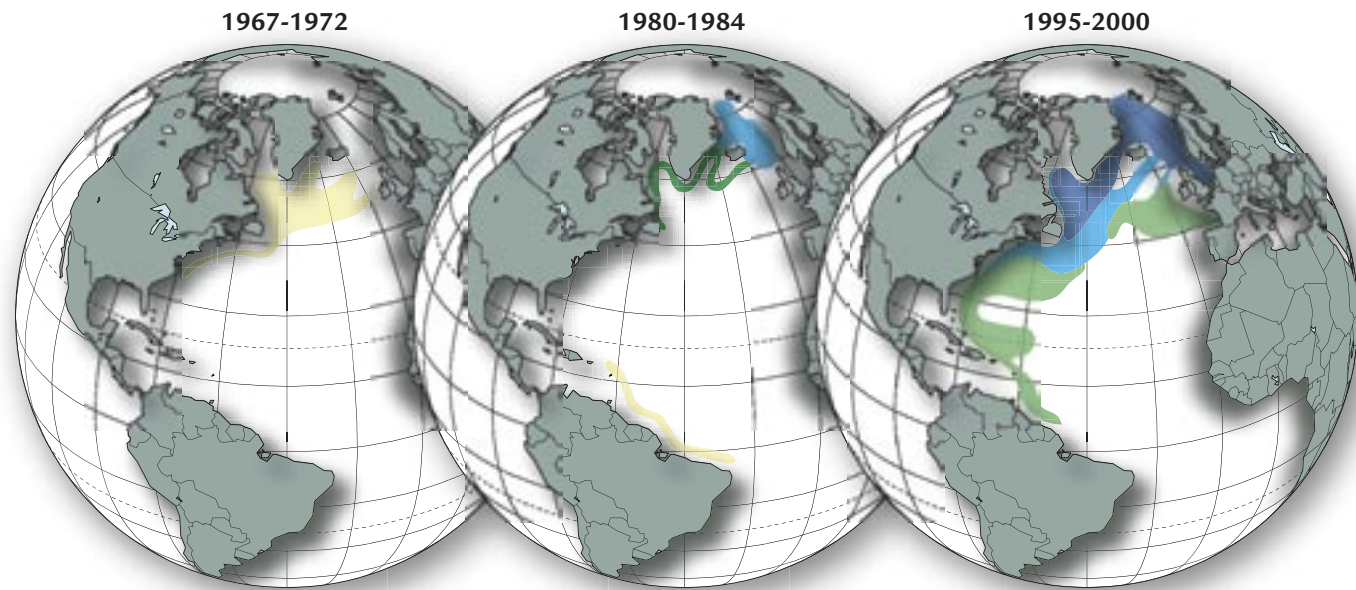
### Shutting down the Ocean Conveyor



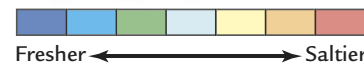
If too much fresh water enters the North Atlantic, its waters could stop sinking. Heat-bearing Gulf Stream waters (red lines) would no longer flow into the northern Atlantic, and European and North American winters would become more severe. (See computer animation at [www.whoi.edu/institutes/occi/climatechange\\_wef.html](http://www.whoi.edu/institutes/occi/climatechange_wef.html))

Illustrations by E. Paul Oberlander, WHOI Graphic Services

## North Atlantic deep waters are becoming fresher...



New data, reported in the journal *Nature* in 2002, show that deep waters are becoming less salty in the strategic North Atlantic locations, where salty, dense waters sink to propel the Ocean Conveyor. The trend has accelerated in the past decade and a mass of fresher deep water is spreading southward.



### Global warming can alter Earth's water cycle

About 86% of evaporation on Earth occurs above the oceans and about 78% of precipitation falls onto the ocean surface. This continual exchange of fresh water between the oceans and atmosphere influences where and when droughts, floods, and storms occur on Earth. A warmer Earth in the future could significantly alter this global water cycle, causing tremendous long-term consequences for society. For example, global warming may intensify evaporation from the oceans. A warmer atmosphere also can hold more water vapor—which is also a potent greenhouse gas that could exacerbate global warming.

Together, these factors could accelerate the atmospheric transport of fresh water from tropical regions to higher latitudes, where it falls into the oceans as rain and can dilute ocean salinity. Changes in ocean salinity affect the density of surface waters, and thus can lead to ocean circulation changes and climate shifts.

Ocean salinity changes that affect the water cycle, ocean circulation, and climate have been inadequately monitored. But new instruments, such as salinity drifters, floats, and autonomous vehicles, now exist to take these critical measurements.

## ...while tropical Atlantic surface waters are becoming saltier

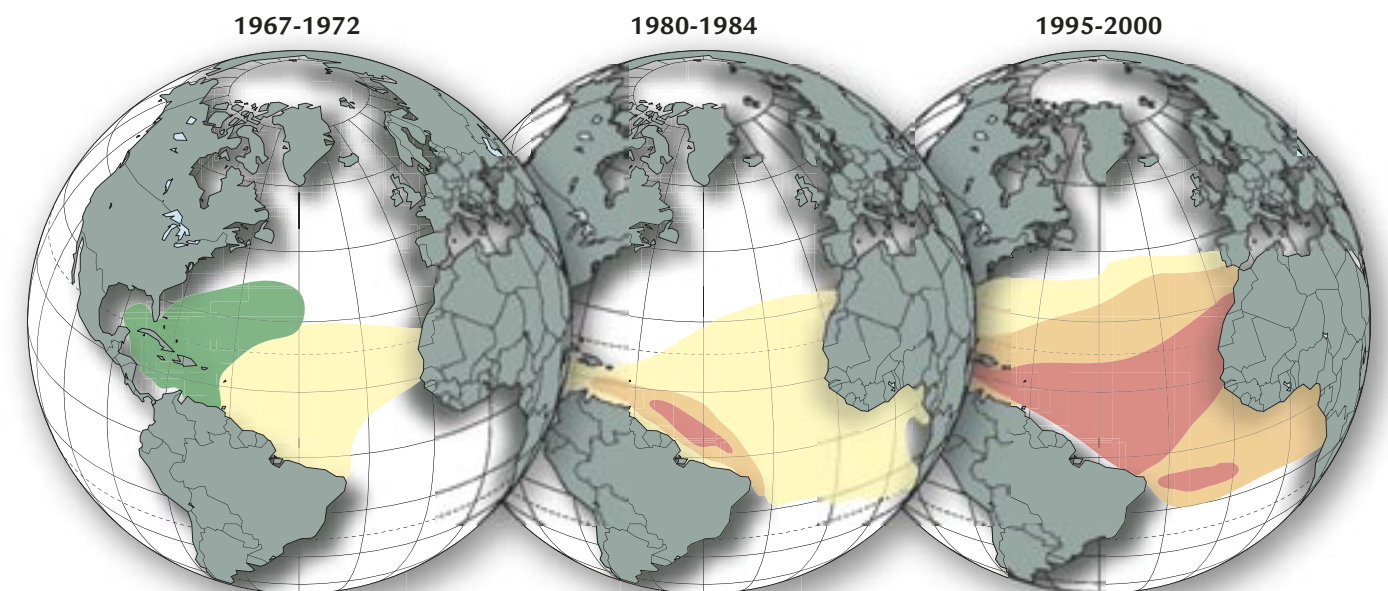
### Large changes are occurring in the Atlantic

Scientists have recently detected the largest, most dramatic oceanic changes ever measured in the era of modern instruments.

- Since the 1960s and especially in the past decade, salinity levels have decreased in strategic North Atlantic locations where cold, salty waters sink to the abyss to propel the Conveyor.<sup>9</sup>
- Simultaneously, the tropical Atlantic has become saltier.<sup>10</sup>

These poorly understood changes may signal fundamental, large-scale shifts in the ocean's circulation and the planet's water cycle. Global warming may be a factor:

- Global warming may intensify evaporation, transporting more fresh water vapor northward and concentrating salt in tropical oceans.
- More precipitation in higher latitudes freshens North Atlantic waters, increasing the likelihood of slowing the Conveyor.
- Global warming may also indirectly add more fresh water to the North Atlantic by melting glaciers and Arctic sea ice.



New research shows that tropical Atlantic surface waters are becoming saltier. Global warming may intensify evaporation, leaving salt in tropical oceans. A warmer atmosphere holds more water vapor and may transport it northward to freshen the North Atlantic.



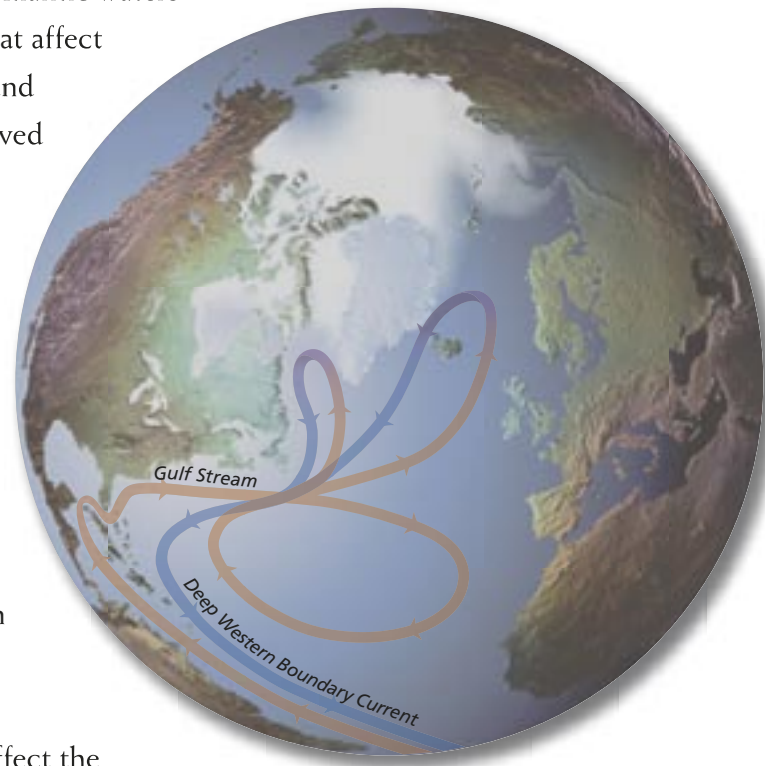
## The Atlantic-Arctic heating and cooling system

The opaque barrier of the oceans and its great breadth conceal a critical planetary “plumbing system” that circulates and ventilates heat around the globe. Within this system, certain locales and conduits are strategic: the Gulf Stream, the Deep Western Boundary Current, and the Arctic Ocean. Changes in these critical areas can precipitate further and more far-flung changes in ocean circulation and climate.

### The Gulf Stream and the Deep Western Boundary Current

The Gulf Stream is a principal conduit by which heat from the low latitudes flows poleward. The Deep Western Boundary Current, hugging the continents of North and South America, acts as an oceanic pipeline transporting cold Arctic and North Atlantic waters southward. The interactions and processes that affect this major north-south thoroughfare of heat and water masses have not been adequately observed and remain largely unknown. Among the outstanding questions are:

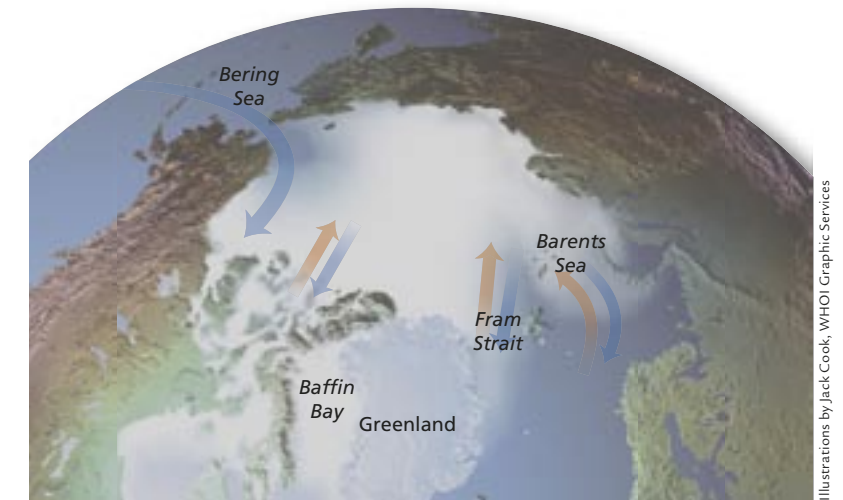
- 1) Do variations in the northward transport of heat and salt via the Gulf Stream affect the sinking of North Atlantic waters and cause climate changes?
- 2) How does the Deep Western Boundary Current transmit oceanic changes from polar regions to the tropics?
- 3) How do changes in the rates of evaporation and precipitation affect oceanic conditions, circulation, and climate—and vice versa?
- 4) How do North Atlantic oceanic changes affect the water cycle in the tropical Atlantic?
- 5) Do ocean and climate changes in the tropical Atlantic get amplified and radiated globally?



### The Arctic Ocean

Waters flow into and out of the largely enclosed, ice-covered Arctic Ocean through four gateways. These gateways regulate a delicate balance of relatively fresh and salty waters in the Arctic Ocean.

Pacific waters enter in the western Arctic, through the Bering Sea gateway. Warmer, saltier waters—originating from the Atlantic—enter the Arctic through three other gateways: the Fram Strait, the Barents Sea, and Baffin Bay. Cold Arctic waters also exit through these same Arctic gateways into the North Atlantic, where they contribute to the sinking mass of cold waters that helps propel the Conveyor.



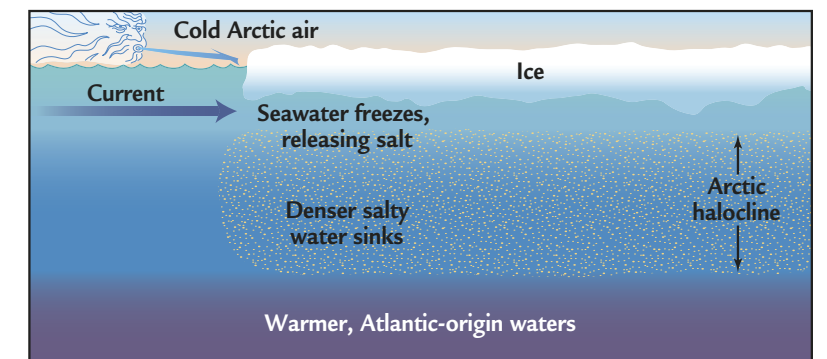
Illustrations by Jack Cook, WHOI Graphic Services

### The Arctic Halocline

Cold Arctic air temperatures freeze seawater into sea ice. When seawater freezes, salt is rejected. Salty waters are denser, and sink. The process creates a thin layer of sea ice and fresh water at the surface, above a layer of denser, saltier waters—called a halocline.

The halocline provides a barrier to mixing that would otherwise bring deeper, warmer waters in contact with the sea ice cover. The heat content of this deeper water is sufficient to melt the ice from below and flood the North Atlantic with fresh water.

Of critical concern are the oceanic mixing and circulation processes that create, maintain, and threaten the Arctic halocline and the sinking of cold, salty waters in the North Atlantic. It is generally believed that future warming will be felt first and most severely in the polar regions.



## Understanding abrupt climate change

### The Challenge

Our ability to predict climate changes is limited by our inadequate understanding of how ocean waters circulate and mix. Despite their importance to the climate system, the North Atlantic and Arctic Oceans are poorly monitored. Thus, oceanographers have had limited ability to observe key, complex processes that drive ocean circulation and influence global climate.

### The Imperative

Many signs indicate that major ocean and climate changes, perhaps induced by global warming, are already occurring. These include evidence of a fresher North Atlantic, a saltier tropical Atlantic, Arctic sea ice melting, increased fresh water river discharge to the Arctic Ocean<sup>11</sup>, and a slower rate of sinking of North Atlantic waters.<sup>12</sup>

### The Opportunity

Several research groups in Europe and North America are launching large-scale, long-term observation programs in the North Atlantic. WHOI itself launched pioneering ocean observatories in the Atlantic in 2001 and in the Arctic in 2002.

The time is ripe and the players are poised to create an Atlantic-Arctic Ocean observing network to:

- 1) reveal mechanisms that drive ocean circulation and affect climate;
- 2) assess the climate system's sensitivity to abrupt change;
- 3) monitor oceanic changes resulting from global warming; and
- 4) improve climate prediction models and provide observations for climate forecasting.

### The Recommendations

To understand the causes of past abrupt climate change and the potential for future rapid disruptions in ocean circulation and climate, scientists in the Ocean Forum on Abrupt Climate Change recommended:

- Extending geological records of past natural climate changes to shed more light on the interconnections between tropical climate changes and changes in Atlantic Ocean circulation.
- Improving knowledge of the "ocean components" in numerical ocean-atmosphere models that simulate climate dynamics.
- Initiating a large-scale effort to understand the surface and deep circulation of the Atlantic and Arctic Oceans and their role in regional and global climate change.

### The Strategy

**Improving ocean-atmosphere models.** Lack of knowledge about complex ocean processes limits the ability of coupled ocean-atmosphere models to simulate and predict climate dynamics. Models will become more accurate with enhanced efforts to measure and understand oceanic processes that drive the mixing and movement of water masses within the oceans. The OCCI proposes studies to explore processes that: 1) create and maintain the Arctic halocline; 2) control how waters sink and mix in subpolar ocean basins to form the Deep Western Boundary Current (DWBC); and 3) affect the circulation of waters between the northern and tropical Atlantic, south via the DWBC and north via the surface Gulf Stream.

**Extending records of past climate change.** New research initiatives to uncover more information on past climate shifts will help predict possible changes in the future.

Was the North Atlantic Ocean a primary cause of past abrupt climate change? Or was the climate system driven by changes in tropical ocean regions? Did North Atlantic changes amplify and transmit climate changes to other areas of the globe?

Clues to past ocean and climate changes are recorded in seafloor sediments. To extract these archives, scientists take core samples. The OCCI proposes three coring expeditions: 1) in the tropical Pacific, to evaluate climate-related interactions between the Pacific and Atlantic Oceans; 2) in the tropical Atlantic, to explore links between ocean and climate processes in the northern and tropical Atlantic; and 3) along a line from Bermuda to Cape Cod (Station W), to determine relationships between past North Atlantic Ocean circulation and past abrupt climate changes.

The principal tool used will be a new long-coring system that can recover cores up to 50 meters long. The long corer will give scientists the ability to extend climate records tens of thousands of years into the past, with resolution high enough to distinguish past climate and ocean circulation changes that occurred within a decade. The long-core system was designed at WHOI with support from several private foundations. The National Science Foundation provided support to build this system and deploy it on the WHOI research vessel *Knorr*.

**Creating an Atlantic-Arctic observation network.** The OCCI—in coordination with other planned observing systems—proposes to apply its expertise in building, deploying, and using ocean-sensing technology to develop a large-scale, long-term observing system to study North Atlantic circulation and its interactions with the Arctic Ocean and the atmosphere. It will measure and monitor critical processes that affect ocean and climate dynamics. (See pages 16-17.)

# Creating an Atlantic-Arctic observation network

## Woods Hole Oceanographic Institution Initiatives

### Arctic Gateways Program

Four lines of ocean observatories—near the Fram Strait, the Barents Sea, Baffin Bay, and the Bering Sea—will monitor the inflow of Atlantic-origin waters and Pacific-origin waters into the Arctic Ocean (a key to predicting the melting of Arctic ice) and the outflow of Arctic waters into the North Atlantic (a key to predicting how increased sea ice melting and precipitation may disrupt the Conveyor and trigger abrupt climate change).

### Arctic Ocean Ice Buoy Program

Buoys deployed in drifting sea ice will monitor the delicately balanced Arctic Ocean halocline, which separates sea ice from warmer deeper waters. A halocline breakdown could accelerate sea ice melting, flood the North Atlantic with fresh water, disrupt the Ocean Conveyor, and cause large, abrupt climate change.

### Station W Program

The Station W mooring transect, from Bermuda to Cape Cod, is a key location to study heat and salinity changes in the northward-flowing Gulf Stream, and changes in the intensity and properties of the southward-flowing Deep Western Boundary Current (DWBC). A transect at 65°W extends DWBC measurements southward. Understanding how these oceanic changes affect North Atlantic climate is the primary focus of this research.

The moorings will be complemented by ocean mixing studies (to understand the processes that drive water masses between the northern and tropical Atlantic via these two currents), and by a long-coring program (to examine relationships between past North Atlantic circulation and past abrupt climate changes).

### Tropical Program

Two additional mooring lines—at 16°N and near the equator—will measure heat and water exchanges between the atmosphere and ocean surface to monitor changes in the global evaporation-precipitation cycle. The moorings will be complemented by surveys by autonomous, long-duration gliders. Long-coring programs in both the tropical Pacific and Atlantic will examine past ocean circulation and climate relationships between the two oceans, and interactions between the northern and tropical Atlantic.

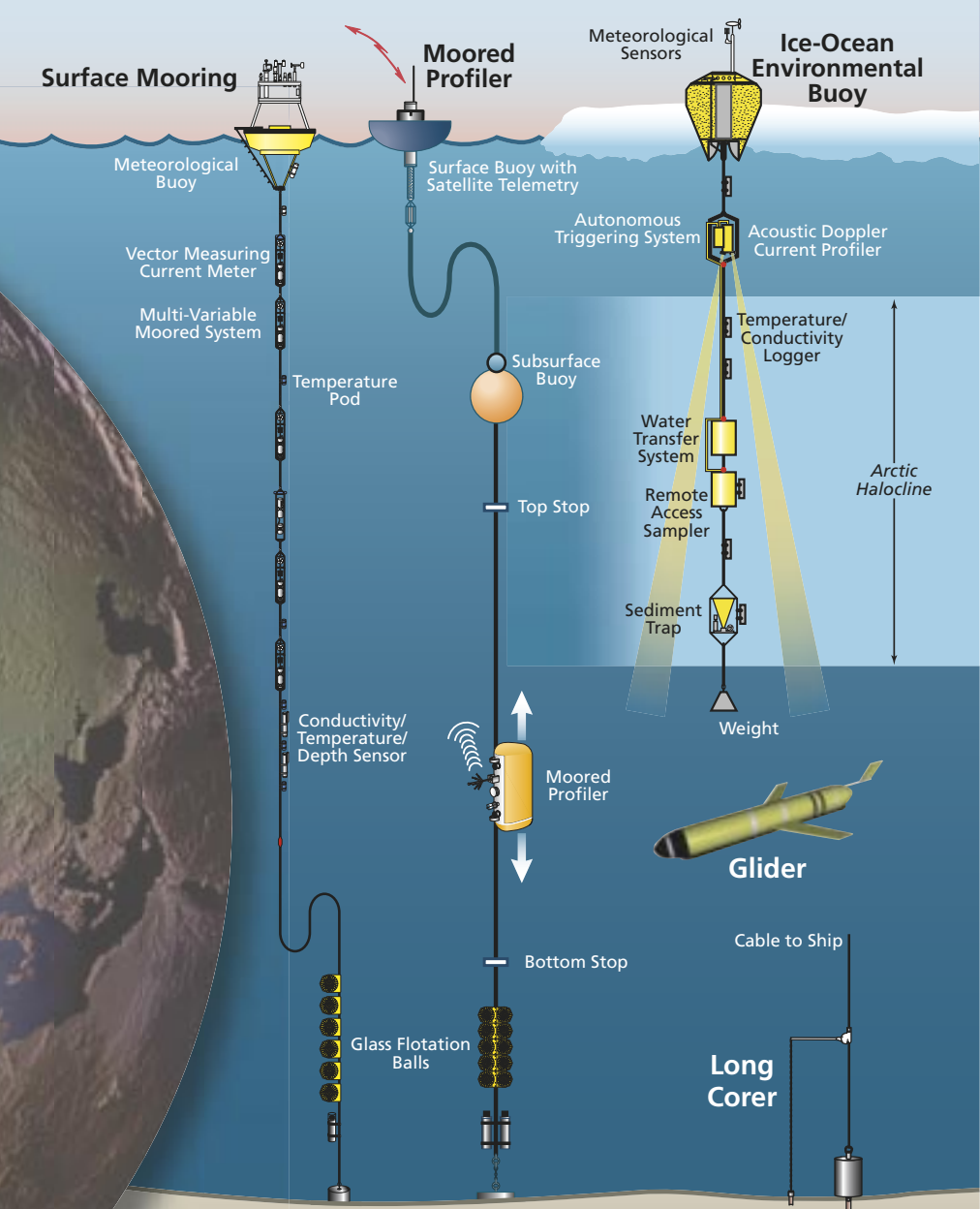
### International Collaborations

#### ASOF (Arctic and Subarctic Ocean Flux) Study

This multi-institutional joint European-US program plans to construct a coordinated ocean observing system to monitor and understand oceanic fluxes of heat, salt, and fresh water in the North Atlantic and Arctic Oceans. The system will provide long-term measurements critical to understanding the factors that control North Atlantic ocean circulation and its influence on global climate.

#### RAPID Climate Change Programme

This mostly UK-funded project will deploy moorings to measure oceanic changes across the Atlantic at 26°N, from Florida to Africa. Two more mooring lines will be deployed farther north to track the Deep Western Boundary Current.



**Surface moorings** have lines of sensors from the seafloor to the surface and floating platforms with meteorological sensors. They monitor oceanic changes and heat and water exchanges between air and sea.

**Moored profilers** move up and down mooring lines, taking continual temperature and salinity measurements over months to several years. Data are stored, or potentially relayed via satellite.

**Ice-Ocean Environmental Buoys** are deployed over several years in drifting sea ice, taking meteorological and oceanographic measurements, especially of the Arctic halocline.

**Gliders** are autonomous vehicles that maneuver through oceans at speeds of 1 knot over 45 days and potentially up to several years, taking temperature, salinity, and other measurements.

**Long corers** collect 50-meter cores of seafloor sediments, which record ocean and climate changes thousands of years into the past.

## The Ocean Forum on Abrupt Climate Change



Ocean Forum scientists gathered with Woods Hole Oceanographic Institution scientists in Woods Hole, MA, on November 11-12, 2002, to identify and recommend research initiatives to accelerate our understanding of the causes of past abrupt climate change and the potential for future rapid climate change.

The Ocean Forum was supported by The Comer Science and Education Foundation. Members of the Oceanographic's Board of Trustees and Corporation participating in the forum were Breene Kerr, Peter Aron, Lou Cabot, Ted Dengler, Chuck Lucas, Jim Moltz, Jeff Thompson, Jack Wise, and Barbara Wu.

Woods Hole Oceanographic scientists attending were: John Toole, Senior Scientist in the Physical Oceanography Department and an Ocean and Climate Change Institute (OCCI) Fellow; Lloyd Keigwin, Senior Scientist in the Geology and Geophysics Department and OCCI Fellow; Ruth Curry, Research Specialist in the Physical Oceanography Department and OCCI investigator; and Fiammetta Straneo, Assistant Scientist in the Physical Oceanography Department.

Toole has been leading the Institute's efforts to establish Station W. Keigwin reconstructs the past history of oceans and climate, with emphasis on how changing Atlantic circulation influenced climate change in time spans ranging from decades to centuries. Curry works with hydrographic data to understand changes in ocean temperature and salinity during the past several decades. Straneo studies the ocean processes that control deep convection and the production of deep water masses in the North Atlantic.

Presentations by scientists participating in the Ocean Forum on Abrupt Climate Change may be viewed on the Web at: [www.whoi.edu/institutes/occi/activities/ocf.htm](http://www.whoi.edu/institutes/occi/activities/ocf.htm).

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## Woods Hole Oceanographic Institution



Doug Weisman

**WOODS HOLE OCEANOGRAPHIC INSTITUTION** (WHOI) is a private, nonprofit research and higher education facility dedicated to the study of all aspects of marine science and to the education of marine scientists. It is the largest independent oceanographic research institution in the US, with staff and students numbering about 1,000.

In an atmosphere that nurtures discovery, WHOI scientists, engineers, and students collaborate to explore the frontiers of knowledge about planet Earth. They develop theories, test ideas, build seagoing instruments, and collect data in hostile marine environments. Their diverse research agenda includes: geological activity deep within the earth; plant, animal, and microbial populations and their interactions in the oceans; coastal erosion; ocean circulation; ocean pollution; and global climate change.

The WHOI fleet includes three large research vessels (R/V *Atlantis*, R/V *Knorr*, and R/V *Oceanus*), coastal craft, remote and autonomous vehicles, and the deep-diving human-occupied submersible *Alvin*. The WHOI annual operating budget of more than \$120 million is supported by grants from federal agencies, including the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration, and by private contributions and endowment income.