The North Atlantic Ocean's Role In Abrupt Climate Change

A Scientific Strategy

Developed by the

Ocean and Climate Change Institute

Woods Hole Oceanographic Institution

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 *within a decade*.

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 (the Ocean Conveyor) can also shift rapidly and change the distribution patterns of heat and rainfall on Earth.

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 system.

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 potentially disruptive shifts 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 impact.

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.

...will some regions turn abruptly colder?

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 (see biographies on pages 18–20). The Ocean Forum Scholars included: **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.

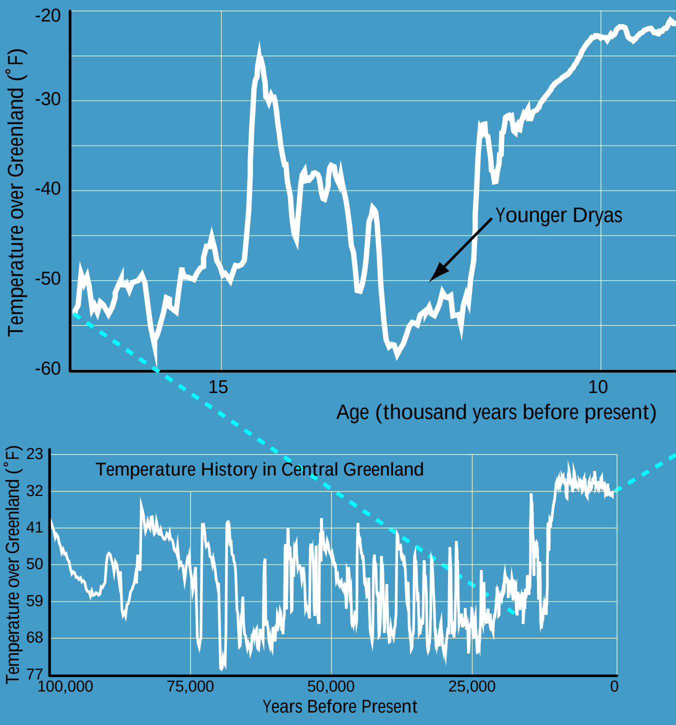
The Forum scientists summarized their work, including:

1) evidence and theories for abrupt climate change (pages 4–5),
2) an assessment of the role of the oceans, particularly the North Atlantic, in climate change (pages 6–7),
3) evidence for recent, dramatic oceanographic changes in the North Atlantic (pages 8–9), and
4) Strategic locations for promising research (pages 10–11).

Given this evidence, the Forum scientists recommended:

5) overall strategies to accelerate advances in abrupt climate change research (page 12), and
6) specific initiatives WHOI can launch to contribute most forcefully to this overall effort (page 13).

Earth history is filled with abrupt climate changes

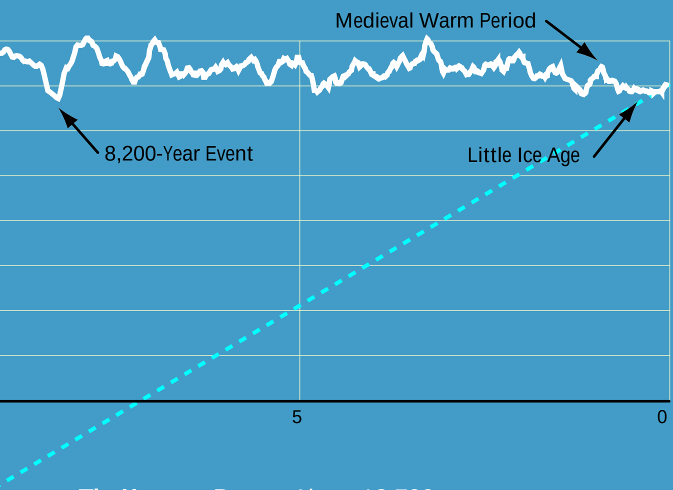


Ice cores extracted from the two-mile-thick Greenland ice sheet preserve records of ancient air temperatures. The records show several times when climate shifted in time spans as short as a decade.

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 finished analyzing cores drilled through the two-mile-thick ice sheet atop Greenland. The ice contained a climate record ranging back about 110,000 years. A graph of past air temperatures over Greenland (above) shows average temperatures repeatedly swinging up and down by 10° to 20° F—in time spans as short as a decade. Additional evidence has reinforced these conclusions:

- Abrupt climate shifts have affected widespread regions, causing large-scale cooling, warming, and drought.[1]
- Earth's climate system has sensitive thresholds. Crossing a threshold can trigger further and faster climate changes.[1]



• **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 700 years ago. Between 1300 and 1850, severe winters had profound agricultural, economic, and political impacts in Europe.

R. B. Alley, from *The Two-Mile Time Machine*, 2000

- The relative stability of Earth's climate since the last ice age ended is no guarantee of continuing stability.[2]
- Greenhouse warming and other anthropogenic changes may be destabilizing factors that increase the likelihood of rapid climate change.[3]
- 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.[4,5]
- 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.[6,7]

The oceans—an under-explored key to our climate

Jayne Doucette, WHOI Graphic Services

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.

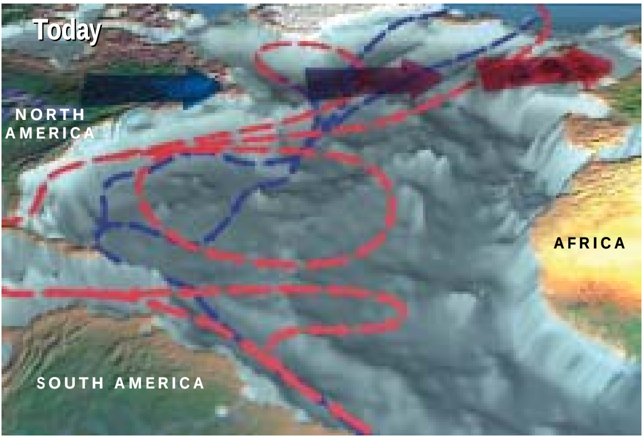
Ocean & atmosphere: partners in creating our climate

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. Scienteists do not fully understand how climate changes in the tropical Pacific and Atlantic Oceans are linked to changes in the North Atlantic and Arctic Oceans. But the Atlantic clearly amplifies and extends climate changes, with significant impacts in Europe and the US East Coast.

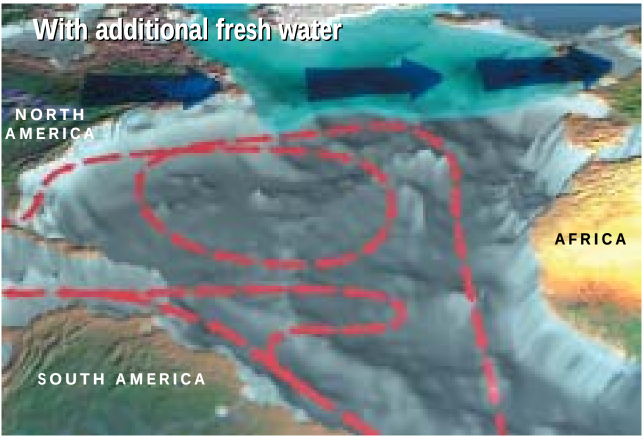
The North Atlantic is a linchpin of our climate system

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.[8]

- 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 show that greenhouse warming can cause a Conveyor slowdown.
- A Conveyor slowdown would rapidly cool the North Atlantic region, while the earth as a whole continues to warm.



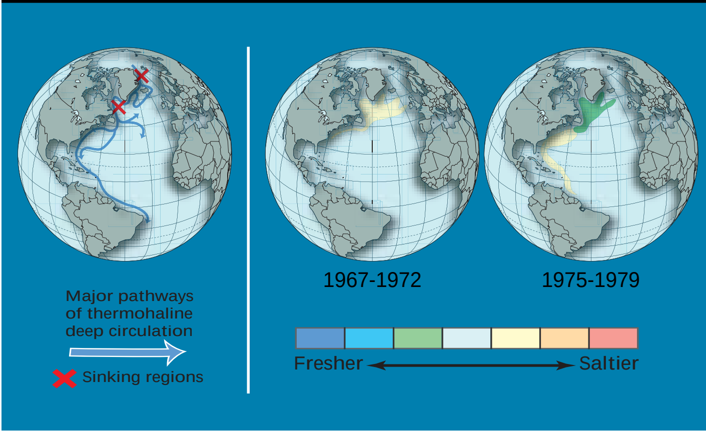
The Ocean Conveyor is driven by the sinking of cold, salty, and therefore denser, waters in the North Atlantic Ocean (blue lines). This draws warm, salty surface waters northward (red lines). The ocean gives up heat to the atmosphere above the North Atlantic Ocean, and prevailing winds (large arrows)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



Jack Cook, WHOI Graphic Services

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)

The North Atlantic is becoming fresher...

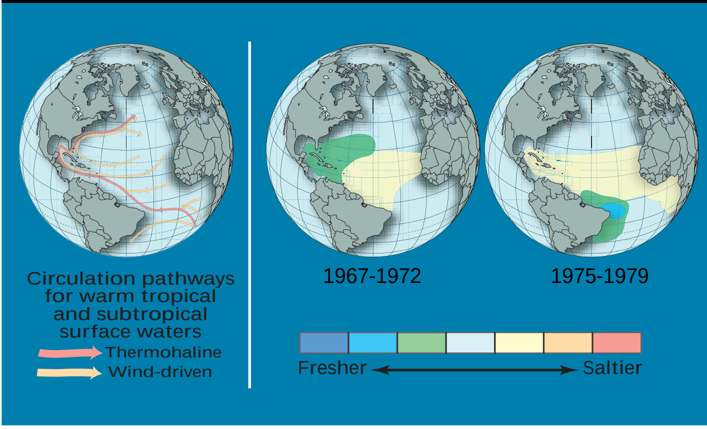


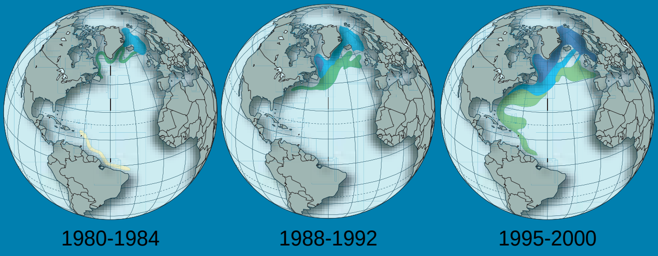
Global warming can alter Earth's water cycle

Since ocean salinity changes affect the density of surface waters, they can also affect ocean circulation and climate. Ocean salinity, in turn, is affected by the exchange of fresh water between the oceans and atmosphere. About 86% of evaporation on Earth occurs above the oceans and about 78% of precipitation falls onto the ocean surface. Changes in this essential water cycle affect ocean salinity. They also influence where and when droughts, floods, and storms occur on Earth.

A warmer Earth in the future could significantly alter the global water cycle, causing tremendous, long-term consequences for society. A warmer atmosphere causes more evaporation from the oceans and allows the atmosphere to transport and hold more water vapor—which is also a potent greenhouse gas that could exacerbate global warming. Ocean salinity changes that affect the water cycle, ocean circulation, and climate have been inadequately monitored, but new instruments, such as salinity drifters, now exist to take these critical measurements.

...while the tropical Atlantic is becoming saltier





New data, reported in the journal *Nature* in 2002, show that deep waters are becoming less salty in the North Atlantic, 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 south.

Data from Ruth Curry, WHOI

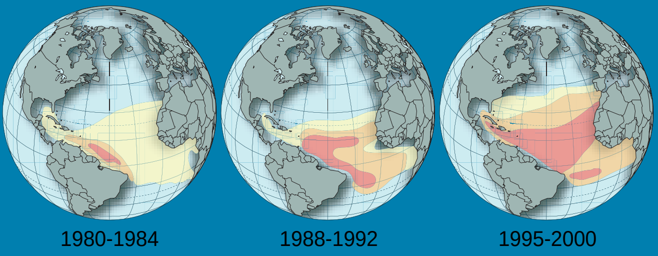
Large changes are occurring in the Atlantic

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.[9]
- Simultaneously, the tropical Atlantic has become saltier.[10]

These changes signal fundamental, large-scale, shifts in the ocean's circulation and the planet's water cycle, which we don't fully understand. 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.[11]



A new report (in press in 2003) 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.

Graphics by Ruth Curry and Jack Cook, WHOI

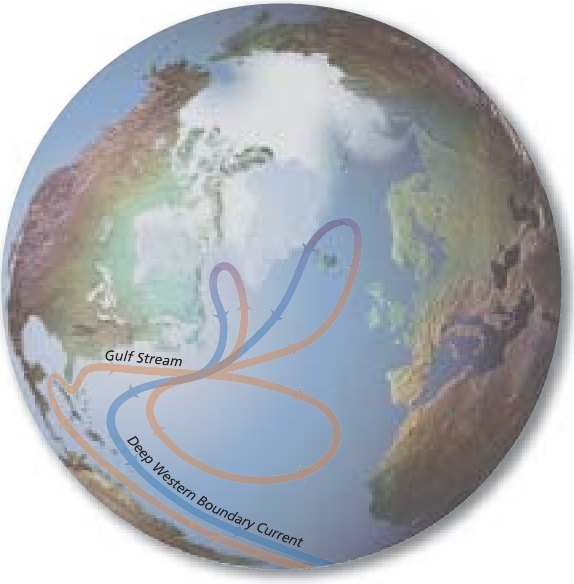
The North Atlantic heating and cooling system

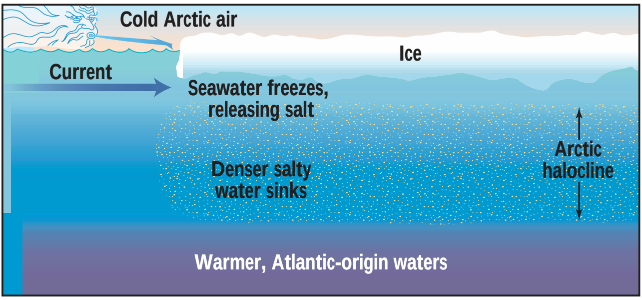
The opaque barrier of the oceans and its great breadth conceal a critical planetary "plumbing system" that circulates and ventilates heat around the globe. Within this system, certain locales and conduits are strategic—because changes in them can precipitate further and farther changes in ocean circulation and climate.

Gulf Stream and 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 North American continent, 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 Gulf Stream transport of heat and salt affect the sinking of North Atlantic waters and cause climate changes?
2) How are North Atlantic oceanic changes transmitted from polar regions to the tropics via the Deep Western Boundary Current.
3) How do changing 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?





Jack Cook, WHOI Graphic Services

The Arctic Ocean

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

Pacific waters enter through the Bering Sea gateway. Above the wide continental shelves in the western Arctic Ocean, cold Arctic air freezes seawater into sea ice. The process leaves behind heavier, saltier waters that sink and move laterally across the entire Arctic Basin. These waters form a thin layer of cold, salty 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.

The warmer, deeper waters originate from the Gulf Stream, and they 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.

Of critical concern are the oceanic mixing processes that create, maintain, and threaten the Arctic halocline and the sinking of cold, salty waters in the North Atlantic.

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—including a fresher North Atlantic and a saltier tropical Atlantic—indicate that major ocean and climate changes, perhaps induced by global warming, are already occurring.

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 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 data for climate forecasting.

The Recommendations

Scientists in the Ocean Forum on Abrupt Climate Change identified two research priorities: 1) the causes of past abrupt climate change, and 2) the potential for future rapid disruptions in ocean circulation and climate. Their recommendations include:

- 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 Ocean and its 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; 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 links between Pacific and Atlantic Ocean and climate changes; 2) to the tropical Atlantic, to explore the interactions between northern and tropical Atlantic ocean and climate processes; 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 in length. 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. A proposal is pending at the National Science Foundation for 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 circulation and dynamics and their impact on climate.

Abrupt Climate Change Forum Nov. 11-12,2002

Tom Kleindinst

Ocean Forum scientists gathered with Woods Hole Oceanographic Institution scientists in Woods Hole, MA, on Nov. 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 an investigator on several OCCI research awards; 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.

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