Remote Sensing and Other Space-Based Applications for Monitoring and Understanding Abrupt Climate Change

M. Rymasheuskaya [a], M. Szabova [b], S.-Y. Tan [c]

[a] Polotsk State University, Blokhin str. 29, 211440 Novopolotsk, Belarus - maryna_456@yahoo.com
[b] Dept. of Geography, University of Victoria, 3800 Finnerty Road, V8P 5C2 Victoria, BC, Canada - martina@szabova.sk
[c] Dept. of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, United Kingdom - syt23@cam.ac.uk

Abstract – Climate has undergone both gradual and rapid changes, occurring in the timeframe of decades to millennia. Paleoclimatic research has made links between past abrupt climate change (ACC) events and major changes in North Atlantic thermohaline circulation. Since this ocean circulation system plays a key role in driving climate, remote sensing and space-based applications for studying ACC events in the North Atlantic region is the focus of this study. This paper describes the nature of ACC events, reviews the applications of Earth observation technology for monitoring and modeling ACC, and provides recommendations for an integrated system for monitoring ocean circulation parameters.

Keywords: abrupt climate change, remote sensing, thermohaline circulation, North Atlantic region

1. INTRODUCTION

Climate change can occur over longer periods of time, such as centuries and millennia, or rapidly over decades. Monitoring of climatic parameters during past decades has revealed significant changes in climate. For example, sea levels increased by 0.1 to 0.2 m during the 20^{th} century, global average temperature increased between 0.4 and 0.8°C during the last decade, the decadal precipitation increase was observed in the Northern Hemisphere, and salinity anomalies have been detected in the North Atlantic Ocean (IPCC, 2001). Recently, there has been growing concern among scientists with respect to the possible role or influence of human activities in changing the Earth's climate.

This paper presents some of the results from the ECOSPHERE student team project, which investigated space applications for monitoring and modeling climate change in the North Atlantic region (Ecosphere, 2003).

2. THE PHENOMENON OF ABRUPT CLIMATE CHANGE

Abrupt climate change (ACC) describes a transition of the climate system to a new state beyond a stability threshold, which occurs on a short timescale of one to several decades (Alley et al., 2003). Numerous paleoclimatic and archeological findings, such as evidence from ice cores, tree rings and sediment samples, suggest that the Earth's climate has shifted abruptly and dramatically in the past (Broecker, 1987). The possibility exists that such ACC events may also occur in the future. Rapid climatic variations have had significant impacts on entire ecosystems and civilizations, as they tend to be unprepared and often incapable of adapting to such rapid changes (Alley et al., 2003).

The Younger Dryas Event (YDE), commencing 12,800 years ago, was the most dramatic ACC event in recent Earth history. It was a sudden and almost global cooling event, which interrupted the warming of the Earth as it moved out of the last ice age (NAS, 2002). Two significant ACC events occurred during the middle Holocene period, namely 8,200 and 4,000 – 5,000 years ago. The first event was characterized by a large influx of melting water, which decreased temperature in the North Atlantic Ocean by 10°C. The second event that followed involved a climatic shift from wet to dry conditions. This period ultimately ended due to unprecedented global warming (NAS, 2002; Renssen et al., 2001). During the later Holocene period, the "Little Ice Age" occurred around 1,450–1,850 AD and was characterized by the extension of polar ice caps, reduction in summer temperatures, and changes in precipitation and the size of mountain glaciers (Tkachuck, 1983).

3. ABRUPT CLIMATE CHANGE MECHANISMS

There are many factors that could behave as triggers, potentially inducing ACC events. Processes that cause ACC have been identified as occurring in three fundamental modes (NAS, 2002): (i) rapidly varying external parameters or forcings that initiate ACC processes, (ii) regime transitions occurring slowly and inducing the crossing of a threshold and transition into a second equilibrium, and (iii) changes to the system occurring spontaneously.

Human beings also have an ability to influence their environment. For example, anthropogenic factors could potentially trigger an ACC event. Increased CO_2 levels in the atmosphere could be induced by increased concentrations of atmospheric greenhouse gases, as well as land-use changes due to urbanization, forestry and agricultural practices.

The Earth's climate can be broken down into five natural or global systems: (i) the atmosphere, (ii) the cryosphere, (iii) the hydrosphere, (iv) the biosphere and (v) the lithosphere. These regimes interact simultaneously to form the complex climate system, which can be influenced by external factors, such as natural and anthropogenic forcings (IPCC, 2001).

Oceans are considered to be an important component of the global climate system. They serve as a thermal reservoir and play a pivotal role in the global distribution of heat and water. Three main processes drive ocean circulation: (i) tidal forces, (ii) wind stress, and (iii) density differences. The density of seawater is controlled by its temperature and salinity. Circulation is ultimately driven by density differences, hence the term *thermohaline circulation*. Links have been made between past ACC events and the major reorganization of the thermohaline circulation system or ocean conveyor belt. The North Atlantic region plays a crucial role in driving the global ocean circulation system and is considered to be one of the key regions that could trigger an ACC event.

4. UNDERSTANDING, MODELING AND MONITORING ABRUPT CLIMATE CHANGE

4.1 Studying and modeling ACC

Most organizations involved in studying climate change focus on observations and recommendations useful for long-term actions. New research programs should be initiated to improve the understanding of those aspects of the climate system that are thought to have participated in past abrupt changes and are likely to trigger such changes in the future.

Due to the complexity of the processes involved in climate, numerical models are the primary tools for testing the hypotheses about ACC. Current climate models range in complexity but the majority of them are complex, comprehensive, coupled models of the ocean and atmosphere. However, model complexity and reliability are often compromised by: (i) integration times, limited resolution and insufficient computing power, (ii) little understanding of several small-scale processes in the oceans and atmosphere, and (iii) the lack of paleoclimatic data for model validation.

4.2 Scientific uncertainties and requirements for modeling ACC

Climate models are being continuously improved. However, there remain many uncertainties in climate science, which result in discrepancies between different climate models. Challenges remain in simulating the effects of anthropogenic influences on the climate system, in understanding air-sea fluxes (including heat and freshwater), in modeling the effects of a changing climate on precipitation and clouds, and in comprehension of deep ocean circulation, among others.

Since the oceans play a crucial role in climate by storing and transferring large amounts of heat, a key to understanding ACC is closely linked to the oceans. From a scientific point of view, and with a focus on the North Atlantic Region, it is important to monitor: (i) the evolution of Arctic and Greenland ice sheet margins to determine whether they influence the area where deep-sea formation occurs, (ii) the trend in ice sheet thickness on the Arctic ice caps and Greenland for the measurement of freshwater balance, (iii) the movement of sea ice (such as icebergs or large shelves) with spatial and temporal continuity over an area of more than 10^5 km^2, and (iv) deep ocean properties, e.g. salinity, including the depths below 2,000 m and the ocean bottom flows for better understanding of the deep-water part of ocean circulation.

Future monitoring systems should also include measurements of the vertical profiles of oxygen and CO_2 content in water, dissolved nutrients, or human induced tracers as they would assist in determining flow paths and identifying possible changes in circulation. Ocean surface temperature and salinity are important for understanding the small-scale processes involved in ocean circulation. While global measurements of sea surface temperature are taken from several remote sensing satellites, ocean circulation science is lacking global surface salinity measurements.

The need for the following ocean-based paleoclimatic scientific goals has been identified, which includes and extends some recommendations from the Committee on Abrupt Climate Change (NAS, 2002): (i) higher spatial and temporal resolution of paleoclimatic data, (ii) substantial and independent duplication of data for validation and reproducibility, (iii) generation of a high resolution-, North Atlantic-, marine record comparable with the Greenland ice records, and (iv) improved modeling simulations of past warm climates.

4.3 Satellite-based monitoring systems

The development of models for accurate simulation of ACC is highly dependent on the collection of good-quality observational data used both for model initialization and validation.

Data acquired by passive microwave radiometers are used to infer the temperature of the sea surface, to delineate sea ice and to observe pollutants, oil spills and slicks. Proposed future satellite missions also aim at providing global sea surface salinity data.

Most LiDAR (Light Detection and Ranging) applications focus on remote sensing of the atmosphere and Earth surface but several ocean-related parameters allowing the calculation of the mass-balance of ice sheets can also be measured.

Radar altimetry data assist both in deriving dynamic sea surface topography, including large-scale ocean currents and eddies (to within a few centimeters accuracy), and in inferring sea surface wind speeds and significant wave heights.

Gravity sensors improve the physical model of the Earth used for ocean current modeling, ice sheet thickness analysis and geodynamic studies.

Synthetic Aperture Radar (SAR) is used to detect the snow and ice properties, ice melting and ice type. Interferometric SAR data provide information about the flow and movements of sea ice. Wind speed is deducted from the ocean surface by measuring wave patterns.

Microwave scatterometers measure the two-dimensional velocity vectors of near-surface sea winds.

4.4 In-situ monitoring systems

Robotic aircraft, balloons carrying radiosonde instruments and weather-rocket buoy systems are typical devices used for atmospheric observations. They measure temperature, humidity, pressure, wind speed and direction in the upper atmosphere to provide complimentary information and verification of satellite data.

Argo is a worldwide system of autonomous diving robots that measure temperature and salinity between the sea surface and 2 km of sea depth. At the surface, a connection is made to the Argos satellite network (Service Argos, 2005) and the diving robot transmits its position and samples of the vertical sea profile.

Sediment samples drilled from the sea floor can reveal information about the past state of the ocean. Specially equipped drilling boats or underwater robots may assist in drilling the sea floor.

5. RECOMMENDATIONS

The purpose of this study was to develop a framework to better understand the ACC phenomenon in the North Atlantic region through the application of space technologies. Although the previous sections have highlighted the scientific uncertainties that exist in studying ACC phenomena, this section describes the components of an integrated system for data collection using satellite and in-situ technologies, designed for monitoring ocean circulation parameters. The objective of the described technological systems architecture was to contribute towards the knowledge of mechanisms that could drive a future ACC event.

The recommendations for a technological systems architecture for studying ACC parameters were focused on three major challenges, namely: (i) quantifying the freshwater flux into the ocean from sea ice and ice sheets, (ii) better understanding of deep ocean circulation dynamics, and (iii) improving the coverage and quality of ocean sediment paleoclimatic data. The resulting recommendations for accomplishing these goals involved an integrated system of deep-sea probes, deep-sea coring, and spaceborne remote sensing of ice and sea surface parameters (Ecosphere, 2003).

The main system elements of the proposed program are illustrated in Fig. 1 and described in the following subsections.

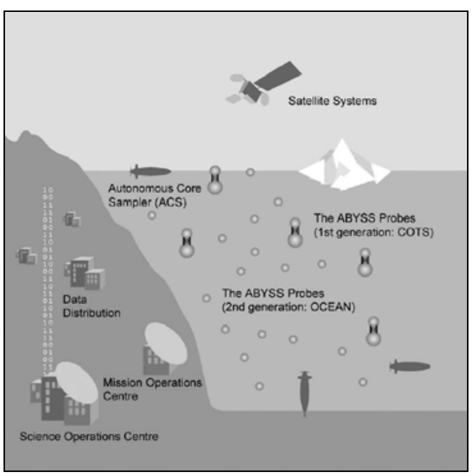

Figure 1. An overview of proposed technologies for an integrated system for monitoring ACC parameters (Ecosphere, 2003).

5.1 Autonomous Core Sampler

The first technological subsystem was comprised of the Autonomous Core Sampler (ACS), which was designed for deep-sea sediment core sample collection at pre-programmed sites. As shown in Fig. 2, the system was designed as a cigar-shaped vehicle, driven by an electric motor, and powered by a fuel cell. The samplers rely on a satellite link for system health checks, collection of sensor data, mission logs, and programming of missions or sample locations. Operating down to a depth of 5,000 m at pre-programmed locations, the samplers depend on a fuel cell power source for long mission durations. Autonomous navigation is achieved by using GPS or GALILEO systems with inertial measurement units (Ecosphere, 2003).

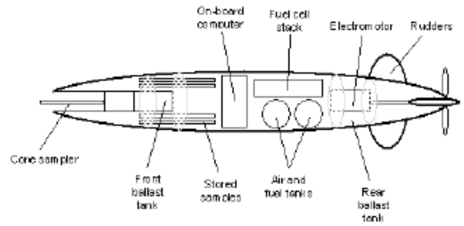

Figure 2. The proposed ocean core sampler (Ecosphere, 2003).

5.2 THE ABYSS System

In order to attain salinity measurements over oceanic depths of 0 to 5,000 m, deep-sea robotic divers or the Thermo Haline Explorer Autonomous BuoY Sea Submersible (THE ABYSS) was designed. Measurements are obtained by deploying deep-sea MEMS probes (micro electromechanical system), which have a 10-day dive-drift-ascent cycle, as illustrated in Fig. 3.

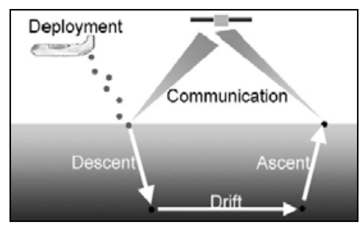

Figure 3. Deployment and mission design of THE ABYSS probes system (Ecosphere, 2003).

The proposed system consists of probes being deployed in large numbers in regions of the ocean that constitute the North Atlantic Ocean Conveyor Belt. Each probe will measure salinity to a preset depth and float along the ocean current. Every ten days, the probes are scheduled to ascend to the ocean surface and relay their stored measurement data via a satellite to a ground station. This cycle repeats itself throughout the probe's five-year mission lifetime.

5.3 Remote Sensing Program

A key subsystem of the proposed framework is a remote sensing program that is designed to monitor ice sheet thickness, ice sheet evolution, sea ice monitoring, and sea surface salinity monitoring. Monitoring such parameters is necessary for the quantitative analysis of freshwater flux into the oceans and to better model deep ocean circulation.

The design concept of this study involves continuous, space-based, ice and salinity monitoring capability by three proposed remote sensing payloads on a near polar inclination platform: (i) L-band radiometer for measuring sea surface salinity, (ii)

LiDAR for high resolution ice topography, and (iii) Advanced Synthetic Aperture Radar for all-weather monitoring of ice topography. Launch of such payloads would ensure continuous monitoring designed to follow currently operating ICESat and planned CryoSat missions (ice monitoring), and planned Aquarius and SMOS missions (sea surface salinity monitoring). Launch of potential long-term ice and salinity monitoring missions in the future could also improve the accuracy and resolution of current remote sensing measurements and sustain the ACC monitoring program. Several design concepts have been reviewed for achieving this goal. For example, LiDAR high-resolution capabilities could be combined with SAR all-weather capability on a single satellite platform, although this would result in a relatively large and heavy platform. However, possible use of new technologies, such as formations of small satellites with single payloads for combining the data from LiDAR and SAR instruments could be another alternative.

In order to develop an integrated system for monitoring ocean circulation parameters, the incorporation of communication payloads for supporting the aforementioned ocean-based systems would be necessary. For example, the deep-sea probe system would demand S-band communication packages for effective data transfer. However, future designs of second-generation deep-sea probes may result in data transfer that could require a Ka-band transponder with a non-tracking antenna instead (Ecosphere, 2003). Nevertheless, it is important to recognize that incorporating remote sensing and communication capabilities are essential to support ongoing ice and global salinity measurements.

5.4 Outreach Plan

A public outreach plan was designed to raise awareness about the potential effects of an ACC event and to provide a facility for education about its possible anthropogenic causes. Two main categories of target groups were identified: (i) government agencies, academia, industry representatives, and policy-makers, and (ii) the general public. The proposed approach involved three phases of implementation including: (i) development of political and scientific infrastructure dedicated to ACC with links to the public education system, (ii) deployment of a media-based training approach to schools and post-secondary education institutions, and (iii) expansion to television and interactive business software distribution. Conferences dedicated to ACC studies and adaptation policy are also proposed, as part of a comprehensive outreach plan to educate the public about potential impacts of ACC and to encourage funding of ACC-related research.

The key components of the proposed public outreach program are illustrated in Fig. 4, where five groups are targeted with the aim of raising public awareness about potential impacts of ACC events.

6. CONCLUSION

The paper discussed the present state of abrupt climate change science and proposed a technological program for the enhancement of that scientific knowledge. To improve the ACC simulation by numerical climate models, the ECOSPHERE project has identified three major areas of scientific uncertainty in the study of ACC and has made recommendations for technology-based solutions to address the areas of: (i) the effect of ice on freshwater flux into the ocean, (ii) deep ocean circulation studies, and (iii) enhanced paleoclimatic data collection.

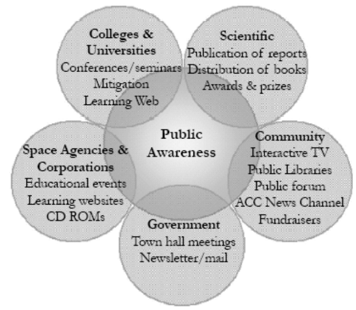

Figure 4. Target groups of a public outreach plan for raising awareness about the potential effects of ACC (Ecosphere, 2003).

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