# THE THERMOHALINE CIRCULATION AND TROPICAL CYCLONES IN PAST, PRESENT, AND FUTURE CLIMATES

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Understanding the interactions between tropical cyclones and the thermohaline circulation (THC) and their contributions to climate and climate change is an intriguing, challenging, and important area of research. The oceanic overturning circulation is a slow process whereas tropical cyclones are a fast process, and both may be subject to abrupt or long-term changes. The Early Career Scientist Association's Junior Faculty Forum explored ways to incorporate modeling, observations, and geologic reconstructions into understanding these interacting components of the climate system in past, present, and future climates. Following an extensive review of the current level of knowledge, including plenary talks by invited speakers, the bulk of the meeting was dedicated to two parallel discussion sessions focusing on the oceanic overturning circulation and tropical cyclones.

### THE EARLY CAREER SCIENTIST ASSOCIATION'S JUNIOR FACULTY FORUM ON FUTURE SCIENTIFIC DIRECTIONS

WHAT: About 40 junior faculty discussed interactions between fast (tropical cyclones) and slow (oceanic overturning circulation) extreme events in the climate system and methods using both paleoclimate proxies and models that could improve our understanding of such events.
WHEN: 8–10 July 2008
WHERE: Boulder, Colorado

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Topic I of the forum focused on the observational needs as well as the modeling and decadal prediction of the THC [or meridional overturning circulation (MOC)]. The terminology used to describe THC has been much discussed and debated. The exact definition and proper use of the terms "THC" and "MOC" have been clarified because of the confusion in the recent literature (e.g., Wunsch 2002), and no ubiquitous metric exists to quantify either. Often, the general term MOC is used to refer specifically to the Atlantic MOC (AMOC), when in reality each ocean basin contains meridional overturning cells that are interconnected through the global circulation. It is agreed in Annex

I of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4; Solomon et al. 2007) is a good reference for the definitions and accurate use of the terms. Furthermore, metrics used to quantify AMOC/MOC variability vary among studies, indicating that a common index, which can be easily measured by observation and computed in models, might be needed. However, some attendees questioned whether a viable index could be devised, partly because common indices for MOC variability in models cannot be reproduced from currently available observations. We concluded that individual studies need to explicitly define the MOC metric being used and to clearly delineate why that metric is chosen.

Recent observations indicate that the MOC exhibits large seasonal variations, making the detection of its long-term trends very difficult. Additionally, the deep ocean may also need to be sampled periodically in order to examine the variation of the deep overturning; extending some of the Argo floats to a depth below 2000 m has been suggested. Thus far, no direct observations show evidence of a trend in the MOC, except for reports on changes in the subpolar North Atlantic, such as the deformation of the subpolar gyre and the changes in salinity and sea ice. The linkage of these changes to MOC is not very clear and requires further studies. Indirectly, the ocean synthesis effort could not produce consistent MOC changes for the last 50 yr because of the lack of enough ocean observations to constrain model simulations. Modeling studies show that abrupt changes of the MOC without external forcing, such as the sudden release of freshwater from ice sheets, are rare events. As concluded in IPCC AR4, the MOC is very likely to slow down in the twenty-first century, and its abrupt collapse is very unlikely; the effect of potential Greenland ice sheet melting on the MOC, however, is uncertain, as is its contribution to sea level rise. Because many coupled models show obvious decadal time-scale MOC variations, questions are raised as to whether the MOC variations can be predicted on decadal time scales. Experiments from two modeling groups suggest that it might be possible to predict the MOC variations outward 10–20 yr, although this MOC predictability may at least partially depend on the initial state of the MOC. In addition, if the MOC can be predicted, it is still uncertain how to link the MOC changes to changes in the regional to global climate.

Topic 2 of the forum focused on how best to advance our understanding of tropical cyclone behavior through the integration of modeling experiments and reconstructions from the geological record. Noticeable trends are beginning to emerge from tropical cyclone proxy records, yet participants recognized that these records are still limited in number and predominantly focus on the western North Atlantic. There was general consensus that greater spatial coverage of data points is required to better assess how past tropical cyclone activity has varied globally. In addition, the development of high-resolution reconstructions of potential forcing factors of tropical cyclone variability are also necessary for assessing both the driving mechanisms and potential feedbacks between past tropical cyclone variability and other climate phenomena (e.g., El Niño, the Atlantic Multidecadal Oscillation, the North Atlantic Oscillation, MOC, and sea surface temperature variability). Finally, it was pointed out that paleorecords for tropical cyclone activity are still primarily based on hurricane-induced overwash deposits preserved within back-barrier environments. Contributors pointed toward many new emerging proxies for tropical cyclone activity, which include, but are not limited to, negative oxygen isotope ($\delta^{18}O$) anomalies in stalagmites, tree rings, corals, and ostracods; event layers deposited within inland lakes; storm-induced beach ridges; and preserved offshore beds and bedforms (as discussed in Frappier et al. 2007). Many of the processes involved in producing these geologic markers are still poorly understood and require study at a basic mechanistic level. It was agreed that this process-level approach promotes the development of new methods for extracting additional information from these valuable natural archives (e.g., potential proxies for storm intensity and ecological/morphological impacts), as well as encouraging high-quality contributions to the growing global database of tropical cyclone reconstructions.

Although the time and spatial scales are quite different between the MOC and tropical cyclones, earlier studies suggest that tropical cyclone variability might be fundamentally linked to the strength of the MOC. Thus, changes in the large-scale climate patterns such as surface temperature appear to impact trends in tropical cyclone variability. On the other hand, it has been hypothesized that tropical cyclones could play an active role in the climate system by contributing to mixing in the upper tropical oceans. An example of the impact of a tropical cyclone on the upper ocean is shown in Fig. 1 for Hurricane Gert. Such mixing may be important for sustaining the MOC, yet mixing sources are missing from our current conceptual and numerical models of the climate system. Therefore, tropical cyclone variability associated with changing surface temperature patterns (related to the strength of the MOC) may provide a positive climate feedback mechanism through changes in oceanic vertical mixing. This potential feedback may be important for understanding

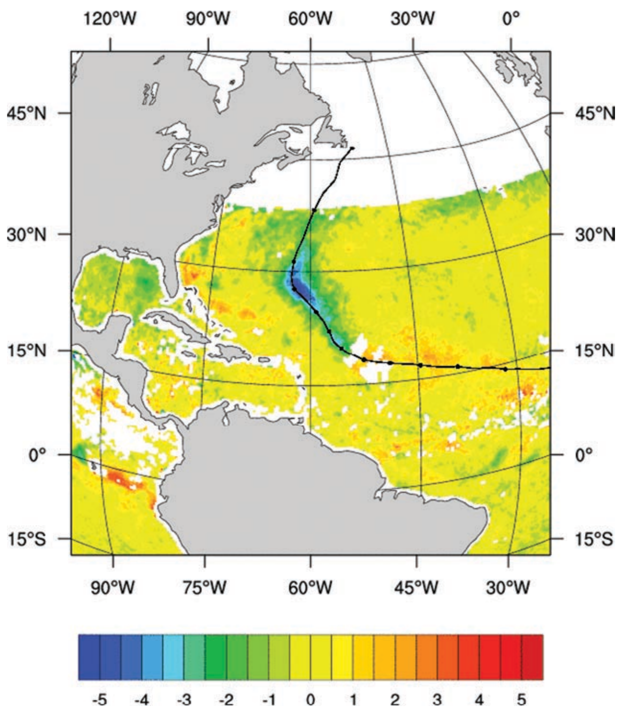


**Fig. 1. Change in sea surface temperature (°C) between 17 and 23 Sep 1999 using data from the Tropical Rainfall Measuring Mission Microwave Imager. Black line indicates the track of Hurricane Gert.**

climate variability, in that increased tropical cyclone activity associated with rising tropical temperatures could increase the strength of the MOC and positively influence the poleward transport of heat by the oceans. This scenario is indicative of some past warm climate periods with weak equator-to-pole temperature gradients, such as the Eocene, where polar regions were typically above freezing and tropical temperatures were consistent with present-day values. However, other results suggest that vertical mixing is not the only contributing factor. Freshwater ocean fluxes, attributable to the torrential precipitation within these events, appear to provide a compensating contribution. These fluxes tend to increase the stratification of the upper ocean by decreasing the density of the surface waters, inhibiting mixing, and limiting the positive effect of cyclones on MOC strength and ocean heat transport. The differing viewpoints and interpretations indicate that further research is needed to better understand the relationship between tropical cyclones and the MOC, and to expose any potential climate impacts. Several areas highlighted as active lines of ongoing research include the use of statistical models, high-resolution atmospheric modeling, and fully coupled modeling frameworks of varying complexity.

During the last day of the forum, several discussion sessions allowed the participants to interact and promote future collaboration. The forum enabled some particularly fruitful discussions of ways to disseminate research results relevant to the broader public living in areas that may be affected by future hurricane activity, and to involve more people in efforts to broaden spatial coverage of studies of coastal overwash deposits. Participants brainstormed ways that exploratory sampling could be done by school groups in coastal locations to collect preliminary data to begin to identify promising sites for new paleotempestological record reconstructions.

Ideas generated included setting up a pilot project to run workshops on how coastal overwash deposits are cored and analyzed to identify past hurricane activity. Such workshops could promote collaboration between professors at primarily undergraduate institutions, scientists from the paleotempestology community, and Earth science teachers from local high schools. Participants were especially interested in trying to put together "coring kits" that could be distributed to schools near likely coastal coring locations. These groups could be trained to collect shallow cores with the goal of finding sites that might help to calibrate the historical record and that could potentially be cored at a later time to yield longer proxy records. Other outreach ideas raised by participants included ways that scientists could assist emergency planners, such as providing enhanced technology for citizens in and around evacuation zones to use to determine whether they live in a flood zone. Many new partnerships between participants are expected to result in future collaborative research plans and scientific publications.

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