Effect of the Atlantic hurricanes on the oceanic meridional overturning circulation and heat transport

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[1] Hurricanes have traditionally been perceived as intense but relatively small scale phenomena, with little effect on the large scale climate system. However, recent evidence has suggested that hurricanes could play a much more significant role in global climate. Here we prescribe Atlantic hurricanes in a global coupled climate model to show that, climatically, the strong hurricane winds can strengthen the Atlantic meridional overturning circulation (MOC) that is responsible for an increased northward meridional heat transport (MHT), and the hurricane rainfall tends to weaken the MOC and to reduce the MHT. The net effect of the hurricanes on the MOC and MHT depends on the outcome of these two competing processes. This result implies that hurricanes may indeed play an important role in the coupled climate system and need to be studied further in high resolution global coupled models. Citation: Hu, A., and G. A. Meehl (2009), Effect of the Atlantic hurricanes on the oceanic meridional overturning circulation and heat transport, Geophys. Res. Lett., 36, L03702, doi:10.1029/2008GL036680.

1. Introduction

[2] Recent observed evidence has suggested that hurricanes could be connected to climate change [Emanuel, 2001, 2005; Webster et al., 2005; Kossin et al., 2007; Landsea, 2005; Knutson et al., 2007]. Estimates based on observations show that hurricanes can transfer a significant amount of momentum into the ocean [Li et al., 2008], and they can also cause the downward pumping of huge amounts of heat into the subsurface ocean along their paths [Emanuel, 2001; Sriver and Huber, 2007; Pásquero and Emanuel, 2008]. These papers also raised the more fundamental issue of what role hurricanes actually play in the global climate system and how hurricanes could affect the long-term oceanic meridional overturning circulation (MOC) and the meridional heat transport (MHT) in the Atlantic.

[3] There are some indications that hurricanes could be contributing to global climate through connections to large-scale fluctuations of sea surface temperatures (SSTs) as well as in possible influences on northward heat transport and the ocean conveyor belt circulation in the Atlantic. For example there is a linkage between hurricane counts and low-frequency variations of tropical SSTs [Emanuel, 2007; Mann and Emanuel, 2006; Holland and Webster, 2007]. These SSTs could be connected to the MOC which is a global scale oceanic circulation that plays a very important role in the redistribution of heat and freshwater globally on decadal, centennial, and millennium timescales [Broecker, 1998]. The collapse and re-establishment of this circulation is thought to be the major cause of past abrupt climate changes, such as Heinrich events [Heinrich, 1988; Timmermann et al., 2005]. Many studies also show that the changes of this circulation may be important for future climate change [Manabe and Stouffer, 1988; Hu et al., 2004; Gregory et al., 2005; Broccoli et al., 2006; Stouffer et al., 2006; Meehl et al., 2007]. If hurricanes affect MHT or MOC, this could be a significant contribution to large scale fluctuations of climate. Without the associated precipitation effect, a coarse resolution ocean general circulation model coupled to a zonal mean atmospheric model that included a parameterized hurricane ocean mixing effect did show increases in both northward heat transport and meridional overturning due to hurricanes under extremely high CO2 conditions [Korty et al., 2008].

[4] Here, we focus on the potential climatic role of the Atlantic hurricane-induced wind, as well as precipitation, on the Atlantic MOC and MHT by comparing global coupled climate model simulations with prescribed hurricanes in the Atlantic to a control simulation that does not resolve hurricanes. The state-of-art global coupled climate model used here is the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) [Collins et al., 2006] that has been used for simulations of 20th and 21st century climate and paleoclimate assessed by the IPCC AR4. As a first attempt to tackle this problem using a fully coupled model, many simplifications are applied in our experiments. However the overall good agreement of the hurricane effect on the Atlantic tropical-subtropical oceanic stratification in the model compared to observations does suggest that our simulations may have captured the major effects of hurricanes on the Atlantic MOC and MHT.

2. Model and Experiments

[5] CCSM3 includes the Community Atmospheric Model (CAM3) at T42 resolution (roughly 2.8°) and 26 hybrid levels in the vertical, a version of the Parallel Ocean Program (POP) with 1° horizontal resolution and enhanced meridional resolution (1/2°) in the equatorial tropics, and with 40 vertical levels, the Community Sea Ice Model (CSIM5) with Elastic-viscous-plastic dynamics, a subgrid-scale thickness distribution, and energy conserving thermodynamics, and the Community Land Model (CLM3). The mean Atlantic MOC defined as the maximum value of the Atlantic meridional streamfunction below 500 meter depth is 19.5 Sv (Sv = 106 m2s−1) in CCSM3 for the 240-year period of the control simulation analyzed here, agreeing...
well with recent observations [Ganachaud and Wunsch, 2000]. The mean MHT in the model at 24°N is 1.02 PW (PW = 10^{15} W), a bit lower than the observational values of 1.2 PW [Ganachaud and Wunsch, 2000; Talley et al., 2003].

[6] Here we prescribe hurricanes in the tropical Atlantic in the model (Figure 1a) and make comparisons with the control simulation without prescribed hurricanes. First, only hurricane induced wind forcing is considered through modifying the model produced wind field. Historically over the last 100 years, on average there are 10 hurricanes each year in the Atlantic [Landsea, 2007]. We use this mean number of hurricanes as our base case where we only prescribe winds from each of the climatological hurricanes (termed “hurricane wind”, HW). The size of the hurricanes varies from a radius of 200 km at the time of formation to a radius of 500 km at the end of the track which is the typical size of tropical cyclones [Liu and Chan, 1999]. The maximum wind speed is 18 m/s initially and increases up to about 53 m/s, equivalent to a category 3 hurricane. In June, July and October, the maximum strength of the hurricanes is category 2 with a maximum wind speed of 43 m/s. The lifetime of the hurricanes varies from 7 to 8 days in June, July, and October to a maximum of 11 days in August and September. In the second experiment, in addi-
tion to the same hurricane wind forcing, the torrential precipitation associated with hurricanes (termed “hurricane winds and rainfall”), HWR is also added. Precipitation rates are derived from TRMM 3B42 3 hourly data [Huffman et al., 2001] and this additional freshwater flux is compensated by a uniformly increased evaporation of an equivalent amount in the domain of the trade winds in the Atlantic between 20°S and 35°N. These additional fluxes are added to the ocean model by modifying the same fluxes produced by the model. The exact water source for season-averaged hurricane rainfall is still an open question from the observations, though there are some indications that individual hurricanes can draw moisture from a radius as large as 1600 km [e.g., Trenberth and Fasullo, 2007]. From a general circulation perspective, the largescale tropical Atlantic moisture convergence must be balanced partly by precipitation, thus supporting our method of treating the freshwater balance in the system.

[7] These experiments are branched from a millennium control run of the CCSM3 and are run for 100 years each with the same set of hurricanes repeating every year. Unless otherwise explicitly stated, the numbers mentioned below are century or 50-year mean anomalies which are used to assess the climatic effect of hurricanes on the MOC.

3. Results

[8] The effect of high winds associated with the imposed hurricanes is to cool the ocean surface and to warm the subsurface water along the hurricane tracks (Figure 1b, daily averaged vertical temperature changes). This cooling effect is caused by increased evaporation from the strong winds, as well as the strengthened vertical mixing with warmer subsurface water mixed upward and cooler surface water mixed downward, leading to a deepening of the thermocline. For example, in an area east of Florida (the blue hollow circle in Figure 1a), a mature hurricane in our model can cool the surface ocean by more than 2°C on daily average and warm the subsurface water by the same magnitude (Figure 1b), and this surface cooling can be as much as 6°C in some regions in the model. After the passage of the hurricane, the surface water is warmed up by solar heating, and the subsurface water is still warmer than before the passage of the hurricane (Figure 1b), resulting in a net downward heat transport in the upper ocean, agreeing well with observations [e.g., Emanuel, 2001; Sriver and Huber, 2007]. This feature appears in our model simulations in all the regions along the hurricane tracks with somewhat different magnitudes of the surface cooling and the subsurface warming. The qualitative agreement of our model simulations with the observations indicates our experiment setup captures the major effect of hurricane winds on upper ocean stratification.

[9] Climatically, the century mean surface temperature anomaly in experiment HW relative to the control simulation without prescribed hurricanes shows a cooling up to 1°C (Figure 2a). As the strong hurricane winds enhance evaporation in HW, salinity increases by about 0.1 psu (up to 0.5 psu) in most areas of the tropical Atlantic (Figure 2c). In the tropical-subtropical region (Figure 1c, blue lines), the regional averaged century mean surface cooling is about −0.1 to −0.15°C and the subsurface warming peaks around +0.3°C centered at 100 meters depth, qualitatively agreeing with observations [Emanuel, 2001; Sriver and Huber, 2007]. The salinity increases by up to 0.04 psu in the upper 800 m ocean (Figure 1d). As this more salty water is carried northward, the regional mean upper ocean salinity increases by about 0.02 psu in the subpolar North Atlantic (Figures 1f and 2c). It is mainly these increases of salinity that raise the density in the upper ocean in the model in that region (Figure 1g). When the upper ocean density increases, the MOC is intensified by 3% (significant at 99% level, Figure 3a), the northward heat transport increase is 2% at 24°N (significant at 90% level, Figure 3b), and SSTs in the subpolar North Atlantic warm by several tenths of a degree (Figure 2a).

[10] A further breakdown of the contributions from changes of the MOC and the changes of the oceanic stratification in the Atlantic to this MHT increase indicates that it is the strengthening of the MOC that leads to the increased MHT. By comparing the MHT in the HW run and the control run that both are calculated by using the control run’s MOC, the changes of the oceanic stratification induce a slightly reduced northward heat transport in the HW run compared to the control run. This explains why the MOC changes are larger than the MHT changes in the HW run relative to those in the control run. Additional sensitivity experiments show that as the hurricane winds strengthen or the number of the hurricanes increases, the changes shown above are also larger and stronger, implying that after a period of more active hurricane seasons, the MOC would spin up and transport more heat into the subpolar North Atlantic if only the hurricane wind effect is considered.

[11] On the other hand, if the climatic effects of hurricane rainfall are included, the pattern of surface cooling in the tropical-subtropical Atlantic is similar to HW case with slightly larger amplitude (Figure 2b) and tropical Atlantic salinity shows mostly a net increase mainly from the regions of enhanced evaporation in the eastern tropical Atlantic (Figure 2d). However, the freshwater from the hurricane-related precipitation contributes to a larger salinity decrease in the Gulf of Mexico and parts of the eastern tropical Atlantic. This freshwater is advected to the subpolar North Atlantic lowering the upper ocean density there (Figures 1f and 2d). That contributes to a reduction of MOC by 5% and a decrease in MHT of 3% relative to the HW case (both changes are significant at 99% level, Figure 3) which leads to cooler SSTs in the subpolar North Atlantic by up to 0.5°C (Figure 2b). Sensitivity experiments indicate that the net effect of the hurricane winds and rainfall on MOC and MHT depends on the source regions for where the freshwater for rainfall is evaporated. If the water vapor is from a large region relative to the size of the hurricane, the MOC would weaken more relative to the HW case and transport less heat northward (see auxiliary material). Although the implementation of the hurricane rainfall and the source of the precipitable water in our experiments is very simple and idealized, our results do indicate that hurricane winds tend to weaken it, and the net effect of hurricanes on the MOC

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1Auxiliary materials are available in the HTML. doi:10.1029/2008GL036680.
Figure 2. (a) Century mean sea surface temperature anomalies (°C) from the hurricane winds-only experiment (HW) relative to the control run. (b) Same as Figure 2a except for the hurricane winds and precipitation experiment (HWR). (c) Same as Figure 2a except for salinity anomalies (psu). (d) Same as Figure 2b except for salinity anomalies (psu). Stippling indicates the anomalies are significant at greater than the 95% level based on a student t-test.

Figure 3. (a) Time averaged percent changes (over the last 50-years) for the Atlantic MOC from the two model experiments. (b) Same as Figure 3a except for MHT at 24°N. Error bars are plus and minus one standard deviation of the multi-century control run. The MOC and MHT changes in HW relative to control simulation (HW–CON) are 97% and 90% significant, and the changes in HWR relative to HW (HWR–HW) are both significant at 99% level, respectively, according to a student t-test.
and MHT relies on the outcome of these two competing processes.

[12] To put these model sensitivity results into context, we compare the anomalies in the HWR run relative to control run with the observed anomalies between a relative active hurricane year (2005) and a relatively inactive hurricane year (2006). Though this must necessarily not be considered a quantitative comparison, the sign of the changes should be indicative of whether the model is qualitatively capturing the sense of the changes hurricanes could induce in the climate system.

[13] The observations show increased heat mixed into the upper ocean in the tropical-subtropical Atlantic (Figure 1c, black lines) with a relative warming for the active hurricane year compared to the inactive year of nearly 0.1°C around depths of 50 to 100 m, while HWR also warms but with greater amplitude. Meanwhile, observations for the active hurricane year show relative cooling of the subsurface in the subpolar North Atlantic with values of −0.1°C near the surface comparable to the cooling in that region in HWR (Figure 1e). This low amplitude cooling in observations and the model simulation extends through the depth of the upper ocean to below 1000m. For changes of salinity and density in the subpolar North Atlantic (Figures 1f and 1d), the HWR simulation agrees well with observations, such that the ocean column is fresher and less dense, except the upper 100 meters, but the HW simulation (less realistic because rainfall effects are excluded) is opposite to the observations.

[14] Further study indicates that the initial surface salinity changes in HWR also show a salinity increase in this region. When the negative surface salinity anomaly from the subpolar North Atlantic in the second decade, it becomes fresher there. This suggests that the freshwater anomaly associated with more hurricanes in 2005 may not have arrived yet at the subpolar ocean in 2006 with observations. This result may also suggest that, in reality, after a period of active hurricane seasons, the cumulative anomalous freshwater flux due to hurricane rainfall would propagate into the subpolar North Atlantic, and lead to a weakening of the MOC.

[15] After a period of inactive hurricane seasons, the MOC may strengthen due to the lack of a cumulative hurricane rainfall induced negative salinity anomaly. These delayed changes of the MOC could also feed back to hurricane activity by modulating the SSTs in the tropical-subtropical Atlantic region. This effect needs to be studied further.

4. Conclusion and Discussion

[16] Results from our model sensitivity experiments indicate that climatologically, Atlantic hurricane winds mix heat downward into the subsurface ocean and the associated evaporation increases the surface salinity in the tropical-subtropical region. When this salinity anomaly is propagated into the subpolar North Atlantic, it destabilizes the oceanic stratification there and strengthens the MOC which transports more heat northward. On the other hand, the hurricane rainfall freshens the western subtropical Atlantic. When this freshwater anomaly reaches the subpolar North Atlantic, it stabilizes the oceanic stratification there and weakens the MOC, reducing the northward heat transport. The net effect of the hurricane winds and rainfall on the Atlantic MOC and MHT depends on the outcome of these two competing processes. In spite of the limitations of our model, these hurricane effects on the climate system are physically consistent from a process point of view. Although these climatological changes are not large, they do statistically significant at at least 90% level, indicating that hurricanes could be an active agent in the mean climate system.

[17] A caveat that must accompany this study is that atmospheric dynamical effects of hurricanes are not included since the hurricanes are specified only as local surface wind and precipitation changes. The vertical structure of the hurricanes would modulate (interact with) the large scale atmospheric circulation which could add somewhat to the effects we describe here.

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