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# Is the basin-wide warming in the North Atlantic Ocean related to atmospheric carbon dioxide and global warming?

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[1] A basin-wide warming in the North Atlantic Ocean has occurred since the mid-1990s; however, the cause of this basin-wide warming is controversial. Some studies argued that the warming is due to global warming in association with the secular increase of the atmospheric greenhouse gas of carbon dioxide ($CO_2$), while others suggested that it is caused by the Atlantic multidecadal oscillation (AMO) – an oscillatory mode occurring in North Atlantic sea surface temperature. Here we show that both global warming and AMO variability make a contribution to the recent basin-wide warming in the North Atlantic and their relative contribution is approximately equal. It is further shown that after removing a linear trend and the seasonal cycle, atmospheric $CO_2$ measured from 1958–2008 varies approximately with the AMO. On the assumption that a linear trend can be removed from the $CO_2$ time series, then there are suggestive similarities between $CO_2$ and AMO temperature anomalies. That is, atmospheric $CO_2$ increases (decreases) when the AMO is in the warm (cold) phase. This would suggest that the recent basin-wide warming of the North Atlantic might contribute to global ocean warming via its associated increase of atmospheric $CO_2$.
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## 1. Introduction

[2] Sea surface temperature (SST) variability in the North Atlantic is important since it affects Atlantic hurricane activity and climate/weather in its surrounding continents even globally. A basin-wide warming in the North Atlantic has occurred since the mid-1990s. However, the cause of this basin-wide warming is controversial. In particular, the extremely active and destructive hurricane season in 2005 fueled an intense debate on whether or not the recent increase in Atlantic hurricane activity is due to anthropogenic global warming or natural climate variability. Some studies suggested that the increase in Atlantic hurricane activity is linked to the North Atlantic SST which is due to global warming [e.g., *Elsner*, 2006; *Trenberth and Shea*, 2006; *Mann and Emanuel*, 2006]. Others argued that the basin-wide warming in the North Atlantic is caused by the Atlantic multidecadal oscillation (AMO) [e.g., *Enfield et al.*, 2001; *McCabe et al.*, 2004; *Knight et al.*, 2005; *Zhang et al.*, 2007], an oscillatory mode occurring in North Atlantic SST that operates primarily at a multidecadal timescale. In this paper, the AMO is defined to be the component induced by natural variability although the issue is not settled yet. In addition, the North Atlantic is a strong sink region for atmospheric carbon dioxide ($CO_2$) [e.g., *Takahashi et al.*, 2009; *Watson et al.*, 2009]. Thus, North Atlantic SST may vary with atmospheric $CO_2$, but the question is how they relate to each other. In this paper, we show that both global warming and AMO variability make a contribution to the recent basin-wide warming in North Atlantic SST and their relative contribution is approximately equal. Global warming can influence AMO variability, and on the other hand the AMO can also affect SST variability over the global ocean. The atmospheric greenhouse gas concentration of $CO_2$ seems to vary with the warm and cold phases of the AMO, in addition to the secular increase and the seasonal cycle. These indicate that global warming and the AMO affect each other and that the North Atlantic is a key region for studying global climate changes.

## 2. Data Sets

[3] The most recent version (v3b) of the extended reconstruction SST dataset [*Smith et al.*, 2008] is used in this study. The data is on 2° latitude by 2° longitude spatial resolution and on monthly temporal resolution. The monthly SST is available since January 1854 and downloadable from NOAA National Climatic Data Center (http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php). Atmospheric $CO_2$ concentrations are measured in two stations located at Hawaii and the South Pole. The $CO_2$ concentration at Mauna Loa, Hawaii is determined from air samples collected continuously from air intakes at the top of four 7 m towers and one 27 m tower. Four air samples are collected each hour since 1958. Unlike at Mauna Loa, air samples at the South Pole are collected bi-weekly. In this study, we use monthly concentration values, which are adjusted to represent 2400 hours on the 15th day of each month. Details about the sampling methods at Mauna Loa and the South Pole, and these $CO_2$ data are available at http://scrippsco2.ucsd.edu/data/atmospheric_co2.html.

## 3. North Atlantic and Global SST Variability

[4] North Atlantic SST anomalies are calculated as the averaged yearly SST anomalies over the region of 0°–60°N and from the east coast of the Americas to 0° longitude. Figure 1a shows that North Atlantic SST varies on two major timescales: a secular trend and a multidecadal variation. The trend displays an overall gradual warming over the past 156 years. The multidecadal variability includes an

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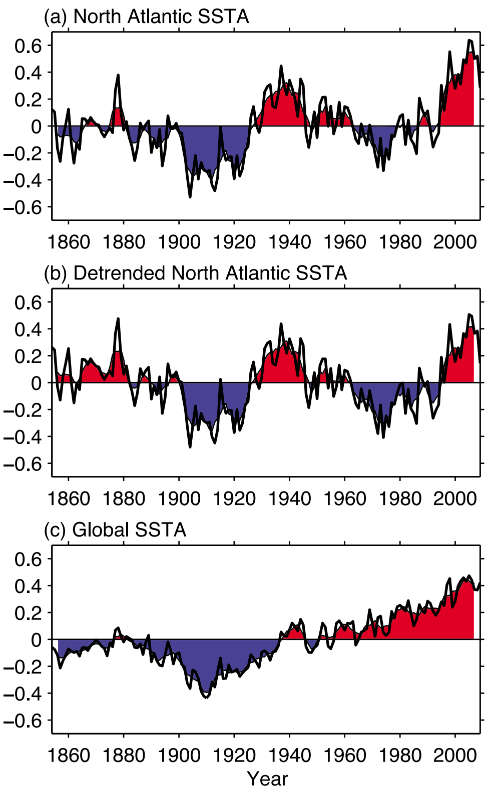


**Figure 1.** Time series of SST anomalies (°C) in the North Atlantic and over the global ocean. Shown are (a) SST anomalies in the North Atlantic (0°–60°N, the east coast of the Americas to 0° longitude), (b) detrended SST anomalies in the North Atlantic, and (c) SST anomalies over the global ocean (60°S–60°N). Shading represents the time series of 5-year running means.

"oscillatory" component with a relatively cold episode from 1900 to 1925, followed by a warm period from 1930 to 1960, another relatively cold period from 1970 to 1990, and finally the recent rapid warming after 1995. The oscillatory component is identified in several previous studies [e.g., *Kushnir*, 1994; *Schlesinger and Ramankutty*, 1994; *Delworth and Mann*, 2000] and is commonly referred to as the Atlantic multidecadal oscillation (AMO) [*Kerr*, 2000; *Enfield et al.*, 2001; *McCabe et al.*, 2004; *Knight et al.*, 2005; *Sutton and Hodson*, 2005]. The combination of an upward trend plus a multidecadal oscillatory component indicates the possible superposition of an anthropogenically forced warming and a naturally generated climate component [*Zhang et al.*, 2007; *Ting et al.*, 2009].

[5] A method for separating the secular warming and multidecadal variation is to remove the linear trend from the North Atlantic SST index, as shown in Figure 1b. This method assumes that the forced trend is linear and uniform over time, all of which are not true in nature. In spite of its weakness, the advantage is that it is simple and can clearly show the multidecadal signal. The detrended time series shows that the warm phases of the AMO occur during 1854–1900, 1925–1965, and 1995–2009 and the cold phases are during 1901–1924 and 1966–1994 (Figure 1b). However, we have to keep in mind that since global warming is probably not linear, the detrended AMO index may still contain the signal of global ocean warming [*Trenberth and Shea*, 2006; *Mann and Emanuel*, 2006]. Previous studies have shown that a secular warming of SST occurs almost everywhere over the global ocean in association with the secular increase of greenhouse gas concentration. Figure 1c shows SST anomalies over the global ocean. In addition to a gradual warming over the past 156 years, global SST index does show troughs and crests. For example, a large trough is around 1910 and crests are located around 1880, 1940 and 2005. These trough and crests are consistent with the cold and warm phases of the AMO. This indicates that global SST index of Figure 1c includes the AMO signal and the AMO can contribute to global SST variability. In other words, global and North Atlantic SST can influence each other instead of one-way influence.

## 4. Influence of Global Warming on North Atlantic SST

[6] There is no question that the anthropogenic increase of greenhouse gas concentration increases global SST including North Atlantic SST. Assuming that global warming is uniform over the global ocean, *Trenberth and Shea* [2006] and *Mann and Emanuel* [2006] use global mean SST anomalies as a proxy for the global warming signal. Then,

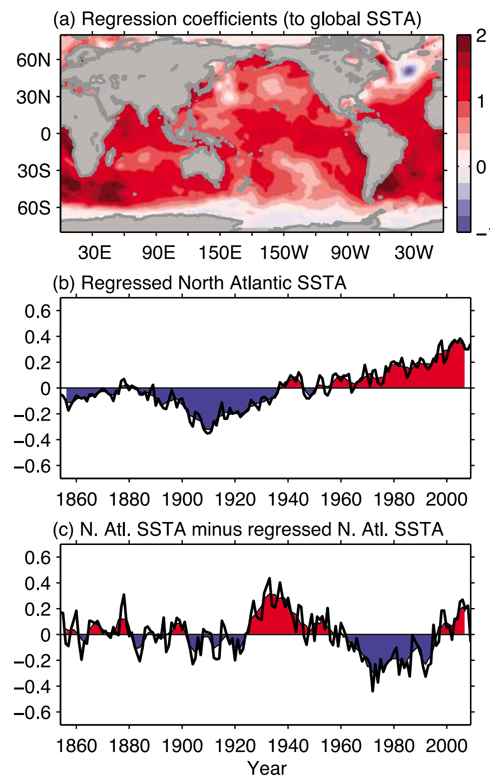


**Figure 2.** Influence of global warming on North Atlantic SST. Shown are (a) regression map of SST anomalies (°C per °C) onto global SST index of Figure 1c, (b) time series of regressed SST anomalies (onto global SST index of Figure 1c) in the North Atlantic, and (c) time series of North Atlantic SST anomalies minus regressed North Atlantic SST anomalies (i.e., Figure 1a minus Figure 2b). Shading in Figures 2b and 2c represents the time series of 5-year running means, and unit in Figures 2b and 2c is °C.

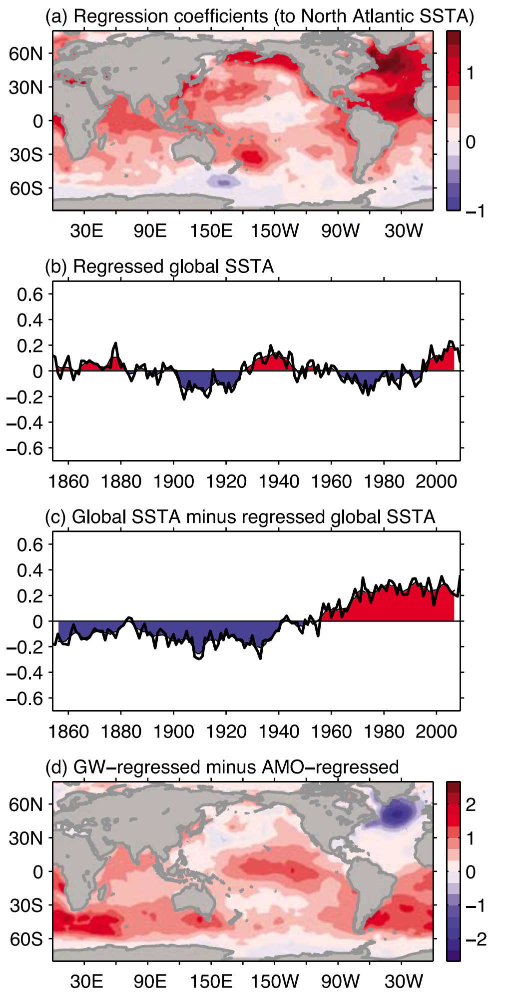


**Figure 3.** Influence of the AMO on global SST. Shown are (a) regression map of SST anomalies (°C per °C) onto detrended North Atlantic SST index of Figure 1b, (b) time series of regressed SST anomalies (onto detrended North Atlantic SST index of Figure 1b) over the global ocean, (c) time series of global SST anomalies minus regressed global SST anomalies (i.e., Figure 1c minus Figure 3b), and (d) the difference between the global warming-regressed and AMO-regressed coefficients (i.e., Figure 2a minus Figure 3a). Shading in Figures 3b and 3c represents the time series of 5-year running means, and unit in Figures 3b and 3c is °C.

they derive a revised AMO index by subtracting global mean SST anomalies from North Atlantic SST anomalies. By doing so, the amplitude of AMO SST anomalies is much reduced in comparison with the linear detrended AMO index. The second assumption of this method is that the AMO does not affect SST of other ocean basins, which is not true.

[7] Here we calculate the regression of SST anomalies onto the global SST index of Figure 1c. As expected, Figure 2a shows that the warming is almost everywhere over the global ocean, with the exception south of Greenland where cooling occurs. The warming is consistent with the expected effect of a secular increase in greenhouse gas concentration, and the regional cooling is suggestive of radiative effects of aerosols and/or oceanic natural variability. Given that the warming is not uniform over the global ocean (Figure 2a), we calculate the regressed (onto global SST index) SST anomalies in the North Atlantic (i.e., North Atlantic SST anomalies that are related to global warming), as shown in Figure 2b. We then obtain an AMO index by subtracting the regressed North Atlantic SST anomalies from North Atlantic SST anomalies. The resulting AMO index (Figure 2c) shows that the amplitude of the recent warming has decreased and the cooling during 1900–1925 has almost disappeared, in comparison with the linear detrended AMO index of Figure 1b. However, the AMO still can reach ±0.3°C. This indicates that both global warming and the AMO make a contribution to the recent warming in the North Atlantic.

## 5. Influence of the AMO on Global SST

[8] In addition to the influence of global ocean warming on the AMO, can the AMO also affect SST anomalies over other ocean basins? The regression of SST anomalies onto the detrended North Atlantic SST index (i.e., the AMO index) shows that the AMO is related to global SST anomalies (Figure 3a). In particular, the warm (cold) phase of the AMO is associated with the warming (cooling) in the North Pacific, subtropical western South Pacific and tropical Indian Ocean. Time series of the regressed global SST anomalies (onto the detrended AMO index) exhibits an AMO signal over the global ocean (Figure 3b). Figure 3b shows that the recent warming of global SST anomalies, associated with the AMO, can reach about 0.2°C. This indicates that the warm phase of the AMO after 1995 largely contributes to the global ocean warming. To remove the effect of the AMO, we subtract the regressed global SST anomalies (onto the detrended AMO index) from global mean SST anomalies (Figure 3c). Since the AMO evolves from the cold to warm phases from 1970 to the present, Figure 3c shows a flat SST over the global ocean during that period after removing the effect of the AMO. Comparison of Figures 1c and 3c indicates that the AMO does account for or contribute to part of the warming over the global ocean. In order to illustrate the spatial pattern of global warming after removing the AMO influence, we subtract the AMO-regressed coefficient from the global warming-regressed coefficient (i.e., Figure 2a minus Figure 3a), as shown in Figure 3d. As expected, the cooling south of Greenland has enhanced and the warming in the North Pacific and the tropical North Atlantic has reduced.

## 6. Variations of Atmospheric $CO_2$

[9] The seasonal cycle and the secular change of $CO_2$ are clearly seen from the $CO_2$ time series observed in both Hawaii and the South Pole (Figures 4a and 4c). The seasonal cycle in the South Pole is weaker than that in Hawaii because there are far less land and less terrestrial vegetation in the Southern Hemisphere than in the Northern Hemisphere. The secular change of $CO_2$ shows a gradual increase since 1958, which is consistent with the secular increase of global SST including North Atlantic SST. Interestingly, after removing a linear trend and the seasonal cycle, atmospheric $CO_2$ anomalies show a multidecadal variation (Figures 4b and 4d). Both $CO_2$ concentrations in Hawaii and the South Pole show negative $CO_2$ anomalies from the 1970s to the 1990s and positive $CO_2$ anomalies during the 1960s

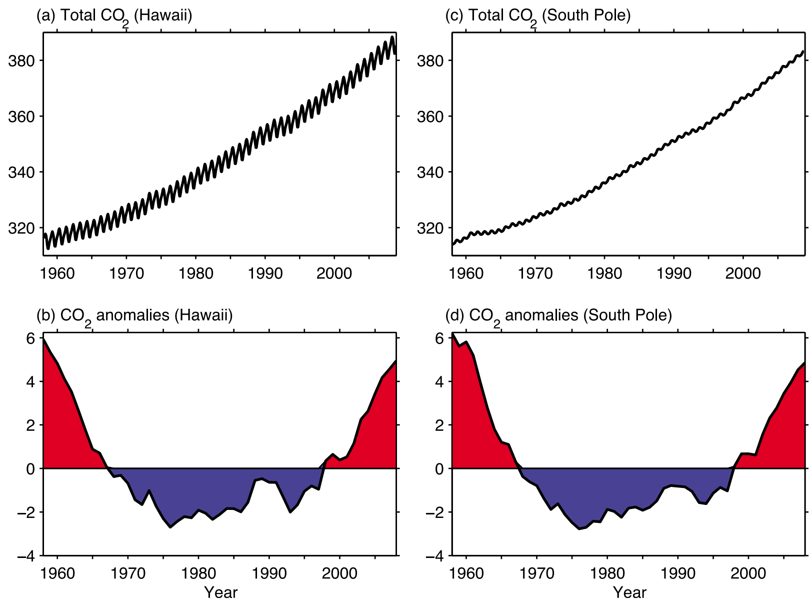


**Figure 4.** Variations of atmospheric $CO_2$ concentration (ppm). Shown are (a) $CO_2$ concentration and (b) $CO_2$ anomalies after removing the linear trend and the seasonal cycle in Mauna Loa, Hawaii from 1958 to 2008, and (c) $CO_2$ concentration and (d) $CO_2$ anomalies after removing the linear trend and the seasonal cycle in the South Pole from 1958 to 2007.

and after the 1990s. These $CO_2$ multidecadal variations approximately coincide with the cold phase of the AMO during 1970–1990 and the warm phases of the AMO from 1930–1960 and after 1995. Atmospheric $CO_2$ concentrations seem to display the AMO signal, in addition to the well-known variations of the secular increase and the seasonal cycle; however, it must be noted that these results are based on the assumption of a linear trend on $CO_2$ growth. Here we would like to point out and discuss caveats in Figure 4. First, the result is obtained by removing the linear trend. Since global warming is probably not linear, the time series of Figures 4b and 4d may still contain the component of global warming. This is the same problem as the detrended AMO index, as discussed earlier. However, the non-linear feature of global warming is unknown and the issue cannot be resolved by observations only. Second, the instrumental measurements of high frequency $CO_2$ data are only available from 1958, which is too short for studying longer-term variations. In addition, considering the model simulated $CO_2$ change induced by ocean temperature [e.g., *Thomas et al.*, 2008], the amplitude of Figures 4b and 4d is too large, again indicating the limitation of removing the linear trend.

[10] Nevertheless, several points can be discussed here based on these time series. First, the observed relationship between the AMO and $CO_2$ may be related to the ocean's $CO_2$ uptake through ocean circulation, given that the North Atlantic is a strong sink region for atmospheric $CO_2$ [*Takahashi et al.*, 2009; *Watson et al.*, 2009]. It is previously shown that the Atlantic meridional overturning circulation (AMOC) is a driving mechanism for the AMO [*Delworth and Mann*, 2000; *Knight et al.*, 2005; *Zhang et al.*, 2007; *Wang et al.*, 2010]. That is, the phases of the AMO are determined by AMOC variability. Thus, it can be inferred that the strength of the AMOC affects the ocean's $CO_2$ uptake which in turn influences on atmospheric $CO_2$ concentration. Second, observations here may reflect the relationship between ocean's solubility pump of $CO_2$ and ocean temperature [*Kravtsov and Spannagle*, 2008]. Because seawater equilibrium shifts toward higher (lower) $pCO_2$ level as the ocean is warmed up (cooled down), the warmer (colder) North Atlantic Ocean during the warm (cold) phase of the AMO leads to a release (uptake) of $CO_2$ to (from) the atmosphere. Thus, the AMO may either increase or decrease atmospheric $CO_2$ concentration dependent upon the AMO phases. Third, the recent observation of the weakening in the $CO_2$ sink since 1990 over the North Atlantic Ocean [*Schuster and Watson*, 2007; *Schuster et al.*, 2009] may be a signal of the AMO, since the AMO is in its positive phase after the mid-1990s. Finally, the basin-wide warming of the North Atlantic due to AMO variability since the mid-1990s may influence global SST via the increase of atmospheric $CO_2$, consistent with the regressed map of Figure 3a.

## 7. Summary and Discussion

[11] The analyses of observational data show that both global warming and AMO variability make a contribution to the recent basin-wide warming of the North Atlantic. The contributions of anthropogenic global warming and AMO variability, to some degrees, are equally important. Additionally, AMO variability also affects SST variability over the global ocean. In other words, global ocean warming and the AMO can influence each other. However, we have to keep in mind that a separation of global ocean warming and natural variability from observations, as attempted in this paper, is a difficult problem. There is no perfect way to separate their contributions from the observational point of view. Numerical models can be used to resolve this issue. However, almost all models have a difficulty in simulating the AMO (e.g., *Kravtsov and Spannagle*, 2008; *Knight*, 2009). This topic deserves further study.

[12] In summary, removal of a linear trend from the time series of atmospheric $CO_2$ measured in Hawaii and the

South Pole suggests that atmospheric $CO_2$ might vary approximately with the AMO, in addition to the recognized secular increase and seasonal cycle. When the AMO is in the warm (cold) phase, atmospheric $CO_2$ tends to increase (decrease). This observed relationship supports the idea of the influence of the recent basin-wide warming of the North Atlantic on global warming. It is implied that the North Atlantic is an important region for studying climate changes, and that concerns for future climate changes should consider AMO variability and possible feedback between atmospheric $CO_2$ and the AMO.

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