LETTERS

Implications of the Recent Trend in the Arctic/North Atlantic Oscillation for the North Atlantic Thermohaline Circulation

THOMAS L. DELWORTH AND KEITH W. DIXON

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey

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ABSTRACT

Most projections of greenhouse gas–induced climate change indicate a weakening of the thermohaline circulation (THC) in the North Atlantic in response to increased freshening and warming in the subpolar region. These changes reduce high-latitude upper-ocean density and therefore weaken the THC. Using ensembles of numerical experiments with a coupled ocean–atmosphere model, it is found that this weakening could be delayed by several decades in response to a sustained upward trend in the Arctic/North Atlantic oscillation during winter, such as has been observed over the last 30 years. The stronger winds over the North Atlantic associated with this trend extract more heat from the ocean, thereby cooling and increasing the density of the upper ocean and thus opposing the previously described weakening of the THC. This result is of particular importance if the positive trend in the Arctic/North Atlantic oscillation is a response to increasing greenhouse gases, as has been recently suggested.

1. Introduction

The dominant pattern of atmospheric variability during winter over the extratropical Northern Hemisphere (NH) is referred to as the Arctic oscillation (AO) (Thompson and Wallace 1998, 2000) and is characterized by a redistribution of mass between the polar latitudes and midlatitudes. A positive phase of the AO corresponds to reduced sea level pressure over the Arctic and increased westerly winds at midlatitudes. The largest changes in midlatitudes associated with the AO occur over the Atlantic sector in NH winter and are known there as the North Atlantic oscillation (NAO). Although there are hemispheric-scale differences between the AO and NAO (Deser 2000), the similarities over the Atlantic sector allow us to view the AO and NAO as effectively identical for the purposes of this study; henceforth we refer only to the AO.

A sustained upward trend in the AO during winter has been documented over the last 30 years (Fig. 1), along with trends in observed NH climate variables associated with the AO (Hurrell 1996; Thompson et al. 2000). It has been postulated recently (Shindell et al. 1999; Fyfe et al. 1999) that the AO trend is a result of increasing greenhouse gas (GHG) concentrations, although this question remains open, because some other coupled models (e.g., Osborn et al. 1999) do not produce such a trend. Whether or not the trend in the AO is a response to increasing GHGs, it is important to assess what effect such a trend has on other components of the climate system.

We specifically investigate the effect of the upward trend in the AO on the North Atlantic thermohaline circulation (THC), which is the northward flow of warm, salty water in the upper layers of the Atlantic Ocean and associated southward flow at depth. Most projections of greenhouse gas–induced future climate change indicate a weakening of the THC in response to a reduction of near-surface ocean density in the subpolar region of the North Atlantic (Manabe et al. 1991; Rahmstorf 1999; Wood et al. 1999). This density reduction, attributable to both warming of the near-surface layers and large-scale freshening arising from projected increases in high-latitude precipitation and river outflow, inhibits the formation of dense water and hence weakens the THC. In this paper, a mechanism is presented that could substantially delay the projected THC weakening. Stronger winds associated with the positive trend in the AO tend to extract more heat from the ocean, thereby cooling and increasing the density of the upper ocean. This process tends to oppose the previously described weakening of the THC.

The competition between these opposing processes is

Corresponding author address: Thomas L. Delworth, GFDL/NOAA, P.O. Box 308, Princeton University, Princeton, NJ 08542.
E-mail: td@gfdl.gov

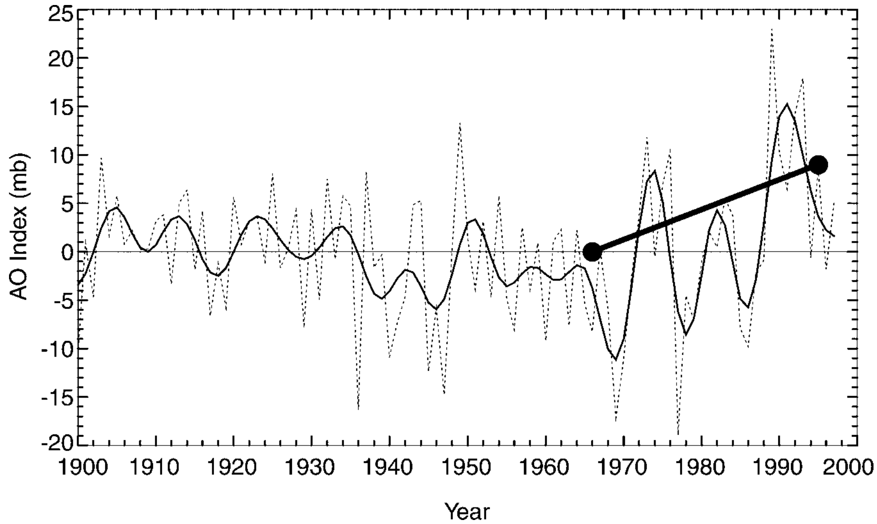

FIG. 1. Time series (dashed line) of an index of the observed AO over the period 1900–98 during winter (hPa). Light solid line indicates time series after removing timescales shorter than 7 yr. The AO index is derived from an EOF analysis of observed sea level pressure over the NH from 20° to 90°N (Thompson and Wallace 1998) using seasonal mean data (Nov–Mar). The AO index is then defined as the EOF time series multiplied by the difference in pressure between the extrema of the EOF spatial pattern. The slope of the idealized AO trend imposed in the model experiments is indicated by the thick line with solid circles at either end.

explored using ensembles of numerical experiments with a coupled ocean–atmosphere model. By introducing trends in the surface fluxes of heat, water, and momentum in the model that mimic those that accompany the trend in the observed AO, we can evaluate the effect of this recent AO trend on the model's THC.

2. Model description

The model employed for this study (Dixon and Lanzante 1999) represents the coupled ocean–atmosphere–land system; versions of this model have been used in many studies of climate change and variability (Manabe et al. 1991, 1992). The model is global in domain, with realistic geography consistent with resolution. The model is forced with a seasonal cycle of solar radiation at the top of the atmosphere. The atmospheric component numerically integrates the primitive equations of motion using a spectral technique in which the variables are represented by a set of spherical harmonics and by corresponding grid points with a spacing of ~4.5° latitude and 7.5° longitude. There are nine unevenly spaced levels in the vertical. The oceanic component of the model uses a finite difference technique with 12 unevenly spaced levels in the vertical and a horizontal resolution of approximately 4.5° latitude and 3.75° longitude. Thermodynamic sea ice is included, which moves with the ocean currents.

The model atmosphere and ocean interact through fluxes of heat, water, and momentum at the air–sea interface. To reduce climate drift, adjustments to the model-calculated heat and water fluxes are applied to the ocean. These flux adjustments are derived from preliminary integrations of the separate atmospheric and oceanic components (Manabe et al. 1991) and do not vary from one year to the next. The computational speed of this relatively low-resolution model allows the opportunity to perform a variety of experiments to isolate the important physical processes. Our key conclusions will need to be reexamined in the future using models with greater spatial resolution and improved physics.

3. Experimental design

An ensemble of climate change projections using this model has been conducted recently (Dixon and Lanzante 1999). We make use of the 1500-yr control integration performed in that study by first diagnosing the control model's AO-like variability. This pattern is subsequently used in forcing the model [in a manner similar to Eden and Jung (2000) as discussed below]. Using seasonal means over the months of November through March, we define the coupled model's AO based on an empirical orthogonal function (EOF) analysis (Preisendorfer 1988) of sea level pressure over the Northern Hemisphere from 20° to 90°N. This result is shown in Fig. 2, along with the observed AO pattern. Although relatively coarse in resolution, the model captures the essential feature of the observed AO involving an exchange of atmospheric mass between the high latitudes and midlatitudes. Differences between the observed and simulated patterns are largest over the Pacific sector, but the relatively good agreement over the North Atlantic is most important for the current study. The standard

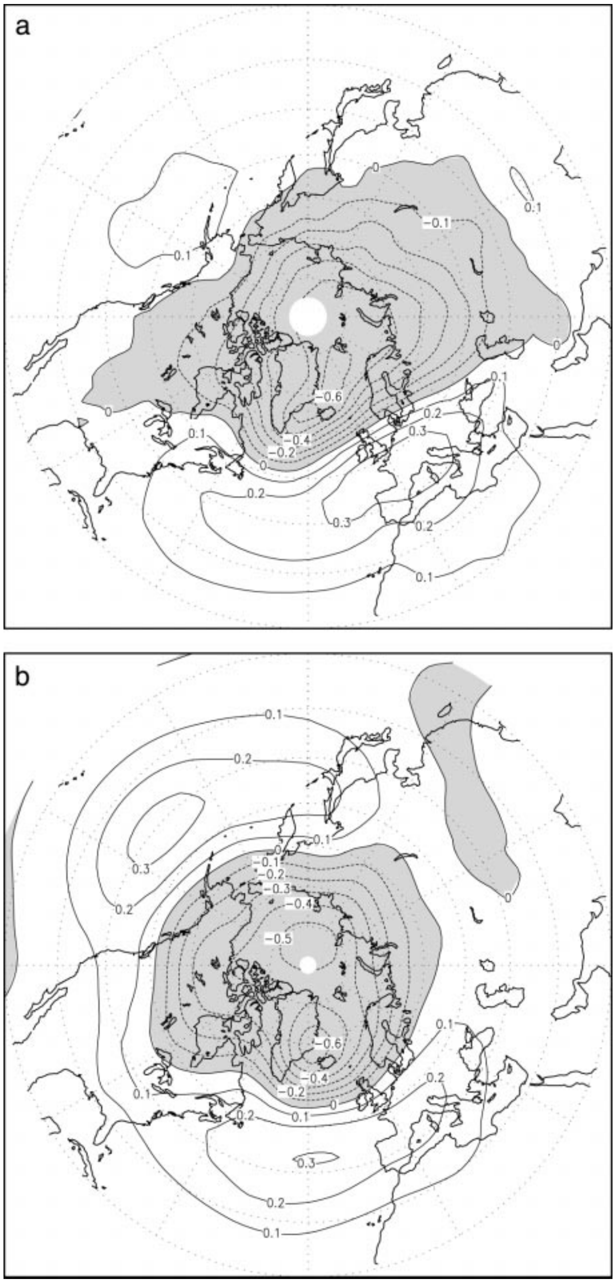

FIG. 2. Spatial patterns of the AO from (a) observations and (b) the control model. The contoured values denote the regression coefficients at each grid point between the time series of sea level pressure (SLP) and the AO index time series and thus reflect the spatial signature of SLP associated with a 1-hPa increase of the AO index. For both the observations and the model, an AO index was defined by the difference in pressure between the extrema of the first EOF spatial pattern multiplied by the corresponding EOF time series. Data for the observed AO are from A. J. Broccoli (2000, personal communication) and Thompson and Wallace (1998).

deviation of the simulated AO time series is 6.3 hPa, somewhat smaller than the 7.3 hPa from the observed AO time series.

Fluxes of heat, water, and momentum at each oceanic grid point were then linearly regressed onto the model's AO time series to characterize the model's AO-related surface flux variability. As before, seasonal means from November through March were used for these analyses. The regression maps shown in Fig. 3 indicate the anomalous surface fluxes associated with a positive phase of the model's AO. The anomalous flux patterns are in good agreement over the North Atlantic with previous observational analyses (Cayan 1992) and with observed and simulated signatures of the NAO (Grotzner et al. 1998). Note in Fig. 3a the region to the south of Greenland where there are anomalously large fluxes of heat from the ocean to the atmosphere, which tend to cool and increase the density of the upper ocean. From approximately 20° to 40°N in the North Atlantic, the anomalously large fluxes of heat from the atmosphere to the ocean tend to warm and lighten the upper ocean. The north–south gradient of density induced by these heat fluxes tends to increase the strength of the model's THC. The anomalies of surface water flux (evaporation–precipitation–river outflow) tend to increase the salinity, and hence the density, of much of the North Atlantic.

To explore the coupled model's response to the observed trend in the AO, we modify the model's calculation of the fluxes at the air–sea interface. Specifically, after the fully interactive calculation of the fluxes based upon the air–sea gradients, extra fluxes of heat, water, and momentum are added to the ocean that have the spatial pattern of the regression coefficients described above and are multiplied by a scale factor corresponding to an index of the AO. This factor increases linearly in time from 0 to 9 hPa over 30 yr, and is held constant at 9 hPa thereafter. The idealized 30-yr trend used is somewhat smaller than the observed AO trend (Fig. 1; the linear trend over 1968–97 is 14 hPa per 30 yr). This anomalous AO-related forcing is applied only in the months of November–March, with a 10-day ramp-up and ramp-down of the forcings at the beginning and end of the period. The application of these extra flux terms is meant to mimic the impact of a trend in the AO on the ocean through the surface flux terms. Note that no flux anomalies are applied over continental regions, nor are any sea level pressure anomalies imposed. We wish to assess the oceanic changes resulting from the AO-induced trends in the surface fluxes.

4. Results using control integration

We perform three experiments that incorporate the above anomalous AO forcing. The experiments start from arbitrary initial conditions which are 500 yr apart in the control integration. Differences between these experiments and the corresponding segments of the control integration will be attributable to the effects of the AO-induced trends in surface fluxes. Ensemble averaging is used to increase the signal-to-noise ratio (i.e., the changes attributable to the AO trends versus the internal variability of the model).

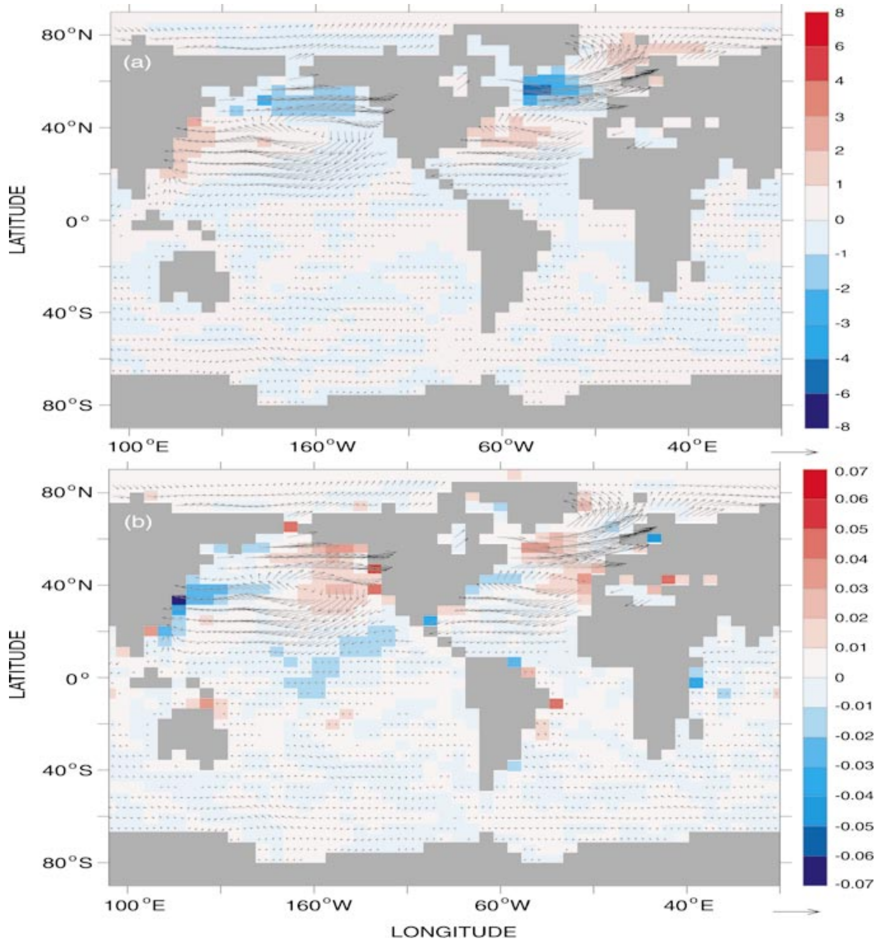

FIG. 3. These maps denote the anomalous flux values associated with a 1-hPa increase in the control model's AO index time series. Using seasonal means from Nov–Mar, linear regressions were computed at each model grid point between the surfaces fluxes of heat, water, and momentum vs the model's AO. The regressions are of the form $y = \alpha x + \beta$, where x is the control model's AO time series and y is the flux of heat, water, or momentum. The quantity plotted corresponds to the coefficient α. (a) Regressions of surface heat flux (denoted by the color shading) and surface wind stress (denoted by the vectors) vs the AO. Units are watts per meter squared per hectopascal for heat and dynes per centimeter squared per hectopascal for wind stress. Negative values for the heat flux regressions denote an enhanced ocean-to-atmosphere heat flux. The vector beneath the color bar indicates a wind stress anomaly of 0.03 dyn cm^{-2} hPa^{-1}. (b) Regressions of water flux (denoted by the color shading) and surface wind stress (denoted by the vectors) vs the control model's AO index time series. Positive values indicate an enhanced flux of freshwater from the ocean to the atmosphere (and hence an increase in upper-ocean salinity). Units are meters per year per hectopascal for the water flux and dynes per centimeter squared per hectopascal for wind stress. Note that the water flux includes evaporation, precipitation, and river outflow. The vector beneath the color bar indicates a wind stress anomaly of 0.03 dyn cm^{-2} hPa^{-1}.

Displayed in Fig. 4 are the results from the experiments described above, indicating an enhancement of the THC in response to the AO trend. The considerable scatter of the individual experiments (various colored circles) emphasizes the importance of internal variability of the coupled system and the need to perform ensembles of such experiments. An additional set of three experiments has been examined in which the AO trend is 13 hPa per 30 yr instead of 9 hPa per 30 yr. The results (not shown) are consistent with a linear response of the THC to the amplitude of the AO forcing.

The fluxes in the above experiments were applied over all oceanic regions based on the regression maps in Fig. 3. We have performed an additional ensemble of three experiments in which the imposed AO-related forcing is confined to the Atlantic basin from the equator to 80°N. The behavior of the THC is similar in those experiments (not shown), indicating that the flux anomalies over the North Atlantic are primarily responsible for the changing behavior of the THC.

In the above experiments, the fluxes of heat, water, and momentum were applied simultaneously. We have

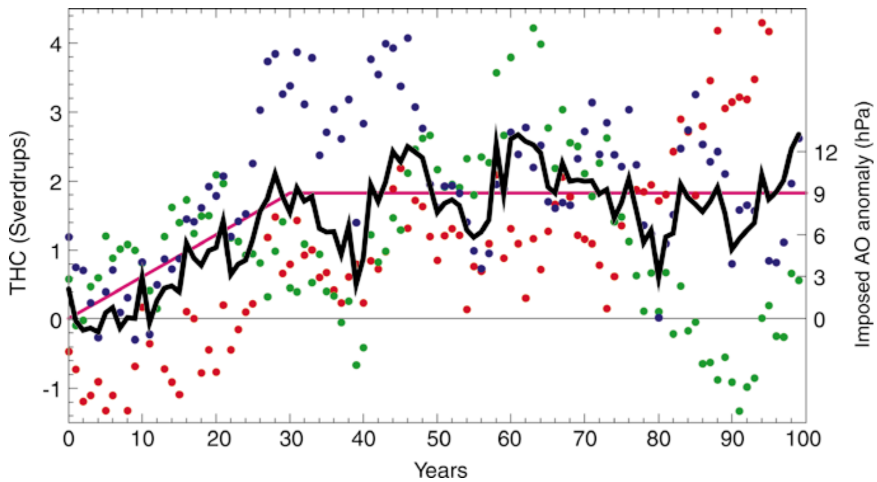

FIG. 4. Solid black line indicates the ensemble mean difference between an index of the THC in the experiments with the AO forcing and the corresponding segments of the control integration. The THC index (Sv; 1 Sv = 10^6 m^3 s^{-1}) is a measure of the zonally averaged flow of water in the North Atlantic, with positive values indicating enhanced northward flow in the upper layers. Prior to calculating the above difference, the THC time series from the control integration was low-pass filtered to remove timescales shorter than 50 yr. The departures of the black line from zero indicate the response of the THC to the anomalous AO forcing. The amplitude of the AO forcing imposed is indicated by the magenta line. The colored circles denote the annual mean THC anomalies for each of the three individual experiments. The statistical significance of the ensemble mean difference was evaluated using a one-sided Student's *t* test. A sequence of 15-yr windows of data were defined for years 1–15, 2–16, and so on. For each of these windows, a *t* statistic was computed using the difference between the mean of the three AO forcing experiments and the mean of the corresponding low-pass filtered control run segments. The differences for all windows centered on years 25 and higher were significant at the 0.05 level, assuming 7 degrees of freedom. Additional testing assuming differing degrees of freedom yielded similar results.

investigated the roles of the individual flux terms by conducting additional experiments in which anomalies of only one of the individual flux terms are used to force the model. Results (not shown) demonstrate that, for this model, the AO-induced trends in the surface heat flux are primarily responsible for the effects seen in Fig. 4, consistent with the results of Eden and Jung (2000) and Delworth and Greatbatch (2000); water flux anomalies are of secondary importance, and the wind stress anomalies have no discernible influence on the THC. Note, however, that the AO-related winds in the model are somewhat more zonal than their observational counterparts; this difference might affect the role that anomalous wind stress anomalies play on the THC changes. Visbeck et al. (1998) examined the response of the North Atlantic ocean to NAO-related wind stress anomalies and found a substantial response of the subpolar gyre to decadal-scale forcing.

5. Results using greenhouse gas forcing

The above experiments were idealized in that the concentration of atmospheric GHGs did not vary in time. The experiments demonstrated that AO-related trends in the surface fluxes can increase the THC. We now wish to evaluate the degree to which AO-related trends in the surface fluxes can counterbalance the projected weakening of the THC in response to increasing GHGs.

We make use of an additional set of three experiments forced by a combination of GHGs and sulfate aerosols (Dixon and Lanzante 1999). For these experiments, a reconstruction of GHGs is used from 1866 to 1990; after 1990 GHGs increase at 1% per year. The effects of tropospheric sulfate aerosols are parameterized through temporal and spatial variations of surface albedo (Haywood et al. 1997). We refer to these experiments as greenhouse plus sulfate (GPS). The individual experiments differ in their initial conditions, which were arbitrarily chosen from points 500 yr apart in the control run.

We perform three additional experiments that incorporate the above anomalous AO forcing in addition to the GHG plus sulfate aerosol forcing. These new experiments (referred to as GPS_AO) start from initial conditions corresponding to 1 January 1966 of each of the three GPS runs described above (Dixon and Lanzante 1999). Differences between the three GPS_AO experiments and the GPS experiments will be attributable to the effects of the AO-induced trends in surface fluxes.

A natural question arises as to why one needs to induce a trend artificially in the AO-related surface fluxes in these GPS experiments if the AO trend is itself a response to increasing GHGs. Although recent work has demonstrated that GHG forcing may induce a positive

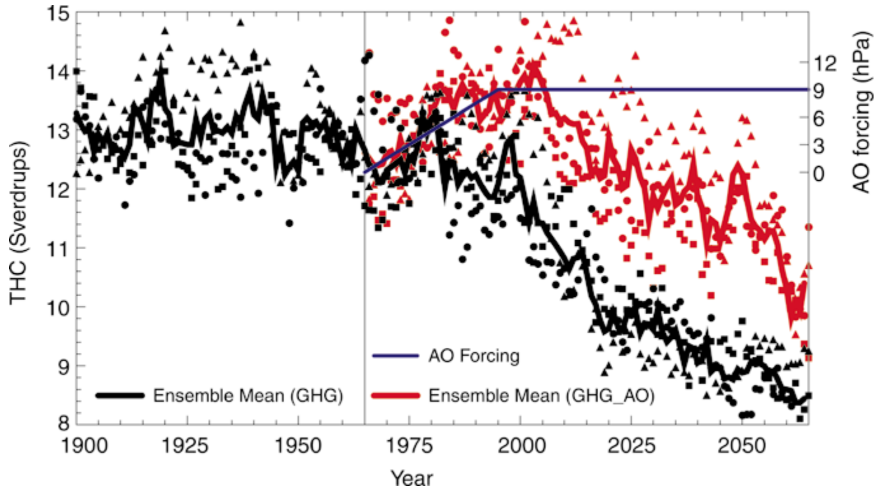

FIG. 5. Time series of the North Atlantic THC from two ensembles of experiments, indicating the effect of the upward trend in the AO on the THC. The ensemble mean of the GPS experiments (see text for definition) is indicated by the thick, black line; the ensemble mean of the GPS_AO experiments is indicated by the thick, red line. The black and red symbols denote THC values from each of the ensemble members from the GPS and GPS_AO ensembles, respectively. The differences between the red and black lines are a measure of the effect of the AO-induced trend in surface fluxes on the THC. The triangles, circles, and squares are used to differentiate the members of each ensemble. The solid vertical line at 1965 denotes the time at which the GPS_AO experiments depart from the GPS experiments by incorporating the effects of the trend in the AO. The amplitude of the AO forcing imposed after 1965 is denoted by the blue line (scale on right axis). Statistical significance was evaluated in a similar method to Fig. 4, using differences between the GPS_AO experiments and the GPS experiments. The differences for all windows centered on years 1983 and higher were significant at the 0.05 level, assuming 10 degrees of freedom (more degrees of freedom are assumed relative to Fig. 4 because no low-pass filtering was used). Additional testing assuming differing degrees of freedom yielded similar results.

trend in the AO, our GPS experiments do not reproduce any such trend. One may interpret this result either as an indication that the observed AO trend is not anthropogenic or that the model has some deficiencies. It has been suggested that a well-resolved stratosphere is necessary to simulate the AO trend (Shindell et al. 1999). Because this model has insufficient vertical resolution to represent the stratosphere properly, it may not be able to simulate such an AO trend as a direct response to GHG forcing. Therefore, we impose this trend. Conversely, if the model did produce an AO trend, the evaluation of its effect on the THC would require an experiment in which the AO trend is removed artificially.

The results of the two sets of experiments are shown in Fig. 5. The THC in the GPS experiments decreases from the late twentieth-century onward because of increased precipitation and river outflow at high latitudes of the NH and warming of the upper ocean at high latitudes (Dixon et al. 1999). By 2065 the ensemble mean THC has been reduced by approximately 40%. A different picture emerges in the GPS_AO experiments. As the upward trend in the AO occurs from years 1966 to 1995, the THC increases by approximately 1.8 Sv. The THC then holds steady for about a decade and subsequently declines from approximately 2005 onward. The rate of decline in the GPS_AO experiments after 2005 is comparable to that in the GHG experiments. The net effect of the imposed AO-related surface flux trends is effectively to delay the weakening of the model's THC by approximately 30–40 yr. These results suggest that the influence of the AO trend on the THC is currently comparable to the influence of increasing GHGs on the THC.

6. Discussion

Projected reductions in the North Atlantic thermohaline circulation in response to human-induced radiative forcing are relatively uncertain. Most climate models show a reduction (Rahmstorf 1999), but the magnitude varies considerably. The results of this study suggest that, if the observed increase in the AO does result from increasing greenhouse gases, these atmospheric circulation changes may have a profound effect on the future behavior of the THC. We have used an idealized estimate of the past and future behavior of the AO in our experiments. Thus, we interpret the results not as a literal prediction of the future behavior of the THC but as an exploration of the physical relationship between trends in the AO and climate change. These results underscore the importance of ascertaining whether the observed trend in the AO is indeed a response to increasing greenhouse gases, or a manifestation of internal variability of the coupled ocean–atmosphere system [see

Osborn et al. (1999) for an examination of this issue]. If the AO trend is a manifestation of internal variability, the postulated delay in THC weakening is less likely to occur. In this case, a future decline in the AO similar in magnitude and duration to the observed increase could serve to accelerate GHG-induced weakening of the THC. These results highlight the important role that decadal to multidecadal changes in the AO play in the North Atlantic Ocean circulation. However, note that the degree to which these results are model dependent cannot be quantitatively assessed at this time. Other factors must also be considered. For example, Latif et al. (2000) suggest that increased evaporation in the subtropical Atlantic could oppose any THC weakening.

The above findings are complementary to previous work that has examined the future behavior of the THC under greenhouse warming. In such scenarios without an imposed increase in the westerly winds over the North Atlantic, a substantial reduction of the THC is typically found. However, when we include the effect of the increasing westerly winds, the reduction in the THC is still projected but is delayed by several decades. Such a delay is of substantial importance to regional climate change over Europe.

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