Impact of Multidecadal Fluctuations in the Atlantic Thermohaline Circulation on Indo-Pacific Climate Variability in a Coupled GCM

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ABSTRACT

Using a multicentury integration of the third climate configuration of the Met Office Unified Model (HadCM3), the authors show that naturally occurring fluctuations in the Atlantic's thermohaline circulation (THC) drive small but statistically significant changes in surface air temperature, sea level pressure, and precipitation over the Indo-Pacific region. The surface temperature component of these variations may be described as an interhemispheric seesaw (consistent with earlier studies), with changes in the Southern Hemisphere smaller than those in the Northern Hemisphere. Links between THC variability and variability related to the interdecadal Pacific oscillation (IPO) are evident: when the THC is strong (weak) the IPO variance decreases (increases) considerably, and cold (La Niña–like) IPO events tend to be stronger and more frequent when the THC is in a weak phase. This highlights the possibility that a small part of Indo-Pacific climate variability at multidecadal time scales, including some of the variability linked to the IPO, may be predictable.

1. Introduction

An important driver of climate variability at decadal–multidecadal time scales is the Atlantic thermohaline circulation (THC; Delworth et al. 1993). Fluctuations in the strength of the THC have been shown to be significantly correlated with surface climate variations in the North Atlantic region as well as in Europe, North America, and the North Pacific (e.g., Manabe and Stouffer 1988; Knight et al. 2005). Many of the previous studies on this topic have considered the climatic impact of a *substantial* change in the strength of the THC, brought about by applying freshwater forcings, typically at a rate of 1 Sv (1 Sv ≡ 10^6 m^3 s^{-1}), to the subpolar North Atlantic (e.g., Vellinga and Wood 2002; Dong and Sutton 2002; Zhang and Delworth 2005; Stouffer et al. 2006; Wu et al. 2008). Changes of this magnitude can trigger a shutdown of the THC within a few decades in the models. This, in turn, causes a reduction in the northward heat transport and the subsequent cooling of the North Atlantic and adjacent areas by up to 12°C (Stouffer et al. 2006).

The THC may also show considerable *natural* fluctuations under present-day climatic conditions (Dong and Sutton 2005; Knight et al. 2005). It is of interest to investigate the climatic response to such natural fluctuations for a number of reasons. First, as the THC has intrinsic time scales spanning decades to centuries (Knight et al. 2005), regions significantly affected by THC fluctuations may have a source of potential predictability. Second, an observed climate variation/shift may be the result of anthropogenic changes in the climate system or a part of the present-day natural climate variability, or a combination of both. To understand this better, we need to first understand the differences (if any) in the nature and strength of the climatic impacts resulting from a naturally fluctuating THC and from a change in THC strength, possibly brought about by global warming. Also, while the Atlantic climate shows a consistent response to substantial THC changes in most water-hosing experiments, the response over the Pacific has

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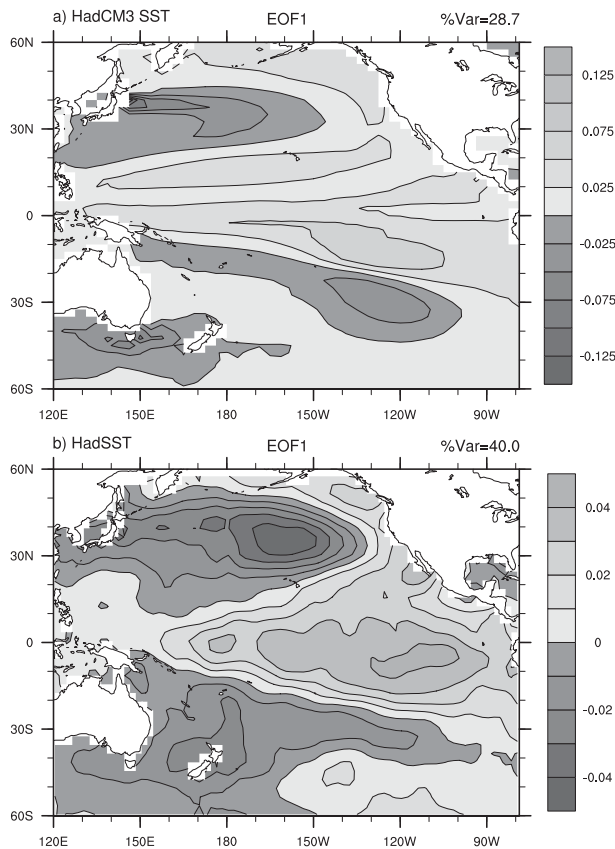E-mail: harun.rashid@csiro.au

FIG. 1. Spatial patterns of the IPO, as represented by the leading EOF of the low-pass-filtered SST anomalies over the Pacific basin (with a cutoff period at 13 years): (a) HadCM3 simulation and (b) observations (Met Office Hadley Centre SST data). The data length is (a) 1600 years and (b) 136 years (1870–2005).

been found to be inconsistent among various coupled GCMs (Timmermann et al. 2007). To better understand the reason behind such inconsistent responses to THC fluctuations in various models, further studies using careful analyses of long simulations of coupled models are needed.

In this paper, we investigate the impact of natural multidecadal fluctuations in the Atlantic THC on surface climate variability in the Indo-Pacific region, with an emphasis on the Pacific. Using a 1600-yr-long control simulation (of preindustrial climate) by the third climate configuration of the Met Office Unified Model (HadCM3; Gordon et al. 2000), we analyze the temporal and spatial characteristics of the responses of surface air temperature (SAT), sea level pressure (SLP), and the precipitation rate to multidecadal fluctuations in the THC. We document the impact of natural THC variability and, where appropriate, compare this with the corresponding impact of a forced, substantial change in the THC reported in previous studies. We examine the covariability

of the THC and the Indo-Pacific climate in two stages, to better understand their relationship. First, we determine the direct impact of the THC on Indo-Pacific climate variability by separating this from the influence of the leading mode of Pacific interdecadal variability: the interdecadal Pacific oscillation (IPO; Power et al. 1999; Folland et al. 1999). We then investigate the interrelationship between the THC and the IPO.

2. The THC index and preliminary processing of data

Covariability between a THC index and the global fields of SAT, SLP, and precipitation rate is examined below. The THC index used here is similar to that used by Knight et al. (2005), which represents the maximum strength of the zonal mean meridional streamfunction in the Atlantic at 30°N. The average strength of the simulated THC and the associated heat transport were shown to compare well with observations (Knight et al. 2005). Investigators also use the maximum value of the meridional overturning streamfunction in the Atlantic as an index of the THC, following Delworth et al. (1993). On time scales of decades and longer, however, there is a good correspondence between the THC index defined at a fixed latitude and an index that is defined as the streamfunction maximum across all latitudes in the Atlantic (Vellinga and Wu 2004). Following Knight et al. (2005), the time series of annual mean values of the THC index and the global fields of the three climate variables were detrended by removing from the data a quadratic least squares fit at each grid point, to eliminate a small drift present in the long simulation. The resulting anomalies were then low-pass filtered to retain only the decadal and longer time scale variability. A Lanczos filter with a cutoff period at 13 years was used to filter the data.

We define the IPO as the first EOF mode of the low-pass-filtered anomalies of annual mean sea surface temperatures (SSTs) in the Pacific basin (60°S–60°N). The corresponding principal component time series is termed the IPO index. The spatial structure of this mode (Fig. 1) is very similar to that of ENSO-like interdecadal variability (Zhang et al. 1997), with warmer SSTs in the tropical central and eastern Pacific flanked by colder SSTs in the North and South Pacific (taken as the warm phase of the IPO). Note, however, that the model IPO pattern (Fig. 1a) differs somewhat from the observed IPO pattern (Fig. 1b; see also Power et al. 1999), with the positive loadings of the model EOF extending too far west into the western Pacific. Also, the regions of lower SSTs in the extratropics occupy a smaller area in the model IPO than in the observed IPO.
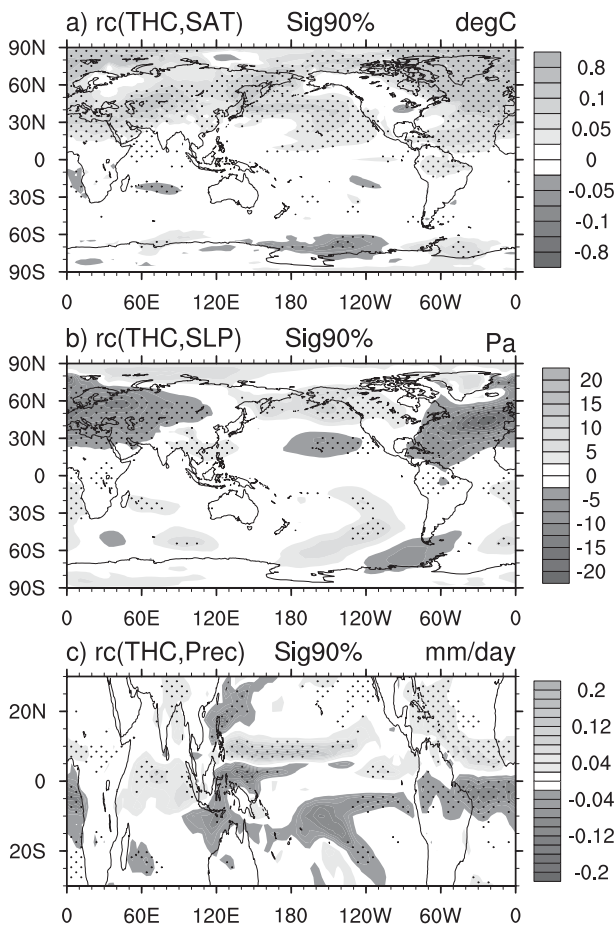
FIG. 2. Geographical distribution of the coefficients of simple linear regression of the anomalies of (a) annual mean surface air temperatures, (b) sea level pressure, and (c) precipitation rate onto the standardized index of the decadal THC, after removing the IPO-related part from the index. The stippling shows the statistically significant values at the 90% level. The statistical significance of the regression coefficients was estimated at each grid point by the Monte Carlo technique; see text for details.

3. Results

Previous studies (e.g., Folland et al. 1999) have shown that the IPO plays a major role in multidecadal global SST variability, including climate variability over and around the Indo-Pacific region (Power et al. 1999, 2006). As Folland et al. (2002) showed, the IPO can be regarded as the quasi-symmetric (hemispherically) Pacific-wide manifestation of the Pacific decadal oscillation (PDO), the leading mode of monthly SST variability in the North Pacific (Mantua et al. 1997).

We investigate the possible relationship between the THC and the IPO later (there is a moderate correlation between these two indexes), but first we examine the direct impact (independent of the IPO) of multidecadal

fluctuations in the THC on Indo-Pacific climate variability. We first make the THC index linearly independent of the IPO by removing from the THC index its IPO-related part computed through a linear regression. We then regress the low-pass-filtered anomalies of annual mean SAT, SLP, and rainfall rate onto this IPO-independent THC index. The THC index was standardized before computing the regression coefficients, so the coefficients have the same unit as their respective fields.

The result of this regression analysis is presented in Fig. 2. The regression coefficients significant at the 90% levels are stippled. The significance level was estimated by first generating 1000 synthetic time series of the THC index, using a resampling technique that accounts for the serial correlation (Ebisuzaki 1997). Regression coefficients between these synthetic time series and the anomalies of the SAT, SLP, and rainfall rate were then computed, and their distribution used, for estimating the significance level at each grid point using a two-tailed test. The SAT response pattern resembles an interhemispheric seesaw, identified by Folland et al. (1999) from observations (see also Knight et al. 2005) with the Northern (Southern) Hemisphere being generally warmer (colder) in the strong THC phase (Fig. 2a). The cooling in the SH is, however, much weaker in magnitude than the warming in the NH. Consistent with previous studies (e.g., Vellinga and Wu 2004; Dong and Sutton 2005), the stronger-than-normal THC is associated with positive SAT anomalies over the extratropical and tropical North Atlantic Ocean, with the warmest anomalies found in the extratropics. The surrounding land areas also experience positive SAT anomalies, except for the central part of North America, where negative anomalies are found. A similar pattern of positive temperatures also occurs over the tropical and extratropical North Pacific. Significant SAT anomalies are also found over central Asia, northern Africa, and over the Weddell Sea. While many of these features are similar to the results found in previous studies, there are also differences, especially over the Pacific basin, due to the removal of the IPO influence from the THC index [cf. Fig. 15 of Dong and Sutton (2005)]. The corresponding SLP anomalies (Fig. 2b) have a pattern that is broadly consistent with the SAT anomalies, with low pressure (high pressure) anomalies coinciding with warm (cold) temperature anomalies (except over the extratropical North and South Pacific, where the SAT anomalies appear to be caused by changes in surface winds implied by the SLP anomalies). The North Atlantic is characterized by the presence of a strong low pressure anomaly, the influence of which extends over to Europe, North Africa,

and central Asia. For rainfall variability, the largest response to THC fluctuations is observed in the tropics (Fig. 2c). Over the tropical Atlantic, the rainfall anomalies occur in the form of a north–south dipole, implying a northward (southward) shift of the ITCZ during the stronger- (weaker-) than-normal phase of the THC. Such a meridional shift of the Atlantic ITCZ has been reported as a robust feature in studies involving substantial changes in the THC (e.g., Vellinga and Wood 2002; Zhang and Delworth 2005; Stouffer et al. 2006; Wu et al. 2008; Okumura et al. 2009) as well as in studies involving natural variability of the THC (e.g., Vellinga and Wu 2004; Knight et al. 2006). The rainfall response in the Pacific is somewhat complicated, but the variation is still mainly in the north–south direction. The response is largest in the western half of the tropical Pacific and over the tropical Indian Ocean. The dipole rainfall pattern in the eastern tropical Pacific appears to be robust, similar to the pattern in the tropical Atlantic, as this feature is also found in some water-hosing experiments (e.g., Vellinga and Wood 2002; Dong and Sutton 2007; Okumura et al. 2009). The rainfall response in the western half of the tropical Pacific, however, differs from those found in the above water-hosing experiments. For example, the large rainfall anomalies in the northern tropical Pacific in Figs. 2c and 3c of Dong and Sutton (2007) have the same positive sign, whereas the opposite signs were expected, given the anomalies in Dong and Sutton (2007) represent a response to the *weakening* of the THC. This partial disagreement between the tropical Indo-Pacific responses due to natural fluctuations and by a substantial change in the THC also holds for SAT and SLP.

In the North Pacific, however, there is agreement between the responses because of the naturally fluctuating THC and because of a substantial change in the THC. This is not surprising, as the THC's impact in this region is quite consistent across different models (e.g., Timmermann et al. 2007; Okumura et al. 2009). The mechanism by which the North Pacific responds to the North Atlantic temperature variability has been discussed by Zhang and Delworth (2007) and Okumura et al. (2009), among others, who emphasized the role of atmospheric and oceanic teleconnections as well as air–sea interactions.

There is small but interesting covariability between the THC and the IPO. The correlation coefficients between the IPO index and the low-pass-filtered THC index are shown for different lags in Fig. 3a. Note that the complete THC index that retains the IPO-related part was used for the calculations presented in Fig. 3. The THC and IPO indices show a small but statistically significant correlation, with the coefficient peaking at 0.27

when the THC index leads the IPO index by 1 year. While small, this correlation coefficient is statistically significant at the 99% level (with the impact of serial correlation taken into account). Significance was assessed in the same way as in Fig. 2, but with 10 000 Monte Carlo trials.

The power spectra of the standardized THC (solid) and IPO (dashed) indices are shown in Fig. 3b. The THC index has substantial power at centennial time scales (see also Knight et al. 2005), whereas much of the power of the IPO index is in the multidecadal period range. It is therefore of interest to examine the behavior of the IPO during extreme phases of the THC. In the case of a substantial weakening of the THC, ENSO variance has been shown to increase in many water-hosing experiments (e.g., Timmermann et al. 2007; Dong and Sutton 2007). However, it is not clear whether the IPO will also show a similar behavior, especially in response to a naturally fluctuating THC. In particular, is there any significant asymmetry in the mean and variance of the IPO index between the periods of strong and weak THC? To address this question, we first identified the periods when the THC index exceeds its plus 1 standard deviation ("strong phase") or minus 1 standard deviation ("weak phase"). We then constructed separate histograms of the IPO index for the strong and weak THC phases, which are presented in Fig. 3c. The difference between these two distributions of the IPO index, corresponding to the strong (solid) and weak (crosshatch) THC phases, is found to be statistically significant at the 99.9% level. We applied the Kolmogorov–Smirnov (K–S) test to estimate the statistical significance of the difference between the two distributions (Press et al. 1992). The IPO during the weak THC phase has a La Niña–like bias, with the tropical (extratropical) SSTs tending to be colder (warmer) than those during the strong THC phase.

Figure 3c reveals that the IPO variance in the weak THC phase is stronger than that in the strong THC phase, as indicated by the larger width of the histogram in the weak THC phase. The ratio of the pooled IPO variances in the weak and strong THC phases is ~1.52; that is, the IPO variance increases by more than 50% when the THC is weak compared to its variance when the THC is strong. We tested the statistical significance of this variance enhancement by using 10 000 synthetic THC indexes to separate the IPO index into pairs corresponding to the strong and weak phases of the synthetic THC indices, as above. The distribution of the variance ratios obtained from these pairs was used to rank the actual variance ratio (1.52), showing that only 4.6% of the values in the distribution are larger than
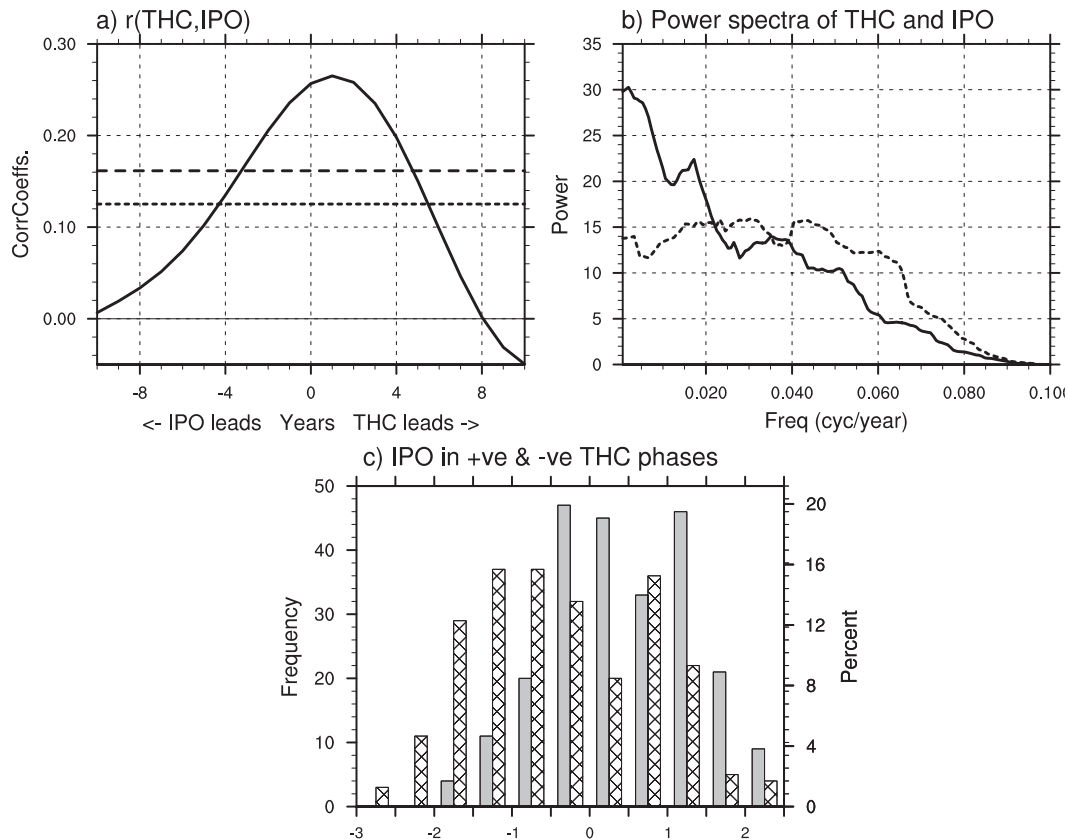
FIG. 3. The mutual relationships between the THC and IPO indexes in a 1600-yr-long control simulation of the HadCM3 model: (a) Lag correlation coefficients between the THC and IPO indices, with statistically significant coefficients (at lag zero) indicated by two thick horizontal lines: short (long) dash for the 95% (99%) level; (b) the power spectra of the standardized indexes of the THC (solid) and the IPO (dash); (c) histograms of the IPO index in the strong (solid) and weak (crosshatch) phases of the decadal THC index. The left and right ordinates show the frequency and percent of occurrences of the IPO values in each bin, respectively. The two distributions are significantly different according to the Kolmogorov–Smirnov test.

1.52. This shows that the IPO variance is larger in the weak THC phase than in the strong THC phase at the 95% significance level (using a one-tailed test). This Monte Carlo test for the difference of variances reinforces the result of the earlier K–S test done for the difference of distributions.

This increased variance of the IPO in the weak THC phase is reminiscent of the enhancement of ENSO variance due to a substantial weakening of the Atlantic meridional overturning circulation (AMOC) found in water-hosing experiments (Timmermann et al. 2007). However, we have not found a corresponding increase in ENSO variance during the weak phase of the THC. Figure 3c also shows that the cold IPO events become more intense and occur more frequently in the weak THC phase. Therefore, there exists a clear, statistically significant distinction in the behavior of the IPO during the strong and weak phases of the THC in HadCM3 simulations.

4. Conclusions and discussion

The impact of natural multidecadal fluctuations in the Atlantic THC on surface climate variability in the Indo-Pacific region has been investigated using a multicentury control simulation of the HadCM3. The main results of this investigation are as follows:

1) THC fluctuations have a detectable impact on Indo-Pacific and Atlantic climate variability at multidecadal time scales. The largest impact is observed in the extratropical Northern Hemisphere, although a significant response is also found in various regions of the Southern Hemisphere. To first order, the response pattern may be described as an interhemispheric seesaw, identified previously in observations (Folland et al. 1999).

2) In the tropical Atlantic, the rainfall response is consistent with a north–south shift in the intertropical convergence zone during the strong and weak phases

of the THC. In the Pacific Ocean, statistically significant responses in all three variables are found, although these are smaller in magnitude than the respective responses in the Atlantic (as expected). One exception is a relatively large rainfall response in the western Pacific north of the equator. While there is a counterpart for the dipole response in the tropical eastern Pacific in water-hosing experiments, the large northwestern Pacific response appears to be unique to natural variations in the THC.

3) There is a small but statistically significant correlation between the multidecadal fluctuations in the THC and the IPO. The temporal variations in the THC index lead to those in the IPO index, indicating that the former is driving the latter. When the THC is strong (weak), the IPO spends more time in its warm (cold) phase.

4) During the strong (weak) phase of the THC, the IPO variance decreases (increases) considerably.

5) Cold IPO events tend to be stronger and more frequent when the THC is in its weak phase.

As noted previously, we did not find any enhancement of ENSO variance (computed from the interannual component of the Niño-3.4 SST index) during the weak phase of the THC, even though the variance of the IPO was enhanced. This is at odds with the similar result (mentioned earlier) obtained from some water-hosing experiments (e.g., Timmermann et al. 2007). One possible explanation for this discrepancy is that the THC changes resulting from natural variability are not strong and persistent enough (compared to water-hosing experiments) to create a detectable change in ENSO variance. While the IPO is thought to arise from a combination of factors that includes random multidecadal changes in El Niño–Southern Oscillation activity (Power et al. 2006), our results suggest that the THC does not influence the IPO through changing El Niño–Southern Oscillation statistics but rather through some other unknown mechanism.

More broadly, this study highlights the possibility that a small part of naturally occurring ENSO-like decadal/multidecadal variability may have a degree of predictability if the surface expression of THC variability exhibits some predictability. It will be very interesting to see if the decadal/multidecadal variability in long control integrations of other climate models exhibits the same characteristics as the model variability evident in the model studied here.

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