North Atlantic weather regimes response to Indian-western Pacific Ocean warming: A multi-model study

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[1]   The extratropical large-scale atmospheric circulation is often described in terms of a few preferred and recurrent patterns referred to as weather regimes. Here, we investigate the influence of the observed Indian and western Pacific Ocean (IP) warming over the last decades, on the frequency of occurrence of North Atlantic weather regimes. A multi-model approach is adopted in which five different atmospheric general circulation models are forced with idealized sea surface temperature patterns mimicking the IP warming. Despite some discrepancies, three models suggest a stronger occurrence of the Zonal regime when IP is warm, compensated by less frequent Greenland Anticyclone regimes, consistently with the observed positive trend of the North Atlantic Oscillation. The other two models simulate instead an increase in the frequency of occurrence of the Atlantic Ridge regime. Variance decomposition into stationary and transient waves suggest two mechanisms at work in the individual models. The AR regime favoured occurrence is associated with a strong transient wave activity along the wave guide in the North Pacific and downstream in the North Atlantic. The Zonal favoured excitation is interpreted as an indirect response to changes in the Tropical Atlantic associated with a global alteration of the Walker cell. **Citation:** SanchezGomez, E., C. Cassou, D. L. R. Hodson, N. Keenlyside, Y. Okumura, and T. Zhou (2008), North Atlantic weather regimes response to Indian-western Pacific Ocean warming: A multi-model study, *Geophys. Res. Lett.*, 35, L15706, doi:10.1029/2008GL034345.

1. Introduction

[2]   It has been suggested that a significant part of the observed changes in the North Atlantic climate in the last decades has been induced by a warming trend in the tropical sea surface temperatures (SST) [*Hoerling et al.*, 2001; *Sutton and Hodson*, 2003; *Hurrell et al.*, 2004]. Some studies show in particular that the Indian Ocean warming plays a dominant role [*Bader and Latif*, 2003; *Selten et al.*, 2004; *Hoerling et al.*, 2001; *Bader and Latif*, 2005] and may be the main contributor to the recent positive trend of

the North Atlantic Oscillation (NAO) [*Hurrell*, 1995]. It has been hypothesized that such a North Atlantic response is mainly eddy driven via a circumglobal pattern along the South Asian and North Atlantic Jets [*Hoerling et al.*, 2001] associated with changes along the local storm track. It appears though that the mechanism are still very unclear and questionable (model dependence in particular).

[3]   The aim of this study is to further investigate the influence of the Indo-Pacific (IP) ocean SST warming on the North Atlantic atmospheric circulation based on a multi-model approach. Five atmospheric general circulation models (AGCMs, Table 1) have been forced with the exact same idealized SST patterns mimicking the observed decadal changes in the IP domain. These experiments have been performed within the European Union Framework 6 DYNAMITE project (Understanding the Dynamics of the Coupled Climate System, http://dynamite.nersc.no/). In difference to previous studies that focused on the NAO, the simulated atmospheric response to the IP SST warming is investigated here in terms of changes in the frequency of occurrence of weather regimes. The latter characterize, in a more discriminant way, the large-scale atmospheric circulation and its associated time-scale interaction. The concept of weather regimes [*Vautard*, 1990] arises from the assumption that the atmosphere stays in a few preferential states considered as peaks in the probability density function of the phase space. These patterns are commonly identified by cluster analysis [*Michelangeli et al.*, 1995].

[4]   The outline of the paper is as follows: In section 2 we briefly describe the coordinated experiments and the methodology. The results are presented in section 3 and we finish with a discussion in section 4.

2. Model Experimental Design and Methodology

2.1. Coordinated Experiments

[5]   Winter (December–February, DJF) SSTs averaged over the Indian and western Pacific basins have significantly increased by $0.5° ± 0.1°$ Celsius since 1950 (Figures 1a and 1b), while concurrently, the difference in DJF geopotential height at 500 hPa (Z500) between 1976–1999 and 1950–1975 projects onto the positive phase of the NAO (Figure 1c). The concomitance between the two decadal remote signals is intriguing and is investigated using forced AGCMs (see Table 1 for their characteristics). Three experiments of 40 years length are performed: a control experiment (CNTL) forced with climatological SST and sea ice concentration computed over 1961–1990 from the HadISST dataset [*Rayner et al.*, 2003], and two experiments where an SST anomaly pattern is either added (WIP) or subtracted (CIP) to the SST climatology of CNTL over the

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Table 1. Summary of Some of the Features of the AGCMs Used in This Study

Institute	AGCM	Resolution	Vertical Levels	Reference
CERFACS	ARPEGE	T63	31	*Gibelin and Déqué* [2003]
U. of Reading	HadAM3	2.5 × 3.75	19	*Pope et al.* [2000]
Ifm-GEOMAR	ECHAM5	T63	31	*Roeckner et al.* [2003]
NCAR	CAM3	T42	26	*Collins et al.* [2004]
IAP	GAMIL	2.8 × 2.8	26	*Li et al.* [2007]

IP region only (Figure 1b). Anomalous SSTs are obtained as follows

$$WIP = Clim + 23.5*IP'$$

$$CIP = Clim - 24.5*IP'$$

where the SST anomaly pattern (IP') is the seasonal mean SST trends in the IP region between 1951 and 1999 interpolated to calendar months. CIP (WIP) corresponds to the SST after 23.5 (24.5) years of cooling (warming) and their difference (Figure 1b for DJF) hence reflects the changes in the IP SST between 1951 and 1999. In all experiments and AGCMs, the solar constant is 1365 Wm^{-2} and greenhouse gas concentrations are set to their 1961–1990 mean. The first year of integration (spin-up) is discarded for all the models and experiments. The volcanos impact has not been taken into account in the experimental setup.

2.2. Methodology

[6] The observed North Atlantic weather regimes are estimated from DJF Z500 using the ERA40 dataset [*Uppala et al.*, 2005]. They are determined from the *k*-means algorithm [*Michelangeli et al.*, 1995], a partitional clustering scheme that classifies all daily maps of Z500 into a predefined number *k* of clusters. Four patterns corresponding to well-known North Atlantic weather regimes are retained here following the literature [*Vautard*, 1990]. The Blocking regime (BL) displays a strong anomalous persistent high over Scandinavia. The Zonal regime (ZO), also considered as the positive phase of the NAO, is characterized by an enhanced zonal flow crossing the North Atlantic basin due to a concomitant reinforcement of the Islandic Low and Azores High. The Atlantic Ridge (AR) regime has a positive anomaly over the North Atlantic basin and low pressure over Northern Europe. The Greenland Anticyclone (GA) pattern is dominated by a strong positive anomaly centered over west of Greenland, and has been frequently referred to as the negative phase of the NAO.

[7] To obtain the model weather regimes in the coordinated experiments, we do not apply the classification algorithm on the model data, since the clustering may produce slightly different clusters for each model in that case. We project instead the model daily Z500 anomalies on the 4 clusters' centroids obtained for ERA40 and treated as a common base. Daily maps are attributed to the respective centroids by a minimization of a similarity criterion. Here, the correlation distance defined as [*Plaut and Simmonet*, 2001]:

$$d_c^i = 1 - corr(C_i, y)$$

is used, where C_i represents the centroid of cluster i and y is a given day in the dataset. The distance d_c ranges from 0 for perfectly correlated patterns to 2 for perfect opposite patterns. Daily Z500 anomalies are computed by removing the daily climatology resulting from the concatenation of CIP and WIP experiments. We only concentrate on the winter DJF season in the following.

3. Results

[8] Differences between WIP and CIP for Z500 suggest that there are two types of simulated responses to IP SST warming given by the five AGCMs taken individually (Figure 2). ARPEGE, HadAM3 and GAMIL show a meridional seesaw pattern over the Atlantic sector which projects onto the ZO weather regime, whereas ECHAM5 and CAM3 responses better reflect the AR regime. The ZO regime emerges in the multimodel ensemble response (Figure 2f), consistently with the dominant positive NAO phase concurrent with the IP warming observed in NCEP (Figure 1c). Note that the models do not capture the Pacific North American pattern (PNA) *Wallace and Gutzler* [1981] signature, clearly seen in Figure 1c, and interpreted as the midlatitudes response to El Niño-Southern Oscillation. Recall that SST climatology is prescribed in all the experiments in the central and eastern equatorial Pacific.

[9] We now investigate the excitation of the simulated North Atlantic regimes in the CIP and WIP simulations estimated in terms of the frequency of occurrence averaged over the 40-years of integration. First, weather regimes obtained in the AGCMs are validated using CNTL runs. Their spatial patterns obtained by composite analysis (not shown) are in good agreement with ERA40 as well as their mean frequency of occurrence, indicating that the projection procedure to obtain the model regimes is satisfactory and that weather regimes themselves are correctly captured by the models. Note though that AR occurrence (Table 2) is underestimated in most models especially in ARPEGE and HadAM3, and except CAM3. By compensation, the GA regime occurrence is overestimated, reaching a bias equal to 10% maximum in GAMIL. No significant biases are found for BL and ZO.

[10] Figure 3 shows the mean frequency of occurrence of the North Atlantic weather regimes for CIP and WIP experiments separately. To see whether these changes are consistent with the "real" world, the ERA40 occurrences are also added. The latter values have been obtained by splitting ERA40 into two periods, 1958–1976 and 1977–2000 corresponding to CIP and WIP respectively. Results for BL show a significant frequency change in ERA40, indicating a decrease of BL episodes in the last decades. The response is consistent and even stronger for ARPEGE, HadAM3 and CAM3, but not significant in the two other
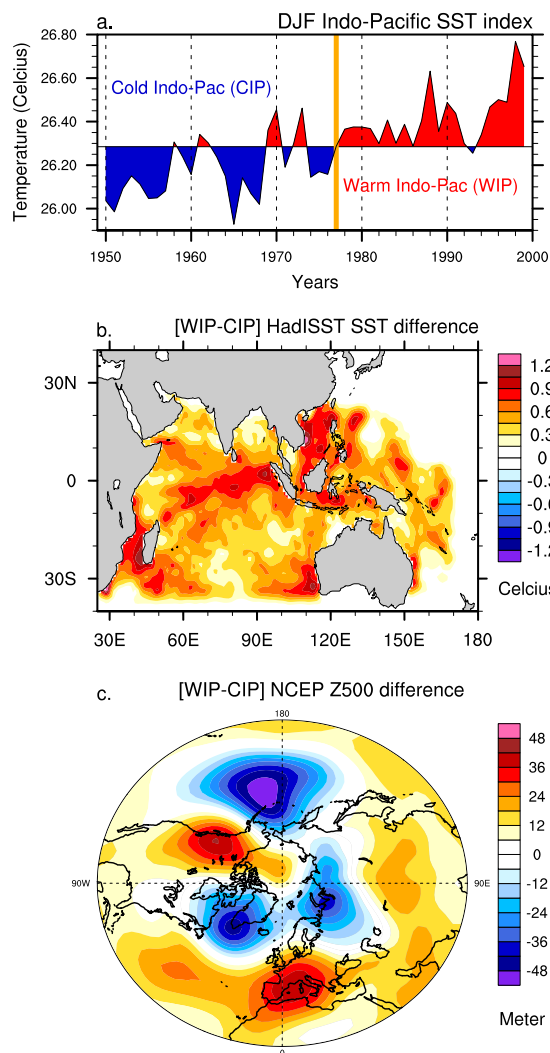
Figure 1. (a) Indian-western Pacific Ocean boreal winter (DJF) SST averaged over (25°E−180°E, 30°S−40°N) from HadISST dataset. (b) SST Indian-western Pacific (IP) pattern of the difference between the period 1976−2000 (warm IP, WIP) minus the period 1950−1975 (cold IP, CIP). (c) Difference of DJF mean Z500 from NCEP reanalyses between the periods 1976−2000 (WIP) and 1950−1975 (CIP).

models. The strongest shift in ERA40 is found for ZO, with a clear increased frequency of occurrence for WIP. As expected from Figure 2, this behaviour is found in ARPEGE, HadAM3 and GAMIL, but not in ECHAM5 and CAM3 which do not simulate any change in ZO in response to IP warming. By contrast, both ECHAM5 and CAM3 suggest a strongest excitation of AR during WIP. The AR response is the least consistent among the 5 models though, with GAMIL response opposite to ARPEGE, ECHAM5 and CAM and no response is found for HadAM3. The frequency of occurrence of GA decreases significantly in ARPEGE, HadAM3, and ECHAM5 to a lower extent, when the IP basin is warm.

[11] Regarding the multi-model ensemble, BL and GA are less excited whereas ZO is clearly favoured. There is no significant changes for AR. These results are in agreement with previous findings, and contributes to assess the robustness of the North Atlantic atmospheric circulation response to the IP SST warming.

4. Discussion

[12] The links between the winter North Atlantic atmospheric circulation and the observed warming in the Indian and West Pacific oceans over the last decades has been addressed within a multi-model approach. In a set of coordinated experiments performed with five different AGCMs where idealized SST patterns mimicking the warming trend are prescribed, we analyse the North Atlantic remote response in terms of changes in the frequency of occurrence of weather regimes. We show in the multi-model ensemble that ZO regimes are more excited when the IP region while GA and BL occur less frequently. No change can be found for AR. This result is consistent with the observation suggesting that part of the observed trend in the North Atlantic such as the NAO could be attributed to the IP influence. We show though that individual model responses
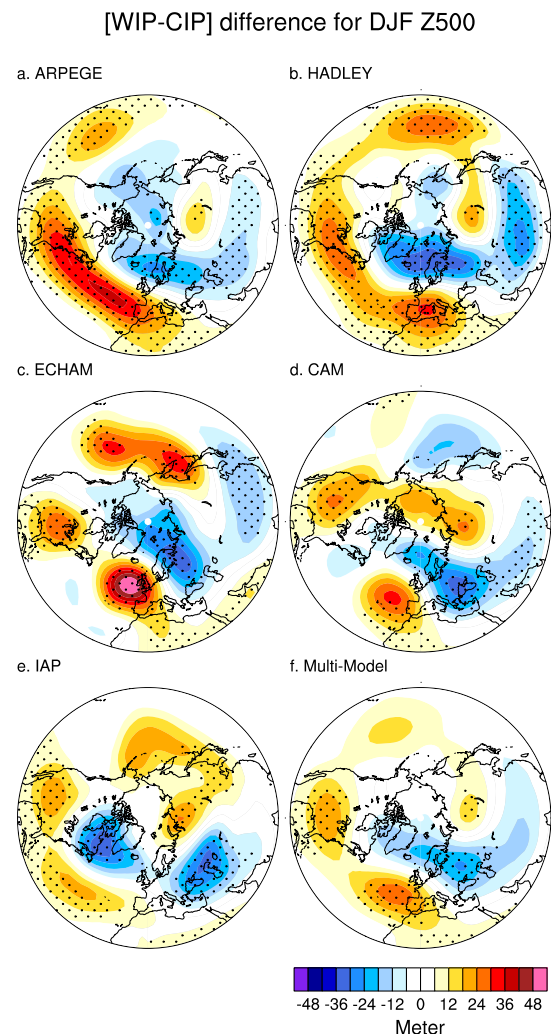
Figure 2. Difference for winter averages (DJF) of Z500 between CIP and WIP idealized experiments for all the AGCMs and the multimodel ensemble. Significant values at 99% are indicated by the dots.
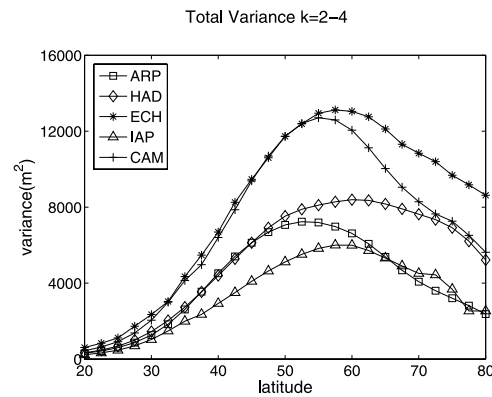
Table 2. Weather Regime Frequency of Occurrence in the ERA40 Reanalysis and in the CNTL Experiment for the Five AGCMs, Shown as a Difference to ERA40[a]

| | Weather Regimes (%) | | | |
	BL	ZO	AR	GA
ERA40	24	30	24	22
ARP	+2	0	−9	+7
HAD	0	+1	−6	+5
ECH	+1	−3	−3	+5
IAP	−2	−4	−4	+10
CAM	−1	−4	−1	+6

[a]The significant differences at 95% significance level are indicated in bold.

Figure 4. Northern Hemisphere variance for the synoptic waves activity of wave numbers 2–4 versus the latitude for the five AGCMs.

are very different and insight on the physical mechanisms responsible for the simulated tropical-extratropical connection may be obtained by studying the individual models.

[13] Based on weather regimes responses, the five AGCMs can be divided into two groups: ARPEGE, HadAM3 and GAMIL together giving a "ZO response" and ECHAM5 and CAM3 leading to increased AR. WIP-CIP differences of the upper level meridional winds show that AR is in fact associated with a Northern Hemisphere wave activity along the waveguide [*Branstator*, 2002] in ECHAM5 and CAM3 but not in the three other models. The "Pacific route" is thus dominant in ECHAM5 and CAM3 whose response is best explained by disturbances associated with transient atmospheric waves propagating eastward along the jet guide from the North Pacific to the North Atlantic. To further test this hypothesis, we decomposed the total space-time variance of Z500 from the CNTL runs into four terms [*Doblas-Reyes et al.*, 2001]: the spatio-temporal mean, the zonal variance of climatological stationary waves, the variance of the zonal mean and the variance associated
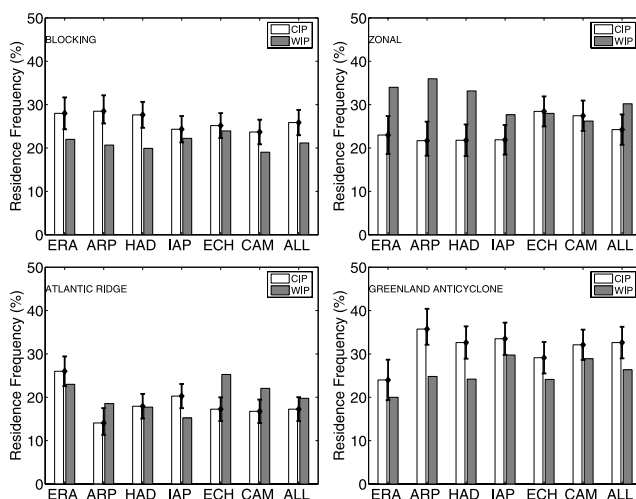
to the space-time transients. Then we applied a wave number-frequency spectral analysis or space-time spectral analysis [*Hayashi*, 1979; *Doblas-Reyes et al.*, 2001] to the transient term leading to its decomposition in low-frequency planetary scale waves and in synoptic waves. The variance for the synoptic waves activity of wave numbers 2–4 and frequency from 2.5 to 8 days as a function of latitude is presented in Figure 4. We observe that ECHAM5 and CAM3 present the highest values of the variance for this specific spatio-temporal window, whereas ARPEGE, HadAM3 and GAMIL are less energetic. This finding based on CNTL suggests that the IP response of the individual models could be explained by the mean different characteristics of the model itself. Figure 4 corroborates the strong possibility of Rossby waves propagation along the waveguide following Branstator's paradigm [*Branstator*, 2002] for ECHAM5 and CAM3 because of favorable climatological background.

[14] ARPEGE, HadAM3 and GAMIL North Atlantic remote responses is probably explained by an indirect route via changes in the Walker cells. Anomalous potential velocity at 200 hPa (not shown) show a strong subsidence over a broad tropical Atlantic in response to IP warming. The latter could be responsible for changes in weather regime occurrences in line with several studies [*Terray and Cassou*, 2002] suggesting enhanced NAO+ events when precipitation is reduced in the Tropical Atlantic.

Figure 3. Relative changes in the frequency of occurrence for the North Atlantic weather regimes in the boreal winter season. Error bars represent the significance levels of the difference between CIP and WIP experiments, determined by building a probability distribution function of frequencies from a number (1000) of weather regimes random classification. Horizontal axis indicates the model: ARP (ARPEGE), HAD (HadAM3), ECH (ECHAM5), IAP (GAMIL) and CAM (CAM3).

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