

Weather Pattern Changes in the Tropics and Mid-Latitudes as an Indicator of Global Changes

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| <ul style="list-style-type: none"> 1. Introduction 2. Observed Changes in Extra-Tropical Patterns <ul style="list-style-type: none"> 2.1. North Atlantic Oscillation (NAO) 2.2. Pacific North America (PNA) | <ul style="list-style-type: none"> 3. Changes in Tropical Patterns <ul style="list-style-type: none"> 3.1. El Niño Southern Oscillation (ENSO) 3.2. Tropical Cyclones 3.3. Monsoons 4. Conclusion References |
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1. INTRODUCTION

It is now widely accepted in the earth-science scientific community that the emission of large amounts of greenhouse gases of anthropogenic origin (namely carbon dioxide and methane), into the atmosphere is partially responsible for recent trends in the climate of our planet at the global scale [1]. However, the separate of the roles of natural and human influences on climate change has only recently been elucidated [2]. This groundbreaking research has quantified the anthropogenic contribution to climate change through studies involving surface air temperature [3,4], precipitation [5] and sea level pressure (SLP) [6]. In spite of this, climate change at a regional level can be more difficult to understand than changes occurring at the global or hemispheric scales. Recent positive trends in temperature and sea level height have

been amplified or partially offset, at the regional scale, by changes of atmospheric circulation. The same rationale seems to apply to climate change scenarios under a warmer planet [7]. It is therefore important to understand the climatic role of the most important large-scale patterns and to provide an assessment on their changes (variability and trends) over the recent historical period.

Two of the most important modes of atmospheric variability, namely the Southern Oscillation (SO) (later associated with El Niño and coined ENSO) and the North Atlantic Oscillation (NAO) were identified in the pioneering works of Gilbert Walker [8,9]. However, the majority of these large-scale circulation patterns (also known as teleconnections) were only identified unequivocally in the 1980s (e.g. [10,11]). These and subsequent studies confirm the climatic influence of both ENSO and NAO but also of the Pacific-North American Pattern (PNA). These teleconnections are known to have large impacts on the climate of entire continents due to their influence on the main physical mechanisms that rule near surface weather, namely controlling the main cyclone trajectories, enhancing heat advection, changing cloud cover and consequently the radiation balance [12–14]. It should be stressed that the relevance of these modes is seasonally dependent, that is, they only have a signature during part of the year [11]. Other modes, usually of a more regional nature, and only relevant during part of the year, may play a minor, albeit relevant role in modulating local climate.

None of the above mentioned teleconnections presents a distinctively symmetric behaviour over either hemisphere. However, two additional modes have been added in the last decade, the Northern Annular Mode (NAM) and the Southern Annular Mode (SAM) and these are characterised by a certain symmetry in their patterns [15]. The NAM is also known as the Arctic Oscillation (AO) pattern and is closely related to the better established NAO pattern [16].

In this chapter, we will present a summary of the main results published in recent literature on changes in frequency and magnitude of the most important large-scale circulation patterns (NAO, PNA). Secondly, we will focus our attention on major trends in the occurrence of other important tropical patterns, such as ENSO, Tropical Cyclones (TCs) and Monsoons due to their relevance to tropical and sub-tropical climate regimes.

2. OBSERVED CHANGES IN EXTRA-TROPICAL PATTERNS

In the last two decades an increasing number of studies have gathered a wealth of information on changes of the most important circulation patterns that affect the climate conditions in the extra-tropical latitudes of both hemispheres. However, the imbalance between the northern and southern hemispheres in the extent of continental dry land, and affected population explains the bias towards Northern Hemisphere (NH) studies.

Different approaches have been developed to derive the main atmospheric circulation patterns that characterise the large-scale circulation over the entire

NH [10,11]. Here, the NAO and PNA teleconnection indices were obtained from the U.S. National Oceanographic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) (<http://www.cpc.noaa.gov/data/teledoc/nao.shtml>). The methodology employed by CPC to identify the teleconnection patterns is based on rotated principal component analysis (RPCA) [11] applied to monthly mean standardized 50 kPa geopotential height anomalies. Spatial patterns of the NAO and PNA can be seen in Figs. 1 and 3, respectively, and represent the temporal correlation between the monthly standardized height anomalies at each point and the monthly teleconnection pattern time series from 1960 to 2000.

2.1. North Atlantic Oscillation (NAO)

The NAO was recognised more than 70 years ago as being one of the major patterns of atmospheric variability in the NH [8,9]. Historically, the NAO has been defined as a simple index that measures the difference in surface pressure between Ponta Delgada in the Azores and the Icelandic station of

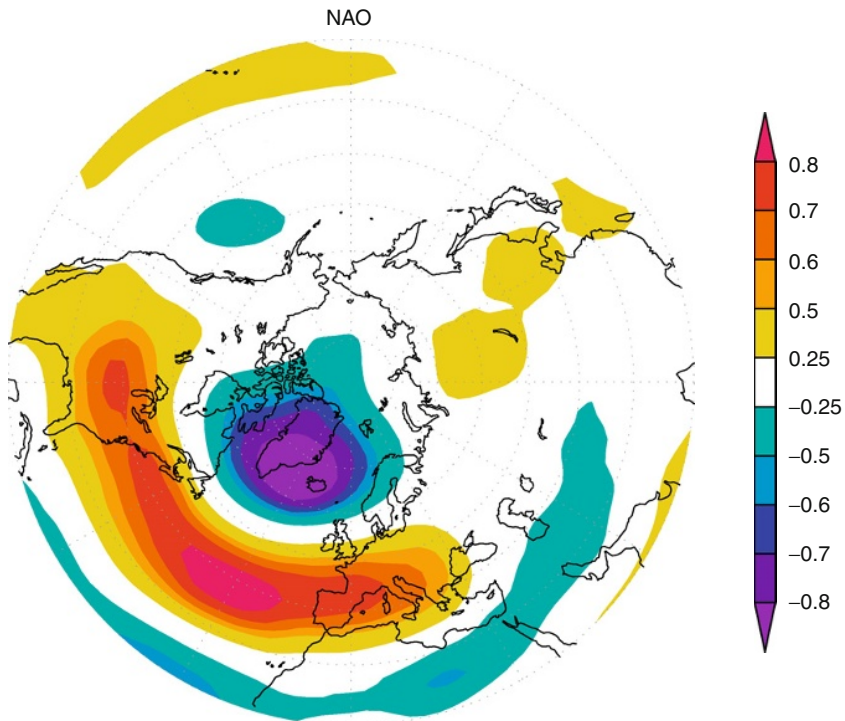


FIGURE 1 Spatial pattern of the NAO as given by the temporal correlation between the Winter (DJFM) monthly standardised 50 kPa geopotential height anomalies at each point and the monthly teleconnection pattern time series from 1960 to 2000.

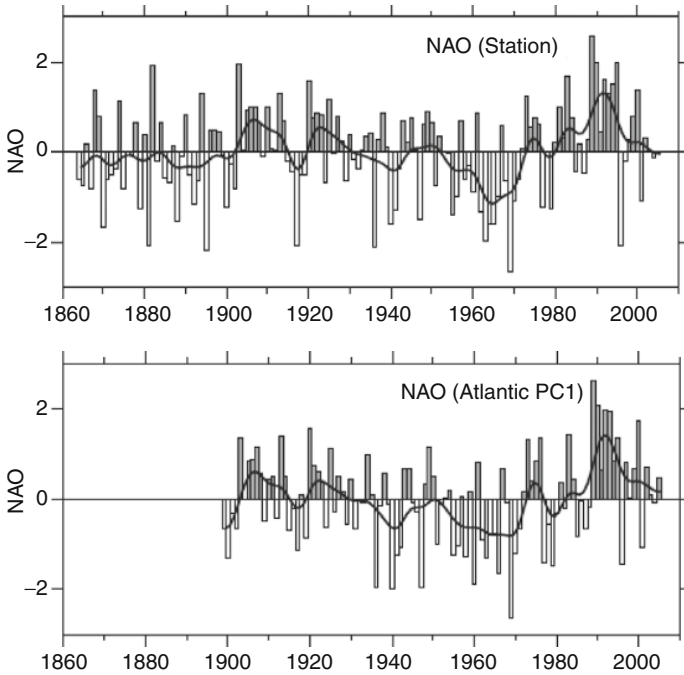


FIGURE 2 (Reprinted from Fig. 3.31 of Ref. [7]). Normalised indices (units of standard deviation) of the mean winter (December–March) NAO developed from sea level pressure data. In the top panel, the index is based on the difference of normalised sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland from 1864 to 2005. The average winter sea level pressure data at each station was normalised by dividing each seasonal pressure anomaly by the long-term (1864–1983) standard deviation. In the lower panel, the index corresponds to the principal component time series of the leading EOF of Atlantic-sector sea level pressure (© Cambridge Press; IPCC report, Chapter 3).

Stykkisholmur (Fig. 2, upper panel). However, a more objective determination of the dipole’s centres of action can be obtained through the application of principal component analysis (PCA) to SLP or tropospheric geopotential height [10,11].

As seen in Fig. 1, the NAO corresponds to a large-scale meridional oscillation of atmospheric mass between the subtropical anticyclone near the Azores and the subpolar low pressure system near Iceland [13]. A number of studies have shown the relevance of the NAO to the winter surface climate of the NH in general and over the Atlantic/European sector in particular (e.g. [13,14,17]). This control is partially responsible for the observed trend towards warmer Northern Eurasian land temperatures that occurred simultaneously with the trend towards a more positive phase of the NAO between the late 1960s and mid-1990s as observed in Fig. 2 [18,19]. Other works have clearly

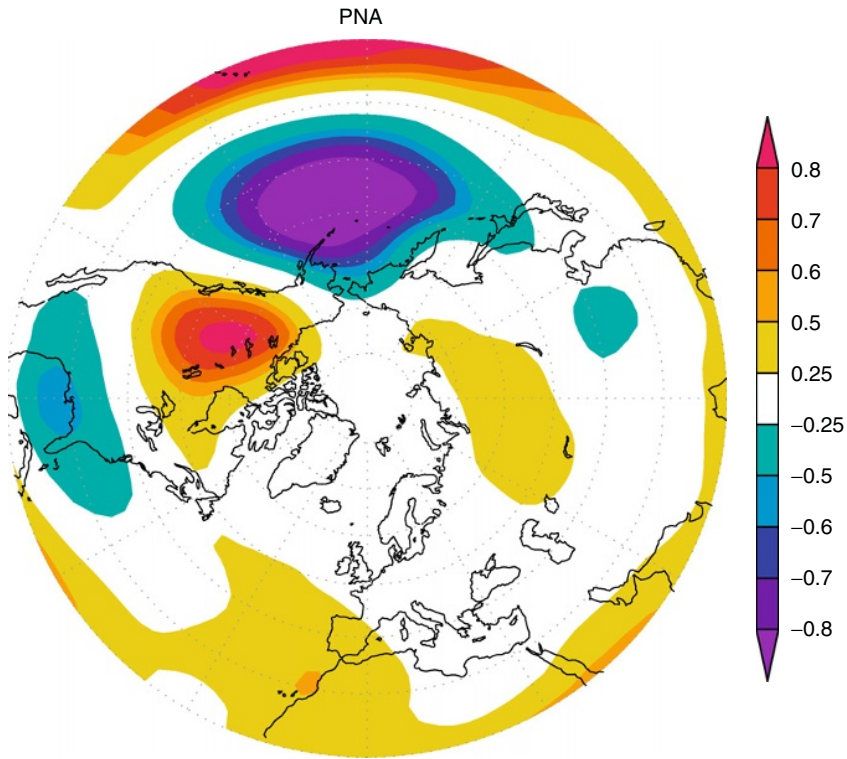


FIGURE 3 Spatial pattern of PNA as given by the temporal correlation between the Winter (DJFM) monthly standardised 50 kPa geopotential height anomalies at each point and the monthly teleconnection pattern time series from 1960 to 2000.

associated the two NAO phases with changes in the activity of North-Atlantic and European storm tracks and precipitation in southern Europe and northern Africa [20–23].

Analyses of SLP and 50-kPa geopotential height over the last five decades reveal negative trends over the Arctic, Antarctic and North Pacific, an increase over the subtropical North Atlantic, southern Europe and Northern Africa and a weakening of the Siberian High [6,7]. The increment in SLP gradients in the NH appears to significantly exceed simulated internal and anthropogenically forced variability [6]. Such changes in within the Euro-Atlantic sector are clearly associated with positive trends in the NAO index (Fig. 2). Moreover, Jung and Hilmer [24] pointed out that the NAO has undergone considerable changes in the location of the main centres, with the northern centre (the Icelandic low) being displaced towards Scandinavia. This shift has major implications for the NH climate, in general, but is particularly important for southern Europe and Northern Africa [22,25].

2.2. Pacific North America (PNA)

Atmospheric circulation variability over the extratropical Pacific is partially dominated by Rossby wave patterns originated in the subtropical western Pacific, associated with anomalous tropical heating [26]. The wave-like pattern that propagates towards the North American Continent is known as PNA pattern, similarly its southern hemisphere counterpart become known as the Pacific-South American (PSA) pattern (not shown). Both patterns can arise from natural atmospheric dynamic internal variability, but also in response to anomalous ocean heating [7]. While the NAO pattern is dominated by two centres of action displaced in latitude (Fig. 1) the typical winter PNA pattern presents four centres of action (with decreasing amplitude) that cover a wide range of latitudinal and longitudinal values between their origin in the subtropical Pacific and North America (Fig. 3). Nevertheless, the PNA impact on the climate of the North American continent is comparable with that imposed by the NAO on the European continent. This influence results from the control exerted by the PNA pattern on weather systems affecting the region, namely the Aleutian Low [27], or the frequency of Alaskan blocking events and associated cold air outbreaks over the Western USA in winter [28].

Long-term variability (decadal scale) of the activity of both PNA and PSA patterns appear to be modulated by the ENSO signal [27]. However, no systematic changes of their frequency or magnitude have been reported [7].

3. CHANGES IN TROPICAL PATTERNS

3.1. El Niño Southern Oscillation (ENSO)

Unlike other large-scale atmospheric circulation patterns mentioned before, ENSO is a truly coupled ocean-atmosphere oscillation mode. The SO represents the atmospheric branch of the ENSO phenomena and refers to the seesaw in pressure across equatorial Pacific, well encapsulated by the Southern Pacific Index or Southern Oscillation Index (SOI); the pressure difference between Tahiti in mid-Pacific and Darwin in northern Australia [8,9]. The El Niño is characterised by a strong warming of tropical waters in central and eastern Pacific following the decrease in strength of the trade winds. This pattern leads to an increase (decrease) of precipitation in central and eastern (western) tropical Pacific [29]. These changes occur intermittently (about once every three to seven years), alternating with the opposite phase – La Niña – that is characterised by below-average temperatures in central and eastern tropical waters. It is also worth noticing that, in contrast to the NAO and PNA patterns, the climatic impacts of ENSO are of a global scale and not restricted to the inter-tropical belt [29,30]. In fact, the signature of these events in SLP extends often into the extra-tropical latitudes (Fig. 4).

The frequency and strength of ENSO has varied over time at the decadal, centennial and millennia scales. A power spectrum analysis applied to the

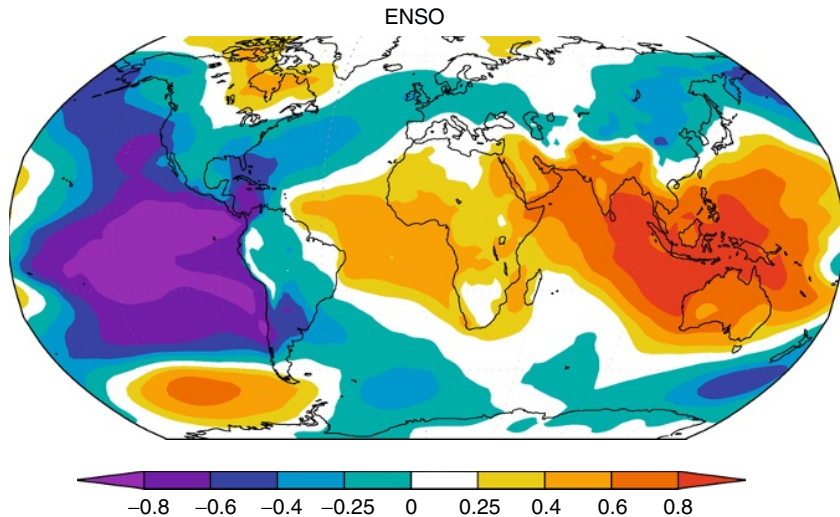


FIGURE 4 Spatial pattern of El Niño as given by the temporal correlation between the annual (May–April) standardised SLP anomalies at each point and the monthly teleconnection pattern time series from 1960 to 2000.

time series of El Niño events since 1500, obtained through the reconstruction of its impacts in Peru, presents a clear peak in power spectrum of about 80–100 a [31]. However, these reconstructions can be misleading because they are highly regionalised and depending on either limited documentary sources or specific natural proxies. Reliable time series of ENSO should take into account the multitude of impacts associated with this phenomenon and are therefore restricted to the last 130 a [7,30]. Based on these authoritative sources one can state that the period spanning between 1870 and 1920 was characterised by frequent El Niño events including several strong cases (Fig. 5). From the 1920s until the early 1970s the ENSO activity was relatively quieter (with the important exception of 1941–1942). However, over the last three decades there has been a resurgence of large (e.g. 1982–1983 and 1997–1998) and prolonged (1991–1995) El Niño episodes (Fig. 5), associated with a tendency towards positive SST anomalies in central and eastern equatorial Pacific. The large El Niño episode of 1997–1998 was the largest on record contributing significantly to the highest global average temperature recorded in 1998. Furthermore, hydrological cycle extremes associated with El Niño events (e.g. drought and floods) will probably be more frequent in a warmer world. The current generation of coupled ocean atmosphere climate models are capable of reproducing El Niño events and their impact relatively well. When forced with distinct climate change scenarios these very same models predict continued ENSO interannual variability [7].

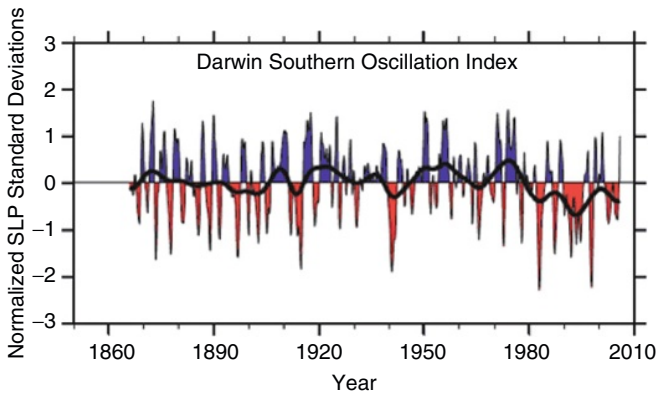


FIGURE 5 (Reprinted from Fig. 3.27 of Ref. [7]). The Darwin-based SOI, in normalised units of standard deviation, from 1866 to 2005 features monthly values with an 11-point low-pass filter, which effectively removes fluctuations with periods of less than 8 months [49]. The smooth black curve shows decadal variations. Red values indicate positive sea level pressure anomalies at Darwin and thus El Niño conditions. (© Cambridge Press; IPCC report, Chapter 3).

3.2. Tropical Cyclones

TCs are among the most destructive natural hazards in the world. Therefore, large fluctuations in tropical cyclone activity are of obvious importance to society, particularly in those coastal areas where populations are affected. In addition, the study of changes in tropical cyclone occurrence and activity has great scientific interest because of their large influence on regional and global climate.

The physical mechanisms responsible for TC development are complex and not fully understood, but it is known that they require high values of sea-surface temperatures (SST), a moderate Coriolis force, a pre-existent synoptic perturbation (usually a monsoon trough or easterly wave) and low wind shear [32]. These pre-conditions limit the development of TC to the five tropical oceanic basins represented in Fig. 6. The dependence of TC on high SST values has opened the debate on a possible increase in the frequency and intensity of TCs in a warmer climate. It has been proposed that a rise in SST induced by anthropogenic global warming has already led to a greater number of intense TCs in recent decades [33,34]. Whether this trend is real or an artefact of the short length and inhomogeneity of records is a matter of keen scientific argument [35]. Methods used for detecting and measuring the intensity of TC in different regions of the world have evolved, making it difficult to assess these trends. Furthermore, there is a considerable level of natural interannual and interdecadal variability, reducing the significance attributable to long-term trends. In particular, studies of TC variability in the North Atlantic basin (the most studied one) reveal large interannual and interdecadal swings in storm frequency that have been linked to different

Tropical Cyclones, 1945–2006

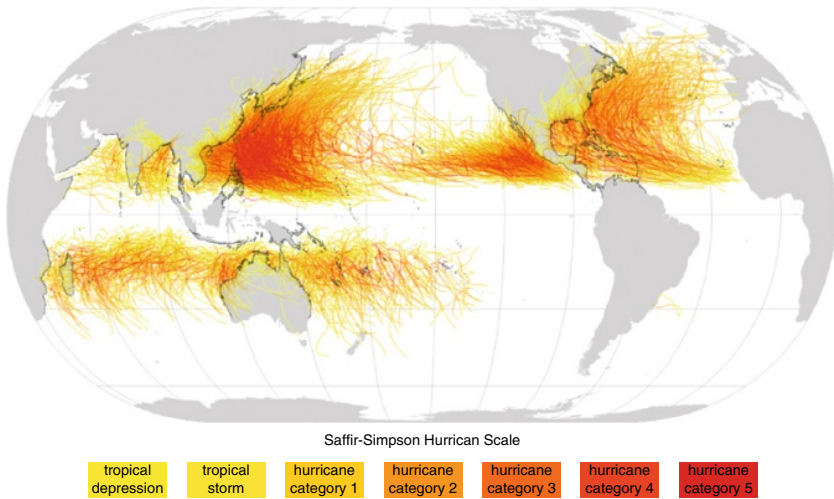


FIGURE 6 Tropical Cyclones, 1945–2006. Data from the Joint Typhoon Warning Center and the US National Oceanographic and Atmospheric Administration (NOAA). Permission is granted to copy, distribute and/or modify this document under the terms of the **GNU Free Documentation License**, Version 1.2 or any later version published by the Free Software Foundation with no Invariant Sections, no Front-Cover Texts and no Back-Cover Texts.

large-scale climate phenomena such as the El Niño/SO, the stratospheric quasi-biennial oscillation and multi-decadal oscillations in the North Atlantic region.

Traditionally, most studies on TC trends focus on the frequency of their occurrence (with weak or no trends detected); however, in recent years studies about trends in intensity have gained importance. In fact the latter is considered nowadays a more relevant index of TC activity (both in scientific and socio-economical terms) than the former, with a strong debate taking place between those authors that support for trends in intensity in the last decades and those that do not. We now summarise both arguments taking into account the most relevant works on this issue.

Two important papers published in 2005 [33,34] found a close relationship between increasing tropical SSTs and intense TCs. Emanuel [33] defined an index for the total power dissipation of a tropical cyclone that is proportional to the cube of wind speed (the Power Dissipation Index, PDI):

$$\text{PDI} = \int_0^{\tau} V_{\max}^3 dt \quad (1)$$

where V_{\max} is the maximum sustained wind speed at the conventional measurement altitude of 10 m. PDI measures the net power dissipation of a TC and, as such, a better indicator of the TC threat than storm frequency or

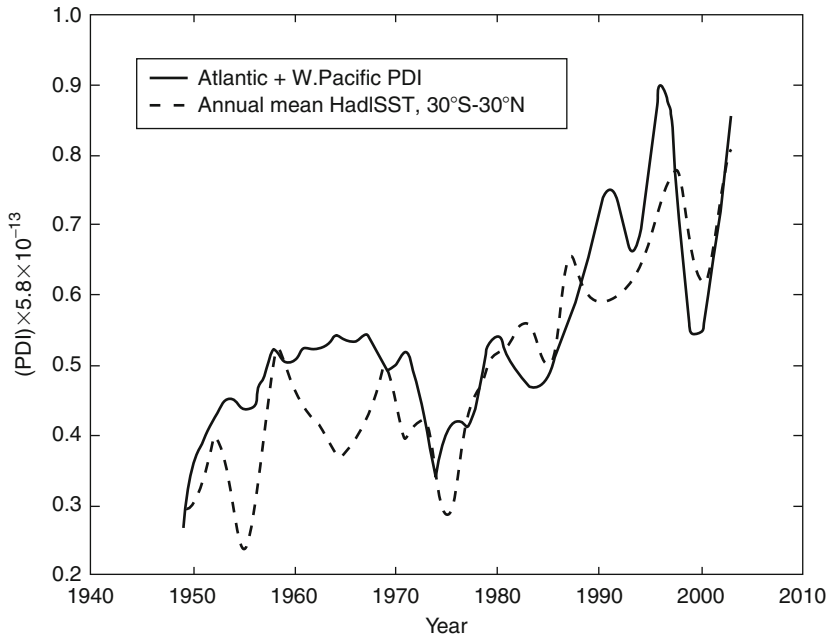


FIGURE 7 (Reprinted from Fig. 3 of Ref. [33]). Annually accumulated PDI for the western North Pacific and North Atlantic, compared to annually averaged SST. The HadISST is averaged between 30°S and 30°N (with a constant offset). Both quantities have been smoothed twice. This combined PDI has nearly doubled over the past 30 a (© Nature Publishing Group).

intensity alone. In a subsequent work [36] the author shows that the PDI has increased by $\sim 50\%$ for both the Atlantic and Northwestern Pacific basins since the mid-1970s (Fig. 7). Webster et al. [34,37] analysed trends and decadal variability of the most intense hurricanes, that is, category 4–5 in Saffir–Simpson classification (maximum sustained winds higher than 115 knots, where 1 knot = $0.5144 \text{ m}\cdot\text{s}^{-1}$) since 1970 for all TC basins. They have found a large increment in the number and proportion of the most intense hurricanes with their numbers nearly doubled between the two consecutive 15-year periods 1975–1989 and 1990–2004. These results have been questioned by other studies (e.g. [38,39]) mainly attending to the poor quality of data prior to 1986, the different intensity attributed to each storm by different research centres [7]. Furthermore, it has also been stressed that the strong association of hurricanes with El Niño events could result in artificial trends when this effect is not removed from the analysis.

Based on the Accumulated Cyclone Energy index (ACE), a wind energy index defined as the sum of the squares of the estimated 6 h maximum sustained wind, Klotzbach [39] found no statistically significant trend in any TC database since 1986 (Fig. 8). In spite of the differences in the results concerning trends, all the previous studies and indices are in agreement on

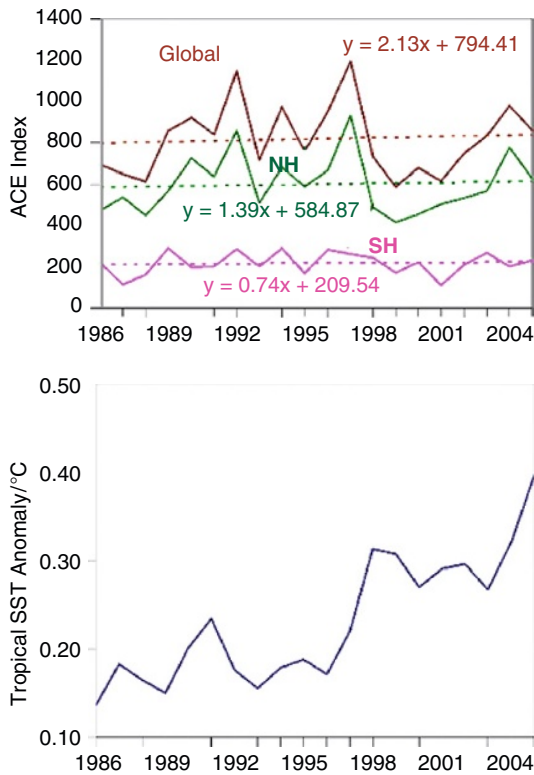


FIGURE 8 (Reprinted from Fig. 2 of Ref. [39]). The upper graph shows Accumulated Cyclone Energy (ACE) index values for 1986–2005 for the Northern Hemisphere (NH), the Southern Hemisphere (SH) and the Global. The dashed lines are linear trends that have been fitted to the three curves. The lower graph shows five-year running mean tropical NCEP reanalysis SST anomalies (23.52°N–23.5°S, all longitudes). The base period for tropical SSTs is 1951–1980 (© AGU).

the strong role played by the El Niño/SO in the activity and occurrence of TCs. Both TC activity indices (PDI and ACE) have attained their highest values during the major El Niño event that took place in 1997–1998. Again, it should be stressed that most of these TC-related index time series are relatively short, in particular the ACE index starts only in 1986 and therefore is not long enough to provide reliable trends [1].

Analysis of longer series and influences of major external forcings and modes of climate variability should be carefully considered due to strong inhomogeneities of the series. Although there is evidence of important changes in the frequency of TC in pre-instrumental periods (e.g. [40,41]), we will limit this short review to the most homogeneous instrumental period. In any case this analysis should be performed for individual oceanic basins [7], in order to accommodate the different measuring methods of TC activity. In the North Atlantic basin, the one with longest register starting in 1851, the period from

the 1930 to 1960 was very active while the following two decades (1970s and 1980s) were characterised with low TC occurrence and activity. Since the mid-1990s, the activity has risen significantly, with all but two seasons presenting activity above normal. The role played by both Atlantic SST and the occurrence of an El Niño appears to be two determinant factors for TC activity in the Atlantic. It is well known that the El Niño acts to reduce TC activity in the North Atlantic basin whereas la Niña acts to increase it. In the Western North Pacific basin there is a high degree of uncertainty in the significance of trends partially due to the high interdecadal variability and also taking into account the way data is analysed. Nevertheless, the most interesting result is the doubling of the PDI values since the 1950s and the trend towards more intense TC (categories 4 and 5). Moreover, the influence of changes in circulation associated to El Niño/SO in this basin seems to be much more important than changes related to local SSTs. During El Niño events TCs tend to be more intense and longer-lived than during La Niña years, a result that contrasts with that obtained for the North Atlantic basin. A similar influence of the El Niño event also occurs in the Eastern North Pacific basin, where above-normal tropical cyclone activity occurs during El Niño years. However, in this case, SST anomalies and the tropical lower stratospheric Quasibiennial Oscillation (QBO) play also a major role [7]. TCs have a higher intensity in the Eastern North Pacific basin when the QBO is in its westerly phase. For the other two remaining basins, the Indian Ocean, Australia and South Pacific, the influence of El Niño is similar to that observed for the North Atlantic basin (although with a minor amplitude) namely with more intense TCs occurring during la Niña years.

The occurrence of the only document TC in the South Atlantic basin close to Santa Catarina, Brazil in March 2004 should be taken carefully, particularly when it is presented as a signal of frequent phenomena in a warmer planet, since the structure of the cyclone did not agree completely the typical one in a TC.

3.3. Monsoons

According to Trenberth et al. [42] ‘the global monsoon system is a global-scale persistent overturning of the atmosphere, throughout the tropics, that varies according to the time of year’. This means that over the tropics there is a region of intense heating where ascent is produced, which is balanced with adiabatic cooling. Such global atmospheric overturning is the common manifestation of the known regional monsoons over six zonal sectors, namely: Africa, Australia–Asia, North America, South America and the Pacific and Atlantic Oceans (Fig. 9). This is clearly associated with seasonal variation of the so-called monsoon precipitation, which plays a key role in driving monsoon circulations through latent heat release. Shaded regions in Fig. 9a delineate the six mentioned global monsoon domains and the main regional

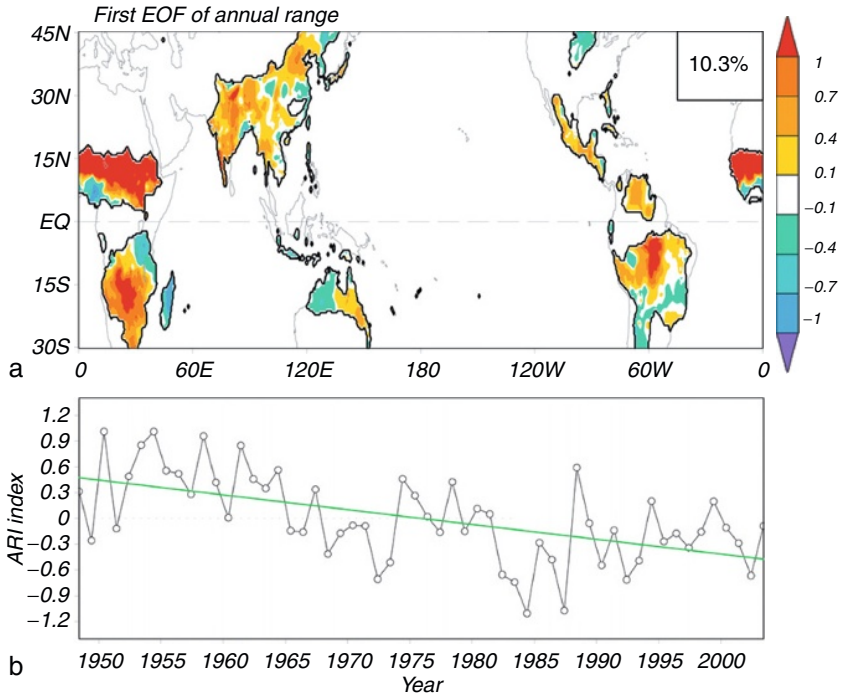


FIGURE 9 (Reprinted from Fig. 3 of Ref. [45]). (a) The spatial pattern of the leading Empirical Orthogonal Function (EOF) mode of the normalised annual range precipitation anomalies over the global continental monsoon regions. The bold contour indicates the boundaries of the monsoon domain; (b) the corresponding principal component or annual range index (ARI) (© Cambridge Press; IPCC report, Chapter 3 and © AGU).

monsoons. The three dimensional structure of monsoon circulation is complex involving three different planetary scale features, namely the Hadley circulation, the Walker circulation and the Inter-Tropical Convergence Zone (ITCZ).

Variability of regional monsoon activity depends on the different interacting circulations from other regions. Its quantification is dependant on the measures of the different monsoon strengths. Therefore, it is not straight forward to address the question of recent regional monsoon changes. Nevertheless, some of the works recently published do present trends in monsoon circulation activity, usually referring to a decrease in strength in the regional monsoonal systems. For instance, Stephenson et al. [43], using reanalysis data and simple shear indices, have shown that summer Asian monsoon strength has been decreasing at a rate of 1–3% per decade. Independently, Chase et al. [44] found that the monsoonal overturning circulations over the Australia-Maritime continent and African regions have diminished since 1950.

More conclusive evidence could be obtained by investigating the topic from a global perspective, that is, from the global monsoon system definition

proposed by Trenberth et al. [42]. In this sense Wang and Ding [45] defined a global monsoon rain domain according to annual precipitation range and quantified the intensity of the global monsoon precipitation using different measures. These authors have applied empirical orthogonal functions (EOF) to the normalised annual range anomalies over the global continental monsoon regions, therefore identifying the leading EOF patterns with 'the global monsoon system' (Fig. 9a). The spatial pattern is clearly coherent with regional monsoons and the corresponding first principal component, coined Annual Range Index (ARI), shows a statistically significant decreasing tendency over the entire period examined (Fig. 9b). In accordance with other studies (e.g. [44]), the trend has been decreasing since 1980. Although ARI presents important interannual and interdecadal variability it is not related to El Niño/SO. Looking at different monsoon regions a strong decreasing trend in monsoon rain intensity was found for Bangladesh/Northern India/Eastern Tibetan Plateau, Northern Africa, the Northern China and Central South America. The only increment in the monsoon strength was seen over northwest Australia.

4. CONCLUSION

Increasing concentration of greenhouse gases in the atmosphere and oceans are bound to further increase the global average temperature by the end of this century [1]. However, this change will not be spatially homogeneous, with polar regions suffering a much higher increment than the tropical belt. Moreover trends in the large-scale driving patterns mentioned in this chapter are especially relevant since they may enhance or damp the warming at the regional scale. Relevant questions in this context are the possible changes of these tropical and extra-tropical modes under global climate change. The results to date seem to indicate that the so-called Annular Modes – the Arctic Oscillation and the Antarctic Oscillation – to which the NAO is linked will tend to become more intense in the future [46], although the signal to noise ratio may be not very large [47]. However, present climate models are still unable to replicate the observed amplitude of the interannual variability and of the multidecadal trends of some modes, for example, the NAO [48].

An enhanced hydrological cycle, with more evaporation and precipitation at the global scale, coupled with changes in frequency of El Niño and TCs and changes in the Monsoon systems may also raise the probability of extremes (floods and droughts). Nevertheless, there is no clear indication of a major shift in the frequency or magnitude of projected El Niño events [7]. Therefore, this ongoing effort should be continued with the aim of determining to what extent climate models yield a realistic picture of the variability in the present climate and evaluating the fraction of future regional climate change that can be attribute to future trends of both tropical and extra tropical circulation patterns, since these patterns will probably be partially responsible for regional differences in the future climate.

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