Chapter 11

The Influence of Natural Climate Variability on Tropical Cyclones, and Seasonal Forecasts of Tropical Cyclone Activity

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In the first part of this chapter, we give a review of the relationship of climate and tropical cyclones on various time scales, from intra-seasonal to decadal. The response of tropical cyclone activity to natural modes of variability, such as El Niño-Southern Oscillation and the Madden Julian Oscillation in various regions of the world are discussed. Genesis location, track types and intensity of tropical cyclones are influenced by these modes of variability. In the second part, a review of the state of the art of seasonal tropical cyclone forecasting is discussed. The two main techniques currently used to produce tropical cyclone seasonal forecasts (statistical and dynamical) are discussed, with a focus on operational forecasts.

1. Introduction

Natural climate variability strongly modulates the seasonal statistics of tropical cyclones (TCs). This modulation of TC activity occurs on multiple time scales (Elsberry, 1997). Here we review these influences as they have been documented in the literature.

We limit our discussion to timescales between the intraseasonal (30–60 day) and multi-decadal (20–50 year). In setting our short-timescale limit at the intraseasonal we exclude consideration of convectively coupled waves (Wheeler and Kiladis, 1999) which significantly influence TC genesis (Dickinson and Molinari, 2002; Frank and Roundy, 2006). At longer timescales, we exclude all variability outside that resolvable in the modern observational record, for which historical (e.g., Liu *et al.*, 2001; Garcia-Herrera *et al.*, 2007) or geological (e.g., Liu and Fearn, 2000; Donnelly *et al.*, 2001) and other proxy data must be used. Recent progress in paleotempestology is expanding the spatial and temporal coverage of the TC record, as well as improving the temporal resolution, dating precision, and accuracy of intensity estimates (Frappier *et al.*, 2007), but this subject is outside our scope. Some further discussion can be found in Knutson *et al.* (this volume).

Our knowledge of the relationships between various modes of climate variability and TCs comes mainly from empirical studies, in which statistical methods are used to extract these relationships. Physical insight naturally enters into such studies in a variety of ways, but ultimately our understanding of the mechanisms which determine the relationships is limited by the same factors that limit our understanding of the mechanisms of the genesis and intensification of individual TCs. For intensity, we have potential intensity theory (Emanuel, 1986, 1988) but this is not a complete theory for the actual intensity of TCs and has been recently challenged (Smith *et al.*, 2008). In any case, potential intensity theory has been relatively little used in statistical studies of TC variability, with some exceptions (Emanuel, 2000; Camargo *et al.*, 2007a; Wing *et al.*, 2007). For TC numbers, we have little theoretical guidance. While there are some theories for aspects of genesis (Bister and Emanuel, 1997; Montgomery *et al.*, 2006) and a number of interesting recent developments (e.g., Raymond *et al.*, 2008; Dunkerton *et al.*, 2008) there is no quantitative theory that goes so far as to give the probability of genesis given some large-scale conditions. We know that variables such as sea surface temperature, vertical wind shear, and midlevel humidity influence genesis (Gray, 1979), and this gives us an empirical basis for understanding how climate variations influence TC numbers. But, first-principles understanding is still very limited. Integrated indices such as accumulated cyclone energy (ACE) and power dissipation depend on intensity, number, and lifetime, and our ability to understand variations in these indices is limited by our lack of understanding of each of the individual factors.

Despite our relative lack of a theoretical foundation for understanding them, the observed relationships between large-scale climate variability and tropical cyclone statistics are strong enough that they make it possible to produce statistical forecasts of tropical cyclone activity on seasonal to interannual time scales. Dynamical forecasts using numerical models are also now feasible, and have hindcast skill that is comparable to the statistical ones.

In the first part of this chapter, the TC-climate relationship on intraseasonal to decadal time-scales will be discussed. In the following section we briefly review the different modes of climate variability whose influences on TCs have been investigated, and in section 3 we review the influences these modes have been found to have, treating each TC basin separately. In the rest of the paper, the state of the art of seasonal TC forecasting will be reviewed.

2. Modes of Variability

The El Niño–Southern Oscillation (ENSO) is a major mode of natural climate variability. ENSO is generated by coupled ocean-atmospheric dynamics in the tropical Pacific (e.g., Trenberth, 1997). ENSO is associated with sea surface temperature (SST) changes in the tropical Pacific, as well as shifts in the seasonal temperature, circulation, and precipitation patterns in many parts of the world (Bradley *et al.*, 1987; Ropelewski and Halpert, 1987). El Niño and La Niña (warm and cold) events usually recur every 3 to 7 years and tend to last for approximately a year. As the ENSO phenomenon can be predicted with some accuracy months in advance (Cane and Zebiak, 1985), ENSO forecasts are routinely used as a major component in the making of probabilistic seasonal climate forecasts (Goddard *et al.*, 2001).

ENSO affects TCs strongly in several basins, though its influence is different in each. The impact of ENSO on North Atlantic TCs (hurricanes) was first discussed by Gray (1984a), and recent reviews of the relationship of ENSO and TCs are presented in Chu (2004) and Landsea (2000). Because of this strong influence and the predictability of ENSO, it is probably the largest single factor in seasonal TC forecasts. A summary of the relationship of ENSO with TCs in all basins is given in Table 1 and is discussed in more detail below.

The North Atlantic basin is the site of several modes of variability, all of which influence TCs. Some aspects of the relationships of these Atlantic modes to each other, and especially of each to global climate change, are controversial. We will be brief on this subject here; we discuss it further to some extent in the Atlantic subsection of section 3, and Knutson *et al.* (this volume) discuss the relationship to climate change in particular in more detail.

The North Atlantic oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region (Hurrell *et al.*, 2003); it is closely related to the global "Arctic Oscillation" pattern (Thompson and Wallace, 2000). The NAO is a large scale atmospheric seesaw between the Atlantic subtropical high and polar low. It is not a true oscillation, but rather has variation at all time scales, with a red spectrum (Stephenson *et al.*, 2000; Feldstein, 2000), and apparently owes its existence largely to the interaction of the jet streams with baroclinic eddies (Woolings *et al.*, 2008; Vallis and Gerber, 2008).

The Atlantic Multi-decadal Oscillation (AMO) is a natural mode of variability in the North Atlantic Ocean on multi-decadal time scales whose existence has been inferred from analysis of the observed sea surface temperature after removing a linear trend (Folland *et al.*, 1986; Delworth and Mann, 2000). It has also been found to exist in coupled numerical models, in which it is a manifestation of variability in the Atlantic Ocean's thermohaline circulation. Further discussion of this mode, and its relationship to other possibly related modes [such as the tropical multidecadal modes (Chelliah and Bell, 2004; Bell and Cheliah, 2006)] as well as to anthropogenically forced global climate change, can be found in Knutson *et al.* (this volume).

The Atlantic Meridional Mode (AMM; Servain *et al.*, 1999; Xie and Carton, 2004; Chiang and Vimont, 2004) is the leading mode of coupled ocean-atmosphere variability in the tropical Atlantic. The AMM is a "meridional mode" (Xie, 1999; Xie and Carton, 2004) associated with meridional displacements of the intertropical convergence zone and attendant shifts in SST and winds. Recent studies (Vimont and Kossin, 2007; Kossin and Vimont, 2007) have shown that Atlantic TC characteristics are closely related to the AMM. Vimont and Kossin (2007) provided evidence that the AMM is likely to be excited on multidecadal timescales by the AMO. While the AMM and the NAO are independent during the hurricane season (Xie *et al.*, 2005c), the AMM was shown to be excited by variations of the NAO (Xie and Tanimoto, 1998; Czaja *et al.*, 2002). The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability with a decadal time scale, impacts in the North Pacific and North American sectors, and secondary signatures in the tropics (Mantua, 2002). The spatial pattern of the PDO is similar to that of ENSO, and it is not entirely clear whether the PDO is a truly independent mode or simply the decadal residual of ENSO variability (e.g., Zhang *et al.*, 1997; Vimont, 2005).

The quasi-biennial oscillation (QBO) is a global-scale, zonally symmetric oscillation of the zonal winds in the equatorial stratosphere (Wallace, 1973) which owes its existence to wave-mean flow interaction (Holton and Lindzen, 1968; Plumb and McEwan, 1978). The QBO has a period of approximately 26 months and its largest amplitude occurs near 30 hPa.

Table 1. Summary of the ENSO impacts on TC activity in the different regions, including references.

Basin	Characteristic	ENSO	Change	References (e.g.)
Western North Pacific	Number of TCs	Strong EN	increase	Wang and Chan (2002)
	Number of TCs	Summer following EN	decrease	Chan (1985), Wu and Lau (1992), Chan (2000)
	Mean genesis location	EN/LN	Displacement to the Southeast/ Northwest	Chan (1985), Chen *et al.* (1998), Wang and Chan (2002), Chia and Ropelewski (2002)
	Lifetime	EN/LN	Increase/decrease	Wang and Chan (2002), Camargo and Sobel (2005)
	Number of intense typhoons and ACE	EN/LN	Increase/decrease	Camargo and Sobel (2005), Chan (2007)
	Track types	EN	Long tracks, recurve northeastward and reach more northern latitudes	Wang and Chan (2002), Wu and Wang (2004), Camargo *et al.*. (2007e)
Eastern North Pacific	Number of intense TCs	EN/LN	Increase/decrease	Gray and Sheaffer (1991), Frank and Young (2007)
	Mean genesis location	EN	Westward shift	Irwin and Davis (1999), Kimberlain (1999)
	Tracks	EN	Longer westward direction	Chu (2004), Camargo *et al.* (2008a)
Central North Pacific	Number of TCs	EN	Increase	Wu and Lau (1992), Chu and Wang (1997), Clark and Chu (2002), Camargo *et al.* (2007a)
Atlantic	Number of TCs, number of hurricanes, number of intense hurricanes, number of hurricane days, number of tropical storms, ACE	EN/LN	Decrease/Increase	Gray (1984a); Gray *et al.* (1983); Landsea *et al.* (1999); Bell *et al.* (2000)
	US landfalls	EN/LN	Decrease/increase	O'Brien *et al.* (1996); Bove *et al.* (1998); Pielke and Landsea (1998); Larson *et al.* (2005)
North Indian	Number intense TCs	EN	Decrease (Bay of Bengal)	Singh *et al.* (2000)
South Indian	Number of TCs east of 70°E	LN	Increases	Kuleshov (2003)
	Peak of the season	EN/LN	February/January	Kuleshov (2003)
	Start of the season	LN	1 month earlier	Kuleshov (2003)
	Mean genesis location	EN	Westward shift — increase (decrease) west (east) of 75°E	Ho *et al.* (2006)
	Tracks	EN	Movement further east	Ho *et al.* (2006), Kuleshov *et al.* (2008)

The Madden-Julian Oscillation (MJO; Madden and Julian, 1972, 1994; Zhang, 2005) is the strongest mode of intraseasonal variability in the tropics. The MJO has a 30–90 day period and consists of large-scale coupled patterns of deep convection and atmospheric circulation, with coherent signals in many atmospheric variables. The MJO propagates eastward across the global tropics, with signatures in deep convection primarily in the Indian and western Pacific Oceans. The MJO is stronger in boreal winter than in boreal summer (e.g., Wang and Rui, 1990) and modulates the formation of tropical cyclones in several basins.

3. Regional Variability

3.1. *Western North Pacific*

There is pronounced interannual variability in TC activity in the western North Pacific, in large part due to ENSO. Wang and Chan (2002) observed an increase in the number of TCs in the western North Pacific during strong El Niño events, though they found no significant linear relationship between TC number and indices of ENSO. A reduction in the number of TCs occurring in the summer following an El Niño event has also been found, and is related to the longitudinal shift of the Walker circulation (Chan, 1985; Wu and Lau, 1992; Chan, 2000).

ENSO has an important and well-documented impact on the mean TC genesis location, with a displacement to the southeast (northwest) in El Niño (La Niña) years, as shown in Fig. 1 (Chan, 1985; Chen *et al.*, 1998; Wang and Chan, 2002; Chia and Ropelewski, 2002). Because of this shift to the southeast, further away from the Asian continent, typhoons in El Niño years tend to last longer (Wang and Chan, 2002) and be more intense than in other years (Camargo and Sobel, 2005; Chan, 2007).

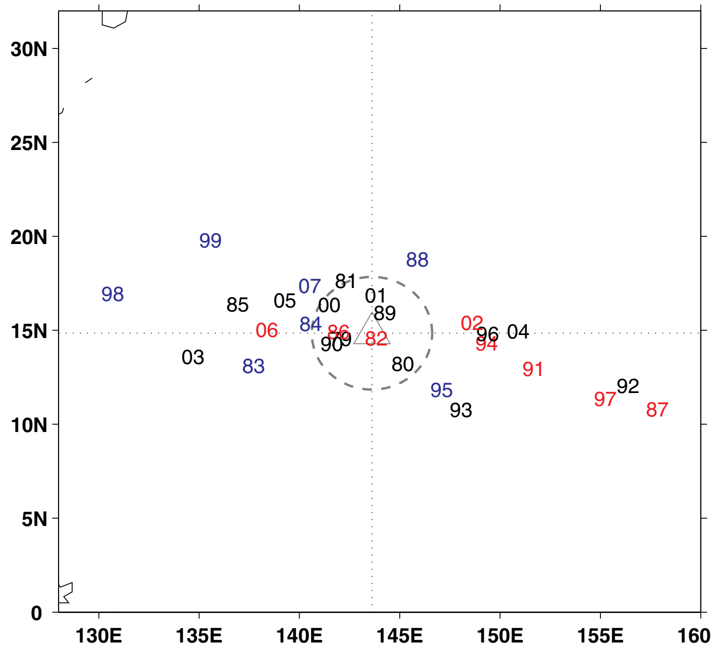

Figure 1. The seasonal mean (July to October) genesis position from 1979 to 2007, "87" is the seasonal mean from 1987, for instance. The triangle shows the long term (1979–2007) seasonal mean genesis position at the center of the circle. The radius of the circle (333 km, i.e., near 3° of latitude) is the standard deviation of the seasonal TC position. El Niño years are shown in red, La Niña years in blue. This is an updated version of a figure that appeared originally in Chia and Ropelewski (2002).

In contrast, in La Niña years, the mean genesis location is shifted to the northwest, so that the storms have shorter lifetimes and tend to be less intense (Camargo and Sobel, 2005).

The genesis location shift has been commonly attributed to the eastward extension of the monsoon trough and westerlies (associated with increased cyclonic low-level vorticity) and the reduction of vertical wind shear near the date line, both of which enhance the likelihood of genesis east of the climatological mean genesis point (Lander, 1994, 1996; Clark and Chu, 2002; Wang and Chan, 2002). The emphasis on these dynamical factors (as opposed to thermodynamic ones) in interannual variability is consistent with the emphasis placed on the monsoon trough more broadly in studies of TC genesis in the western north Pacific (e.g., Harr and Elsberry, 1995; Lander, 1996; Ritchie and Holland, 1999; Chen *et al.*, 2006). While concurring with this, Camargo *et al.* (2007e) also presented evidence that a decrease of mid-level relative humidity near the Asian continent in El Niño years may play a role in the eastward shift as well, by suppressing genesis in the western part of the basin. ENSO affects not only the starting points and lengths of TC tracks but also the shapes of the tracks. In El Niño years, the TCs have a tendency to recurve northeastward and reach more northward latitudes, due both to the shift in mean genesis location and ENSO-induced changes in the mean steering flow (Wang and Chan, 2002; Wu and Wang, 2004). Wang and Chan (2002) and Wu and Wang (2004) showed that in strong El Niño years, the deepening of the east Asian trough in the midtroposphere provides a favorable anomalous steering flow that leads to TCs recurving northward to the extratropics.

Camargo *et al.* (2007d,e) stratified western North Pacific tropical cyclone tracks into seven clusters. Two clusters which start from genesis locations southeastward of the climatological mean and are relatively intense occur more frequent in El Niño years while the largest cluster type is more typical of La Niña events. Consistent with this, storms affect the southern South China Sea more frequently during La Niña years (Zuki and Lupo, 2008), but affect the Central Pacific more frequently in El Niño years (Chu and Wang, 1997; Clark and Chu, 2002). Some Central Pacific storms reach the western North Pacific.

The ENSO's influence on western North Pacific TC tracks is reflected in the landfall rates throughout the region, with different landfall patterns according to the ENSO phase (Saunders *et al.*, 2000; Elsner and Liu, 2003). Wu *et al.* (2004) found a significant relationship between late season landfalls over China and ENSO. Fudeyasu, *et al.* (2006a) noticed an increase in landfalls in the Korean Peninsula and Japan during the early monsoon and in the Indochinese peninsula during the peak monsoon months in El Niño years. The interannual variability of typhoon landfalls in China shows a north-south anti-correlation in the historical and modern records. This is related to sea-level pressure differences between Mongolia and western China, as well as SST over the western North Pacific (Fogarty *et al.*, 2006).

While ENSO has clearly been shown to influence TCs in the western north Pacific, it has also been argued that TCs may play an active role in the dynamics of ENSO itself. El Niño years feature the relatively frequent occurrence of tropical cyclone pairs north and south of the equator over the central and western Pacific Ocean, associated with westerly wind bursts on the equator (Keen, 1982; Lander, 1990; Harrison and Giese, 1991; Ferreira *et al.*, 1996). It has been argued that the twin TCs themselves contribute to the generation of the equatorial westerlies and thus amplify El Niño events, through the standard Bjerknes' mechanism (Keen, 1982; Gau, 1988). While cyclone pairs are spectacular, they are not actually necessary to this scenario, as a single cyclone can generate equatorial westerlies if it is close to the equator (Harrison and Giese, 1991; Kindle and Phoebus, 1995). Since Pacific cyclones tend to form closer to the equator and reach greater intensities in El Niño years, there is the possibility of a positive feedback between ENSO and TCs, with single as well as twin cyclones playing a role (e.g., Sobel and Camargo 2005; see also Yu and Rienecker, 1998; Yu *et al.*, 2003; Eisenman *et al.*, 2005). On the other hand, the causality is difficult to extract from observations, because equatorial westerlies are associated with off-equatorial cyclonic vorticity and other conditions conducive to genesis. It is possible that the westerlies occur primarily for other reasons and that cyclones are largely a passive by-product, as argued by Lander (1990).

The relationship of the quasi-biennial oscillation (QBO) to TC activity in the western North Pacific was examined by Chan (1995), who found that in the westerly phase of the QBO, there are more TCs in the western North Pacific. Chan (2005) attributed this to a decrease in the upper-tropospheric vertical shear over the tropics in the westerly phase. The QBO-TC relationship will be discussed further in the Atlantic subsection, below. Associations on the interannual time scales between western north Pacific TCs and a number of other factors, besides ENSO, have been found. These factors include Tibetan plateau snow cover (Xie *et al.*, 2005b; Xie and Yan, 2007), North Pacific sea-ice cover (Fan, 2007), the large-scale circulation in the extratropical southern hemisphere (Ho *et al.*, 2005; Wang and Fan, 2007), and various other empirically-derived oscillations such as the Asian-Pacific oscillation (Zhou *et al.*, 2008), and the North Pacific oscillation (Wang *et al.*, 2007).

A few studies have examined the decadal and multi-decadal variability of tropical cyclone activity in the western North Pacific. The subject is important, but any results on this time scale must be interpreted with great caution due to the shortness of the data record. The observational record in the western north Pacific is unreliable before the 1950s, and perhaps even before the 1970s (e.g., Wu *et al.*, 2006). Matsuura *et al.* (2003) related the decadal variability in the western North Pacific to long term variations of sea surface temperature in the tropical Central Pacific and westerly winds anomalies associated with the monsoon trough. Chan (2008a) examined the decadal variability of intense typhoon occurrence. Using wavelet analysis, besides the ENSO time-scale (3–7 years), he identified another major oscillation with a multi-decadal period (16–32 years) for intense typhoons, and argued that the environmental conditions conducive to periods of intense typhoons occurrence are largely modulated by ENSO and the Pacific Decadal Oscillation. The decadal variability of TC tracks has also been largely attributed to the Pacific Decadal Oscillation (Liu and Chan, 2008). Ho *et al.* (2004) associated the inter-decadal changes of typhoon tracks with the westward expansion of the subtropical North Pacific High since 1970. The regions with the greatest inter-decadal changes identified in Ho *et al.* (2004) are the East China Sea and the Philippine Sea.

On the intraseasonal time scale, tropical cyclone activity in the western north Pacific is strongly modulated by the MJO. The MJO changes the distribution of TC tracks (Camargo *et al.*, 2007e), and genesis is favored during the active phase of enhanced deep convection (Nakazawa, 1986; Liebmann *et al.*, 1994). The environment during the active phase is favorable to genesis in multiple ways. Midlevel humidity and low-level relative vorticity are both enhanced during the active phase, and the increased occurrence of convection is more likely to generate potential seed disturbances which can undergo genesis. Sobel and Maloney (2000) argued that MJO-induced modulation of wave accumulation (Chang and Webster, 1988; Holland, 1995; Sobel and Bretherton, 1999; Kuo *et al.*, 2001), by which large-scale convergence can amplify synoptic-scale disturbances which can be precursors to TC genesis, might play a role. The idealized numerical calculations of Aiyyer and Molinari (2003) show in particular how MJO-related circulation anomalies can, through dry dynamics alone, amplify mixed

Rossby-gravity waves and change their structure to be "tropical depression type" (e.g., Takayabu and Nitta, 1993) and thus more favorable candidates for genesis.

3.2. *Central and Eastern North Pacific*

During its peak season, the eastern North Pacific is the most active tropical cyclogenesis region per unit area (Molinari *et al.*, 2000). Tropical cyclogenesis in the eastern North Pacific is influenced by wind surges, African easterly waves, topographical effects, ITCZ breakdown, upper-level potential vorticity, and the confluence between the monsoon westerlies and trade easterlies (e.g., Avila, 1991; Bosart and Bartlo, 1991; Zehnder, 1991; Bister and Emanuel, 1997; Ferreira and Schubert, 1997; Zehnder *et al.*, 1999; Molinari and Vollaro, 2000; Vincent and Fink, 2001).

There has been considerable investigation into the influence of ENSO on TC activity in the eastern north Pacific. With very few exceptions (e.g., Whitney and Hobgood, 1997), these studies have found clear relationships between ENSO and various measures of TC activity. Frank and Young (2007) obtained a strong relationship between storm counts and a multivariate ENSO index. Gray and Sheaffer (1991) found an increased number of intense hurricanes during El Niño events. Several studies have found a westward shift in the mean genesis region during El Niño events (Irwin and Davis, 1999; Kimberlain, 1999; Chu and Zhao, 2007; Wu and Chu, 2007; Camargo *et al.*, 2008a). A consequence of this westward shift is that more hurricanes propagate into the central North Pacific region (Chu, 2004).

Some studies have attempted to understand the environmental factors by which ENSO influences eastern north Pacific TCs. Using composites of a genesis potential index keyed to the ENSO state, Camargo *et al.* (2007a) concluded that wind shear is the main contributor, with potential intensity also playing a contributing role. Collins and Mason (2000) identified differing environmental parameters affecting TC activity for the regions east versus west of 116°W. They observed that in the eastern part of the region, the environmental parameters are nearly always at levels conducive to TC formation during the peak season, while in the western region, there are some years when the parameters are conducive to cyclogenesis but other years when they are less so.

Several studies have found a see-saw of TC activity between the North Atlantic and the eastern North Pacific, with enhanced activity in the eastern Pacific when the Atlantic is suppressed, and vice versa (Elsner and Kara, 1999). Stronger anti-correlations are found for stronger TCs (Frank and Young, 2007). It is not entirely clear whether this is simply a result of the fact that ENSO influences the two basins in opposite ways (which is certainly the case), or whether in fact the TC activity in one basin directly influences that in the other by another route.

On decadal time scales, Zhao and Chu (2006) examined the variability of TC activity in the eastern North Pacific using a Bayesian multiple change-point analysis. Their results indicated that hurricane activity in the eastern North Pacific had two inactive eras (1972–1981, 1999–2003) and an active era during 1982–1998.

The probability of cyclogenesis in the eastern North Pacific is strongly modulated by the MJO, as shown in Fig. 2 (Molinari *et al.*, 1997; Molinari and Vollaro, 2000; Maloney and Hartmann, 2000b, 2001; Aiyyer and Molinari, 2008; Camargo *et al.*, 2008a). In the convective MJO phase, anomalous westerlies and cyclonic vorticity occur over the eastern Pacific and Gulf of Mexico. Four times the number of tropical cyclones form in the active phase of the MJO than in the suppressed phase. Additionally, storms forming in the active MJO phase tend to do so closer to the Mexican coast, further increasing the chance of hurricane landfall compared to the suppressed phase (Maloney and Hartmann, 2000b).

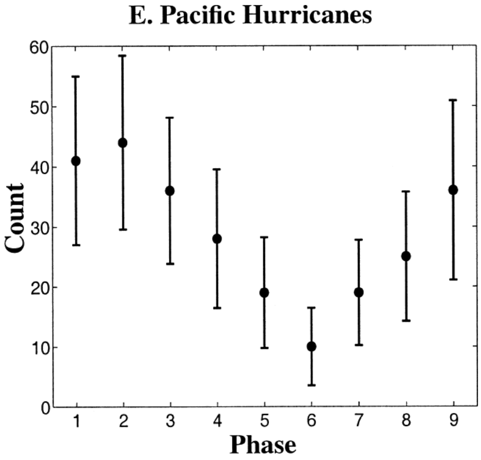

Figure 2. Number of hurricanes as a function of MJO phase for the eastern North Pacific during May — November for 1979–95. Error bars represent 95% confidence level (figure originally from Maloney and Hartmann 2000a).

Various studies have suggested that to a first order, barotropic dynamics can be used to understand the influence of the MJO on eastern north Pacific TCs. Significant barotropic energy conversion from the mean state to the eddies occurs during the convective phase of the MJO (Molinari *et al.*, 1997; Maloney and Hartmann, 2001; Hartmann and Maloney, 2001; Aiyyer and Molinari, 2008). This is consistent with, but more general than, the hypothesis of wave accumulation made in the western North Pacific by Sobel and Maloney (2000); wave accumulation involves barotropic conversion, but the conversion can also happen by other means such as barotropic instability. Aiyyer and Molinari (2008) noticed that in the active phase of the MJO, the vertical shear is relatively weak and tropical cyclones tend to form mainly within the ITCZ. In contrast, during the suppressed phase, the vertical wind shear exceeds $10\,\mathrm{m\,s^{-1}}$ over much of the region, and tropical cyclone development is shifted northward, nearer the Mexican Pacific coast. While these studies have focused on dynamics over thermodynamics, recent work (Camargo *et al.*, 2009) using a genesis potential index to compare thermodynamic and dynamic factors in a quantitative way suggests that MJO-induced variations in thermodynamic variables, particularly midlevel humidity, are important. This is consistent with results from the EPIC field experiment on the MJO's influence on generalized ITCZ convection (Raymond *et al.*, 2003).

The central North Pacific is sometimes considered as a distinct TC basin, though it can share storms (during the course of their lifetime) with either the eastern or western North Pacific. Tropical cyclone occurrence in the central North Pacific is low, with an average of four to five TCs per year. In El Niño years, the number is greater. The higher level of activity in the central North Pacific in warm ENSO events has been attributed to smaller vertical shear and greater low-level vorticity in that region (Wu and Lau, 1992; Chu and Wang, 1997; Clark and Chu, 2002; Camargo *et al.*, 2007a).

Chu and co-workers (Chu and Clark, 1999; Chu, 2002; Chu and Zhao, 2004) also examined the decadal-scale variability in the central North Pacific. They found change points in 1982 and 1995, with fewer cyclones during the 1966–1981 and 1995–2000 periods, and more during the 1982–1994 epoch. In the more active period, warmer sea surface temperatures, lower sea level pressure, stronger low-level anomalous cyclone vorticity, reduced vertical wind shear, and increased total precipitable water were present in the tropical North Pacific, compared to the reduced activity periods. The atmospheric steering flows were also different in October and November of the active period, so that eastern North Pacific cyclones had a higher chance of entering the central North Pacific. During the more active period, the storms that formed within the region were more likely to affect the Hawaiian Islands.

3.3. *North Atlantic*

North Atlantic TC activity has a strong relationship with ENSO. Gray (1984a,b) used this relationship to develop the first Atlantic TC seasonal forecasts. In El Niño years, hurricane activity in the Atlantic is reduced, while in La Niña, it is enhanced. The negative correlation of Atlantic TC activity with ENSO is evident in a wide range of TC activity indices: the number of hurricanes, number of hurricane days, number of tropical storms and ACE (accumulated cyclone energy). The influence of ENSO is very significant for the number of intense hurricanes, as in La Niña years there are usually twice as many intense hurricanes as in El Niño years. The correlations of the number of intense hurricanes with ENSO indices are higher than for weaker storms (Gray *et al.*, 1993; Landsea *et al.*, 1999).

ENSO is generally thought to influence Atlantic TC activity by altering the large-scale environment for genesis and intensification, particularly in the so-called Main Development Region (MDR), where many tropical cyclones form from African easterly waves. During an El Niño year, the vertical wind shear is larger than normal in most of the tropical Atlantic and especially in the Caribbean. This inhibits the formation of TCs. Reductions in vertical wind shear typically occur in La Niña years (e.g., Goldenberg and Shapiro, 1996; Knaff, 1997). Besides these dynamical influences of ENSO, thermodynamic effects have also been identified. Knaff (1997) argued that increased midlevel dryness during El Niño events might be responsible for some of the TC suppression during those events, while Tang and Neelin (2004) argued for the importance of increased moist stability, due to increased tropospheric temperature during El Niño (e.g., Yulaeva and Wallace, 1994; Soden, 2000; Sobel *et al.*, 2002). Camargo *et al.* (2007a) used variants on an empirical genesis index to compare the dynamic and thermodynamic effects of ENSO directly, and found the dynamic effects of wind shear to be more important than the thermodynamic effects in the North Atlantic. In addition to modulating Atlantic TC activity as a whole, ENSO also influences the probability of landfalling hurricanes in the U.S., with an increased probability of landfall in La Niña years (O'Brien *et al.*, 1996; Bove *et al.*, 1998; Pielke and Landsea, 1998; Larson *et al.*, 2005). The probability of two or more hurricane landfalls during a La Niña event is 66%, while in El Niño years it is 28% (Bove *et al.*, 1998). On a more regional basis, the differences in landfall frequencies in the cold and warm ENSO phases are particularly significant for the U.S. East coast (Georgia to Maine), and smaller for the Florida and Gulf coasts (Smith *et al.*, 2007). On a still finer scale, significant differences between specific U.S. Southeast states have been found (Xie *et al.*, 2002). U.S. hurricane losses, unsurprisingly, are also significantly related to ENSO, with much more damage occurring in La Niña events (Pielke and Landsea, 1999). An ENSO influence on landfalling storms has also been found in the Caribbean, both in the modern record (Targlione *et al.*, 2003) and in proxy records from the past 5,000 years (Donnelly and Woodruff, 2007).

A robust relationship existed between Atlantic TC activity and the QBO (Gray, 1984a; Shapiro, 1989; Gray *et al.*, 1992a,b) from approximately 1950–1994. The influence of the QBO appeared to be especially significant for intense hurricane days. Gray *et al.* (1993) found that the number of intense hurricane days which occurred in the easterly phase of the QBO was half that which occurred in the westerly phase. The largest correlation between storm activity and stratospheric winds occurred in June, three months prior to the peak of the Atlantic hurricane season (Shapiro, 1989). The relationship of QBO with the Atlantic TC activity is not statistically significant since 1995 (Klotzbach and Gray, 2004; Camargo and Sobel, 2010).

In our view the mechanism of the QBO-TC relationship is not yet satisfactorily explained. Gray (1988) and Gray *et al.* (1992a,b) argue that the influence comes about due to QBO modulation of vertical wind shear, a finding echoed by Chan (1995) in his study of the QBO influence on western north Pacific TC activity. However, the QBO modulates vertical shear substantially only in the stratosphere, with perhaps a very weak modulation in the very uppermost troposphere. If the shear variations at these high levels are responsible for the QBO-induced TC variations, it means that TCs are quite sensitive to shear even when that shear is confined to their very tops. We know of no evidence to rule this out, but on the other hand we are aware of no studies of any kind (observational, modeling, or theoretical), apart from those on the QBO influence itself, which directly examine the influence of shear at such high levels on TC formation or development, and which thus might provide support for shear as the mechanism of the QBO TC signal. There is a large modeling literature on the influence of shear on TCs, but to our knowledge all those studies examine only the role of tropospheric shear (e.g., Kepert, this volume, and references therein).

Besides the direct effect of shear on TCs, other mechanisms can be considered. Shapiro (1989) conjectured a mechanism involving the difference between the tropospheric and lower stratospheric winds and its influence on the vertical structure of pre-cyclogenesis easterly waves. The QBO also affects lower stratospheric temperature, and the temperature anomalies might be expected to influence TC intensity by the arguments of potential intensity theory. However, the phasing of the QBO-TC activity is inconsistent with this as an explanation for the observed TC variations. TC activity is enhanced during the westerly QBO phase, when the lower stratosphere is warm. This would tend to reduce the potential intensity, not increase it, and thus would be unfavorable rather than favorable for TC activity (Shapiro, 1989).

Atlantic TCs show strong variations on decadal and multi-decadal time scales in the observed record. The literature on these variations is large, and uses a variety of different concepts and nomenclature to describe and interpret them. Our understanding of the decadal and especially multi-decadal variability is somewhat related to that of anthropogenic climate change and its possible long-term influence on TC activity. These issues are discussed in detail in Knutson *et al.* (this volume) and we address this time scale only briefly here, leaving the relationship to global climate change to those authors.

At least until recently, the dominant paradigm for describing these low-frequency TC variations has been the "Atlantic Multidecadal Oscillation" (AMO). The relationship of the AMO to major hurricane activity in the Atlantic through changes in vertical wind shear was discussed by Gray, *et al.* (1997) and Goldenberg *et al.* (2001). The increase in hurricane activity in the Atlantic since 1995 was related by those authors to the modulation of the MDR by the AMO, with above normal SSTs and decreased vertical shear. More recently, a metric was created to describe the AMO based on North Atlantic SST anomalies and basin-wide North Atlantic sea level pressure anomalies, which shows a remarkable agreement with observed multidecadal variability of Atlantic TC activity and U.S. landfall frequency (Klotzbach and Gray, 2008). Normalized U.S. hurricane damage also shows a modulation following the AMO. The 1970s and 1980s saw very little damage compared with other decades, while the 1920s and 1930s, as well as the recent period from 1996–2005 saw very high levels of damage (Pielke *et al.*, 2008). Bell and Chelliah (2006) related the interannual and multidecadal variability of TC activity in the Atlantic to ENSO and two tropical multidecadal modes (TMM). Comparing periods of high activity in the Atlantic, they showed that the most recent increase in TC activity is related to one of the first tropical modes, associated with exceptionally warm SSTs in the Atlantic; while the high activity period in the 1950s and 1960s was more closely associated with the second tropical mode, associated with the West African monsoon.

Other work has related seasonal TC activity in the Atlantic on both interannual and decadal time scales to the so-called Atlantic Meridional Mode (AMM) (Xie *et al.*, 2005a,c; Vimont and Kossin, 2007; Kossin and Vimont, 2007). An attractive feature of this interpretation is that the AMM is not defined purely statistically,

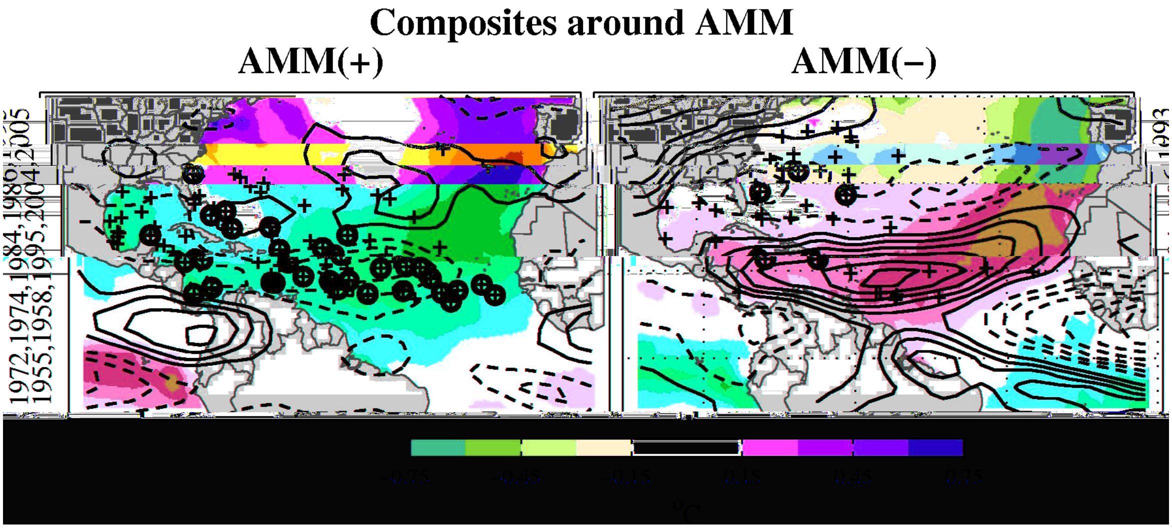

Figure 3. Tropical cyclogenesis points for the five strongest and five weakest AMM years, superimposed on composites of SST (shaded) and shear (contours) anomalies. Crosses show the genesis points for all storms that reached tropical storm strength. Storms that reached major hurricane strength also have a circle around their genesis point. Solid (dashed) shear contours denote positive (negative) values. The contour interval is 0.25 ms^{-1}, and the zero contour has been omitted. Figure originally from Kossin and Vimont (2007).

but has a dynamical interpretation as a natural mode of the climate system in the Atlantic (Xie and Carton, 2004). [Interestingly, the eastern Pacific also appears to have an analogous meridional mode, though ENSO must be removed from the data in order to see it (Chiang and Vimont, 2004). Figure 3 shows the TC genesis locations, SST and vertical shear anomalies in the different phases of the AMM. The AMM modulation comes about through its influence on a number of environmental variables that influence TC activity, such as SST and vertical wind shear. During the positive AMM phase (above normal SSTs in the North Atlantic) there is an overall increase of TC activity in the Atlantic, with the mean genesis location shifting eastward and towards the equator. Also associated with a positive AMM is an increase in storm duration and the intense hurricane frequency (Kossin and Vimont, 2007). The relationships between Atlantic TC variability and various other aspects of regional climate variability implicit in the AMM have been documented previously. For instance, the relationship of African Sahel rainfall to Atlantic hurricane activity is well known (Gray, 1990; Gray and Landsea, 1992; Landsea and Gray, 1992), as is the relationship of the AMM to Sahel rainfall (Folland *et al.*, 1986). The AMO influence on TCs can also be viewed as manifesting itself through the excitation of the AMM by the AMO (Vimont and Kossin, 2007). The value of the AMM is that it provides a unified, physically-based framework for interpreting a variety of influences on Atlantic TCs on a range of time scales.

Similarly to the Pacific, the MJO also modulates TC activity on intraseasonal time scales in the Atlantic. When the MJO is in its active phase over the eastern Pacific, four times more hurricanes form in the Gulf of Mexico and western Caribbean than in the suppressed MJO phase (Maloney and Hartmann, 2000a). During the active phase (westerly over the eastern Pacific), cyclogenesis tends to be shifted northward, to near the Mexican Pacific coast and the Gulf of Mexico. Idealized numerical calculations of the MJO show that in the active phase, easterly waves tend to propagate westward into the eastern Pacific, while during the suppressed phase, they are steered into the Gulf of Mexico (Aiyyer and Molinari, 2008).

The role of easterly waves in Atlantic TC variations on all time scales is an interesting question. In general, interannual and longer-timescale variations in Atlantic TC activity tend to be interpreted in terms of variations in the large-scale environment. This amounts to assuming a constant supply of precursor disturbances, so that variations in TC number (for example) are assigned to variations in the probability that those disturbances will undergo genesis. However, one might also ask whether TC variations might be related to variations in the supply of easterly waves impinging on the Atlantic from Africa. African easterly waves have considerable interannual variability, in number, intensity and tracks. The low-frequency (i.e., decadal) variability of the easterly waves is correlated with Atlantic TC activity, as well as with the west African monsoon and Atlantic SSTs. However, on interannual time scales the Atlantic TCs and the number of easterly waves are not significantly correlated, though a synoptic-scale measure of easterly wave activity (variance of meridional wind filtered to synoptic time scales) does show a significant positive correlation with TC activity on interannual time scales (Hopsch *et al.* 2007). Similarly, the number of easterly wave disturbances is not correlated with ENSO on interannual time scales, though the variance of filtered meridional wind is (S. Hopsch, personal communication). Since enhanced wind variance could be partly a result as well as a cause of enhanced TC activity, it seems reasonable to conclude tentatively that easterly wave variability is not an important factor responsible for the ENSO signal in Atlantic TCs. Nonetheless, the relative importance of variations in the supply of precursor disturbances vs. variations in the large-scale environment is worthy of further study in all basins, including the Atlantic.

3.4. *North Indian Ocean*

In contrast to other ocean basins, where the TC activity has a peak in the late summer or early fall of the corresponding hemisphere, North Indian Ocean cyclones primarily form in the traditional monsoon seasons — spring and autumn. One interpretation is that this is the case because it is only during these periods that the monsoon trough is located over open water (e.g., Lee *et al.*, 1989; Singh *et al.*, 2000), though it seems to us likely that the strong vertical wind shear associated with the peak monsoon may play a role in suppressing cyclones during that time.

There is a link between western North Pacific TCs and monsoon depressions over the Indian Ocean (e.g., Chen and Weng, 1999). Many monsoon depressions can be traced back to northwest Pacific TCs. Remnants of these TCs can propagate into the Bay of Bengal, where they can reintensify under the influence of warm SSTs and high moisture content that is present in the monsoon flow. Depending on the season, these monsoon depressions can then redevelop as cyclones in the Indian Ocean (Fudeyasu *et al.*, 2006b). In 1997, an El Niño year, there was a particularly close association between intense monsoon depressions and strong tropical cyclone activity in the northwest Pacific (Slingo and Annamalai, 2000). In El Niño years, during the months of July and August, there is also a higher number of monsoon depressions in the Bay of Bengal (Singh *et al.*, 2001).

There is a strong association between the variability of sea surface temperatures in the Indian and Pacific Oceans (Pan and Oort, 1983). During most El Niño events, the overall SSTs in the Indian Ocean increase, with a lag of 3–6 months after the peak SST in the central and eastern Pacific. The Indian Ocean warming is often associated with weaker surface wind speeds, though the tropospheric temperature increase throughout the global tropics, leading to increased stability to deep convection, may also play a role (Chiang and Sobel, 2002). Singh *et al.* (2000) noticed fewer intense tropical cyclones in the months of May and November in the Bay of Bengal during El Niño years.

Frank and Young (2007) observed a positive correlation between Indian Ocean TC activity and that in the Atlantic, and related this to reduced activity in the Indian Ocean during the positive phase of the NAO.

On the intraseasonal timescale, cyclone activity in the North Indian Ocean is strongly modulated by the MJO, with more activity when the MJO convective phase is over the Indian Ocean (Liebmann *et al.*, 1994).

A role for tropical cyclones in influencing large-scale climate variability in the Indian Ocean has also been suggested. Francis *et al.* (2007) argued that positive Indian Ocean dipole events (Saji *et al.*, 1999) could be triggered by the occurrence of severe cyclones over the Bay of Bengal during April–May.

3.5. *South Indian Ocean*

Several studies have examined ENSO's influence on TC activity in the South Indian Ocean basin. Jury (1993) did not find a statistically significant relationship, and attributed this to the opposing influences of increased upper-level westerly winds and enhanced convection during El Niño years. Xie *et al.* (2002) found an association between local ENSO-related SST anomalies and TC activity in the southwestern Indian Ocean. Kuleshov (2003) and Kuleshov and de Hoedt (2003) found an increase in TC numbers east of 70°E during La Niña years. Maximum TC frequency in the Southern Hemisphere occurs at the end of January during La Niña years and at the end of February to early March during El Niño years. The TC season usually starts one month earlier in the South Indian Ocean in La Niña years.

The tracks of the South Indian Ocean TCs are significantly more zonal during a La Niña event, and tend to be more frequent when local SSTs are warmer. The combination of both conditions in 2000, led to an exceptional number of TCs landfalls in Mozambique, which could be reproduced using a high-resolution coupled ocean-atmosphere model (Vitart *et al.*, 2003).

Ho *et al.* (2006) found that TC genesis is shifted westward during El Niño years, enhancing cyclogenesis west of 75°E and reducing it east of that longitude. They explained this shift through the changes in the Walker circulation associated with ENSO, with the formation of an anomalous anticyclonic low-level circulation in the eastern part of the South Indian Ocean during warm events. There are also changes in tracks between cold and warm events, with a decrease of activity southeast of Madagascar and a moderate increase in activity in the central subtropical South Indian Ocean during El Niño events compared to La Niña events. These track changes indicate that South Indian Ocean TCs move farther east during El Niño events, possibly due to anomalous southwesterly winds east of Madagascar. This shift in the TC activity was recently confirmed by Kuleshov *et al.* 2008 using an updated TC dataset for the southern hemisphere.

Jury (1993) obtained a relationship between TC frequency in the Southwest Indian Ocean and the QBO. They found that more TCs occur in the easterly phase than in the westerly phase. This is a somewhat surprising result, since it is of opposite sign to that found in the western North Pacific and North Atlantic basins, as discussed above, and the dynamical signals associated with the QBO itself are quite uniform throughout the tropics. More investigation of this relationship would be worthwhile.

Bessafi and Wheeler (2006) and Ho *et al.* (2006) analyzed the modulation of South Indian Ocean tropical cyclones by the MJO. Bessafi and Wheeler (2006) attributed the MJO modulation to perturbations in vorticity and vertical shear. Ho *et al.* (2006) noticed changes in TC tracks depending on the MJO phase.

3.6. *South Pacific and Australian Region*

Neville Nicholls was the first to relate tropical cyclone activity to ENSO in a series of papers in which he explored the environmental factors affecting TC activity in the Australian region (Nicholls, 1979, 1984, 1985, 1992). The predictability of TC activity in the Australian region was then explored, and a seasonal forecast scheme for TC activity was developed.

Years with many Australian TCs are usually preceded by below normal SST in the equatorial Pacific (La Niña event), low Darwin pressure and high North Australian SST, while years with relatively few TCs are preceded by El Niño events. As the strongest relationships occur before the start of the TC season, these variables can be used to predict TC activity in the Australian region. The relationship with ENSO is clearest for moderate intensity TCs; there is only a weak relationship with the numbers of either intense or weak TCs (Nicholls *et al.*, 1988). Various follow up studies have confirmed the relationship between ENSO and Australian TCs found in Nicholls' early studies (Dong, 1988; Hasting, 1990; Solow and Nicholls, 1990), and have shown them to be in some cases indicative of larger-scale signals for the entire basin. For example, the total number of TCs in the southwest Pacific tends to increase with El Niño (Basher and Zeng, 1995).

The region of mean TC genesis shifts with ENSO in the southwest Pacific, similarly to the western North Pacific. There is a well-documented eastward shift in the warm ENSO phase (Evans and Allan, 1992; Basher and Zeng, 1995; Kuleshov, 2003; Camargo *et al.*, 2007a; Kuleshov *et al.*, 2008) so that TCs are more likely to form away from the Australian coast and closer to the dateline in El Niño years. In some El Niño events TCs occur in French Polynesia, a location usually not affected by TCs. During La Niña events, the mean genesis location shifts westward, and TCs are more likely to make landfall in northeast Australia (Evans and Allan, 1992). The relationship of western Australian TCs with ENSO, on the other hand, is weaker than when the whole Australian region is considered (Broadbridge and Hanstrum, 1998).

In addition to the east-west shifts in TC genesis location with ENSO, there are also north-south shifts, with mean genesis shifting northward during El Niño and southward during La Niña (Revell and Goulter 1986a; Camargo *et al.*, 2007a). Among other impacts, this implies that TC landfall in Indonesia is more likely during El Niño years than in other years, a result which might be counter-intuitive since precipitation overall is suppressed there during El Niño years. Preliminary analysis of best track data (not shown) indicates that this is the case, though the statistics are poor since there are very few cyclone landfalls altogether in Indonesia.

A number of studies have used the ENSO signal to examine the influence of specific environmental factors on TC statistics. Ramsey *et al.* (2008) found larger correlations between TC activity and ENSO indices than between TC activity and local SST in the region of most frequent cyclogenesis. This is somewhat similar to findings in the western north Pacific (Chan, 2007). Correlations of TC frequency with low-level relative vorticity and vertical shear over the main genesis area are also significant.

As elsewhere, the MJO modulates TC activity in the Australian region, with more cyclones forming in the active phase of the MJO and fewer in the suppressed phase. The modulation is more pronounced to the northwest of Australia and is strengthened during El Niño events (Hall *et al.*, 2001). Low-level relative vorticity anomalies related to the MJO have been associated with changes in large-scale cyclogenesis patterns (Hall *et al.*, 2001).

4. Seasonal Forecasts of Tropical Cyclone Activity: Background

Nicholls (Nicholls, 1979, 1985, 1992) used the relationship between Australian TCs and ENSO to develop a statistical forecast scheme to forecast the number of cyclone days in a season based on the preceding July–September sea level pressure at Darwin — one of the two stations used to formulate the ENSO-related Southern Oscillation Index (SOI). Gray (Gray, 1984a) developed a statistical forecast methodology for forecasting seasonal Atlantic hurricane activity in early June and early August, which has been issued several times each year thereafter. We will discuss these forecasts in more detail below.

A discussion of the historical developments preceding the appearance of routine Atlantic seasonal hurricane forecasts appeared in Hess and Elsner (1994). They discussed the early work that uncovered the physical relationships among various factors such as sea level pressure (Brennan, 1935; Ray, 1935), easterly waves (Dunn, 1940) and mid-latitude troughs, and their influences on Atlantic hurricane frequency (Riehl, 1956). A summary of the early Atlantic forecasts as well as their verification is presented in Hastenrath (1990).

Currently, many institutions issue operational seasonal TC forecasts for various regions. In most cases, these are statistical forecasts, the seasonal typhoon activity forecasts of the City University of Hong Kong (Chan *et al.*, 1998, 2001), the Atlantic hurricane forecasts of Colorado State University (Gray, 1984a,b; Gray *et al.*, 1992c; Klotzbach and Gray, 2003, 2004; Klotzbach, 2007a,b), and Tropical Storm Risk (Saunders and Lea, 2005). The National Oceanic and Atmospheric Administration (NOAA) issues hurricane outlooks based on a blend of statistical techniques, climate model outputs, and forecasters input. More recently, dynamical forecasts have started being issued (Vitart, 2006; Vitart *et al.*, 2007; Camargo and Barnston, 2008). We will briefly discuss these forecasts, and their strengths and weaknesses. A more complete recent review of TC seasonal forecasts can be found in Camargo *et al.* (2007c).

The public and media interest in seasonal TC forecasts has increased tremendously since the time they were first produced. The disastrous impacts of the Atlantic basin hurricane seasons of 2004 and 2005 along with discussions of the possible impacts of global warming on Atlantic hurricane activity brought Atlantic seasonal hurricane forecasting to the forefront of the media.

Landfall forecasts are particularly important to users, as discussed in Elsner (2003) for the case of Florida residents. However, landfall forecast skill is quite limited. As seasonal TC forecasts improve, more attention will be able to be given to particular details such as local landfall probabilities, and the use of such specific forecasts will become more widespread and significant to decision makers and residents in coastal areas. However, the probability of a small area along the coastline being impacted by a tropical cyclone in any year is minimal, and therefore, landfall probabilities at the local level, based on seasonal forecasts, will always be quite low.

Predicting ENSO well in advance is fundamental for producing accurate seasonal TC forecasts. ENSO predictability follows a well-known seasonal cycle, in which the ENSO state for 4–6 months into the future is more accurately predicted from a starting time between July and November than between January and March. This is due to a "predictability barrier" that exists between April and June such that forecasts made just before this period are hindered by the barrier. The seasonal timing of the predictability barrier is related to the life cycle of ENSO episodes, which often emerge between April and June and endure until the following March to May. Once an episode has begun, predicting its continuation for the next 9 to 12 months is a much easier task than predicting its initial appearance. Even a strong El Niño, such as the one in 1997–98, was not well anticipated before signs of the initial onset were observed in the Northern Hemisphere spring of 1997 (Barnston *et al.*, 1999). Even after becoming apparent in the observations in late April and May 1997, the strength of this extreme El Niño event was under-predicted by most models, although a few models did correctly anticipate the rapid weakening in the spring of 1998 (Landsea and Knaff, 2000).

Due to the predictability barrier, the predictive skill for ENSO forecasts made in March is high for only 2–3 months, while for forecasts made in August the skill extends to longer lead times. Improvements in predictive skill using today's more advanced dynamical models have been small, and it remains to be seen whether or not improvements are possible (Chen and Cane, 2008) given the inherent signal-to-noise characteristics of the ocean-atmosphere system. The "slow physics" relevant to ENSO dynamics may become better predicted by both statistical and dynamical models of the future. However, better prediction of the shorter time-scale events that can also be important in triggering El Niño onset, such as the Madden-Julian Oscillation, may prove to be nearly impossible at multi-month lead times. Westerly wind bursts are often associated with MJO events and can have an impact on the magnitude and/or timing of an El-Niño event, like in 1997 (Slingo, 1998; van Oldenborgh *et al.*, 2000; Lengaigne *et al.*, 2003), although they may not be necessary for the occurrence of the event itself (Kleeman and Moore, 1997).

The ENSO predictability barrier has clear-cut implications for predictions of TC activity in the Northern Hemisphere when compared to predictions of TC activity in the Southern Hemisphere. TC activity in the Northern Hemisphere is considerably more challenging to predict because its peak TC seasons occur shortly after the ENSO predictability barrier. When an ENSO event appears somewhat later than usual, such as was the case in the late Northern Hemisphere summers of 1986 and 2006, the inhibiting effect on North Atlantic TCs is unanticipated until the peak season of August to October is already beginning. This can necessitate a sudden change as a final update to the seasonal TC prediction, and can potentially disrupt plans already being followed in accordance with an earlier seasonal TC prediction. The peak season for Southern Hemisphere TC activity occurs at least 6 months after the Northern Hemisphere spring ENSO predictability barrier, which provides a safer cushion of lead time in which to become fairly certain about the ENSO state to be expected during the peak season. Thus, last-minute surprises in seasonal TC outlooks for basins south of the equator are less likely to occur. Nonetheless, it is clear that a major hurdle in improving TC predictions for any ocean basin is the far-from-perfect quality of today's state-of-the-art ENSO forecasts. Indeed, Landsea and Knaff (2000) showed that it is still very difficult to outperform a simple statistical model that uses as predictors only the recent evolution of SST anomalies in a few tropical Pacific regions. This modest skill level for detecting El Niño onset still exists currently, as illustrated by the poor predictions of the late-starting 2006–07 El Niño. If the ENSO forecast challenge could be overcome, the skill of TC predictions could improve significantly — most notably in the Northern Hemisphere.

5. Statistical Forecasts

5.1. *Operational Statistical Forecasts*

Initial seasonal predictions for the North Atlantic basin (Gray, 1984a,b) were issued from Colorado State University in early June and early August beginning in 1984 and used statistical relationships between tropical cyclone activity and ENSO, the Quasi-Biennial Oscillation (QBO) and Caribbean basin sea-level pressures. Statistical forecast techniques for North Atlantic TCs have evolved since these early forecasts. Additional predictors have been added to the original forecast scheme, and the

QBO is not used as a predictor any more. In addition, seasonal forecasts are now issued as early as December of the previous year. Klotzbach and Gray (2004) and Klotzbach (2007a,b) explain the current forecast scheme.

Owens and Landsea (2003) examined the skill of Gray's operational Atlantic seasonal tropical cyclone forecasts relative to climatology and persistence. Their analysis indicated that for the analyzed period (1984–2001), their statistical forecasts demonstrated skill over climatology and persistence, with the adjusted forecasts being more skillful than the basic statistical forecasts. Figure 4 shows the correlation skill of the CSU seasonal forecasts for different variables.

NOAA has been issuing seasonal hurricane outlooks for the Atlantic and the eastern North Pacific regions since 1998 and 2003, respectively. These outlooks are provided to the public in both a deterministic and probabilistic format, using terciles. The deterministic prediction is given as a range — rather than a single number — and it represents about a 2/3 chance of the forecasts being in that range. The NOAA outlooks are based on the state of ENSO (Gray, 1984a) and the state of the tropical multi-decadal mode (TMM) (e.g., Chelliah and Bell, 2004), which incorporates the leading modes of tropical convective rainfall variability occurring on multi-decadal time scales. Important aspects of this signal that are related to an active Atlantic hurricane season include a strong West African monsoon, reduced vertical wind shear in the tropical Atlantic, and suppression of convection in the Amazon basin and high tropical Atlantic SSTs (Goldenberg *et al.*, 2001).

Tropical Storm Risk (TSR) issues statistical forecasts for TC activity in the Atlantic, western North Pacific and Australian regions. In a recent paper (Saunders and Lea, 2005), TSR describes their new forecast model, issued in early August,

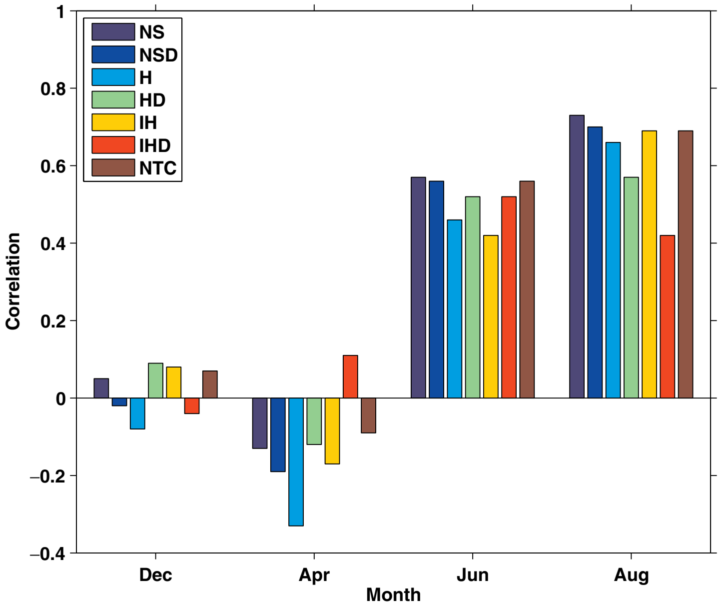

Figure 4. Correlations of the CSU seasonal forecasts for different leads: December (1992–2006), April (1995–2006), June (1984–2006 or 1990–2006) and August (1984–2006 or 1990–2006). The correlations are given for: number of named storms (NS), number of named storm days (NSD), number of hurricanes (H), number of hurricane days (HD), number of intense hurricanes (IH), number of intense hurricane days (IHD), and net tropical cyclone activity (NTC). Significant correlations at the 95% significant level are June — NS, NSD, H, HD, IH, IHD, NTC, August — NS, NSD, H, HD, IH and NTC. None of the correlations is significant for the December and April leads. Figure originally from Camargo *et al.* (2007c).

for seasonal predictions of hurricane landfall activity for the United States coastline. The model uses July wind patterns to predict the seasonal U.S. ACE index (effectively the cumulative wind energy from all U.S.-striking tropical cyclones). The July height-averaged winds in these regions are indicative of atmospheric circulation patterns that either favor or hinder hurricanes from reaching U.S. shores. The model correctly anticipates whether U.S. hurricane losses are above- or below-median in 74% of the hindcasts for the 1950–2003 period. As far as we know, this forecast is the only statistical forecasts that uses the steering flow. If this finding is corroborated, it would be a major advance for statistical foreasts. The western North Pacific seasonal prediction model uses Niño 3.75 (5°S–5°N, 180°–140°W) forecasts (Lloyd-Hughes *et al.*, 2004) to predict ACE.

Johnny Chan and colleagues at the City University of Hong Kong have issued seasonal TC forecasts for the western North Pacific basin (number of TCs and typhoons) since 1997. The statistical predictions are based on various environmental conditions in the prior year, up to the Northern Hemisphere spring of the forecast season. The most prominent atmospheric and oceanic conditions include ENSO, the extent of the Pacific subtropical ridge and the intensity of the India-Burma trough (Chan *et al.*, 1998, 2001). For a few years, forecasts of the number of TCs making landfall were also issued (Liu and Chan, 2003). Currently, the landfall forecast scheme for the South China Sea is being improved. More recently, a simple method was proposed to update seasonal prediction of the annual number of TCs in a given ocean basin, based on the cumulative number of TCs up to a given month in the early season (Chan, 2008b).

Various other agencies have been issuing forecasts for different regions of the world. The National Meteorological Services of Mexico has produced eastern North Pacific statistical seasonal forecasts since 2001. The China Meteorological Administration and the National Climate Center in China issue forecasts of typhoon activity for the western North Pacific, as well as landfalling typhoon frequency in the whole South China Sea and eastern China. The Cuban Meteorological Institute has been issuing seasonal forecasts of Atlantic hurricane activity, including hurricane landfall in Cuba, since 1996. The North Carolina State University forecast group developed a seasonal forecast methodology for Atlantic hurricane activity and landfall based on ENSO, vertical wind shear, the Atlantic dipole mode and the NAO (Xie *et al.*, 2005a,c; Keith and Xie, 2008). Forecasts for the Australian/Southwest Pacific region are presented annually in the December issue of the Experimental Long-Lead Forecast Bulletin since the 2004–5 season for the Southern Hemisphere tropical cyclone season. These forecasts are based on a Poisson regression model and use as predictors the September saturated equivalent potential temperature gradient and the SOI (McDonnell and Holbrook, 2004a,b).

5.2. *Methodology for statistical forecasts*

The first statistical seasonal forecasts for TCs in the Australian regions were developed using the values of the pressure in Darwin in the months preceding the Australian TC season to forecast the number of TCs (Nicholls, 1979). Other indices for ENSO and North Australia SST were also examined by Nicholls (1984). The performance of the forecasts using the SOI in the months prior to the season as the predictor (Solow and Nicholls, 1990) was discussed in Nicholls (1992).

James Elsner and colleagues at Florida State University (FSU) have been developing techniques for modeling seasonal hurricane activity and landfall (e.g., Elsner and Jagger, 2004). Although their forecasts are not produced operationally, their methodology is currently used to issue region-specific forecasts for various companies. The FSU group pioneered various topics in TC seasonal forecasting such as the use of a Poisson distribution for hurricane counts (Elsner and Schmertmann, 1993), the influence of the phase of the North Atlantic Oscillation (NAO) on Atlantic hurricane tracks and U.S. coastal hurricane activity (Elsner *et al.*, 2001), and the development of a skillful statistical model for seasonal forecasts of landfall probability over the southeastern United States (Lehmiller *et al.*, 1997). More recently, Elsner and Jagger (2006) built a Bayesian model for seasonal landfall over the U.S. using as predictors May–June values of the NAO, May–June values of the SOI, and May–June values of the AMO, and then extended the methodology to long-lead seasonal forecasts (Elsner *et al.*, 2006). Similar statistical techniques are used for multi-seasonal forecasts (Elsner *et al.*, 1998; Elsner *et al.*, 2008) and for building climatological models for extreme hurricane winds near the U.S. (Jagger and Elsner, 2006). It should be noted though, that only a statistical link between May–June NAO and subsequent Atlantic hurricane tracks was found. There has been no corroboration of the physical connection between the NAO and the tropospheric steering flow, either concurrent or predictive.

Two different methods, a binary classification scheme and a Poisson regression, are used to forecast annual Atlantic TC counts. Modeling the annual counts as a state-dependent Poisson process using a binary classification approach, only two factors are necessary to explain a large portion of the variance: ENSO and MDR SST. If a Poisson regression is used, the most skillful statistical model also considers the NAO as a predictor (Sabatelli and Mann, 2007).

Chu and Zhao (2007) developed a seasonal forecast for the Central North Pacific in the peak season (July to September), using a linear regression model in a Bayesian framework. Five large-scale environmental variables in the antecedent May and June months are used as predictors and the cross-validated procedure applied to the period 1966–2003 produced satisfactory results.

A statistical multivariate prediction model for the number of tropical cyclone days in the Southwest Indian Ocean one season in advance was developed by Jury *et al.* (1999). The chosen predictors are SST anomalies, OLR anomalies, upper level winds and surface winds in different regions, depending on the forecast lead time.

6. Dynamical Forecasts

6.1. *TCs in climate models*

Extended integrations of global climate models in principle allow for an assessment of the frequency, intensity, duration, structure, and tracks of tropical cyclone-like features in the model. In practice, simulation of realistic intensities and detailed structures of TCs is hampered by the coarse resolution generally required of such global models, as discussed below. In addition, the fidelity of the global model's TC genesis process compared to that of the real world has not been well established.

For the global models, TCs are located and tracked in model data using objective techniques that are usually based on a local maximum of cyclonic relative vorticity at 850 hPa and often involving other criteria such as: system lifetime, evidence of a warm core, maximum winds above a threshold, and a local minimum in sea level pressure (e.g., Tsutsui and Kasahara, 1996; Vitart *et al.*, 1997; Camargo and Zebiak, 2002; Sugi *et al.*, 2002; McDonald *et al.*, 2005). The location and tracking method tends to be unique to each study which makes it difficult to compare the results of the different studies directly. Walsh *et al.* (2006) provide recommendations for providing homogeneous comparisons of various resolution models for determining tropical cyclone frequencies. They base this upon an analysis of how minimal tropical storms (with maximum winds at 17.5 m/s) would be depicted under various resolutions. Use of such resolution-based criteria for determining tropical cyclone occurrence should allow for more rigorous quantitative comparisons of global (and regional) climate model output of tropical cyclones frequencies. For seasonal forecasting, however, simulated interannual variability of TC activity is more important than evaluation of the models' absolute performance in TC simulation. Model-specific detection thresholds which adjust for model biases (Camargo and Zebiak, 2002) may be more appropriate for this application.

The global climate models used for tropical cyclone analysis have tended to be of low (300 km) horizontal resolution (e.g., Vitart *et al.*, 1997; Tsutsui, 2002; Bengtsson *et al.*, 2006) or of medium (120 km) resolution (e.g., Sugi *et al.*, 2002; McDonald *et al.*, 2005; Hasegawa and Emori, 2005; Yoshimura and Sugi, 2005; Bengtsson *et al.*, 2007; LaRow *et al.*, 2008). The grid-scale of the low and medium resolution models is larger than the typical scale of tropical cyclones. This can lead to a poor simulation of tropical cyclones (e.g., Vitart *et al.*, 1997; McDonald *et al.*, 2005). The simulated cyclones tend to have a larger horizontal scale, and although they have warm cores, the intense inner core is not well-simulated. Thus, the simulated cyclones have lower wind speeds than occurs in observed tropical cyclones (Vitart *et al.*, 1997). Minimum central pressures tend to be better simulated than the maximum surface wind speeds. Recent studies have used higher resolutions of 50 km (Chauvin *et al.*, 2006) and 20 km (Oouchi *et al.*, 2006), but models of this resolution are too expensive for most modeling centers to use for long climate change experiments, though they may soon become practical for seasonal forecasting. An alternative approach is to use a global model with a stretched grid (i.e., higher resolution) over the region of interest (e.g., Chauvin *et al.*, 2006), although this limits the study to the region where the resolution is high. Even at that resolution, the highest simulated TC intensity reported by Oouchi *et al.* was about 932 hPa, compared with the observed record of 870 hPa, indicating the limitation of their global model in simulating very intense TCs.

Even though smaller-scale features of the individual cyclones are typically not well simulated in the global models, these models are able to reproduce some aspects of the observed climatology and inter-annual variability of tropical cyclones (Tsutsui and Kasahara, 1996; Sugi *et al.*, 2002; Camargo *et al.*, 2005; McDonald *et al.*, 2005; Bengtsson *et al.*, 2007). Most models are able to simulate tropical cyclone-like disturbances in roughly the correct location and at the correct time of the year, although all models exhibit some biases. Several models simulate tropical cyclones in the South Atlantic (Vitart *et al.*, 1997; Sugi *et al.*, 2002; McDonald *et al.*, 2005; Oouchi *et al.*, 2006) where they are rarely observed (Pezza and Simmonds, 2005). It should also be pointed out that not all models simulate storms in the South Atlantic (Camargo *et al.*, 2005).

The global models' simulated TC tracks are sometimes shorter than observed (Tsutsui and Kasahara, 1996; Sugi *et al.*, 2002; Camargo *et al.*, 2005). High resolution models such as that of Oouchi *et al.* (2006) are able to better simulate the length of TC tracks. Low resolution models such as ECHAM3 and ECHAM4 exhibit TC tracks that are too long (Camargo *et al.*, 2005). Some of these differences in length may be due to the objective techniques used to identify and track the cyclones in the model data.

The simulated global annual frequency of TCs in global models varies, with some models simulating too many TCs (e.g., McDonald *et al.*, 2005) while others simulate too few (Camargo *et al.*, 2005). Both from comparing results among different models (e.g., Camargo *et al.*, 2005) and from sensitivity experiments with a given model (Vitart *et al.*, 2001; Emori *et al.*, 2005), it is evident that both model resolution and model physics can play important roles in determining the frequency of TC occurrence in the global models. The dynamics of the genesis process in a coarse resolution model was explored by Camargo and Sobel (2004).

The genesis process in that model was found to be qualitatively similar to that in observations (though with major quantitative differences), featuring a convectively coupled vortex, which intensifies, partly due to enhanced surface fluxes, after an initial period of constant intensity or slight weakening.

While models in many existing studies have demonstrated an ability to simulate many aspects of the seasonal variability of tropical cyclone frequency in each basin, all of the models have some errors in both frequency and timings. These errors are basin-, season- and model-dependent. Increasing the horizontal resolution of global models typically improves the simulation of individual cyclones (Bengtsson *et al.*, 1995) but may not improve the tropical cyclone climatology and interannual variability. One reason for that may be biases of the variability in large-scale climate itself. On the other hand, a comparison of several models suggests that differences in the simulation of the large-scale environment for TC genesis do not translate in a simple way to differences in simulated TC statistics (Camargo *et al.*, 2007f).

More realistic maximum TC intensities have been simulated by downscaling individual storm cases from a coarse-grid global model into an operational regional high-resolution hurricane prediction system (Knutson *et al.*, 1998) or into a regional climate model (Walsh and Ryan, 2000). Another promising approach involves embedding a regional climate model within a global model or atmospheric reanalysis in order to simulate the seasonal evolution of more realistic TC formation, evolution, and intensities (e.g., Walsh *et al.*, 2004; Knutson *et al.*, 2007; Stowasser *et al.*, 2007; Feser and Von Storch, 2008; Knutson *et al.*, 2008). However, the TC simulations using a regional climate model have uncertainties due to model domain choices, parameterizations, and other issues (Landman *et al.*, 2005; Camargo *et al.*, 2007b).

Climate models also must simulate realistic ENSO and decadal variability under present day and future climate conditions as a necessary condition for providing reliable future projections of TC activity in these regions (e.g., Nguyen and Walsh, 2001). The interannual variability of TC occurrence in global models can be tested by comparing cyclones simulated in models forced with observed SSTs to tropical cyclone observations from the same period (Wu and Lau, 1992; Tsutsui and Kasahara, 1996; Vitart *et al.*, 1997; Sugi *et al.*, 2002; McDonald *et al.*, 2005; Camargo *et al.*, 2005; Bengtsson *et al.*, 2007; LaRow *et al.*, 2008). The nine-member ensemble of Vitart *et al.* (1997) and the 40-yr experiments used by Camargo *et al.* (2005) are better suited for analysis of the interannual variability than are the shorter experiments used by Tsutsui and Kasahara (1996), Sugi *et al.* (2002) and McDonald *et al.* (2005) because of the larger sample sizes. The correlation of the global annual number of tropical cyclones with the observed number varies from 0.15 in the JMA model (Sugi *et al.*, 2002) to 0.41 in the GFDL model (Vitart *et al.*, 1997). The correlations are better in some seasons, basins and models than in others. The correlations tend to be highest in the western North Pacific and North Atlantic basins (Vitart *et al.*, 1997; Camargo *et al.*, 2005), possibly because of the importance of ENSO in those regions. In the case of the Atlantic, La Row *et al.* (2008) obtained correlations of 0.78 for the interannual variability of number of tropical cyclones using a T126 horizontal resolution model, four-ensemble member, and 20 years of integration. The interannual variability performance of the 20 km grid global model of Oouchi *et al.* (2006) has not yet been assessed.

The longer time-scale variability of TCs in global models was explored in a few studies. Vitart and Doblas-Reyes (2007) analyzed the inter-decadal variability of tropical storm frequency for the period from 1958–2001 in various regions. The inter-decadal variability of TCs in the model is more realistic for varying greenhouse gas concentrations than for fixed concentrations. However, the natural inter-decadal variability plays a more important role in this period than does anthropogenic forcing. Matsuura *et al.* (2003) and Yumoto *et al.* (2003) showed that a coupled ocean-atmosphere global model could reproduce the inter-decadal TC frequency variability in the western North Pacific, which was related to the decadal variability of the monsoon westerlies in the model and in the reanalysis.

Nguyen and Walsh (2001) analyzed the interannual and decadal variability of TCs in the South Pacific using a regional climate model. A higher incidence of TCs on the Australian east coast occurred in La Niña conditions, while in El Niño conditions, the formation and occurrence shifted towards the central Pacific, as in observations. The TC activity in the model also exhibited coherent decadal variability similar to observed patterns on these time-scales. Knutson *et al.* (2007) used a high-resolution regional model over the North Atlantic and were able to reproduce the observed ENSO and multidecadal variability in Atlantic TC activity over the period from 1980–2006, with a 0.87 correlation between observed and model-derived hurricane frequency.

An alternative approach to explicit global model simulation is to use an empirical "seasonal genesis parameter" (e.g., Ryan *et al.*, 1992; Watterson *et al.*, 1995; Thorncroft and Pytharoulis, 2001) to infer a genesis frequency from climate model data (Tsutsui and Kasahara, 1996; Royer *et al.*, 1998; McDonald *et al.*, 2005; Chauvin *et al.*, 2006; Camargo *et al.*, 2007f). In this approach, the focus is on using the models' predictions of seasonal variations in the large-scale environment for TC genesis and intensification, rather than their predictions of the TCs themselves. The strength of this approach is based on the fact that the ability of climate models to simulate large-scale climate is clearly superior to their ability to simulate TCs. Great caution is required when applying a parameter developed for present day climate to future predictions, as the statistical relationships may not be valid under altered climate conditions (Ryan *et al.*, 1992). Royer *et al.* (1998) and Emanuel and Nolan (2004) (see also Nolan *et al.*, 2007; Caron and Jones, 2008) have proposed refined versions of Gray's (1979) genesis index that avoid the use of factors such as threshold SSTs that themselves may well vary in an altered climate (e.g., Henderson-Sellers *et al.*, 1998). These methods typically produce plausible maps and seasonal cycles of TC genesis. Camargo *et al.* (2007a) showed that the index developed by Emanuel and Nolan (2004) was able to reproduce the interannual variations of the observed frequency and location of genesis in several different basins.

6.2. *Current operational dynamical forecasts*

While low-resolution simulations are not adequate for forecasting individual cyclones' tracks and intensities, some climate models have skill in forecasting levels of seasonal TC activity. These climate models are able to reproduce typical ENSO influences on seasonal TC activity (e.g., Vitart *et al.*, 1997).

Currently, three institutions produce seasonal forecasts of tropical cyclone activity by dynamical methods. The European Centre for Medium-range Weather Forecasts (ECMWF) issues experimental seasonal forecasts of tropical storm frequency based on dynamical models for various regions since 2001 and are only available to institutions affiliated with the ECMWF. The ECMWF forecasts are based on coupled ocean-atmosphere models (Vitart and Stockdale, 2001; Vitart, 2006), with tropical cyclone-like vortices being identified and tracked in the atmospheric model output. The European multi-model (EUROSIP) dynamical forecasts of TC frequency skillfully distinguished the very-active Atlantic hurricane season in 2005 from the below-average season in 2006, as shown in Fig. 5 (Vitart *et al.*, 2007). The EUROSIP forecasts have been produced in real time since 2005, but are not currently available to the public. The United Kingdom Met Office started issuing dynamical seasonal forecasts for the

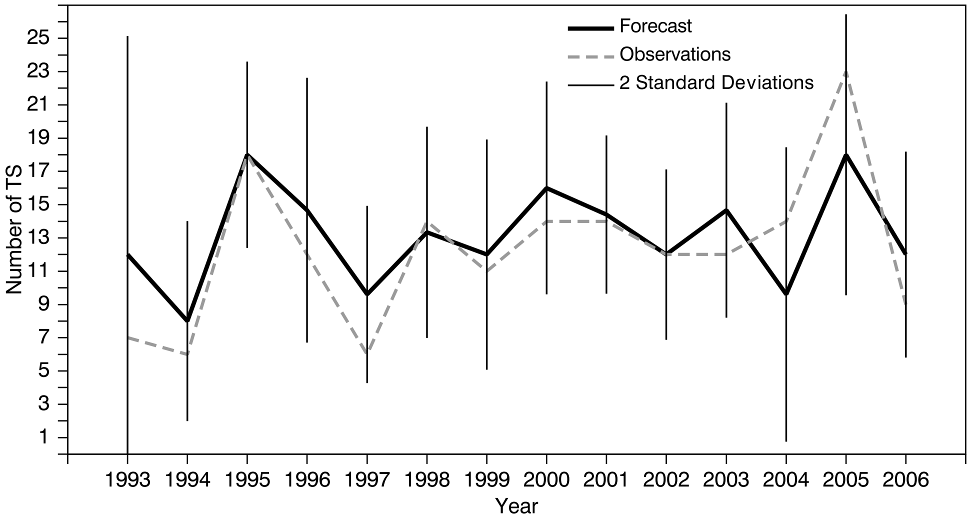

Figure 5. Number of tropical storms from July to November predicted by the EUROSIP (median) starting on 1 June (black thick solid line) for the period 1993–2006. Hindcasts were used for the period 1993–2004, and real-time forecasts in 2005–2006. The observations are given in the dashed line and vertical lines represent two standard deviations within the multi-model ensemble distribution. (Reproduced from Vitart *et al.*, 2007, by permission of the American Geophysical Union.)

Atlantic basin operationally in June 2007, also using a coupled ocean-atmosphere model (one of the EUROSIP models, discussed in Vitart *et al.*, 2007) and a methodology similar to the ECMWF forecasts.

The International Research Institute (IRI) for Climate and Society also issues experimental seasonal forecasts based on dynamical models for tropical storm frequency and accumulated cyclone energy (ACE; Bell *et al.*, 2000) in Northern Hemisphere regions since 2003. The experimental IRI forecasts are obtained using a two-tier procedure. First, various possible scenarios for SSTs are predicted using statistical and dynamical models. Then, atmospheric models are forced with those predicted SSTs. Similar to the ECMWF procedure, the tropical cyclone-like vortices are then identified and tracked (Camargo and Zebiak, 2002). The IRI forecasts are probabilistic by tercile category (above normal, normal, below normal).

The skill of some of the best performing dynamical models in predicting the frequency of tropical storms is comparable to the skill of statistical models in some ocean basins. Over the North and South Indian Oceans, dynamical models usually perform poorly (Camargo *et al.*, 2005; Bengtsson *et al.*, 2007). It is not clear to what extent this is due to model errors or due to a lack of predictability. Similar to the experience with seasonal climate forecasts, combining different model forecasts (multi-model ensemble forecasts) appears to produce overall better forecasts than individual model ensemble forecasts (Vitart, 2006). The hindcast skill of various dynamical climate models in predicting seasonal TC activity is discussed in Camargo *et al.* (2005) and Vitart (2006), and the real time performance of the IRI forecasts is analyzed in Camargo and Barnston (2009).

Seasonal prediction of tropical cyclone landfall represents a major challenge for dynamical models. Tropical cyclones take an unrealistically poleward track in some of the models used in seasonal forecasting systems due partly to the coarse horizontal model resolution, which leads to larger vortices than observed ones. These larger vortices would likely be more influenced by the beta effect (Rhines, 1975) leading to stronger "beta drift", (e.g., Chan, 2005) and thus more poleward tracks. Finer resolution climate models are able to reproduce landfall differences related to ENSO impacts, such as in Mozambique (Vitart *et al.*, 2003).

7. Summary

In this chapter, we reviewed the influence of various climates modes on tropical cyclone activity in intraseasonal to decadal time scales. Globally, ENSO and the MJO, and to some extent the QBO modulate TC activity. How this modulation occurs depends on the region considered. On a regional scale, other climate modes also affect TC activity, modifying the timing, genesis location, frequency, tracks and landfall frequency.

Using the relationships between TC activity and these climate modes on intraseasonal and interannual time scales, statistical forecasts of TC activity can be constructed. Dynamical TC seasonal forecasts based on TCs in climate models are now also issued by some centers.

In most cases, the modulation of TC activity by the climate has been focused on specific time scales and modes of variability. It would be interesting in the future to have a better understanding of the interactions and relationships of these modes. This would lead to a better framework for understanding TC variability.

Reflecting the literature, our discussion has focused on the influence of climate on TCs. The influence of TCs themselves on the large-scale climate has been mentioned only briefly, because relative few studies have tried to assess that influence. Besides a possible role in ENSO dynamics (Keen, 1982; Sobel and Camargo, 2005) or the Indian Ocean dipole (Francis *et al.*, 2007), roles for TCs in controlling the global thermohaline circulation (Emanuel, 2001; Korty *et al.*, 2008) and in creating a multi-year persistence in TC activity (Pasquero and Emanuel, 2008) have been hypothesized. A better understanding of the role of TCs in the global climate is desirable and more work in this area would be worthwhile.

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