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Trends in seasonal forecasting of tropical cyclone activity

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This paper presents a review of the development of Seasonal Tropical Cyclone Forecast Models (STCFM) for the western north Atlantic, Australian and western north Pacific Ocean basins. Current hypotheses on the climatic controls affecting the interannual variability of tropical cyclone activity are described. Although doubt remains concerning the correlation between El Niño-Southern Oscillation (ENSO) and the yearly frequency of tropical cyclones in the western north Pacific, much of the interannual variability of cyclone activity in the western north Atlantic and Australian basins can be explained by ENSO and related phenomena. An association between the Quasi-Biennial Oscillation and hurricane activity has also been well established for the western north Atlantic, but not for the Australian and western north Pacific basins. A rigorous evaluation of seasonal hurricane forecasts in the western north Atlantic is described. It is proposed that future research focus on: (a) more appropriate statistical methodologies, and (b) the physical relationships between tropical cyclone activity and possible new seasonal predictors.

Introduction

As we enter the new millenium it seems appropriate to review our seasonal forecasting methodologies of tropical cyclone (TC) activity. DeMaria (1996), in a recent review, has divided the history of hurricane forecasting during the past 75 years in the US into 8 periods: 1920-1934 (hurricane diagnosis and extrapolation), 1935-1942 (the use of upper air data and forecast office reorganisation), 1943-1955 (technological advancements: aircraft reconnaissance and radar), 1956-1965 (increased research efforts and the development of objective forecast methods), 1966-1973 (the use of satellite observations and improved forecast models), 1974-1987 (geostationary satellites and three-dimensional forecast models), 1988-1994 (increased interaction with the research community and the use of global model output) and 1995-2005 (present status and future outlook).

It can be seen from that assessment that numerous attempts have been made to develop short-range predictions of hurricane movement and intensity. It may also be noted that despite the application of statistical, numerical, and ensemble hurricane track forecast

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models, errors in track forecasts can easily be made due to the uncertainty of the initial positioning of tropical cyclones. The nonlinearity of the governing numerical equations signifies that a slight difference in the initial conditions can result in quite divergent movements (Lorenz 1993). The physics and models of tropical cyclogenesis are still incomplete. The lack of synoptic-scale tropospheric wind information near the storm and insufficient hurricane data from our archives preclude accurate forecasting of unusual hurricane tracks (Elsberry 1995). Additionally, rapid intensity change is still difficult to forecast in a timely manner by conventional techniques, which has resulted in major disasters. Examples are the case of hurricanes *Hugo* in 1989 and *Andrew* in 1992 (US Department of Commerce 1990, 1993).

After the termination of PROJECT STORMFURY (1962-1983) (Willoughby et al. 1985), it was realised we had to co-exist with tropical cyclones rather than try to conquer them. This change of view led to approaches to forecast hurricane activity for the coming hurricane season so that the appropriate hurricane disaster precautions could be undertaken. The history of seasonal hurricane forecasts in the Atlantic Ocean basin has been outlined by Hess and Elsner (1994a). However, a comprehensive review of Seasonal Tropical Cyclone Forecast Models (STCFM) has never been done. This paper is hence intended not only as an evaluation of the developments in forecasting interannual hurricane activity for the Atlantic basin but also as an investigation into the application of STCFM for the western north Atlantic, Australian and western north Pacific basins. Before examining the problems of STCFM and identifying trends and prospects for their development, a brief review of the important climatic controls on interannual variability of TC activity is described.

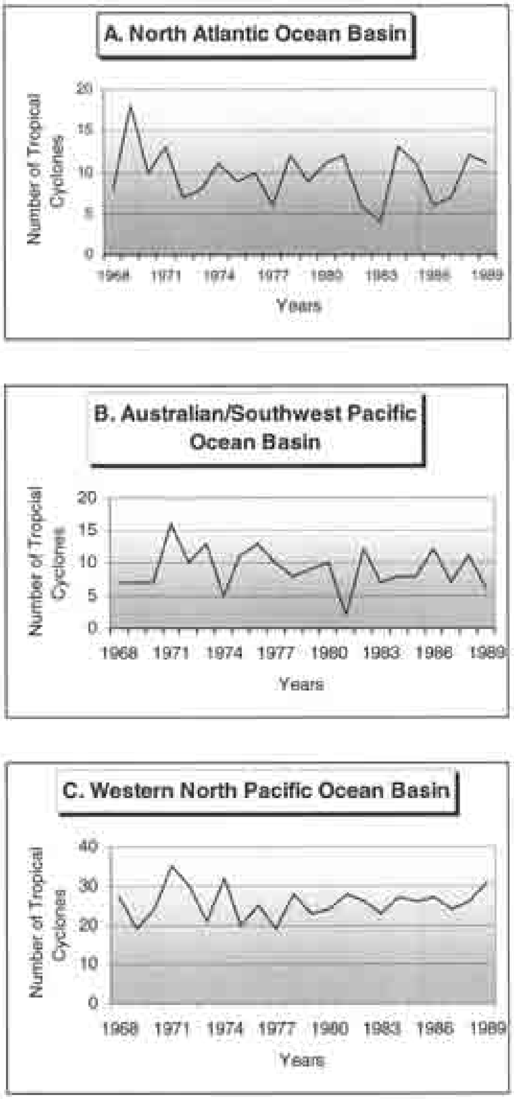
Climatic controls on interannual variability of tropical cyclone activity

The interannual variability of tropical cyclone activity for the north Atlantic (0°-60°N, 100°-30°W), Australian (0°-45°S, 105°-160°E) and western north Pacific (0°-45°N, 100°-180°E) basins for the period 1968-1989 is shown in Fig. 1.

North Atlantic Ocean basin

The variations are largest in the Atlantic basin, including the Atlantic Ocean, Caribbean Sea and Gulf of Mexico (Gray and Sheaffer 1991), where the sensitivity of tropical cyclone activity to El Niño-Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO) is most pronounced (Gray 1984a,b).

Fig.1 **Time series of tropical cyclone variations in the north Atlantic Ocean (a), Australian/southwest Pacific (b), and western north Pacific (c), for the period 1968-1989 (Data from Neumann 1993).**



Shapiro (1982a,b) points out that the QBO only explains a very small portion of the total variance of hurricane incidence in the Atlantic basin; on the contrary, higher sea-surface temperature (SST) just west of Africa, lower sea-level pressure (SLP) over the Caribbean and weaker August-October 500 hPa westerlies also often precede more active seasons. Gray (1984a,b) has identified that ENSO, the QBO and sea -level pressure anomalies (SLPA) over the Caribbean are related to hurricane activity in the north Atlantic Ocean as follows:

(a) El Niño – less Atlantic basin tropical cyclone activity occurs in those seasons when a warm sea-surface temperature anomaly (SSTA) exists in the eastern Pacific Ocean and when the associated Southern Oscillation Index (SOI) is negative (an El Niño event) and vice versa.

The physical mechanisms responsible for suppression of hurricane activity by El Niño and the QBO are elaborated by Gray (1984a,b). An anomalous increase in upper tropospheric westerly winds over the Caribbean Sea and the equatorial Atlantic occur during El Niño events. Such anomalous westerly winds inhibit tropical cyclone activity by increasing tropospheric vertical wind shear and giving rise to a regional upper-level environment which is less anticyclonic and consequently less conducive to cyclone development and maintenance.

(b) QBO – the 12 to 15 months stratospheric easterly QBO is believed to increase lower stratospheric to upper tropospheric wind (and hence increase vertical shear) which may disrupt the tropical cyclone structure in the Atlantic basin. The following 13 to 16 months of westerly QBO does the opposite. The greater the thickness of the stratospheric layer of westerly winds (or thinness of the layer of easterly winds), the greater the amount of hurricane activity.

The basic characteristics of the QBO are illustrated in Fig. 2. During the easterly phase of the QBO, a strong easterly zonal wind in the stratosphere at low latitudes (10°-15°N) causes a large net advection of latent heat at the upper level of developing cumulonimbus clouds and thus restricts further development of hurricanes. During the westerly phase of the QBO, the absolute value of the zonal wind in the stratosphere (over hurricanes) at 10°-15°N is weak. So, comparatively small horizontal wind ventilation may occur in the lower stratosphere. The accumulation of latent heat release can strengthen the warm-core intensity of developing hurricanes (Fig. 3).

(c) SLPA – during seasons of lower than average surface pressure around the Caribbean Sea, Atlantic hurricane activity is enhanced. When it is higher than average, tropical cyclone activity is diminished. It is suggested that higher pressure indicates either a weaker intertropical convergence zone (ITCZ) or a more equatorial position of the ITCZ, or both.

Over a period of fifteen years study the Colorado State University (CSU) hurricane forecast team has associated additional global and regional physical parameters (Caribbean 200 hPa zonal wind anomalies; West African Sahel rainfall, temperature and pressure; strength of the subtropical ridge and warmer SST in the north Atlantic) with the interannual variability of the hurricane activity in the western north Atlantic Ocean. Work is ongoing to understand these and other relationships.

Fig. 2 **Illustration of the east phase QBO (left diagram) and west phase QBO (right diagram) wind conditions that occur over the tropics at 50 hPa and 30 hPa during the summer season (Gray et al. 1992c)**

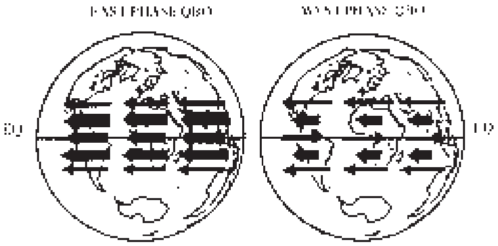
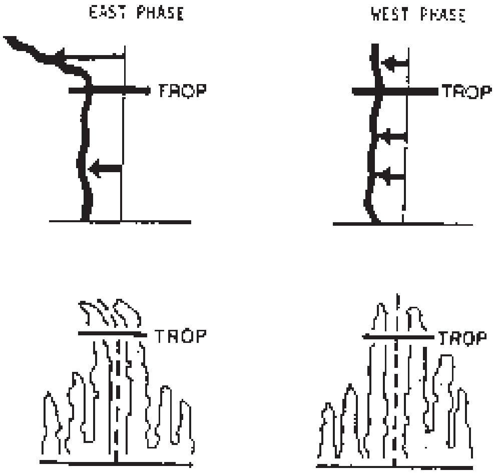


Fig. 3 **Vertical cross-section illustration of the types (east/west phase QBO) of vertical wind shear and cloudiness associated with Atlantic tropical cyclones that extend through the tropopause (TROP) into the stratosphere (Gray et al. 1992c).**



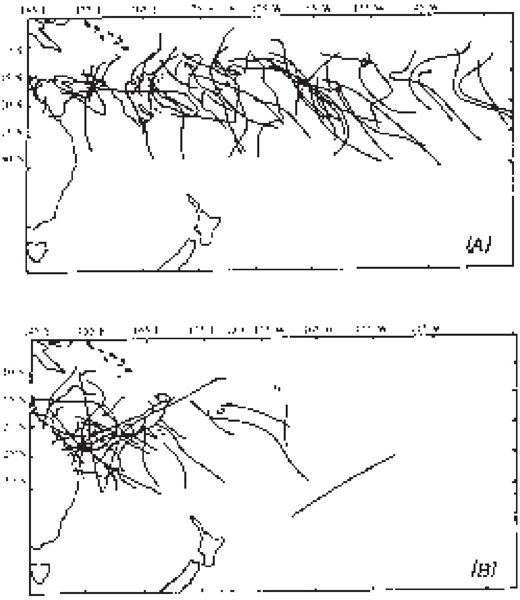
Australian ocean basin

The interannual variability of tropical cyclone activity in the Australian ocean basin is also worth noting (Fig. 1). Nicholls (1979, 1984) statistically examined the relationship between interannual variations of the number of tropical cyclones and the Southern Oscillation (SO). Years with relatively many tropical cyclones were found to be preceded by high north Australian SST, low east Pacific SST and low Darwin pressure. Hastings (1990) also comes to the same conclusion (Fig. 4). Additionally, he notes from the intraseasonal temporal distributions of Australian region tropical cyclogenesis that there is a slightly higher tendency for late-season tropical cyclogenesis in ENSO seasons relative to anti-ENSO seasons. Genesis points are clustered relatively closer to the northeast Australian coastline during anti-ENSO seasons compared with ENSO seasons. Genesis points during ENSO seasons occur in a more extensive band centred further east on the date-line. Both Revell and Goulter (1986a,b) and Basher and Zheng (1995) also find the area in which genesis points occur, varies with the phase of the SO, being farther to the north and east when the phase is negative. Moreover, the latter authors propose that the primary influence on tropical cyclone incidence west of 170°E is the local SST, while to the east of 170°E it is the eastward extent of favourable atmospheric conditions, as indicated by the SOI or Tahiti pressure.

Evans and Allan (1992) suggest that during ENSO phases, the summer monsoon trough is weak and is displaced equatorward, vertical wind shear is reduced and warmer SSTs are found to the northwest of Australia and in the central equatorial Pacific Ocean. Tropical cyclone activity is thus reduced to the northeast of Australia, but increases to the north and northwest of the continent. However, the latest research on the relationship between tropical cyclones near Western Australia and the Southern Oscillation Index, does not show an increased occurrence of tropical cyclones to the northwest with negative SOI values. An overall increase in tropical cyclone frequency was found with strong positive SOI values (Broadbridge and Hanstrum 1998).

Nicholls (1992) demonstrated a successful hindcast of the interannual variations of cyclone activity with prior values of the SOI throughout the post-1979 period. However he notes that the sudden drop in cyclone numbers within the region from 1986/87-1990/91 was not accompanied by a corresponding decrease in the SOI. This sudden change in the SOI-cyclone numbers relationship may represent a real physical change, or an indication of other important controls, or may be a result of changes in satellite imagery interpretation.

Fig. 4 **The southwest Pacific region tropical cyclone tracks for the ENSO composite (a) and the anti-ENSO composite (b) (Hasting 1990).**



More specifically, Nicholls et al. (1998) demonstrate that the relationship between tropical cyclone activity in the Australian region and the SOI is clearest for moderate systems, but less obvious for intense and weak cyclones.

At present the study of the relationships between interannual variability of tropical cyclone activity and the QBO is still inadequate, although Collimore (1990b) finds that the total number of cyclones is reduced considerably in the east phase of the QBO over the entire Australian region.

Western north Pacific Ocean basin

The interannual variability of tropical cyclone activity in the western north Pacific Ocean can be quite large (Fig. 1). There can be as many as 32 tropical cyclones in an active year (1974) and as few as 20 in a quiet year (1975). Tropical cyclones attaining typhoon intensity also fluctuate considerably, varying from 12 typhoons in 1970 to 24 in the following year (Neumann 1993).

Tropical cyclone variability is believed to be related to ENSO, the QBO (Chan 1985, 1995a), the 850- and 500 hPa zonal wind fields (Chan 1990) and the SST distribution (Chan 1995b). During an ENSO year, tropical cyclone activity is above normal over the eastern part of the western north Pacific but below normal over the northern part of the South China Sea (Fig. 5). However, tropical cyclone activity is likely to be below normal over the eastern part of the western north Pacific the year after an ENSO event (Fig. 6). Westerly phase of the QBO corresponds to an increase in tropical cyclone activity and this is consistent with the findings of Gray (1984a,b) and Gray et al. (1992a,b). It has also been stressed that the 850 hPa flow has a significant correlation with tropical cyclone activity in the northern part of the South China Sea and the eastern part of the western north Pacific but not over the entire western north Pacific. A significant correlation between tropical cyclone activity and 500 hPa zonal wind only exists over the eastern part of the western north Pacific.

Aoki (1985) finds that the average number of annual typhoons shows a minimum of 25 in an El Niño year and a maximum of 31 in the second year thereafter. Dong (1988) shows a 40 per cent reduction in cyclone frequency in the core of the northwest Pacific basin during El Niño years. Bao and Xiang (1993) reveal that the numbers of tropical cyclones and landfalls on China are much larger in anti-El Niño years. Liu and Qu (1992) indicate that tropical cyclones making landfall are fewer and at lower latitudes in China in an El Niño year and vice versa. For the South China Sea there are also clear ENSO signals in tropical cyclone occurrence (McGregor 1995). Statistical calculations for Nansha Island and its vicinity also indicate that fewer tropical cyclones are formed in an El Niño year (Lin and He 1997). Lin et al. (1998) also confirm that tropical cyclone genesis and landfall in the western north Pacific is reduced in El Niño years.

We may question whether the reduced number of tropical cyclones in the western north Pacific is really a suppression of their activity caused by El Niño or only a westward shifting of their activity. Landsea and Gray (1989) and Hastenrath and Wendland (1979) indicate that stronger convection in the eastern north Pacific in El Niño years causes an increase in occurrence of strong cyclones (i.e., wind speeds exceeding 51 m/s) by more than 50 per cent. But there are no seasonal El Niño/non-El Niño differences observed when all northeast Pacific cyclones (including tropical storms) are compared. There are more tropical cyclones in the central north Pacific (between the equator and 70°N and 180°-140°W) during an El Niño year than during a non-El Niño year (Chu and Wang 1997). This is not only because the longer tropical cyclone tracks in the eastern north Pacific would traverse into the central north Pacific, mainly in the latitudinal band 10°–20°N, but also because of the westward shift of the warm pools of water and the monsoon trough at the height of El Niño (Chu and Clark 1999).

Fig. 5 **Average anomalous number of tropical cyclones over the western north Pacific for all ENSO years (Chan 1990).**

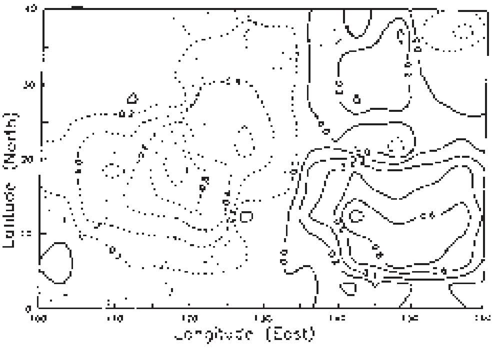
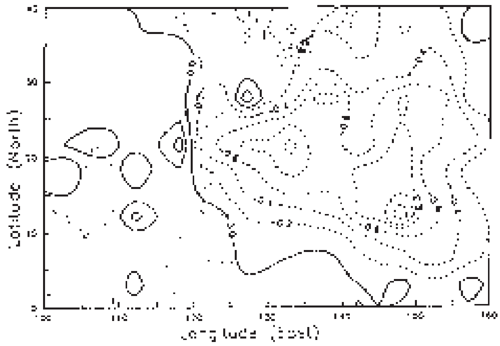


Fig. 6 **As in Fig. 5 except for the year after an ENSO event (Chan 1990).**



Over the western north Pacific, Pan (1982) points out that when the east equatorial Pacific SST is warmer than normal in an El Niño event, convection is reduced in the western north Pacific Ocean. Through sea-air interaction, formation of typhoons in the ITCZ is reduced in the western north Pacific, and the cyclogenesis region shifts eastward. Pan (1987) adds that easterlies at 850 hPa from the Pacific make a more anticyclonic divergent atmosphere which is not favourable to typhoon generation in El Niño years, while stronger westerlies in the lower troposphere make a more cyclonic convergent region in La Niña years. Li (1987) indicates that in El Niño years the subtropical high pressure belt is anomalously strong and hence the ITCZ will be restricted to lower latitudes, where the Coriolis force is smaller. Additionally, baroclinicity and vertical wind shear are enhanced, which in turn inhibits tropical cyclogenesis. Through an analysis of the correlation of the 500 hPa circulation and tropical cyclone activity, Luo and Shi (1991) confirm that tropical cyclone activity is less in an El Niño year and the first half of the following year, but more active in the second half of the following year.

Observations, however, do not show that tropical cyclone activity over the whole Pacific Ocean is suppressed in El Niño years. There were, for example, 49 tropical cyclones in the Pacific Ocean in 1982 (an El Niño year) and in 1985 (a non-El Niño year) (see Table 1.3, Neumann 1993). Hence, it appears that the reduced number of tropical cyclones in the western north Pacific could result from the zonal displacement of the monsoon trough. The shifting of the tropical cyclogenesis region eastward (westward) when the SOI is low (high) and the SST is warmer (cooler) than normal, is primarily governed by the location and behaviour of the monsoon trough (Lander 1994).

Chen et al. (1998) confirm that the increase (decrease) of tropical cyclone genesis frequency in the western north Pacific during summer (June-August) with anomalous cold (warm) SST over the NINO3 region is related to the interannual south-north/west-east variability of the monsoon trough location.

Wu and Lau (1992) and Wu (1993), applying a low-resolution Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model, also find negative correlation coefficients, i.e., less (more) tropical cyclones are generated in El Niño (La Niña) years in the western north Pacific, western South Pacific and western north Atlantic but not in the eastern north Pacific, eastern north Atlantic, Indian Ocean and the summertime value for the western South Pacific.

Nevertheless, the association between ENSO and the frequency of tropical cyclones is not universally accepted. For example, Ramage and Hori (1981) failed to establish any clear relationship between El Niño and tropical cyclone development in the western Pacific, the southwest Pacific or the eastern Pacific. Lander (1994) was unable to find any evidence to prove that annual storm totals or intense cyclones would be suppressed during ENSO years. For example, there were 29 tropical storms and typhoons (TSTY) and 22 typhoons (TY) in 1972, during an El Niño event, but fewer TSTY (22) and TY (12) in 1973, when a La Niña event occurred. The correlation coefficients for the relationships between ENSO indices and tropical cyclone activity are small and account for at best about seven per cent of the variance.

It has been noted by Collimore (1990c) that the interannual variations of tropical cyclone activity in the western Pacific may be a result of equatorial low-level zonal wind anomalies. Westerly (easterly) low-level winds near the equator create comparatively high (low) environmental vorticity in the lower troposphere which is generally favourable (unfavourable) for tropical cyclogenesis. Furthermore, these interannual fluctuations of low-level winds in the western Pacific are not necessarily associated with an ENSO circulation. Moreover, Gray and Sheaffer (1991) indicate that the large reduction in the total seasonal frequency of tropical cyclones which occurs during El Niño years in the northwest Atlantic does not appear to be as prominent in other tropical cyclone basins.

Wang (1994) emphasises that the relationship between ENSO and tropical cyclone activity is more complex than was thought. He found that more tropical cyclones made landfall in China in 1957–1958 (a strong El Niño year) and that the correlation between landfalling tropical cyclones in China and equatorial east Pacific SST in the last decade of the 20th century was not good. The appearance of an SSTA in the east and central Pacific does not mean that its influence will be felt at large distance; on the contrary, it is necessary to have a combination of appropriate conditions: sign, magnitude, season and location (Kagan 1995). Actually, the large inter-El Niño variability (Torres 1991) is of vital importance in explaining why the influence of ENSO upon the atmospheric circulation will not always be the same.

Cheung (1998) has suggested that reasons for the inconsistencies in research findings may be: (a) the use of a variety of data sources; (b) differences in the period chosen for the investigation; (c) variations in the choice of the boundary of the western north Pacific basin; and (d) divergences in the definition of both the typhoon season and ENSO. There is also the issue of hitherto undetected physical controls on TC activity.

With regard to the QBO, although Collimore (1990a) shows a reduction in the frequency of intense cyclones in the west Pacific region during the east phase of the QBO (Table 1), Li and Long (1992) note that the relationship between QBO and interannual variability of tropical cyclones in the western Pacific is exactly the opposite of the theory of Shapiro (1982b), Gray (1984a,b) and Chan (1995a). More (less) tropical storms and typhoons are favoured to generate in easterly (westerly) QBO. As stated by McBride (1995), a statistically significant relationship of interannual fluctuations of hurricanes with the QBO has been established only for the Atlantic basin.

Table 1. Total number of intense cyclones occurring during different QBO phases for the northwest Pacific and Australia regions (roughly 90°E to 180°E) (from Collimore 1990b).

	Total number occurring during:			
Cyclones with maximum winds exceeding:	*QBO west phase*	*QBO east phase*	*Intermediate QBO period*	*Ratio of west to east phase*
		Northwest Pacific, 0-20°N		
160 knots	15	3	4	5.0
150 knots	31	13	6	2.4
140 knots	45	20	8	2.3
130 knots	63	35	10	1.8
		Entire Australia region, 0-20°S		
100 knots	17	9	0	1.9
80 knots	40	23	2	1.7
65 knots	87	50	8	1.7
		Australia region 0-20°S, east of 145°E		
80 knots	23	7	0	3.3
65 knots	52	21	3	2.5
		Australia region 0-20°S, west of 145°E		
80 knots	17	16	2	1.1
65 knots	35	29	5	1.2

In summary, ENSO-QBO can be linked, with some confidence, to a large interannual variability of tropical cyclone activity only in the western north Atlantic Ocean while exhibiting slight, or no, influence in the eastern north Pacific Ocean. The connections between SOI and the frequency of tropical cyclones have also been well verified in the Australian region even if the effect of QBO on tropical cyclogenesis is not obvious. Finally, at present, it seems impossible to reach a consensus on the associations between large scale parameters and variations of tropical cyclone activity in the western north Pacific.

Development of seasonal tropical cyclone forecast models: problems and prospects

Experience in the western Atlantic Ocean basin

In the Atlantic Ocean, Gray (1984a,b), utilised indices of El Niño, the phases of the stratospheric QBO and regional SLP data from the Caribbean region, and, through multiple linear regression analysis, and the Wilcoxon two sample rank test, developed a statistical forecast scheme (based on historical data) for the prediction of future seasonal hurricane activity at 1 June and 1 August. The seasonal forecast equations, which are based on the principle of correcting the average number of hurricanes by adding or subtracting numbers representing the values of physical predictors have been developed as follows:

Predicted number of hurricanes per season

$$= \text{average number of hurricanes} + (QBO_1 + QBO_2) + EN + SLPA \qquad ...1$$

Predicted number of hurricanes plus tropical storms per season

$$= \text{average number of hurricanes plus tropical storms} + QBO + EN + SLPA \qquad ...2$$

Predicted number of hurricane days per season

$$= \text{average number of hurricane days} + (QBO_1 + QBO_2) + EN + SLPA \qquad ...3$$

where QBO_1 is the 30 hPa equatorial wind direction correction factor, QBO_2 is the correction factor for change in 30 hPa equatorial zonal wind during the hurricane season, EN is the El Niño influence and SLPA is the average sea-level pressure anomaly for April-May in the Caribbean region. For example, two hurricanes are subtracted for a moderate El Niño event, four for a strong event, and none for a weak or non-El Niño event.

This simple and easily applied forecast scheme performed quite well in some years. However, Mielke (1984, 1985, 1986) noted that analysis by the classical linear rank test statistics, for example, matched-pairs t-test, two-sample t-test, one-way analysis of variance and significance test of Pearson's correlation coefficient, are almost always nonmetric and even prohibit the detection of major relationships between variables. He concluded that Least Absolute Deviations (LAD) regression is preferable to the traditional Ordinary Least Squares (OLS) multiple regression in that LAD methodology is based on minimising the absolute linear differences between predicted and observed values instead of the square of the differences (Gray et al. 1992c, 1993). Thus outliers do not overly influence the prediction equations. The amount of skill is estimated by the regression applied to the entire dataset with a standard degradation (Landsea et al. 1995).

Therefore, the CSU hurricane forecast team (Gray et al. 1992c, 1993, 1994), in order to set up a new model, used different combinations of predictors from 13 global and regional predictors in three groups. These are: (a) an extrapolation of QBO of 50 and 30 hPa zonal winds and the vertical shear between the 50 and 30 hPa zonal winds (three predictors); (b) western African rainfall, in the previous year, SLP, and temperature data (four predictors); (c) Caribbean basin and ENSO information, including Caribbean 200 hPa zonal winds and SLP, equatorial eastern Pacific SST and SOI values, and their changes in time (six predictors) to set up three new seasonal forecast equations to forecast the likely number of each of the seasonally dependent variables such as named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), intense hurricanes (IH), intense hurricane days (IHD), hurricane destruction potential (HDP) and net tropical cyclone activity (NTC). Forecasts were made on 1 December of the previous year (Eqn 4); 1 June, the official beginning of the hurricane season (Eqn 5); and 1 August of the current year, the start of the active hurricane season (Eqn 6):

$$\text{Predictand} = \beta_0+\beta_1(a_1U_{50}+a_2U_{30}+a_3|U_{50}-U_{30}|) +\beta_2(a_4R_S + a_5R_G) \quad ...4$$

$$\text{Predictand} = \beta_0+\beta_1(a_1U_{50}+a_2U_{30}+a_3|U_{50}-U_{30}|) +\beta_2(a_4R_S + a_5R_g + a_6\Delta_xP + a_7\Delta_xT) +\beta_3(a_8\text{SLPA}+a_9\text{ZWA}+a_{10}\text{SST}+ a_{11}\Delta_t\text{SST} + a_{12}\text{SOI} +a_{13}\Delta_t\text{SOI}) \quad ...5$$

$$\text{Predictand} = \beta_0+\beta_1(a_1U_{50}+a_2U_{30}+a_3|U_{50}-U_{30}|) +\beta_2(a_4R_S+a_5R_G)+\beta_3[a_6(\text{SLPA})+ a_7(\text{ZWA}) +a_8(\text{SOI})+ a_9(\text{SSTA})] \quad ...6$$

where the β and 'a' parameters are empirically derived coefficients and U_{50} and U_{30} are winds extrapolated to September the next year for the 50 and 30 hPa level, an indication of the QBO; R_S is standardised rainfall in the western Sahel during August and September of the prior year; R_G is standardised rainfall in the Gulf of Guinea during August through November of the prior year; Δ_xP and Δ_xT are the west African zonal pressure and temperature gradient anomalies from February to May; SLPA and ZWA are the sea-level pressure and zonal wind anomalies in the lower Caribbean during April-May; SOI and Δ_tSOI are the SOI in April-May and its change from January-February to April-May; SST and Δ_tSST are the SST in NINO3 anomalies during April-May and its change from January-February to April-May; and the June-July R_S, SLPA, ZWA, SOI and SSTA will be used for the August forecast.

To avoid the problem of over-fitting many meaningful predictors (Wilks 1995), an improved forecast scheme was introduced in August 1995. Forecasts were then made on 1 December, 1 June and 1 August for the following tropical cyclone season. The procedure is that the best individual predictor or any other best predictors-combinations are statistically tested. Only if the predictors can improve the hindcast by at least five per cent of the remaining variance (as measured by the agreement coefficient) are they included in the LAD regression equation. Normally four to seven predictors are accepted. The different best predictors combinations are made from pools of different potential predictors to forecast the numbers NS, NSD, H, HD, IH, IHD, HDP, NTC, and Maximum Potential Destruction (MPD) in November of the prior year, and April, June and August of the prediction year. The potential predictors incorporated in extended range, April, June and August forecasts are tabulated in Table 2 and Fig. 7. The MPD is implied, as it is the seasonal total of the squared values of each cyclone's peak maximum wind. Squared wind velocities better indicate the amount of damage the tropical cyclones can inflict on property than do winds themselves (Landsea 1993). In addition to the entire June-November season forecast, an August-November hurricane forecast is also done. This new scheme distinguishes the hurricane activity before and after 1 August. Only the hurricane activity of the current hurricane season is forecast with the most up-to-date atmospheric and oceanic conditions in early August. Then the predicted figures are added to the recorded tropical cyclone numbers before 1 August in order to make a whole year forecast.

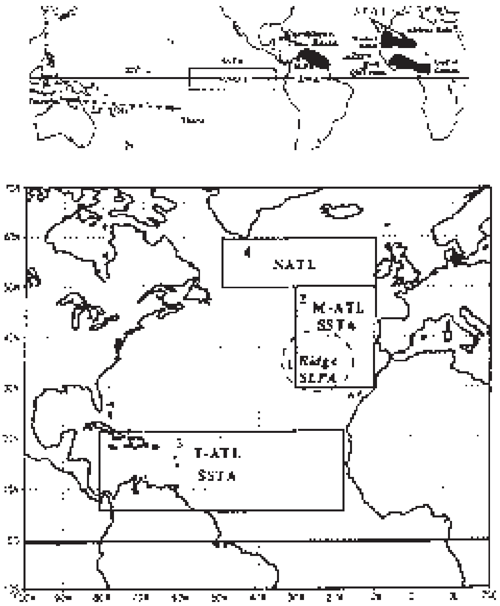
A seasonal hurricane forecast is defined as successful when the number of hurricanes occurring is at or above the average and an above average hurricane season is forecast. Otherwise, it is a failure. It also

Table 2. Potential predictors for the new and improved forecast scheme of four phases of seasonal hurricane forecast using the CSU model. (Data derived from Gray et al. (1996e, 1997a,b,c).)

Extended range	*April*	*June*	*August*
U_{50} 10-month extrapolated to Sept of the predicting year	U_{50} 6-month extrapolation to Sept of the predicting year	U_{50} 4-month extrapolation to Sept of predicting year	U_{50} July extrapolated to Sept in m/s
U_{30} 10-month extrapolated to Sept of the predicting year	U30 6-month extrapolation to Sept of the predicting year	U30 4-month extrapolation to Sept of predicting year	U30 July extrapolated to Sept in m/s
$\lvert U_{50}–U_{30}\rvert$ 10-month extrapolated to Sept of the predicting year	$\lvert U_{50}–U_{30}\rvert$ 6-month extrapolation to Sept of the predicting year	$\lvert U_{50}–U_{30}\rvert$ 4-month extrapolation to Sept of predicting year	$\lvert U_{50}–U_{30}\rvert$ July extrapolated to Sept in m/s
R_G (Aug-Nov)	Atlantic Ridge (Oct-Nov of prior year)	R_G (Aug-Nov) of prior year	R_G (Aug-Nov) in standard deviation
R_S (Aug-Sept)	Atlantic Ridge (March of the predicting year)	R_S (Jun-Sept) of prior year	R_S (Jun-Jul) of prior year in Standard Deviation
Atlantic Ridge (Oct-Nov)	R_S (Aug-Sept) of prior year	$\Delta_x T$ (Feb-May) of current year	$\Delta_x T$ (Feb-May) in Standard Deviation
Darwin (May-Jul)	R_G (Aug-Nov) of the prior year	SLPA April-May Caribbean basin	SLPA (Jun-Jul) in hPa
Nino-4 Trend (Aug-Oct) –(May-Jul)	North Atlantic SSTA for 12°N to 20°N, 50°W to 18°W (Jan-Mar of the current year)	ZWA April-May Caribbean basin	ZWA (Jun-Jul) in hPa/s
SOI (Aug-Oct)	North Atlantic SSTA for 50°N to 60°N, 10°W to 50°W (Jan-Dec of the prior year)	Atlantic Ridge (Oct-Nov of prior year)	SSTA 3.4 (Jun-Jul) in °C x 10^{-2}
SOI Trend (Aug-Oct) -(May-Jul)		Atlantic Ridge (Mar)	Δ_t SST 3.4 (Jun-Jul minus April-May) in °C x 10^{-2}
		Niño 3.4 SSTA in April-May	MATL (May-Jun) 30°-50°N, 10°-30°W in °C x 10^{-2}
		ΔNiño 3.4 SSTA for April-May minus Feb-Mar of current year	TATL (May-Jun) 6°-22°N, 18°-80°W in °C x 10^{-2}
		(SATL) South Atlantic SSTA anomaly (Mar-April)	SATL (May-Jun) 22°S - 2°N, 35°W-1°E in °C x 10^{-2}
		(TATL) Tropical Atlantic SSTA anomaly (Mar-April)	Atlantic Ridge (Mar)
		(MATL) Mid Atlantic SSTA anomaly (Mar-April)	

fails when a reversing trend of hurricane activity is forecast but not observed. Generally, the August NS forecasts were quite good for 1985, 1986, 1987, 1988, 1991, 1994 and 1995 while the August H forecasts were successful for 1985, 1986, 1991, 1992, 1994 and 1995. Table 3 shows there was reasonable success in forecasting the numbers NS, H, and IH, especially in the June and August updated forecasts. The average absolute errors of these parameters are less than 1 standard deviation of the observed number.

Fig. 7 Meteorological parameters used in late November, early April, early June and early August forecasts (from Gray et al. 1997a,d).



The failures of recent forecasts (1996, 1997, 1998) have been explained by the north-south SST differences in the Atlantic Ocean due to a major change in the Atlantic Ocean thermohaline or 'conveyor belt' circulation (see Gray et al. 1997e).

In addition to the above interpretation it should also be emphasised that the possibility of a reliable extended-range forecast depends on the accurate prediction of two key measures: El Niño and Western Sahel rainfall. The failures in 1993 and 1997 were largely due to the unanticipated prolonged El Niño event (1991-94) and the extreme El Niño event which occurred from June through October in 1997. As a consequence the seasonal hurricane forecasts which depend on an accurate and difficult ENSO prediction are affected.

The predicted values from the statistical seasonal hurricane forecast equations can also be adjusted qualitatively by considering some significant features in the atmosphere not explicitly incorporated in the forecast model. However, qualitative, subjective adjustments may reduce forecast skill. For example, the inclusion of very cold 100 hPa temperature anomalies at Singapore (14°N) observed during June-November 1996 and the recent north-south SST differences in the Atlantic Ocean due to a major change in the Atlantic Ocean thermohaline circulation led the CSU team to make a wrong upward adjustment of the extended 1997 forecast (Table 4). These two factors are believed to favour the formation of more hurricanes in the Atlantic Ocean (Gray et. al. 1996e). Verification suggests that factors affecting hurricane activity in the western north Atlantic should be weighted statistically and objectively incorporated in the model.

Undoubtedly, the CSU methodology is a statistical-climatological approach. In addition to the sophisticated statistical equations, historical hurricane information is also considered in preparing the seasonal forecasts. Attempts are made to compare previous analogous years with near-identical forecast parameters, to the current season in order to categorise hurricane activity into: very active, active/above average, average, below average/inactive, and very inactive. For instance, the year 1996, following an unusually active hurricane season (1995) was thought to be one of somewhat below average hurricane activity in the Atlantic Ocean. The Atlantic hurricane activity of 1997, on the other hand, was predicted to be above average as the occurrence of a consecutive three-year period of above average activity was very common during the 1930 through 1950 period and during the 1880s and 1890s (see Gray et al. 1997a,b,c). Unfortunately, the hurricane activity was very active in 1996 (underforecast) and below normal in 1997 (overforecast). Lorenz (1993) suggests that weather variations are not periodic. Even if the atmosphere may really be behaving periodically, it may be doing so with a period whose length exceeds that of any weather records. Nebeker (1995) pointed out that weather prediction had three requisites: (a) the ability to specify the present state of the atmosphere; (b) a vast archive of descriptions of past states of the atmosphere; and (c) the ability to select from the archive the past state most closely resembling the present state. Technically we are not able to fulfil all of these three conditions at the present moment.

The question that may thus legitimately be posed is: 'Can the statistical equations without adjustments be skilful enough to forecast accurately the interannual variability of tropical cyclone activity in the western north Atlantic?' Table 4 shows that the answer is conditional. For example, the forecasts in April and June of 1995, the extended range forecast and April update in 1997 and both June and August statistical calculations in 1998 were better than adjusted forecasts. But there were occasional failures. The forecast NTC (66%) was only about one-third of the actual observed figure (198%) in June 1996. Even though the 1995 forecast was regarded as quite successful in predicting an upswing of hurricane activity, the forecast values computed from the statistical equations were still far from

Table 3. Comparison of extended range (1992-1998), April (1996-1998), June (1984-1998) and August (1984-1998) forecast values. The data for H, NS, HD, NSD are from 1984-1998; HDP from 1988-1998; IH, IHD from 1990-1998 and NTC from 1994-1998. (Data derived from Gray et al. (1998e).)

(Extended range)

Forecast parameters	*Mean of forecast*	*Mean of observed*	*S.D. of the observed*	*Average absolute Error*
No. of Hurricanes	5.9	6.1	3.1	2.9
No. of Named Storms	9.9	10.6	4.5	4.1
No. of Hurricanes Days	23.6	28.1	20.8	18.3
No. of Named Storm Days	50	57.7	33.4	31.7
Hurr. Destruction Potential	67.1	80.7	61.8	62.4
Intense Hurricanes	2.3	2.4	2.1	1.9
Intense Hurricane Days	5.4	5.7	5	4.8
Net Trop. Cyclone Activity	107	137.8	78.1	82.8

(April)

Forecast parameters	*Mean of forecast*	*Mean of observed*	*S.D. of the observed*	*Average absolute Error*
No. of Hurricanes	6.7	7	2.8	3
No. of Named Storms	10.7	11.3	3.1	3.3
No. of Hurricanes Days	23.3	34	17	20.7
No. of Named Storm Days	53.3	62	24.1	26.7
Hurr. Destruction Potential	71.7	101	53.1	62
Intense Hurricanes	2.3	3.3	2.1	2.3
Intense Hurricane Days	4.7	8.1	4.5	5.3
Net Trop. Cyclone Activity	103.3	141.3	62.7	75.3

(June)

Forecast parameters	*Mean of forecast*	*Mean of observed*	*S.D. of the observed*	*Average absolute Error*
No. of Hurricanes	5.9	5.7	2.5	1.9
No. of Named Storms	9.7	10.3	3.6	2.5
No. of Hurricanes Days	23.3	22.7	16.4	12.9
No. of Named Storm Days	45.7	51.1	26.3	18
Hurr. Destruction Potential	63.6	75.7	53.3	42.5
Intense Hurricanes	2	2.2	1.9	1.6
Intense Hurricane Days	3.5	5.1	4.9	3.3
Net Trop. Cyclone Activity	103	137.8	78.1	70.8

(August)

Forecast parameters	*Mean of forecast*	*Mean of observed*	*S.D. of the observed*	*Average absolute Error*
No. of Hurricanes	5.6	5.3	2.8	2.1
No. of Named Storms	9.7	10.3	3.6	1.9
No. of Hurricanes Days	21.1	22.7	16.4	11.1
No. of Named Storm Days	43	51.1	26.3	15.1
Hurr. Destruction Potential	57.7	75.7	53.3	37.5
Intense Hurricanes	1.8	2.2	1.9	1.3
Intense Hurricane Days	3	4.7	4.8	3.3
Net Trop. Cyclone Activity	102	137.8	78.1	65.8

Table 4. Comparison of statistically forecast and qualitatively adjusted values and observed values of tropical cyclone activity in the western north Atlantic Ocean basin for the period 1995-1998 (data derived from Gray et al. (1995a,b,c,d; 1996a,b,c,d,e; 1997a,b,c,d,e; 1998a,b,c,d,e))

1995

(Extended range) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	7.4	8	11	-3.6	-3
No. of Named Storms	11.69	12	19	-7.31	-7
No. of Hurricanes Days	34.26	35	62	-27.74	-27
No. of Named Storm Days	65.35	65	121	-55.65	-56
Hurr. Destruction Potential	91.42	100	173	-81.58	-73
Intense Hurricanes	2.94	3	5	-2.06	-2
Intense Hurricane Days	6.62	8	11.5	-4.88	-3.5
Net Trop. Cyclone Activity	128.41	140	229	-100.59	-89

(April) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	7.4	6	11	-3.6	-5
No. of Named Storms	11.69	10	19	-7.31	-9
No. of Hurricanes Days	34.26	25	62	-27.74	-37
No. of Named Storm Days	65.35	50	121	-55.65	-71
Hurr. Destruction Potential	91.42	75	173	-81.58	-98
Intense Hurricanes	2.94	2	5	-2.06	-3
Intense Hurricane Days	6.62	5	11.5	-4.88	-6.5
Net Trop. Cyclone Activity	128.41	100	229	-100.59	-129

(June) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	10.4	8	11	-0.6	-3
No. of Named Storms	12.6	12	19	-6.4	-7
No. of Hurricanes Days	49.5	35	62	-12.5	-27
No. of Named Storm Days	77.9	65	121	-43.1	-56
Hurr. Destruction Potential	135.4	110	173	-37.6	-63
Intense Hurricanes	2.3	3	5	-2.7	-2
Intense Hurricane Days	5.7	6	11.5	-5.8	-5.5
Net Trop. Cyclone Activity	153.5	140	229	-75.5	-89

(August) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	10.23	9	11	-0.77	-2
No. of Named Storms	16.42	16	19	-2.58	-3
No. of Hurricanes Days	26.06	30	62	-35.94	-32
No. of Named Storm Days	63.72	65	121	-57.28	-56
Hurr. Destruction Potential	70.43	90	173	-102.57	-83
Intense Hurricanes	2.69	3	5	2.31	-2
Intense Hurricane Days	3.29	5	11.5	-8.21	-6.5
Net Trop. Cyclone Activity	123.38	130	229	-105.62	-99

Table 4. Continued.

1996

(Extended range) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	5.4	5	9	-3.6	-4
No. of Named Storms	8.3	8	13	-4.7	-5
No. of Hurricanes Days	21.2	20	45	-23.8	-25
No. of Named Storm Days	39.5	40	78	-38.5	-38
Hurr. Destruction Potential	42	50	135	-93	-85
Intense Hurricanes	2.1	2	6	-3.9	-4
Intense Hurricane Days	6.2	5	13	-6.8	-8
Net Trop. Cyclone Activity	85.2	85	198	-112.8	-113

(April) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	9.2	7	9	0.2	-2
No. of Named Storms	12.8	11	13	-0.2	-2
No. of Hurricanes Days	19.7	25	45	-25.3	-20
No. of Named Storm Days	62.7	55	78	-15.3	-23
Hurr. Destruction Potential	95.6	75	135	-39.4	-60
Intense Hurricanes	2.4	2	6	-3.6	-4
Intense Hurricane Days	4.6	5	13	-8.4	-8
Net Trop. Cyclone Activity	118.2	105	198	-79.8	-93

(June) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	4.39	6	9	-4.61	-3
No. of Named Storms	7.99	10	13	-5.01	-3
No. of Hurricanes Days	14.75	20	45	-30.25	-25
No. of Named Storm Days	24.88	45	78	-53.12	-33
Hurr. Destruction Potential	57.6	60	135	-77.4	-75
Intense Hurricanes	2	2	6	-4	-4
Intense Hurricane Days	4.1	5	13	-8.9	-8
Net Trop. Cyclone Activity	66.34	95	198	-131.66	-103

(August) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	6.85	7	9	-2.15	-2
No. of Named Storms	11.06	11	13	-1.94	-2
No. of Hurricanes Days	24.24	25	45	-20.76	-20
No. of Named Storm Days	56.07	50	78	-21.93	-28
Hurr. Destruction Potential	68.49	70	135	-66.51	-65
Intense Hurricanes	2.63	3	6	-3.37	-3
Intense Hurricane Days	4.57	4	13	-8.43	-9
Net Trop. Cyclone Activity	104.2	105	198	-93.8	-93

Table 4. Continued.

1997

(Extended range) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	5.33	7	3	2.33	4
No. of Named Storms	8.46	11	7	1.46	4
No. of Hurricanes Days	17.14	25	10	7.14	15
No. of Named Storm Days	36.89	55	28	8.89	27
Hurr. Destruction Potential	46.96	75	26	20.96	49
Intense Hurricanes	1.93	3	1	0.93	2
Intense Hurricane Days	3.78	5	2.2	1.58	2.8
Net Trop. Cyclone Activity	73.07	110	54	19.07	56

(April) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	6.11	7	3	3.11	4
No. of Named Storms	9.7	11	7	2.7	4
No. of Hurricanes Days	13.39	25	10	3.39	15
No. of Named Storm Days	37.56	55	28	9.56	27
Hurr. Destruction Potential	37.65	75	26	11.65	49
Intense Hurricanes	1.78	3	1	0.78	2
Intense Hurricane Days	3.6	5	2.2	1.4	2.8
Net Trop. Cyclone Activity	72.62	110	54	18.62	56

(June) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	6.47	7	3	3.47	4
No. of Named Storms	10.66	11	7	3.66	4
No. of Hurricanes Days	34	25	10	24	15
No. of Named Storm Days	43.59	55	28	15.59	27
Hurr. Destruction Potential	116.34	75	26	90.34	49
Intense Hurricanes	5.97	3	1	4.97	2
Intense Hurricane Days	8.78	5	2.2	6.58	2.8
Net Trop. Cyclone Activity	128.74	110	54	74.74	56

(August) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	7.37	6	3	4.37	3
No. of Named Storms	11.81	11	7	4.81	4
No. of Hurricanes Days	30.93	20	10	20.93	10
No. of Named Storm Days	63.04	45	28	35.04	27
Hurr. Destruction Potential	90.82	60	26	64.82	34
Intense Hurricanes	3.09	2	1	2.09	1
Intense Hurricane Days	8.22	3	2.2	6.02	0.8
Net Trop. Cyclone Activity	150.89	100	54	96.89	46

Table 4. Continued.

1998

(Extended range) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	4.57	5	9	-4.43	-4
No. of Named Storms	9.36	9	14	-4.64	-5
No. of Hurricanes Days	15.88	20	47	-31.12	-27
No. of Named Storm Days	35.13	40	80	-44.87	-40
Hurr. Destruction Potential	43.59	50	142	-98.41	-92
Intense Hurricanes	1.67	2	3	-1.33	-1
Intense Hurricane Days	0.91	3	9	-8.09	-6
Net Trop. Cyclone Activity	78.32	90	172	-93.68	-82

(April) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	6.1	6	9	-2.9	-3
No. of Named Storms	8.71	10	14	-5.29	-4
No. of Hurricanes Days	21.14	20	47	-25.86	-27
No. of Named Storm Days	49.95	50	80	-30.05	-30
Hurr. Destruction Potential	64.22	65	142	-77.78	-77
Intense Hurricanes	2.88	2	3	-0.12	-1
Intense Hurricane Days	3.61	4	9	-5.39	-5
Net Trop. Cyclone Activity	86.78	95	172	-85.22	-77

(June) *Forecast parameters*	*Statistical forecast values Highest (lowest) 25%*	*Adjusted forecast values*	*Observed*	*Errors of stat. values Highest (lowest) 25%*	*Errors of adj. values*
No. of Hurricanes	7.9 (4.9)	6	9	-1.1 (-4.1)	-3
No. of Named Storms	11.2 (8.9)	10	14	-2.8 (-5.1)	-4
No. of Hurricanes Days	27.8 (18.9)	25	47	-19.2 (-28.1)	-22
No. of Named Storm Days	54.1 (46.1)	50	80	-25.9 (-33.9)	-30
Hurr. Destruction Potential	86.7 (51.5)	70	142	-55.3 (-90.5)	-72
Intense Hurricanes	2.4 (1.5)	2	3	-0.6 (-1.5)	-1
Intense Hurricane Days	6.1 (2.3)	4	9	-2.9 (-6.7)	-5
Net Trop. Cyclone Activity	110.7 (76.7)	100	172	-61.3 (-95.3)	-72

(August) *Forecast parameters*	*Statistical forecast values*	*Adjusted forecast values*	*Observed*	*Errors of stat. values*	*Errors of adj. values*
No. of Hurricanes	7.89	6	9	-1.11	-3
No. of Named Storms	9.73	10	14	-4.27	-4
No. of Hurricanes Days	31.8	25	47	-15.2	-22
No. of Named Storm Days	47.58	50	80	-32.42	-30
Hurr. Destruction Potential	87.76	75	142	-54.24	-67
Intense Hurricanes	1.98	2	3	-1.02	-1
Intense Hurricane Days	8.18	5	9	-0.82	-4
Net Trop. Cyclone Activity	133.48	110	172	-38.52	-62

the actual numbers. For instance, the number of hurricane days (26.06) and hurricane destruction potential (70.43) inferred from those equations were less than half of their actual figures (62 and 173 respectively) in the August 1995 forecast.

Much effort has been made to improve statistical analysis methods in order to improve the seasonal Atlantic hurricane forecasts (Elsner and Schmertmann 1993; Hess and Elsner 1994b; Hess et al. 1995). All the above attempts are primarily refinements of the Gray et al. model for Atlantic hurricane forecasts.

A new approach has been introduced recently by the Florida State University (FSU). Realising that the presence or absence of hurricanes in one specific region (the Caribbean, the Gulf of Mexico, the SE Coast and NE Coast) is more significant than the prediction of specific numbers of tropical cyclones in the western north Atlantic generally, Lehmiller et al. (1997) applied multivariate discriminant analysis techniques in making extended-range forecasts of hurricane activity by classifying an observation into either group 1 (yes) or 2 (no). Knowing that the Gray et al. (1992, 1993) predictors were not enough for forecasting hurricanes which are influenced by mid-latitude systems in the north western Atlantic, some additional potential predictors were considered. These were: (a) July monthly mean SLP at several east coast reporting stations; (b) the July monthly coastal SLP averaged over these same east coast stations; (c) the magnitude of the vertical shear of the average July monthly 700 and 200 hPa winds for several east coast sounding locations; (d) the least squares estimated meridional component of the gradient of the SLP along the East Coast; and (e) the least squares estimated meridional component of the gradient of the geopotential heights on several constant pressure surfaces. It was shown that extended-range forecasts of all hurricane activity are possible within the Caribbean Sea. Intense hurricane activity can be successfully predicted in both the Gulf of Mexico and the Caribbean Sea. Moreover, lead-time forecasts of landfalling hurricanes on the southeastern Atlantic coast of the US are better than climatology.

Actually, the FSU model is an OLS linear regression model which predicts the number of hurricanes by adding the tropical-only hurricanes and the average number of baroclinically enhanced hurricanes. Note that the average is also adjusted conditionally on the number of tropical-only hurricanes as the two components are negatively correlated. Since the FSU and CSU models also use nearly the same predictors, there would not be a lot of difference in their forecasts for an individual year (Elsner and Kara 1999).

The CSU Seasonal Hurricane Forecast Model has now started incorporating the prediction of the probability of hurricane landfall along eleven different coastal regions from the Gulf Coast to the northeast of US from August 1998 (see Gray 1998; Gray et al. 1999a,b,c). Bove et al. (1998) indicate that the numbers of landfalling hurricanes in the US are also reduced in El Niño events and the reverse occurs in La Niña events. The landfall probability forecasting equations are derived on the basis of both the annual Atlantic basin NTC activity (and implied ENSO effect) and on prior observed measurements of the strength of the Atlantic Ocean thermohaline circulation.

Finally, for extended-range forecasts, two approaches, the autoregressive-moving average (ARMA) models and the iterative approach, are suggested. However, when used operationally, these merely yield marginally more skilful predictions compared to climatology (see Elsner and Kara 1999). Another possibility would be to rely on a better understanding of the linkage between north Atlantic hurricane activity and low frequency changes in the Atlantic SSTs on a multi-decadal time-scale (Elsner et al. 1998).

In summary, the concept of a seasonal hurricane forecast for the western Atlantic Ocean basin has been developed to a relatively sophisticated level. Nevertheless, despite considerable advances, there are still major difficulties to be resolved if the approach is to be considered operationally reliable.

Australian seasonal tropical cyclone forecast models

A considerable amount of attention has been given to seasonal tropical cyclone forecasts in the southern hemisphere in the last couple of decades. In the Australian region, Nicholls (1985), using the established strong relationships between July-September 0900 mean sea-level pressures in Darwin and the number of cyclone days in a cyclone season, developed a linear regression equation:

$$\text{Cyclone days} = 224.5 - [\,11.6 \times (\text{pressure} - 1000\text{hPa})\,] \quad ...7$$

to predict the number of cyclones expected in the subsequent cyclone season (i.e., from October to April). This relationship is stable enough to allow prediction of seasonal cyclone activity several months prior to the start of the tropical cyclone season. However, this method still represents an early stage in the development of seasonal tropical cyclone forecasting. Other predictors, e.g. SSTs around north Australia (Nicholls 1984), have also been found useful.

Another statistical model (Solow and Nicholls 1990) of the relationship between tropical cyclone frequency in the Australian region and an index of the strength of, and phase of, the SO has been developed:

$$m^*_t = \exp(2.30 + 0.021X_t) \qquad ...8$$

to predict the number of tropical cyclones in year t ($t = 0, \dots, n$), where m^*_t is the estimated mean function of true cyclone counts, X_t is the average value of the index for the month of September preceding the onset of the Australian cyclone season in October. The fitted model indicates that the mean annual number of cyclones during a major cold event is twice that during a major warm event. Nonetheless, the authors realise that both of these two statistical equations are nonstandard because the cyclone record is incomplete early in the 1910-1988 period.

Recently, Nicholls (1992) points out that use of the SOI to predict the change in cyclone numbers from last season to the coming season, rather than predicting the expected numbers directly from the SOI, could reduce the confounding effect of possible secular changes in cyclone numbers, the SOI, or of relationships between them. Nicholls et al. (1998) adds that the SOI, although a good predictor of the number of tropical cyclones in the Australian region, is not a good predictor of the intensity of cyclones.

Research in the Australian region will be on potential cyclogenesis parameters, e.g. the QBO.

Prediction of the interannual variability of tropical cyclone activity in the western north Pacific Ocean basin

Aoki (1987), applying a stepwise regression program, using the possible independent sea-surface temperature $X_1,\dots,X_{12}$ variables defined in Table 5, developed the following equation for hindcasting the frequency of typhoon formation:

$$Y_f = 41.50 - 2.970\,X_2 - 5.040\,X_4 + 4.963\,X_7 + 2.277X_{10} \qquad ...9$$

The predicted frequencies of typhoon formation were quite skilful (Table 6); however, since only four years of data (1951, 1952, 1983, and 1984) were chosen for verification, the results are inconclusive. Despite that, Raper (1992) who correlated tropical cyclone numbers for seven cyclone basins with the three-monthly average SST near the beginning of the season (May-July for northern hemisphere basins and either September-November or October-December for southern hemisphere basins) for the period 1900-1986, states ‘the separation between the regions of SST influence and the storms themselves argues that these positive correlations are not a direct result of higher SSTs being more favorable for tropical cyclone formation and intensification. Rather, the cause for the link appears to be the atmospheric conditions to which both the SSTs and the tropical cyclone frequencies are intimately related’.

Chan (1991, 1994) developed a multiple linear regression technique for predicting the annual number of tropical storms and typhoons over the entire western north Pacific (WNP) and two of its sub-regions: the northern part of the South China Sea (NSCS) and the eastern part of the western north Pacific Ocean (EWNP). The technique showed useful skill but requires further enhancement before it can be used operationally.

Recently, researchers in mainland China have tried to apply statistical methodologies, such as artificial neural networks (Li and Deng 1995) and Projection Pursuit Regression (PPR) (Li et al. 1998) to forecast the number of landfalling typhoons in South China. The results are encouraging and their forecasting performances are better than that of stepwise regression model.

Chan et al. (1998) also applied the PPR technique to derive prediction equations for seasonal forecasting of the interannual variability of tropical cyclone activity over the western north Pacific and the South China Sea (SCS). This approach is useful for hindcasting tropical cyclone activity over the entire western north Pacific but only showed the correct trend of cyclone activity for the South China Sea in a 1997 trial. With regard to landfalling tropical cyclone forecasts, Fong and Chan (1993) tried to correlate the interannual variability of the landfalling tropical cyclones over China with ENSO and the QBO. Their results suggest more work is needed in this area.

In addition to the existing predictors, there may also be other undetected atmospheric or oceanic parameters which are more significant for forecasting the yearly variations of tropical cyclone frequency. For instance, tropical cyclogenesis and the genesis locations in the western north Pacific are also governed by the seasonal variability and types of the Tropical Upper Tropospheric Trough (Sadler 1978; Habjan 1997; Wu 1992). The initial disturbances most frequently (about 80 per cent) form in the monsoon trough (McBride 1995). Therefore, the climatological characteristics of the monsoon trough (its strength and location) may need to be incorporated in any future seasonal typhoon forecast.

Furthermore, it is interesting to note that depressions, storms, and typhoons preferentially develop during the wet phase of the 30 to 60-day Madden-Julian Oscillation (MJO) (Gray 1993) and this is related to the large-scale low-level cyclonic relative vorticity and convergence anomalies that develop westward and poleward of the anomalous MJO convection (Liebmann et al. 1994). While propagating southward, this low-frequency oscillation in the northern hemisphere can trigger a low-frequency wave in the southern hemisphere, which in turn can

Table 5. Possible independent variables X1, …,X12 , representing average sea-surface temperature on each of four grid-points for various seasons and times (after Aoki 1987).

	Grid-points				*Season**	*Year***
X_1	30°N, 125°E	30°N, 130°E	25°N, 125°E	20°N, 125°E	SU	-2
X_2	30°N, 135°E	30°N, 140°E	25°N, 135°E	25°N, 140°E	AU	-1
X_3	40°N, 150°E	40°N, 155°E	40°N, 160°E	35°N, 150°E	SU	-2
X_4	20°N, 145°E	20°N, 150°E	15°N, 145°E	15°N, 150°E	SP	-2
X_5	25°N, 165°E	25°N, 170°E	25°N, 175°E	25°N, 180°E	AU	-2
X_6	5°N, 180°E	EQ, 180°E	EQ, 175°W	EQ, 170°W	AU	-2
X_7	5°S, 160°W	5°S, 155°W	10°S, 160°W	10°S, 155°W	SU	-1
X_8	5°N, 155°W	EQ, 155°W	EQ, 150°W	EQ, 145°W	WI	-1
X_9	5°N, 145°W	5°N, 140°W	5°N, 135°W	5°N, 130°W	AU	-2
X_{10}	10°N, 120°W	10°N, 115°W	10°N, 110°W	10°N, 105°W	WI	-1
X_{11}	5°N, 120°W	5°N, 115°W	EQ, 120°W	EQ, 115°W	AU	-2
X_{12}	5°S, 115°W	5°S, 110°W	5°S, 105°W	5°S, 100°W	AU	-2

* SP: spring SU: summer AU: autumn WI: winter

** -1: preceding year; -2: 2 years before

Table 6. Predicted and observed frequencies of typhoon formation for independent data (Aoki 1987).

	1951	1952	1983	1984
Prediction	23.2	25.0	24.0	27.9
Observation	21	27	23	27

influence the typhoon activity in the northern hemisphere by changing the cross-equatorial flow (Liu and Lin 1990). Unfortunately, its application to long-range forecasting, at least presently, is limited (Liebmann et al. 1994).

Conclusions

Numerous seasonal typhoon forecast models have been developed and continually modified in order to help synoptic meteorologists make reliable statistical typhoon forecasts. The CSU model is still the state-of-the-art seasonal tropical cyclone forecast although recent failures indicate the need for ongoing research. The FSU model does bring new light to the research in this area. The models developed in the Australian and western north Pacific Ocean basins also seem to need further enhancements. More research is required to (a) devise new predictors, (b) develop more appropriate statistical analysis methods, and (c) develop further insights into the physical control of large-scale processes on TC activity.

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