GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 8, PAGES 1147-1150, APRIL 15, 2000

Atlantic hurricanes and NW Pacific typhoons: ENSO spatial impacts on occurrence and landfall

M. A. Saunders[1], R. E. Chandler[2], C. J. Merchant[1], and F. P. Roberts[1]

[1]Benfield Greig Hazard Research Centre, Department of Space and Climate Physics, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, U.K.
[2]Department of Statistical Science, University College London, Gower Street, London WC1E 6BT, U.K.

Abstract. Hurricanes are the United States' costliest natural disaster. Typhoons rank as the most expensive and deadly natural catastrophe affecting much of southeast Asia. A significant contributor to the year-to-year variability in intense tropical cyclone numbers in the north Atlantic and northwest Pacific is ENSO - the strongest interannual climate signal on the planet. We establish for the first time: (1) the spatial (0.5 degree grid) impacts of ENSO on the basin-wide occurrence and landfall strike incidence of hurricanes and typhoons; (2) the spatial (7.5 degree grid or US state level) statistical significance behind the different incidence rates in warm and cold ENSO episodes; and (3) the effect of strengthening ENSO on regional strike rates and significances (hurricanes only). Our data comprise 98 years (1900-97) for the Atlantic and 33 years (1965-97) for the NW Pacific. At the US state level, we find several regions where the difference in landfalling incidence rate between warm and cold ENSO regimes is significant at the 90% level or higher. Our findings offer promise of useful long-range predictability to seasonal forecasts of landfalling tropical cyclones.

Introduction

Tropical cyclones rank above earthquakes and floods as the major geophysical cause of property damage in the United States. The annual hurricane damage bill in the continental US for 1926-1995 is estimated as US \$5.0 billion (1997 \$) [*Pielke and Landsea*, 1998]; for the period 1990-1998 the annual figure is US \$5.2 billion (1997 \$). In much of Japan, South Korea, Taiwan, the Philippines, and other southeast Asian coastal regions, tropical cyclones are the most costly and deadly of all natural disasters. The southeast Asian damage bill and mortality rate from tropical cyclones averages US \$3.1 billion (1997 \$) per year and 740 deaths per year for 1990-1998 [based on information from Munich Re]. Intense tropical cyclones (maximum 1-min sustained winds of at least 33 ms^{-1} or 64 knots) – termed hurricanes in the Atlantic and typhoons in the NW Pacific - are responsible for 98% of US damage [*Pielke and Landsea*, 1998] and the vast majority of southeast Asian damage. While satellites and numerical weather models provide warnings of impending landfall up to a week ahead, efforts are increasingly being given to the seasonal probabilistic forecasting of these landfalls. Such long-range forecasts can benefit a range of industry including insurance, agriculture and tourism.

When considering potential long-range (out to 6 months) predictors of landfalling tropical cyclones, ENSO – the strongest interannual climate fluctuation on the planet [eg *Philander*, 1990] - would appear a promising candidate. (See [eg *Trenberth et al.*, 1998, and *Latif et al.*, 1998] for recent reviews of ENSO's teleconnections and predictability). It is well accepted that the ENSO warm phase (El Niño) leads to reduced hurricane numbers in the north Atlantic as a whole [*Gray*, 1984; 1993], to fewer hurricane strikes on the continental US as a whole [*Gray*, 1984; *O'Brien et al.*, 1996; *Bove et al.*, 1998], and to a lower US hurricane damage bill [*Pielke and Landsea*, 1999]. *Gray* [1984] reports a factor of three reduction in total US landfalling intense hurricane impacts from 0.74 per year during La Niña (ENSO cold phase) years to 0.25 per year during El Niño years. Recently *Bove et al.* [1998] analysed the probability of hurricane and intense hurricane strikes for the whole continental US as a function of the concurrent ENSO phase. They find the probability of at least one intense hurricane strike is 63% and 23% for La Niña and El Niño years respectively. These differences are statistically significant. The spatial impacts of ENSO on the local frequency and strike incidence of NW Pacific typhoons has, to our knowledge, not been reported in the refereed literature. However, *Chan* [1985, 1990] shows that the frequency of tropical cyclones in the north Pacific between 140° and 160°E increases during El Niño years, while tropical cyclone occurrence in the South China Sea increases in La Niña years (see also *Gray* [1993] and *Lander* [1994]).

We extend the above previous work by quantifying for the first time: (1) the spatial impacts of ENSO on the basin-wide occurrence and local landfalling strike rates of hurricanes and typhoons. This is achieved through use of a 0.5° x 0.5° in latitude and longitude basin-wide grid which permits coastal and islands regions to be resolved; (2) the formal significance behind the different incidence rates in warm and cold ENSO episodes (on a 7.5° x 7.5° grid or US state level scale); and (3) the effect and significance of strengthening ENSO on regional landfalling intense tropical cyclone incidence.

We use the NOAA/NESDIS/NCDC best track global historical tropical cyclone database. To obtain frequencies on a 0.5° grid we linearly interpolate the six-hourly records onto hourly positions, and compute for equal area circles of radius 140 km centered on each grid point, the number of hurricanes/typhoons that pass through the circle. If an event exits a circle and reenters (a rare occurrence) it is counted once. The 140 km distance is chosen as a representative radius of damage loss [*Neumann and Pryslak*, 1981]. For the Atlantic we use hurricane records from 1900-1997, and for the northwest Pacific from 1965-1997. Landfalling records are complete in both. For ENSO we use Niño 3.4 monthly index values (5°N-5°S, 120°W-170°W) computed from the U.K. Met. Office's Historical Sea Surface Temperature data set version 6 (MOHSST6) [*Parker et al.*, 1995]. MOHSST6 values are a bulk temperature retrieval

Paper number 1999GL010948.
0094-8276/00/1999GL010948\$05.00

between 1m and 10m depth and, for the tropics, contain the best available historical quality controls and bias corrections.

Statistical Analysis and Modelling

We first compute, for each 0.5° grid cell, the annual incidence rate (*IR*) of hurricanes/typhoons in both El Niño and La Niña years. The ENSO sign is determined using monthly Niño 3.4 data and by whether the Niño 3.4 anomaly is greater than or less than 0.0°C. By taking the ratio of incidence rates under the two ENSO conditions we obtain the incidence rate ratio, a statistic commonly used in investigations of the causes of diseases [e.g., *Rothmann and Greenland*, 1998]. This ratio is shown colour-coded for the north Atlantic and the NW Pacific in Figure 1 (upper numeric panel marked 'La Niña/El Niño').

We use two models to determine the statistical significance of any difference in hurricane/typhoon frequencies between warm and cold ENSO episodes. MODEL 1 is based on incidence rate ratios and is the numerically simpler model. We apply it to landfalling events only. MODEL 2 employs logistic regression [*Cox and Snell*, 1989; *McCullagh and Nelder*, 1989]. We apply it to landfalling and to non-landfalling events. Both models give similar results for landfalling events.

MODEL 1 uses the incidence rate ratios (*IRRs*) of events for El Niño (*EL*) and La Niña (*LN*) conditions applied to different landfall regions. If the *IRR* differs significantly from 1.0, it indicates an association between the phase of ENSO and the incidence of landfalling intense tropical cyclones. The statistical significance test arises through the logarithm of the *IRR* being approximately Gaussian distributed with a standard deviation of:

$$\left(\frac{1}{N_{EL}}+\frac{1}{N_{LN}}\right)^{1/2}$$

[see e.g. *Rothmann and Greenland*, 1998], where N_{EL} and N_{LN} are the total number of landfalling events in our record in *EL* and *LN* years respectively. In terms of sample size, the normal approximation for log *IRR* is reasonable providing both N_{EL} and N_{LN} are greater than about 10. This criterion is met by 95% of our regional landfalling subsets – the exceptions being a few categories of hurricane impacts on the Lesser Antilles, and typhoon strikes on South Korea.

In applying MODEL 1 we use significance levels of 90% and 95% in a two-tailed test, i.e., a test for difference from unity in either direction. Despite there being a 10% probability that an isolated result at the 90% level could occur by chance, we include these results because *IRRs* at nearby locations are spatially dependent.

Since the four most active months for intense tropical cyclones in both basins are July, August, September and October (JASO months), we first show results using JASO landfalling events and the JASO-averaged Niño 3.4 anomaly. In the NW Pacific, we also show results based on the August to October (ASO months) averaged ENSO conditions with the annual number of landfalling events. In the Atlantic, where our data time series is three times the length of our NW Pacific time series, we additionally compute three separate *IRRs* for *EL*, *LN* and *Neutral* ENSO conditions. The Niño 3.4 anomaly thresholds used for these are: *EN* > 0.3°C, 0.3°C ≥ *Neutral* ≥ –0.3°C, *LN* < -0.3°C. The latter investigation probes the impact of strengthening ENSO on changing hurricane incidence, and clarifies how *EN IR* and *LN IR* values differ from *Neutral IR* values.

MODEL 2 employs logistic regression and takes the form:

$$\ln\left(\frac{p}{1-p}\right)=\beta_o+\sum_{i=1}^{k}\beta_i x_i$$

where p is the probability of 1 or more hurricanes at a given location in a given month, the xs are the predictor values, and the βs are the coefficients to be estimated, via Maximum Likelihood, from historical data. For large samples, likelihood ratio tests [*Cox and Hinkley*, 1974] can be used to compare models. Such tests

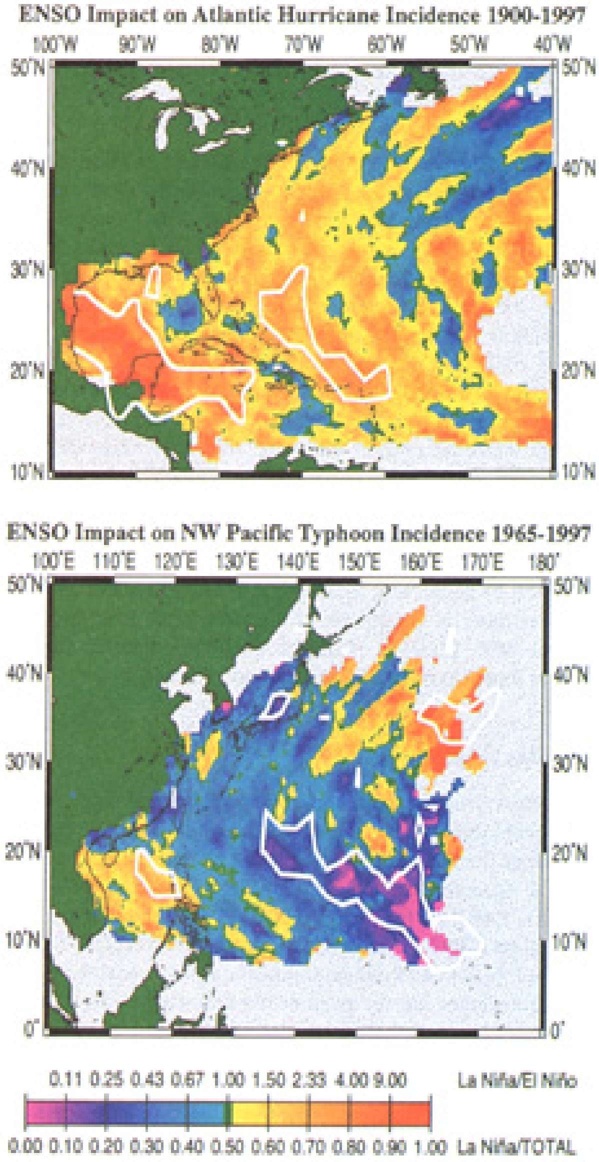

Figure 1. ENSO spatial impacts on (top) north Atlantic hurricane incidence (1900-1997) and (bottom) northwest Pacific typhoon incidence (1965-1997). The grid spatial resolution of 0.5° permits coastal, island and regional impacts to be resolved. The colour bar displays two scales: the ratio of the number of intense tropical cyclone numbers occurring in La Niña months to the number present in El Niño months (upper scale), and the ratio of the said same to the total number of intense tropical cyclones (lower scale). These ratios are computed after first normalising to ensure equal numbers of El Niño and La Niña months. Grid cells containing fewer than 5 events are not plotted. White lines enclose regions where the difference in intense tropical cyclone numbers between ENSO warm and ENSO cold episodes is statistically significant at the 95% level when averaged over an area of 7.5° x 7.5° grid size centred on the point (MODEL 2).

involve computing the difference in log-likelihood between two competing models, doubling, and comparing with a percentage point of the appropriate chi-squared distribution. If, for example, the computed value exceeds the 95% point of the distribution, we reject the simpler model in favour of the more complex one, at the 5% significance level.

In the present context, a 'large' sample is one in which a reasonable number of hurricane occurrences are observed. This dictates a lower bound to the areal size used in applying the model. When analysing the effect of ENSO at any point in space, we find it necessary to consider a region of 7.5° x 7.5° in latitude and longitude centred on that point, to ensure that likelihood ratio tests can be used with this model. Seasonality in hurricane/typhoon occurrence is represented by using a set of 12 indicator variables (one for each month). We refer to this as the 'seasonal only' prediction model.

To study the effect of ENSO upon hurricane occurrence an extra predictor, coded 0 for a cold episode month and 1 for a warm episode, is added to the 'seasonal-only' model. The associated regression coefficient, β_{ENSO}, has the interpretation that $\exp[\beta_{\mathrm{ENSO}}]$ is the proportional increase in the odds for hurricane occurrence during a warm episode month relative to a cold episode month (the odds for occurrence are defined as $p/(1\text{-}p)$ where p is the probability of occurrence; see *Dobson* [1990] for further details on coding and interpretation of predictors in regression-type models). The regions of ≥95% significance obtained with MODEL 2 are marked in Figure 1 by the white lines. They are all based on likelihood ratio tests comparing the 'seasonal only' model to the 'seasonal plus ENSO' model. A naive analysis, which ignores seasonality, produces noticeably different results (the effect of ENSO is masked by the stronger seasonal variation): this emphasizes the need for the methodology used here if ENSO effects are to be studied at sub-annual timescales

Atlantic Hurricanes

Figure 1 (top) shows that in the Atlantic, ENSO cold episodes are associated with higher hurricane incidence rates over nearly the entire basin, the only exception being the northeast quadrant. Using the basic criterion of a zero Niño 3.4 anomaly threshold to distinguish warm and cold ENSO episodes, we find highest *IRR (LN/EN)* values of ~4 occurring in a band stretching from the Caribbean through the central Gulf of Mexico to Texas. When averaging *IRR* values over a 7.5° x7.5° grid we find, as indicated, that the *IRRs* in this region are significant to >95% as they are also in a band reaching from the Lesser Antilles to the northeast of the Bahamas.

Results for regional landfalling hurricane incidence from MODEL 1 are displayed in Table 1(a). Six areas are considered: US northeast, US southeast, Florida, Gulf of Mexico, Lesser Antilles and the Greater Antilles. The *IRR (LN/EN)* values in all regions exceed 1.0, with typical values being 1.6 (JASO events only, JASO Niño 3.4 – no threshold), and 2.8 (JASO events only, JASO Niño 3.4 - ±0.3°C threshold). Largest values of ~ 3 to 4 occur for the Lesser and Greater Antilles with the ±0.3°C Niño 3.4 threshold. In terms of statistical significance, 33% (50%) of the 12 *IRR* values in Table 1(a) are significant to levels >95% (>90%). The regions exhibiting the highest (lowest) significance for *IRR (LN/EN)* are the Greater Antilles (US southeast). Lack of a significant result in a given area does not mean there is no effect, merely that any effect is small enough to be indistinguishable from random variations on the basis of the available data.

Table 1. The magnitude and significance of ENSO's impacts on regional Atlantic (Table 1(a)) and regional NW Pacific (Table 1(b)) landfalling intense tropical cyclone incidence. Results are from MODEL 1. Table 1(a) shows values for July-August-September-October (JASO) landfalling events 1900-1997 based on the JASO Niño 3.4 index with two SST thresholds. Table 1(b) shows values for all landfalling events 1965-1997 based on the August-September-October (ASO) Niño 3.4 index. The landfalling incidence rates *(IR)* per year for El Niño *(EN)*, Neutral, and La Niña *(LN)* conditions are shown, together with the landfalling Incidence Rate Ratio *(IRR)* - the ratio of incidence rates in *LN* to *EN* periods. Shading indicates whether the latter is significant at either the 90% (light fill) or 95% level (dark fill) levels. Shading in the *'EN IR'* column indicates that these values differ from the *'Neutral IR'* values at the level indicated. The coastal regions in Table 1(a) are defined as follows: *'US Northeast'*: Cape Hatteras to Maine, *'US Southeast'*: Jacksonville (Florida) to Cape Hatteras, *'Florida'*: Jacksonville to Pensacola, *'Gulf Coast'*: Pensacola to Brownsville (Texas), *'Lesser Antilles'*: Trinidad to Anguilla, and *'Greater Antilles'*: Puerto Rico to Cuba, including Jamaica. The countries in Table 1(b) are self-evident except that *'Philippines'* refers to the region centred on Manilla (14°N – 16°N), and *'Vietnam'* refers to the region 10°N – 20°N only. The effect of strengthening ENSO on landfalling *IRR* is not examined in Table 1(b) due to the shortness (33 years) of the NW Pacific timeseries.

Table 1(a). ENSO Regional Impacts on Atlantic Landfalling Hurricanes: JASO Events 1900-1997

Coastal Region	JASO Nino 3.4 No SST Threshold			JASO Nino 3.4 ±0.3° C SST Threshold			
	EN IR (52 yrs)	LN IR (46 yrs)	IRR (LN/EN)	EN IR (31 yrs)	Neut. IR (39 yrs)	LN IR (28 yrs)	IRR (LN/EN)
US Northeast	0.19	0.33	1.74	0.16	0.28	0.32	2.00
US Southeast	0.35	0.48	1.37	0.32	0.33	0.61	1.91
Florida	0.44	0.67	1.52	0.29	0.56	0.82	2.83
Gulf Coast	0.42	0.78	1.86	0.42	0.54	0.86	2.05
Lesser Antilles	0.15	0.26	1.73	0.10	0.18	0.36	3.69
Great. Antilles	0.48	0.80	1.67	0.23	0.69	1.00	4.35

Table 1(b). ENSO Regional Impacts on NW Pacific Landfalling Typhoons: 1965-1997

Coastal Region	All Events ASO Nino 3.4 No SST Threshold			JASO Events JASO Nino 3.4 No SST Threshold		
	EN IR (18 yrs)	LN IR (15 yrs)	IRR (LN/EN)	EN IR (19 yrs)	LN IR (14 yrs)	IRR (LN/EN)
Japan	4.50	3.67	0.82	4.16	3.29	0.79
South Korea	0.44	0.53	1.20	0.42	0.57	1.35
Taiwan	2.11	1.60	0.76	1.84	1.21	0.66
Philippines	1.56	2.13	1.37	0.53	1.21	2.28
Vietnam	1.00	1.40	1.40	0.89	1.00	1.12

Strengthening ENSO (using a ±0.3°C SST threshold, rather than a 0.0°C threshold) increases the Atlantic landfalling ENSO incidence rate ratio *(IRR (LN/EN))* in all regions. The size of the increase varies with region but is typically twice as large for hurricanes as for tropical storms (not shown). It is also twice as large when computed using the 'JASO landfalling events and JASO Niño 3.4' data than with the 'annual landfalling events and ASO Niño 3.4' data set. For the latter data, the average hurricane *IRR (LN/EN)* increases by 69% when using a ±0.3°C SST threshold rather than a 0.0°C threshold. The effects of strengthening ENSO noted above are statistically significant. They indicate that: (a) the stronger the ENSO the larger the impact on landfalling frequency and (b) the calculation of the maximum *IRR (LN/EN)* for each sub-region is sensitive to a combination of the months selected for landfalling events and the months chosen for ENSO.

NW Pacific Typhoons

Figure 1 (bottom) shows that in the NW Pacific, ENSO warm periods are associated with higher typhoon frequencies over the majority of the basin. The exceptions are the South China Sea and adjacent areas, plus the region northeast of 30°N and 145°E. These findings appear to differ from those of *Lander* [1994] who, based on 1960-1991 data, does not observe an ENSO effect on annual typhoon numbers. With the basic criterion of a zero Niño 3.4 anomaly to distinguish warm and cold ENSO episodes, we observe smallest *IRR (LN/EN)* values of ~0.25 in a band reaching from 10°N, 170°E to 20°N, 135°E. When averaged over a 7.5° x 7.5° grid, these smallest *IRR* values are significant to >95%, as they also are locally in the South China Sea, over western central Japan, and over the western central Philippines. A few localised hot spots of high significance also exist elsewhere.

Results for regional landfalling typhoons from MODEL 1 are displayed in Table 1(b). Five countries are considered: Japan, South Korea, Taiwan, Philippines and Vietnam. In general the ENSO impacts on landfalling typhoons are less than for Atlantic landfalling hurricanes. Also, use of the 'JASO event and JASO Niño 3.4' criterion does not change the magnitude of *IRR (LN/EN)* values as in the Atlantic. The only areas exhibiting landfalling incidence rates which are significantly different between warm and cold ENSO episodes are the Philippines region centered on Manilla (14°N – 16°N) for typhoons, and the 'Vietnam' region 10°N – 20°N for tropical storms (not shown).

Conclusions and Further Work

We quantify for the first time the spatial impacts and significance of ENSO on Atlantic and NW Pacific intense tropical cyclone occurrence and landfall. We find several regions, notably in the Atlantic, where differences in the landfalling incidence rate between warm and cold ENSO regimes are statistically significant at the 90% or 95% level. These results do not prove causality between ENSO regimes and changing storm landfalling frequency. Such claims should be supported by sound evidence of a physical mechanism - for example - hurricane suppresion in the Atlantic via enhanced tropospheric wind shear [e.g. *Jones and Thorncroft*, 1998]. Further work is also required to determine the maximum *IRR (LN/EN)* for each sub-region. This will depend upon the months selected for the landfalling events and for Niño 3.4, the optimum months probably varying with region.

Most importantly our findings offer promise of long-range predictability to landfalling intense tropical cyclones. At present, 25% of the observed Niño 3.4 variance is predictable 9 months in advance [*Latif et al.*, 1998]. As ENSO's predictability improves with future developments in coupled climate models so will the skill of seasonal forecasts of landfalling hurricanes and typhoons.

Acknowledgements. Chris Merchant is funded by the UK TSUNAMI Initiative for this work. Frank Roberts gratefully thanks the Benfield Greig Group for sponsorship. We thank Justin Mansley for helpful assistance.

References

Bove, M.C., J.B. Elsner, C.W. Landsea, X.Niu and J.J.O'Brien, Effect of El Niño on U.S. landfalling hurricanes, revisited, *Bull. Amer. Meteor. Soc.*, **79**, 2477-2482, 1998.

Chan, J.C.L., Tropical cyclone activity in the northwest Pacific in relation to the El Niño/Southern Oscillation phenomenon, *Mon. Wea. Rev.*, **113**, 599-606, 1985.

Chan, J.C.L., Regional interannual variability of tropical cyclones over the western North Pacific, *Research Report (AP-90-06)*, City Polytechnic of Hong Kong, 40pp., 1990.

Cox, D.R. and D.V.Hinkley, *Theoretical Statistics*, Chapman and Hall, London, 511pp, 1974.

Cox, D.R. and E.J.Snell, *Analysis of Binary Data (2nd Edition)*, Chapman and Hall, London, 236pp, 1989.

Dobson, A.J., *An Introduction to Generalised Linear Models*, Chapman and Hall, London, 174pp, 1990.

Gray, W.M., Atlantic seasonal hurricane frequency: Part I: El Niño and 30mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, **112**, 1649-1668, 1984.

Gray, W.M., Seasonal Forecasting. Chapter 5 in Global Guide to Tropical Cyclone Forecasting. WMO/TD-No.560, 21pp, 1993.

Jones, C.G. and C.D.Thorncroft, the role of El Niño in Atlantic tropical cyclone activity, *Weather*, **53**, 324-336, 1998.

Lander, M.A., An exploratory analysis of the relationships between tropical storm formation in the western North Pacific and ENSO, *Mon. Wea. Rev.*, **122**, 636-651, 1994.

Latif, M., D.Anderson, T.Barnett, M.Cane. R.Kleeman, A.Leetmaa, J.O'Brien, A.Rosati and E.Schneider, A review of the predictability and prediction of ENSO, *J. Geophys. Res.*, **103**, 14,375-14,394, 1998.

McCullagh, P. and J.A.Nelder, *Generalised Linear Models* (2nd Edition), Chapman and Hall, 511pp, 1989.

Neumann, C.J. and M.J.Pryslak, Frequency and motion of Atlantic tropical cyclones. *NOAA Technical Report NWS 26*, US Department of Commerce, Washington DC, 1981.

Parker, D.E., C.K.Folland and M.Jackson, Marine surface temperature: observed variations and data requirements, *Clim. Change*, **31**, 559-600, 1995.

Pielke, R.A., Jr., and C.W.Landsea, Normalised hurricane damages in the United States: 1925-1995, *Wea. Forecasting*, **13**, 621-631, 1998.

Pielke, R.A., Jr., and C.W.Landsea, La Niña, El Niño, and Atlantic hurricane damages in the United States, *Bull. Amer. Meteor. Soc.*, **80**, 2027-2033, 1999.

O'Brien, J.J., T.S.Richards and A.C.Davis, The effect of El Niño on U.S. landfalling hurricanes. *Bull. Amer. Meteor. Soc.*, **77**, 773-774, 1996.

Philander, S.G.H., *El Niño, La Niña and the Southern Oscillation*, Academic Press, San Diego, 280pp, 1990.

Rothman, K.J. and S.Greenland, *Modern Epidemiology (2ndEdition)*, Lippincott-Raven, Philadelphia, PA, 737pp, 1998.

Trenberth, K.E., G.W.Branstator, D.Karoly, A.Kumar, N-C.Lau and C.Ropelewski, Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures, *J. Geophys. Res.*, **103**, 14,291-14,324, 1998.

M. A. Saunders, C. J. Merchant and F. P. Roberts, Benfield Greig Hazard Research Centre, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Dorking Surrey, RH5 6NT, U.K. (e-mail: mas@mssl.ucl.ac.uk).

R. E. Chandler, Department of Statistical Science, University College London, Gower Street, London WC1E 6BT, U.K. (e-mail: richard@stats.ucl.ac.uk).

(Received July 27, 1999; revised January 13, 2000;
accepted January 21, 2000.)