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On the secular variation of storms in the tropical North Atlantic and Eastern Pacific

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ABSTRACT

Variations in the annual frequency of tropical cyclones in the North Atlantic and of tropical cyclones and temporales in the Eastern North pacific are studied in relation to sea surface temperature (SST), sea level pressure (SLP), and vertical wind shear, the observation period common to most parameters being 1911–72.

Both oceans exhibit a secular SST increase until the 1950's. Tropical cyclone frequency has a strong negative correlation with SLP in the realm of the subtropical highs, but only a weak negative one with SST in the areas of common storm occurrence. Temporales are positively correlated with SLP but negatively with SST and tropical storms in the Pacific. A minimum threshold of area-averaged SST and a maximum threshold of vertical wind shear can be specified for one or more tropical cyclones to occur.

Principal component analysis was performed on indicative time series from both oceans. As prominent constituents of the first principal component, Pacific SLP, temporales, and Atlantic tropical cyclones have factor loadings of one sign, while Pacific tropical cyclones have the opposite sign. The second principal component is made up primarily of parallel SST variations in both oceans.

Spectral analysis reveals a coupling of SLP variations over the two oceans around 33–34 and 5.5 years. In the Atlantic, SLP minimum precedes the SST maximum at about 12.5 years. Maxima of Pacific SLP and temporales and minima of Ecuador/Peru SST and Atlantic tropical cyclone occurrence broadly coincide at a common frequency of about 8 years. At the 13.6–14.8 year time scale in the Pacific, minima of Ecuador/Peru SST, and minima of tropical cyclone frequency and maxima of SLP in the North Pacific are approximately synchronous. Spectral analysis details the time scale of spatial linkages borne out by linear correlation and principal component analysis.

1. Introduction

Tropical cyclone formation is confined to distinct regions and seasons. Three simultaneous prerequisites for their origin have been identified (reviews in Atkinson, 1971, and Gray, 1968): A sufficiently large Coriolis parameter corresponding to latitudes poleward of about 5 degrees; weak vertical wind shear; and sufficiently large ocean areas with sea surface temperature (SST) above about 27 °C. It is not intended to study details of tropical cyclone formation as such in this paper. However, cyclone frequency varies markedly between years and over longer periods, possibly in response to changes in the gross features of the atmospheric–hydrospheric environment. As a contribution towards understanding the vagaries of large-scale circulation and climate, the present paper examines the annual frquency of storms in relation to SST and sea level pressure (SLP) conditions over the tropical North Atlantic and eastern North Pacific Oceans.

2. Observations and data processing

Up-to-date compilations of tropical cyclone occurrence over the tropical North Atlantic since the latter decades of the past century, and over the Eastern Pacific since 1947 are available in published form (Rosendal, 1963; U.S. Weather Bureau, 1965; U.S. Weather Bureau, ESSA,

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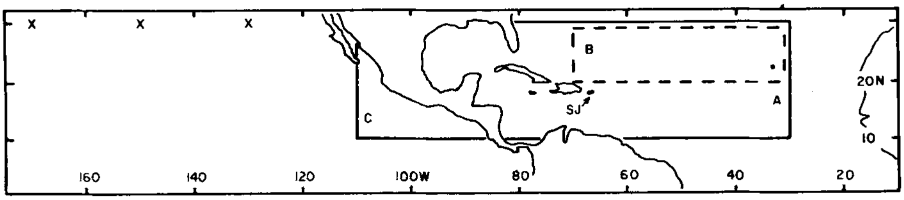

Fig. 1. Areas A and C have time series of SST, B of sea level pressure, compiled from ship observations. SJ signifies rawin station San Juan, Puerto Rico. Crosses indicate longitudes for which sea level pressure was obtained from Historical Weather Maps.

NOAA, 1963–73). An inhomogeneity of record is to be expected because of better detection since the advent of aircraft and satellite technology. The occurrence of temporales in El Salvador, Central America, has been recorded since 1952, the series being essentially homogeneous. These are disturbances originating in the Intertropical Convergence Zone over the Eastern Pacific and causing disastrous floods in the Pacific coastal regions of Central America, with preference in May/June and September/October.

Ship observations in the tropical Atlantic and Eastern Pacific Oceans have been compiled for the period 1911–72 (Hastenrath, 1976a; Hastenrath and Lamb, 1977), elements of interest here being SST and SLP. From this data bank, time series of SST were retrieved for ocean areas A in the North Atlantic and C in the Eastern Pacific, as identified in Fig. 1. These blocks were chosen because they contain the locations of reported origin of nearly all tropical cyclones. In addition to area-averaged SST for each individual month, time series were also constructed of the percentage area of the respective block with SST above 27 °C and other threshold temperatures prompted by the work of Wendland (1977).

A time series of SLP for ocean area B in the North Atlantic (Fig. 1) was also constructed from the long-term ship observations. This block represents the equatorward side of the North Atlantic high, and was found to be particularly sensitive in earlier work on the dynamics of climatic variations (Hastenrath, 1976a). Our ship observations do not cover the analogous region of the North Pacific. Instead, a time series of SLP was retrieved from the Historical Weather Maps (Hastenrath, 1976a) as follows. For each individual month, the highest pressure was read at longitudes 130°, 150°, and 170° W (Fig. 1) and figures were then averaged. the resulting time series is regarded as representative of the Eastern sector of the North Pacific high. A time series of annual mean SST for the waters off the Ecuador/Peru coast has been composited from port and ship observations (Hastenrath, 1976a, b), as an index for El Niño and counter-El Niño conditions.

Monthly mean resultant winds for upper-air stations in the Americas are being published regularly (U.S. Weather Bureau, ESSA, NOAA, 1955–73).

3. Storms, sea temperature, and atmospheric macro-circulation

Fig. 2 for the North Atlantic depicts the annual frequency of tropical cyclones and length of the storm season in relation to SST, SLP, and wind shear conditions. Fig. 3 is a similar plot for the eastern Pacific, containing also a plot of temporales; for lack of a suitable rawin station no curve of wind shear is entered. The length of the storm season is counted from the month of the first to the month of the last cyclone occurrence in a given calendar year. Since the tropical cyclone season is essentially confined to summer and autumn, compilation by calendar years is appropriate.

Table 1 lists correlation coefficients between variables referred to in Figs. 1 and 2. In estimating the significance of correlation coefficients, Quenouille's (1952, p. 168) method was used to account for the reduction of effective degrees of freedom due to persistence.

As expected, there is a high correlation between annual mean SST and percentage area above various threshold temperatures; and between annual cyclone frequency and length of the storm season. Therefore above-threshold area and length of storm season shall not be considered further.

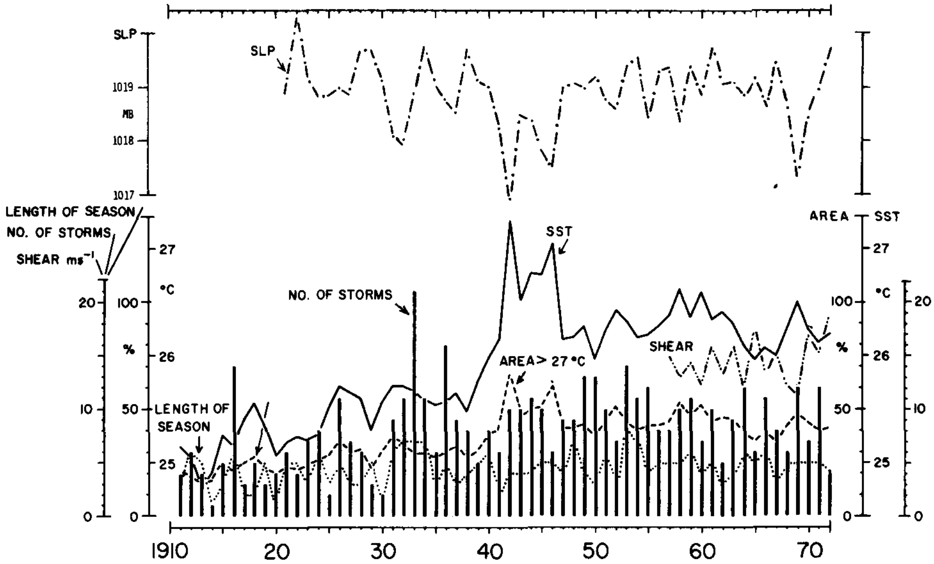

Fig. 2. North Atlantic. Annual frequency of tropical cyclones, solid vertical columns; length of storm season dotted, SLP dash-dotted, SST solid, and percentage area above 27 °C, broken lines; May–October mean vertical shear of zonal wind component 200–850 mb at San Juan, Puerto Rico dash-double-dotted line.

Table 1. *Correlation coefficients, in hundredths, between sea level pressure* (SLP), *sea surface temperature (SST), ocean area above 27 °C (AREA), index of sea surface temperature conditions off the Ecuador–Peru coast (Ec/P SST), tropical cyclone frequency TS, duration of tropical cyclone season (SEASON), temporales (Te), and vertical wind shear over San Juan, Puerto Rico (SHEAR), annual values (Figs. 2 and 3). One, two, and three asterisks denote significance at the 5%, 1%, and 0·1% levels, respectively. Period is generally 1921–71, but correlations with Atlantic SHEAR are limited to 1957–72, correlations with Pacific TS to 1947–71, and correlations with Pacific Te to 1952–69*

	Pacific	Atlantic
SST-AREA	+83***	+98***
SST-SLP	−16	−55***
SHEAR-SLP	—	+67***
SHEAR-TS	—	−49
TS-SEASON	+66***	+50*
TS-SST	+5	+24
TS-SLP	−50*	−22
Ec/P SST-SLP	−24	—
Te-Ec/P SST	−24	—
Te-SST	−30	—
Te-SLP	+55**	—
Te-TS	−43	—

More interesting is the relation between storms, SST, SLP, and vartical wind shear. SLP and shear are highly correlated, presumably reflecting the southward extension of upper-tropospheric Westerlies associated with the equatorward expansions of the subtropical high. There is a weak negative correlation between SLP and SST, as has been noted earlier (Hastenrath, 1976a). Tropical cyclone frequency shows only a weak positive correlation with SST, but strong negative ones with SLP and vertical wind shear. This is consistent with Namias' (1969) observation on the relation of SLP and tropical cyclone frequency. The temporales of the Pacific show an altogether different behavior in that they are favored by a strong subtropical high and thus are inversely correlated with tropical cyclone frequency and SST.

Aside from shorter-period variations, a long-term upward trend in SST is apparent in both oceans until around the 1940's or 1950's, followed by some decrease. A cooling of the mid-latitutde North Atlantic since the 1950's has been repeatedly mentioned (Teich, 1971; Rodewald, 1973; Perry, 1974; Wahl and Bryson, 1975). Milton (1974) and Cohen and Sweetser (1975) noted an increase of tropical cyclone frequency in the North Atlantic from 1910 to the 1950's, and Moran (1975) has related the subsequent reduction in Atlantic tropical cyclone frequency to decreased

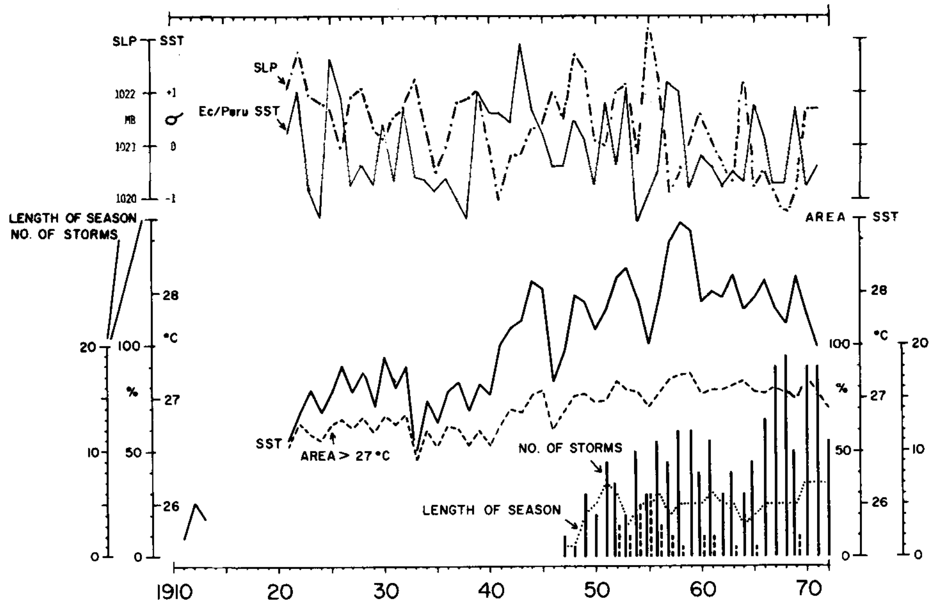

Fig. 3. Eastern Pacific. Annual frequency of Temporales, broken vertical columns; index of sea surface temperature off Ecuador–Peru coast, Ec/Peru SST, thin solid line (departures from mean in terms of standard deviation, $\sigma = 0.8$ °C); other symbols as in Fig. 2.

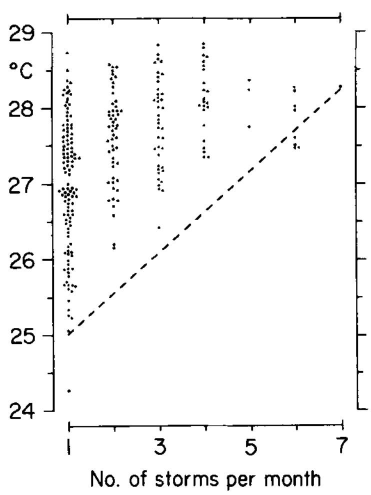

Fig. 4. North Atlantic. Area-averaged SST for individual months with given number of tropical cyclones.

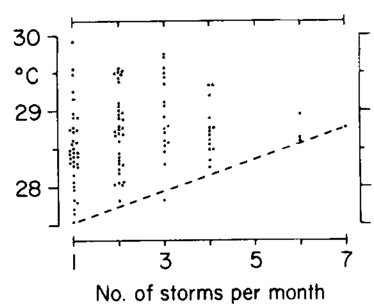

Fig. 5. As Fig. 4 but for Eastern North Pacific.

SST. Not all of the above claims are verified in our Figs. 2 and 3 and Table 1, possibly in part because our observations were limited to latitutdes equatorward of 30° N whereas other SST evaluations were of mid-latitutde data, or were averaged over a considerable range of latitudes.

Figs. 4 to 6 present further detail on the relationship between tropical cyclone frequency, SST, and wind shear. Fig. 4 for the North Atlantic and Fig. 5 for the Eastern North Pacific illustrate that the area-averaged SST must be above a certain threshold for a given minimum number of cyclones per month to occur. This threshold temperature, tentatively entered as a straight broken line, increases with the minimum frequency of cyclones per month. However, once SST exceeds this threshold, a large variety of storm frequencies *can* occur. Corresponding plots were constructed on an annual basis, and also using percentage area above

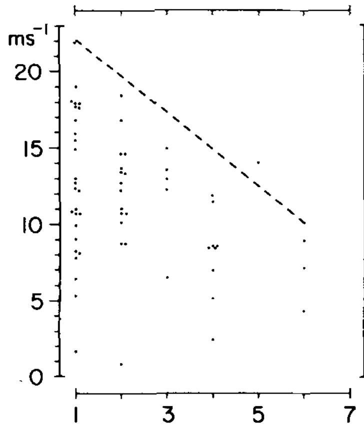

Fig. 6. North Atlantic. Vertical shear of zonal wind component 200–850 mb over San Juan, Puerto Rico, for individual months with given number of tropical cyclones.

a threshold of 27 °C, rather than area-averaged temperature. Since implications of these plots are similar to Figs. 4 and 5, they are not reproduced here. Figs. 4 and 5 corroborate Wendland's (1977) earlier findings.

Fig. 6 shows the vertical shear of the zonal wind component 200–850 mb over San Juan, Puerto Rico (U.S. Weather Bureau, ESSA, NOAA, 1955–73), for individual months with the observed number of tropical cyclones. Results are similar to Figs. 4 and 5, in that as wind shear decreases the minimum number of tropical cyclones per month tends to increase. Months with shear below this critical value exhibit a variety of storm frequencies. A plot using May–October means of wind shear, corroborates the monthly graph, Fig. 6, but is not reproduced here.

Figs. 4–6 thus bear out a rather definite relation between sea temperature conditions or wind shear and the minimum number of storms, but not the frequency as such. This may in part explain the weak correlations between tropical cyclone frequency and SST or shear, borne out by Table 1.

4. Principal component analysis

Relationships between variables were further investigated by three principal component analyses. The first included SST and SLP of both oceans, and Atlantic tropical cyclones for the period 1921–71. The second run also included Pacific tropical cyclones, and the record was reduced to 1947–71. The third run added the temporales data, and the record was further reduced to 1952–69. Interestingly, the principal components of each of these separate analyses were essentially the same, i.e., components were related to one another with similar magnitudes and the same sign. Of course, as each new variable was added to the basic data, its presence was reflected in the composition of the principal components. Because of the persistence of the composition of principal components, only the analysis with all variables will be discussed here. Table 2 shows the factor loadings of each of the first two principal components (eigenvalue > 1.0), which explain 31% and 26% of the total variance, respectively. Table 2 is consistent with the linear correlation coefficients in Table 1, but provides additional information.

The first principal component consists primarily of Pacific SLP, temporales, and tropical cyclones of both oceans. In the Pacific, tropical cyclones are of opposite sign to both SLP and temporalses. The only prominent Atlantic parameter is tropical cyclone frequency. Its sign is opposite to Atlantic SLP and Pacific tropical cyclones, and thus the same as for Pacific SLP and temporales.

The second principal component consists primarily of SST of both oceans. The identical sign of the loading indicates an essentially parallel variation. North Pacific and Ecuador/Peru SST

Table 2. *Factor loadings (in 10^{-2}) of the first two principal components, explaining 31% and 26% of the total variance, respectively. Symbols as for Table 1 and Fig. 7*

	First	Second
Atlantic		
SLP	−14	+28
SST	+6	−47
TS	+29	−28
Pacific		
SLP	+57	+2
SST	−27	−51
TS	−47	+24
Te	+50	+4
E/P SST	−17	−55

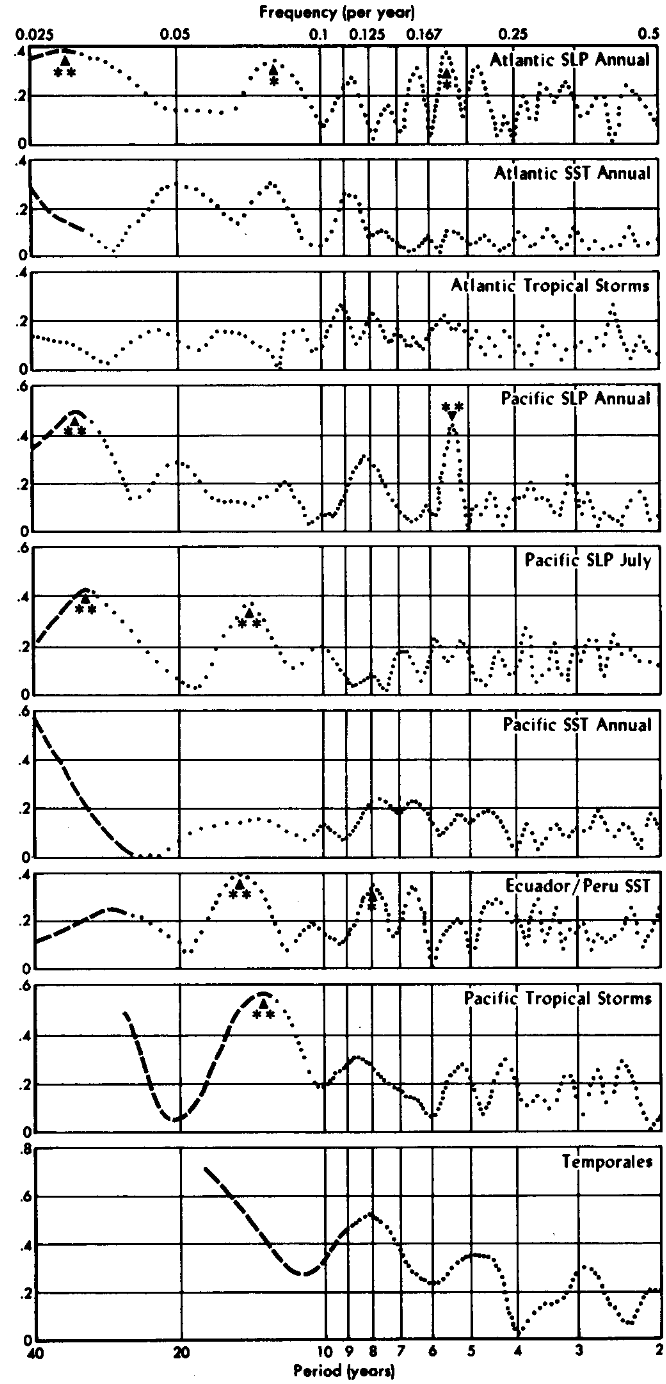

Fig. 7. Square root of normalized spectral density of nine selected time series with periodities from 2 to 40 years. Dashed segments indicate periods longer than one-half time series length. One and two asterisks denote significance at the 5% and 1% levels, respectively.

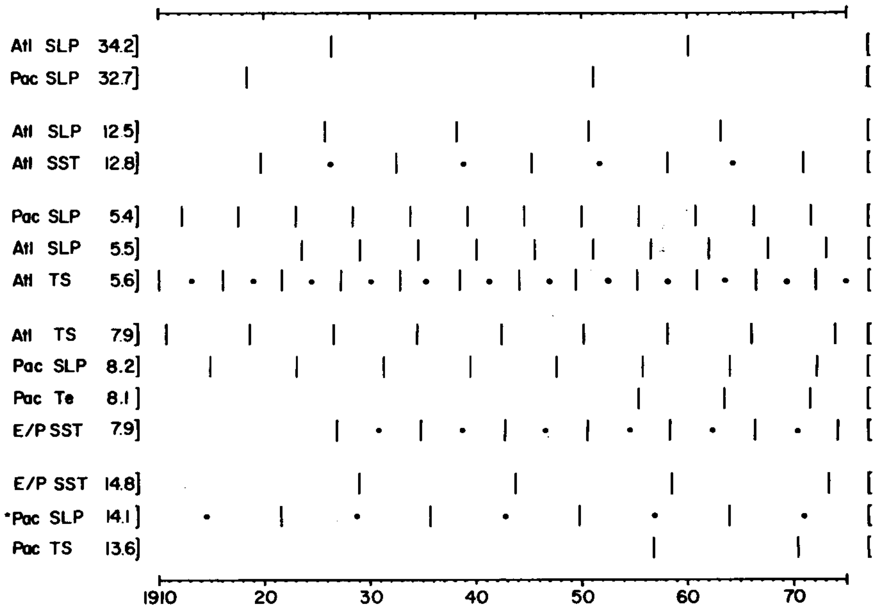

Fig. 8. Times of maximum, bar, and minimum, dot, for selected periodicities. Atl. Pac, and E/P refer to Atlantic, Pacific, and Ecuador/Peru coast; SLP, SST, TS, and Te, signify sea level pressure, sea surface temperature, tropical cyclones, and temporales, respectively; numbers indicate periodicity in years. Time series are annual data, except for asterisk identifying July series.

have factor loadings of the same sign in both principal components. This is consistent with the significant positive correlation between the two hemispheres found earlier (Hastenrath, 1976b).

5. Spectral analysis

Tables 1 and 2 and Figs. 2 to 6 bear out broad relationships between variations in storm frequency and indicative large-scale parameters of the atmospheric–hydrospheric environment. In an attempt to elucidate the variance characteristics of changes in large-scale circulation and storm occurrence, the aforementioned time series were subjected to spectral analysis.

The power spectra were calculated by means of an Illinois State Water Survey program developed by Schickendanz and Bowen (1977). This innovative procedure produces spectral estimates for equal increments of wavelengths by utilizing non-integer values in the sine and cosine waveforms. This procedure is particularly suited to identifying periodicities in relatively short data records. Analyses were performed on time series of annual values and successive Januarys and Julys. Results are summarized in Table 3 and Fig. 8 for periodicities reaching at least the 10% significance level relative to a white noise model. Fig. 7 shows plots of spectral density by frequency for the time series depicted in Fig. 8.

SLP shows highly significant periodicities around 33–34 and around 5.5 years over both oceans (Table 3, Figs. 7, 8). Other SLP major periodicities in the two oceans do not match, although one of 12.5 years is highly significant in the Atlantic and is closely paired with a peak of 12 years in Pacific SLP (Table 3, Fig. 7). Another near-match at about 8 years is noted (Fig. 7) in Pacific SLP, Pacific Te, Ecuador/Peru SST, Pacific TS, Atlantic SLP, and Atlantic SST, although periodicities do not reach the 10% significance level for the latter three series. Atlantic SST shows significant periodicities at 12.8 and near 20 and 9 years (Table 3, Fig. 7). All of these are unmatched in the Pacific, where only one significant periodicity of 4.5 years is found in July SST data (Table 3, Figs. 7, 8). North Pacific SLP in July shows a significant periodicity of 14.1 years, and Ecuador/Peru SST has a highly significant periodic

Table 3. *Spectral frequencies of sea level pressure, sea surface temperature, tropical cyclones, and temporales. ANN, JAN, JULY denote time series of annual, January, and July data, respectively. Only periods significant at or above the 90% level are given, with significance at the 5% and 1% levels indicated by one and two asterisks, respectively.*

	Atlantic			Pacific		
	Years of record	Period (years)	Year of first max.	Years of record	Period (years)	Year of first max.
Sea level pressure						
ANN	1921–72	**34.2	1926.3	1911–72	**32.7	1918.4
		*12.5	1925.7		20.1	1914.8
		6.3	1923.0		8.2	1914.8
		*5.5	1923.5		**5.4	1912.2
		4.7	1921.0			
JAN	1921–72	None		1911–72	5.6*	1911.5
					3.0	1911.0
					2.3*	1912.5
					1.5	1911.1
JULY	1921–72	22.2	1943.1		**30.4	1923.7
		*9.6	1921.9		*14.1	1921.6
		**6.4	1922.8		3.8	1914.3
Sea surface temperature						
ANN	1911–72	20.0	1925.6	1922–71	None	
		12.8	1919.7			
		8.8	1918.0			
JAN	1911–72	20.8	1924.1	1922–71	None	
		**12.8	1919.9			
		8.6	1919.0			
JULY	1911–72	20.4	1925.9	1922–71	*4.5	1922.3
ANN	EC/Peru SST			1921–71	**14.8	1928.9
					*7.9	1926.8
					6.6	1926.4
Tropical cyclones						
ANN	1871–1974	*9.2	1879.5	1947–72	**13.6	1956.8
		7.9	1871.2			
		5.6	1871.3			
		*2.5	1872.1			
Temporales						
ANN				1952–69	8.1	1955.4

of 14.8 years (Table 3, Figs. 7, 8). In this spectral region, Pacific tropical cyclone frequency shows a highly significant periodicity of 13.6 years (Table 3, Figs. 7, 8). Periodicities of Atlantic tropical cyclones are quite different, but are in part similar to the ones reported earlier by Cohen and Sweetser (1975) for a slightly different record. Their graph shows corollaries to our 9.2 and 7.9 year peaks. However, we did not obtain their 11.3 year periodic. The rather short 18 year record of temporales exhibits only one significant peak at 8.1 years. Similarly, a periodicity of 8.2 years is found in North Pacific SLP, and one of 7.9 years in Ecuador/Peru SST.

A comparison of phase of these similar periodicities (Table 3 and Fig. 8) is interesting in relation to the spatial linkages described by Tables 1 and 2.

The maxima of the 33–34 year periodicities in

SLP of the two oceans are related, with those of the Atlantic lagging those of the Pacific by about 8 years during the time of coincident record. The SLP periodics around 5.5 years are about synchronous in both oceans.

In the Atlantic, the 12.5 year SLP periodicity has its minima somewhat before the maxima in the 12.8 year SST periodic. This is consistent with the weak negative correlation coefficient in Table 1, and the opposite sign of factor loadings in both principal components in Table 2. The maximum of the Atlantic SLP periodicity of 5.5 years precedes the minimum of tropical cyclone frequency by about 2 years.

The 8.2 year periodicity in Pacific SLP appears directly related to the 8.1 year temporales periodicity, but inversely related to the 7.9 year periodic found in Ecuador/Peru SST during the mutual times of observation. The phase relationship of Pacific SLP, temporales, and Ecuador/Peru SST corresponds to the sign of factor loadings of both eigenvectors in Table 2.

In the Pacific, the minimum of annual cyclone frequency at 13.6 years occurs somewhat after the SLP maximum at 14.1 years in the July series, for the years of mutual record. Likewise, the minimum of Ecuador/Peru SST at 14.8 years occurs around the maximum of North Pacific SLP at 14.1 years in the July series; thus maxima of Ecuador/Peru SST and North Pacific tropical cyclone frequency broadly coincide for the period of common record. These phase relationships find their correspondence in the negative correlation coefficient between annual SLP and tropical cyclone frequency in Table 1; the opposite sign of SLP and TS factor loadings in the first principal component in Table 2; and the opposite sign of factor loadings for SLP and E/P SST in both principal components in Table 2.

It is realized that statistical tools as power spectrum analysis are unable to prove physical relationships. Moreover, geophysical time series are as a rule not stable, in that sub-series of a record may not exhibit the identical significant spectral peaks. Accordingly, a predictive potential is not suggested. However, the results presented in Table 3 and Fig. 7 may contribute towards an inventory of preferred time scales of variability, and they detail the spatial linkges borne out by linear correlation and principal component analysis (Sections 3 and 4).

6. Conclusions

Long-term ship observations that have recently become available provide an optimal basis for the study of secular variations in storm frequency and near surface parameters. The relationship between the monthly number of tropical cyclones and area-averaged SST is complicated, in that a large variety of monthly frequencies can occur with the same SST. However, a relationship was identified between minimum tropical cyclone frequency and a given threshold temperature. A similar relationship is apparent with vertical wind shear.

Over both oceans, tropical cyclone frequency has a strong negative correlation with SLP, presumably as a result of increased vertical wind shear, associated with the equatorward expansion of the subtropical highs and concomitant southward extension of upper-tropospheric Westerlies. By contrast, the positive correlation between tropical cyclone frequency and SST is weak.

The temporales of the Pacific appear favored by a strong subtropical high and are negatively correlated with tropical cyclone frequency and SST. Although it is believed that temporales form as disturbances in the "Intertropical Convergence Zone" over the Eastern North Pacific, their genesis is inadequately known, and the record is short.

Preferred modes of spatial coupling are identified by principal component analysis. The first principal component presented in Table 2 shows for the Pacific the inverse relation of SLP to tropical cyclone frequency, but a direct coupling between SLP and temporales. There is a weak indication for inverse SLP variations over the two oceans. For the Atlantic, both the first and the second principal components show the inverse coupling between SLP and tropical cyclone frequency. The second principal component is made up mainly of parallel SST variations in both oceans.

Spectral analysis permits inference on preferred time scales of variations and spatial linkages in storm occurrence and circulation parameters. Prominent spectral frequencies are found around 5.5, 8.1, 12.5, and 14 years. Of these, the spectral regions around 8.1 and 14 years appear preferred for spatial couplings involving variations in the occurrence of tropical weather systems.

Power spectrum analysis thus substantiates in part the patterns of spatial coupling apparent from Tables 1 and 2. In part, however, the large-scale linkages indicated by linear correlation and principal component analysis may be of a non-periodic nature. Physical mechanisms on the climatic time scale are suggested by the present statistical analysis. These merit further study, especially as related to the atmospheric macro-circulation, SST pattern, and occurrence of temporales in the Eastern North Pacific.

7. Acknowledgements

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О ВЕКОВЫХ ВАРИАЦИЯХ ШТОРМОВ В ТРОПИЧЕСКОЙ СЕВЕРНОЙ АТЛАНТИКЕ И В ВОСТОЧНОЙ ЧАСТИ ТИХОГО ОКЕАНА

Изучаются вариации годовой частоты тропических циклонов в Северной Атлантике и тропических циклонов и темпоралей в Северо-восточной части Тихого океана в их связи с температурой поверхности моря (ТПМ), давлением на уровне моря (ДУМ) и вертикальным сдвигом ветра для периода наблюдений 1911–72 гг. для большинства параметров.

Оба океана проявляют вековое увеличение ТПМ до 1950-х гг. Частота тропических циклонов имеет сильную отрицательную корреляцию с ДУМ в окрестностях субтропической области высокого давления и лишь слабую отрицательную корреляцию с ТПМ в областях, где обычно наблюдаются штормы. Темпорали положительно коррелируют с ДУМ, но отрицательно — с ТПМ и тропическими штормами в Тихом океане. Можно определить минимальный порог осредненной по площади ТПМ и максимальный порог вертикального сдвига ветра для того, чтобы образовался один или несколько тропических циклонов.

Для представительных временных рядов для обоих океанов был выполнен анализ главных компонент. В качестве заметной составляющей первой главной компоненты ДУМ в Тихом океане, темпорали и тропические циклоны в Атлантике имеют фактор нагрузки одного знака, в то время как тропические циклоны Тихого океана имеют противоположный знак. Вторая главная компонента состоит преимущественно из параллельных вариаций ТПМ в обоих океанах.

Спектральный анализ выявляет связь вариаций ДУМ над обоими океанами на периодах около 33–34 года и 5.5 дет. В Атлантике минимум ДУМ опережает максимум ТПМ на, примерно 12.5 лет Максимумы ДУМ и темпоралей в Тихом океане и минимумы ТПМ вблизи Экватора и Перу и образование тропических циклонов в Атлантике более или менее совпадают на общей частоте около 8 лет. Для Тихого океана на временном масштабе 13.6–14.8 лет минимумы ТПМ у Эквадора и Перу, и минимумы частоты тропических циклонов вместе с максимумами ДУМ в северной части Тихого океана приблизительно синхронны. Спектральный анализ детализирует временные масштабы пространственных связей, выявленных линейным корреляционным анализом и анализом главных компонент.