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Time-Series Analyses of the Relationship Between Nesting Frequency of the Kemp's Ridley Sea Turtle and Meteorological Conditions

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Abstract. – A time-series record of nesting frequencies of the Kemp's ridley (*Lepidochelys kempii*) and climatic variables measured at four meteorological stations near Rancho Nuevo (Tamaulipas, Mexico) were analyzed using spectral methodology to determine the climatic and meteorological variability of the area and correlate environmental changes with nesting frequency. Meteorological records from Soto la Marina represented the regional fluctuations and showed cycles consistent with annual, six-monthly, and shorter variations. At a daily scale, cycles associated with synoptic temperature and wind-related events were detected, some of which exhibited a high coherence to nesting which varied between 3 and 22 days. A phase-difference analysis indicated that these occurred almost simultaneously, which supports the empirical association between these variables previously suggested by some authors.

Key Words. – Reptilia; Testudines; Cheloniidae; *Lepidochelys kempii*; sea turtle; climatic variables; environmental changes; spectral analysis; nesting frequency; Mexico

Sea turtles are poikilothermic organisms with reproductive patterns associated with environmental variations (Whittier and Crews, 1987; Whittier and Tokarz, 1992). The Kemp's ridley (*Lepidochelys kempii*) nests during the day in spring and summer, when environmental conditions are suitable for the development of embryos (Rostal et al., 1998). The primary nesting area for this species is at Rancho Nuevo beach, Tamaulipas (Pritchard, 1969; Márquez, 1994), along Mexico's northeast coast of the Gulf of Mexico.

This species nests in groups (*arribadas* or *arribazones*); a behavior that has been linked to sea surface temperature, wind patterns, and tides by Casas-Andreu (1978) and Castro et al. (1998). These authors related these variables at a point in time and assumed that the fluctuations were random. However, it has been suggested that in numerous biological processes these oscillations are periodic and allow organisms to keep an inner temporal order while anticipating environmental changes (Lewis, 1995; Goldman, 1999).

Platt and Denman (1975) suggested that the biosystem can be "seen as an ensemble of nonlinear oscillators, coupled together in various functional configurations at each hierarchical level of system description." They stated that the cycle is a basic element and that a system can be described through a list of the dominant frequencies of the cycles. A spectral analysis allows one to obtain these frequencies (also known as "harmonics") and order them in a spectrum according to their magnitude and relative importance (Bloomfield, 1976). In this way, the Kemp's ridley nesting pattern during a reproductive year may be seen as a sum of cycles with different periods and amplitudes, related to the variations of the abundance of females on the beach. In this paper, Kemp's ridley nesting, air temperature, wind, and precipitation periodicities during the nesting seasons are described through a time-series spectral analysis.

METHODS

The Kemp's ridley nesting beach is located in the central region of the coast of the State of Tamaulipas, Mexico, and its north-south limits are the outlet of the Soto la Marina River and an area known as "Punta Jerez". The greatest abundance of nests is near Rancho Nuevo, an area demarcated as a Natural Reserve (Fig. 1). This beach is a continuous sandy fringe, oriented in a north-south direction and divided by sand bars that open occasionally to the sea.

The weather is mild, with an average annual temperature of 23°C. During winter periods, the region is affected by polar air masses known as "Nortes" (Gutiérrez de Velasco and Winant, 1996), whereas during summer months the trade winds prevail from the east and southeast (Sturges, 1993; Wang et al., 1998). Rains are more abundant from June to November. The driest months are March and April (Servicio Meteorológico Nacional, 1975).

The biological variable used in the present study was the number of nesting females and "solitary" nests observed daily between 1979 and 1996 on the 38.3 km of the Natural Reserve (see Márquez et al., 1999, 2001). During most seasons, staff from Mexico's National Fisheries Institute and the U.S. Fish and Wildlife Service worked at this site from late March until August.

Figure 1. Location of the study area (taken from Márquez, 1994). Flags and WS indicate the meteorological stations.

At least three daily surveys were carried out on the beach (at approximately 0600, 1100, and 1500 hrs) and data were recorded using techniques described by Pritchard et al. (1983) and Márquez et al. (1990). When a nesting event was not observed, the nest was identified by a fresh turtle track on the beach and classified as a "solitary" nest. Given the frequency of the surveys and the fidelity of Kemp's ridleys to the nesting beach (Márquez et al., 1998), it is estimated that the observed nesting occurrence was higher than 90% during the study period.

The meteorological variables used in the study were air temperature, pluvial precipitation, wind direction, and wind speed, measured at four meteorological stations (Fig. 1) along with data recorded at the Rancho Nuevo camp between 1981 and 1985 with an electromechanical meteorological station (Khalsico 40AM160). The main problem of this study was obtaining long-term time-series of the meteorological variables that were representative of nesting conditions. The oldest meteorological station in the region is located in Soto la Marina (23°46'N, 98°13'W; altitude 12 m), 63 km north of the nesting beach.

Monthly records of the average temperature and total pluvial precipitation in Soto la Marina (SM) were compared with those from three localities (Aldama, Barra del Tordo, and Punta Jerez; see Fig. 1), to determine the climatic variability and evaluate their usefulness as representatives for the region. Additional comparisons were made with daily average temperatures at SM and Barra del Tordo (BT) recorded from March to August between 1989 and 1996. It was not possible to compare other variables due to methodological differences among stations.

Temperatures were compared among localities by means of one-way analysis of variance (ANOVA) and the Pearson correlation method, while precipitation was analyzed using the Kruskal-Wallis and the Spearman non-parametric tests (Zar, 1996). All analyses were done using Statistica 4.5 for Windows (StatSoft, Inc., 1995). Cycles were described with a time-series spectral analysis (Bloomfield, 1976), for which a special program in Fortran 7.0 (1990) was developed. The characteristics of the series used are summarized in Table 1. These time-series were long enough to apply the spectral analysis.

Segments of time-series containing no data or clearly erroneous information were less than 0.5% of the total, and they were replaced with results obtained with the cubic spline interpolation method. Data were standardized by substracting the mean and dividing by the standard deviation for each variable.

The spectral analysis was done in three steps. First, a Fourier transformation of the time-series to obtain a sum of sine and cosine functions of different frequencies was applied. Second, the estimation of the periodogram, which is the sum of the squared coefficients of sine and cosine functions multiplied by N/2 for each frequency, was obtained. The third step was to estimate the spectrum by smoothing the periodogram every five frequencies to obtain spectral densities, $S(\omega)$, which consist of many adjacent frequencies that contribute most of the overall periodic behavior of the series (Statsoft, 1995).

Spectral density of a time-series represents the distribution on frequencies (from lowest $\omega_1 = 1/T$, where T is length of a time-series, up to Nyquist frequency $\omega_N = 1/2\Delta t$, where Δt is a sampling rate of a time-series). This enables, for each frequency of a spectrum, calculation of its mean square amplitude (see Emery and Thomson, 1997:425). The mean square amplitude for each frequency (or for each period) was calculated from its spectral density by the formula $a = [4S(\omega)/N]^{0.5}$. The spectral analysis method is briefly described in the Appendix.

The average spectra of the nesting frequency and those of the meteorological variables (recorded at SM) were

Table 1. Characteristics and frequencies of the time-series used; Ta = temperature of the air, Pp = pluvial precipitation, Ws = wind speed, Wd = wind direction, n = number of data points.

Locality	Freq.	Variables	Units	Begin	End	n
Soto la Marina	monthly	Ta, Pp	°C, mm	1927	1995	828
	daily	Ta, Pp	°C, mm	1979	1996	6575
	daily	Ws, Wd	m/s, degr.	1979	1996	6575
Punta Jerez	monthly	Ta, Pp	°C, mm	1925	1961	444
Barra del Tordo	daily	Ta	°C	1989	1992	1460

Table 2. Results of the application of ANOVA and correlation analyses comparing monthly temperature and precipitation records from Soto la Marina (SM) with localities in column 1. Correlation coefficients were significant at a confidence level of 95%.

			Temperature (°C)				
Localities	Degrees of freedom	Variance ratio F	Significance *p*	Mean ± SD at SM	Mean ± SD at Localities	Pearson Correlation Coefficient	Data (months)
Punta Jerez	1, 841	1.81	0.17	23.97±4.6	23.59±3.7	0.90	383
Barra del Tordo	1, 233	4.07	0.04	24.38±4.5	23.27±3.9	0.96	108
Aldama	1, 545	0.03	0.85	23.30±4.5	23.23±4.0	0.96	252
			Pluvial Precipitation (mm)				
Localities	Data (months)	K-W test statistic H	Significance *p*	Median at SM	Median at Localities	Spearman Correlation Coefficient	Data (months)
Punta Jerez	865	30.08	0.000	28.00	40.9	0.60	397
Barra del Tordo	235	1.40	0.235	36.05	45.5	0.71	109
Aldama	1233	8.47	0.003	29.60	34.0	0.62	527

calculated with daily records gathered each year between 1 March and 31 August from 1979 until 1996. The use of these segments allowed the exclusion of the annual and six-month cycles. During this period, 17,556 nests were deposited in 804 days. For an estimation of statistical relations between prevailing harmonics for pairs of time-series the coherency functions and phase differences were calculated. The confidence intervals for the spectra and the coherency function were estimated by means of algorithms described in the literature (Jenkins and Watts, 1969; Konyaev, 1990; Emery and Thomson, 1997). The interpretation of coherence is analogous to that of the Pearson correlation, although it varies between 0 and 1, indicating no dependency and absolute dependency, respectively, between the series in a frequency of ω (Bloomfield, 1976).

RESULTS

Regional Meteorological Variations. — Comparisons of mean monthly temperature and precipitation averages done with ANOVA tests showed the existence of microclimatic differences among the various meteorological stations (Table 2). Temperature was higher at Soto la Marina (SM), the meteorological station located in the northern edge of the zone, while precipitation was more abundant at Punta Jerez (PJ) and Aldama (A), located south of the study area (Fig. 1). On the other hand, Pearson and Spearman correlation coefficients between SM and the localities listed in Table 2 were significant ($p < 0.05$), suggesting that variations in temperature and precipitation were similar along the nesting beach. Pearson coefficients were higher (0.9) than Spearman (ca. 0.7) indicating that temperature variations among the stations were more correlated than those of precipitation. In a similar way, the daily average temperatures at RN and SM were significantly correlated ($r = 0.7, p < 0.01, n = 360$ days) and there were significant differences ($F_{1,0.5} = 39.35$, $p < 0.01$) between them. Average temperature at SM was approximately 1.6°C higher than at RN between 1981 and 1985. The analyses of monthly and daily data indicate that the variables fluctuated in a similar way along the nesting beach, in spite of the microclimate differences detected between some localities.

The regional climatic variability described by the spectral analysis of monthly records from SM and PJ showed cycles of between 0.5 and 11 years. Temperature data from SM exhibited 7 cycles, two more than at PJ (5 cycles), probably because its time-series was longer, allowing for detection of a two-year and Wolf sunspot cycle. The amplitude (Table 3) indicated that the most conspicuous cycles were annual and six-monthly, which reflect the normal periodicity of the seasons. These were followed by cycles that varied between 2 and 7 years, which coincide with the El Niño Southern Oscillation (ENSO) event (Philander, 1990), even though their amplitude was only about 5% of the annual. The amplitude in most of the cycles was similar in both localities. Nevertheless, the amplitude of the temperature cycles from SM with periods shorter than 2.5 years was slightly higher than that of similar cycles detected at PJ, but the differences were minor. On the other hand, the amplitude of the precipitation cycles with periods of 0.5 and 7 years from PJ was greater than those at SM (Table 3). The spectra of daily

Table 3. Period and amplitude of the cycles obtained from the monthly time-series. Cycle periods are registered in years. Values of the mean squared amplitude are shown in parentheses.

Temperature (°C)							
Soto la Marina (SM)	0.5 (0.72)	1.0 (3.15)	2.0 (0.13)	2.5 (0.13)	3.5 (0.12)	7.0 (0.14)	11.0 (0.28)
Punta Jerez (PJ)	0.5 (0.70)	1.0 (3.10)	2.5 (0.07)	3.5 (0.12)	7.0 (0.14)		
Precipitation (mm)							
Soto la Marina (SM)	0.5 (6.50)	1.0 (24.20)	2.5 (5.40)	7.0 (5.30)	11.0 (5.20)		
Punta Jerez (PJ)	0.5 (8.30)	1.0 (24.00)	2.5 (5.40)	3.5 (4.70)	7.0 (6.30)		

Table 4. Periods (days) and mean squared amplitudes of the cycles obtained from daily time-series recorded at Soto la Marina (see also Fig. 2). Values of the mean squared amplitude are shown in parentheses.

Variables	Mean periods of the oscillations
Temperature (ºC)	3 (0.20), 4 (0.31), 5 (0.31), 7 (0.65), 12 (0.57)
Wind speed (m/sec)	3 (0.25), 4 (0.31), 5 (0.27), 7 (0.57), 12 (0.48)
Wind direction (º)	3, 4, 5, 7.5, 12
Nests (unit)	3 (2.4), 4 (2.6), 5 (2.5), 7 (3.1), 12 (2.7), 22 (2.8)

average temperature, wind direction, and wind speed data between March and August at SM showed several significant cycles with periods ranging from 3 to 12 days (Table 4, Fig. 2). In contrast, the spectrum of the pluvial precipitation decreased slightly and did not have harmonics, meaning that the changes of this variable at this time scale were not cyclic, possibly due to the wide variation in rainfall in the tropical zone, even between close localities (Riehl, 1979). Most of the observed cycles in the average daily temperature at SM were also present in the spectra for BT, and the coherence between both localities was greater to 0.5 (the 95% upper confidence limit for the squared coherence was 0.5).

The similarity of the periods between the compared localities suggests that the meteorological variables oscillated in a similar manner throughout the area and that the time-series from Soto la Marina are representative of the regional fluctuations. It is important to note that the small differences detected in the amplitude for temperature and precipitation reflected the microclimatic differences outlined by the ANOVA tests.

Analyses of Nesting Frequency. — In the average nesting frequency spectra, six cycles were outlined. The most significant amplitudes belonged to periods of 7 days (Table 4). Periods of 3 and 7 days were similar to the most frequent intervals between the *arribadas*, and that of 22 days was similar to one of the internesting intervals of Kemp's ridleys females (Márquez, 1994). The spectra of daily average temperature, wind speed, and wind direction data during the nesting season in SM showed several significant cycles, with periods ranging from 3 to 12 days (Fig. 2, Table 4). The coherence between nesting frequency and fluctuations of air temperature considerably exceeded 95% of upper confidence limit on the periods of 3, 4, 5, 7, 12, 26, and 42 days (Fig. 3). The coherence between nesting frequency and wind

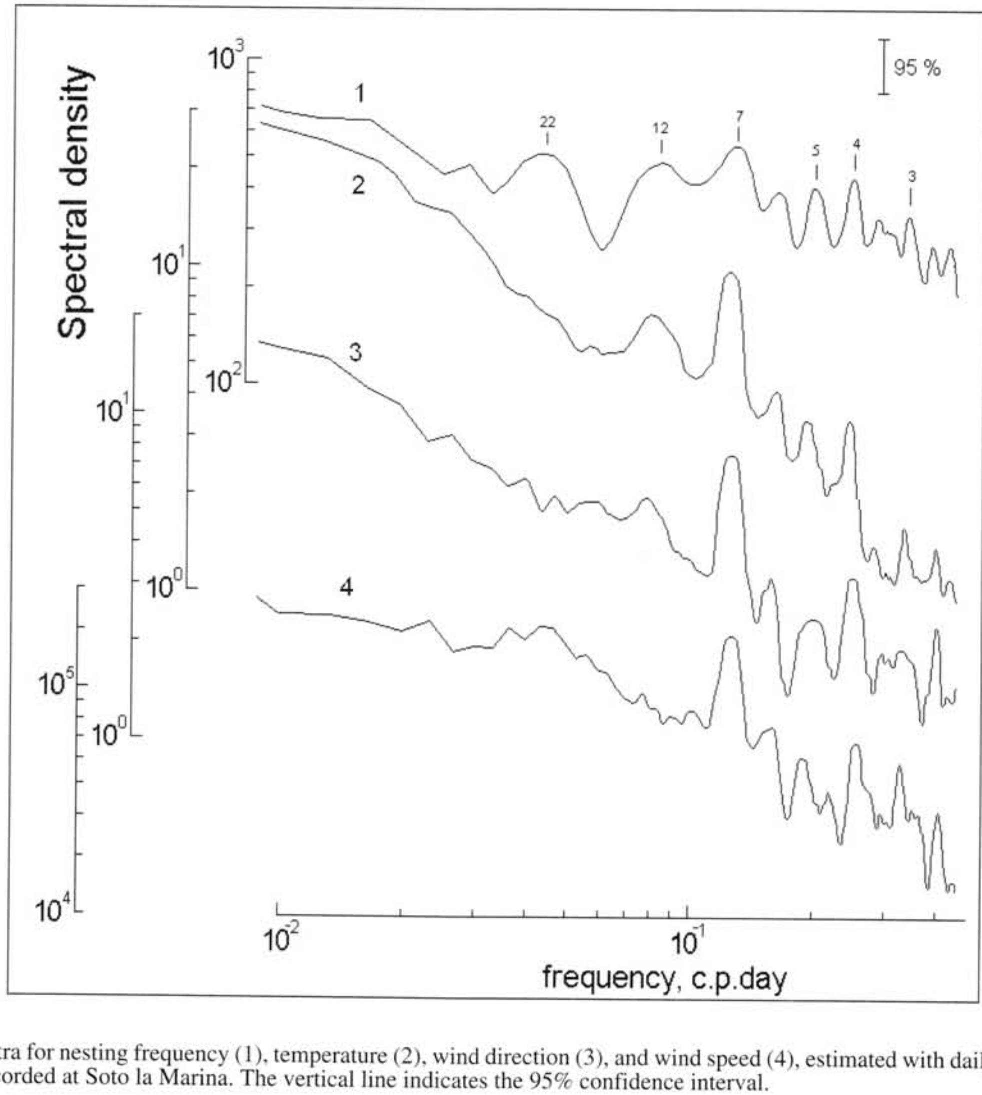

Figure 2. Spectra for nesting frequency (1), temperature (2), wind direction (3), and wind speed (4), estimated with daily data from 1979 to 1996 and recorded at Soto la Marina. The vertical line indicates the 95% confidence interval.

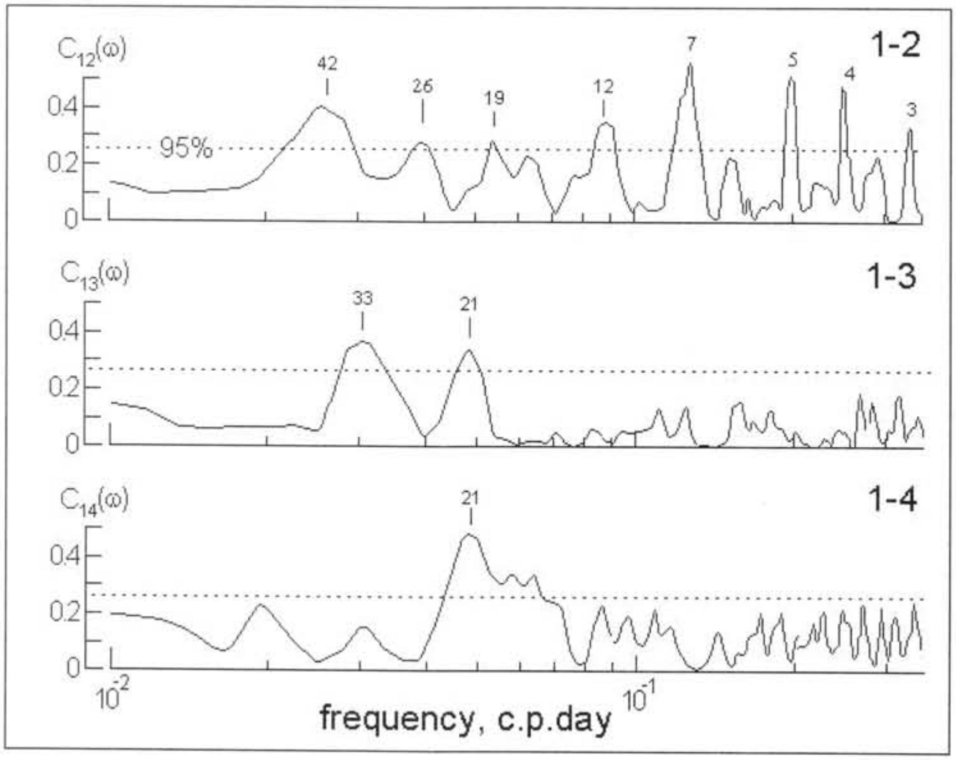

Figure 3. Coherence for pairs of spectral valuations: 1-2: nesting frequency (NF) – temperature; 1-3 NF-wind direction; 1-4: NF-wind velocity. The dotted horizontal line indicates the 95% upper confidence limit for the squared coherence.

speed was high only on the periods of 21 and 33 days, and for nesting frequency and wind direction only on the period of 21 days. The results showed that the most important characteristic influencing the nesting frequency was air temperature, and wind fluctuations were essential only with the large periods. The phase difference was close to zero for most of the frequencies, suggesting that the variation in meteorological factors and nesting activity by Kemp's ridleys occurred simultaneously.

Some frequencies that stood out in the coherence graphic, such as that of 19 days detected between temperature and nesting did not appear in the corresponding spectra. The cause of these discrepancies was probably a very profound smoothing of the initial periodogram (Konayev, 1990). This may occur if the periods mentioned were not present every year when the measurements were made, they may disappear or their amplitudes may diminish significantly in the smoothened spectra averaged by 18 segments (years).

DISCUSSION

The description of the meteorological characteristics indicates that there are microclimatic differences among the locations monitored in the study. SM is slightly dryer and warmer than locations monitored in the South, but in spite of those differences, the variables fluctuated in a similar way. Spectral analysis of monthly data showed that the sunspot cycle, the change of the seasons, and ENSO influenced the variability of temperature and rainfall at the nesting beach. Analysis of daily data showed different cycles associated with the migration of dominant high pressure cells, which can occur over scales as large as the Gulf of Mexico (Gutiérrez de Velasco, 1996). Similar daily air temperature cycles have been recorded in other localities of the Gulf of Mexico's coast (Salas de León et al., 1992). It was not possible to analyze the wind variations with spectral methods, but Gutiérrez de Velasco (1996) reported that the changes in the direction and speed of the wind occur more or less simultaneously in the region that includes the continental shelf of Veracruz and the center and south of Tamaulipas.

Several authors have suggested that environmental variables can contribute to synchronize *arribadas* (Pritchard, 1969; Casas-Andreu, 1978; Pritchard and Gicca, 1980; Márquez, 1994). Nevertheless, given the microclimatic differences it is probable that the periodicity of the variables is more important than their value. The similarity of the cycles exhibited by the air temperature, besides the coherence between their harmonics and those of nesting, suggests that it is closely related to nesting frequency. In contrast, the coherence with the wind is lower and is observed only with the cycles of 21 and 33 days. The periodicity of the variables could be a cue in the synchronization of nesting, since despite the microclimatic differences detected along the nesting beach, observations indicate that *arribadas* occur more or less simultaneously along more than 100 km of beach (J. Díaz, *pers. comm.*). The air temperature cycles and wind associated with events of wide geographic cover (synoptic) could serve as stimuli for the turtles when far from the nesting beach, i.e., during the internesting intervals, when some females travel long distances (Mendoça and Pritchard, 1986). In contrast, when they are closer, local phenomena, like the wind regime, may be more important.

Behavior of Kemp's ridleys at sea is largely unknown. Therefore, it is difficult to establish a hypothesis about how they could detect air temperature oscillations. Most marine turtles bask at the sea surface to absorb sunlight (Sapsford and van der Riet, 1979; Dodd, 1988; Spotila et al., 1997), a behavior that could perhaps allow them to detect these fluctuations. However, telemetry efforts indicate that Kemp's ridleys remain at the surface only for short periods (Mendoça and Pritchard, 1986; Byles, 1989; Renaud, 1995). There are variations in the mixed surface layer that are associated with the presence of synoptic winds. Cold fronts, for example, drastically reduce the temperature in the neritic zone (Mann and Lazier, 1996), possible to a degree that could be detected by turtles in April and the beginning of May, when these events are present in the northeastern Gulf of Mexico (Tápanes and González-Coya, 1980).

In conclusion, the coherence between nesting cycles and environmental variables suggests that temperature and wind fluctuations could be useful to predict *arribadas*, thus enhancing protection measures. However, it is necessary to expand the area studied as well as the number of variables.

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APPENDIX

The amplitude spectrum $C_x(\omega)$ was estimated for each group of time-series (Bendat and Piersol, 1967; Jenkins and Watts, 1969; Konyaev, 1990; Emery and Thomson, 1997) as follows:

$$C_x(\omega) = \int_0^T x(t) \cdot \exp - i2\pi\omega t dt,$$

where $x(t)$ is the time-series, T is the total length of the series, and ω is the frequency. Autoperiodogram $Sxx\ (\omega)$ and cross-periodogram $S_{xy}(\omega)$ were defined as:

$$S_{xx}(\omega) = \frac{1}{T} C_x(\omega) \cdot C_x^*(\omega),$$

and

$$S_{xy}(\omega) = \frac{1}{T} C_x(\omega) \cdot C_y^*(\omega) = P_{xy}(\omega) - iQ_{xy}(\omega),$$

where $P_{xy}(\omega)$ and $Q_{xy}(\omega)$ are the true and imaginary parts of the crossed periodogram and (*) is the complex conjugate. The spectral estimate was obtained by smoothing the frequencies of the periodograms:

$$\hat{S}_{xx}(\omega) = \int_{-\Delta\omega/2}^{+\Delta\omega/2} S_{xx}(\omega')Z(\omega - \omega')d\omega'$$

where $\Delta\omega$ is the band of smoothing, and $Z(\omega)$ is a smoothing function. The estimates of the square coherence function $C^2_{oxy}(\omega)$ were also calculated for pairs of time-series:

$$C^2_{o_{xy}}(\omega) = \frac{\left|\hat{S}_{xy}(\omega)\right|^2}{\hat{S}_{xx}(\omega) \cdot \hat{S}_{yy}(\omega)}$$

and the phase difference:

$$\Delta\varphi_{xy}(\omega) = arctg\left(\hat{Q}_{xy}(\omega) / \hat{P}_{xy}(\omega)\right).$$