Length Scales of Interannual Sea Level Variations along the Pacific Margin*

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ABSTRACT

Correlations of monthly mean sea level variations along the Pacific Ocean margin are used to define length scales. In the northeast quadrant a minimum length scale at about 38°N separates two distinct regimes of longer length scale. This transition corresponds to a change from a regime north of 38° that is dominated by local atmospheric forcing to a regime south of 38° that is dominated by remote forcing. In the northwest quadrant a transition occurs near 35°N near the point of the separation of the Kuroshio. A transition at about 30°S in the southwest quadrant is associated with the southernmost extent of the Great Barrier Reef off the coast of Australia. In the southeast quadrant, a transition is observed at 18°S that may be due to a sharp change in the direction of the South American coastline. In general, tropical length scale values of 800 to 3100 km are separated from midlatitude values of 700 to 1300 km by a narrow region in which length scales are as short as 250 km. These results suggest the need for latitude-dependent criteria for the spacing of tide gauges in a global oceanographic sea level system.

1. Introduction

Sea level is one of the most fundamental quantities of physical oceanography. Historically, measurements from tide gauges have aided commercial activities such as shipping, harbor navigation and coastal engineering. Unfortunately, the resulting concentration of measurements in harbors and near river mouths is not optimal for today's oceanographic purposes. Still, the existing tide gauge records have proven useful. Studies of large-scale modes of variability (Thompson 1986; Wyrtki 1979a) and El Niño (Wyrtki 1979b, 1985), for example, have been done successfully and have led to an effort to establish a system better suited to oceanographic studies. This is evident in the decision of the Intergovernmental Oceanographic Commission (IOC 1986) to design and install a global sea level system. The design of such a system requires the adoption of spacing criteria for the placement of new gauges. Economic considerations which limit the number of new stations must be balanced against the need to establish a system that will provide a record of interannual variation that is spatially continuous at an acceptable level of statistical reliability. By analyzing correlations of sea level changes on the Pacific rim, we find systematic latitudinal variations in correlation length scales which should be considered in the design of such a system.

Woodworth (1986) has recently discussed this problem. He points out that the proposed IOC (1986) plan suggests a 1000 km spacing along continental margins, but also states that this estimate of the required spacing needs further study and verification. This is the primary intent of this paper. More general studies of the Pacific sea level variability, particularly along the coast of the Americas (for example, Enfield and Allen 1980; Chelton and Davis 1982), have been done. We will refer to these previous studies of the variability, but will focus on the problem of choosing spacing criteria for selecting stations to form a global monitoring network.

The four groups of stations on the Pacific margin that are used in this study are shown in Fig. 1 (see also Table 1). The selection of stations and the preparation of the data are described in section 2. Correlation length scales within each group are defined and presented in section 3 in a manner which brings out the structure of the length scale variations. Length scale minima that occur in the northeast and northwest quadrants are well resolved. Indications of structure in the southeast and southwest are more tentative due to the limited latitudinal range of the available data but transitions are clearly evident. The most obvious transitions in the Northern Hemisphere appear to be associated with the structure of the major wind systems and ocean current gyres. A summary and a brief discussion of the length scale results are presented in section 4.

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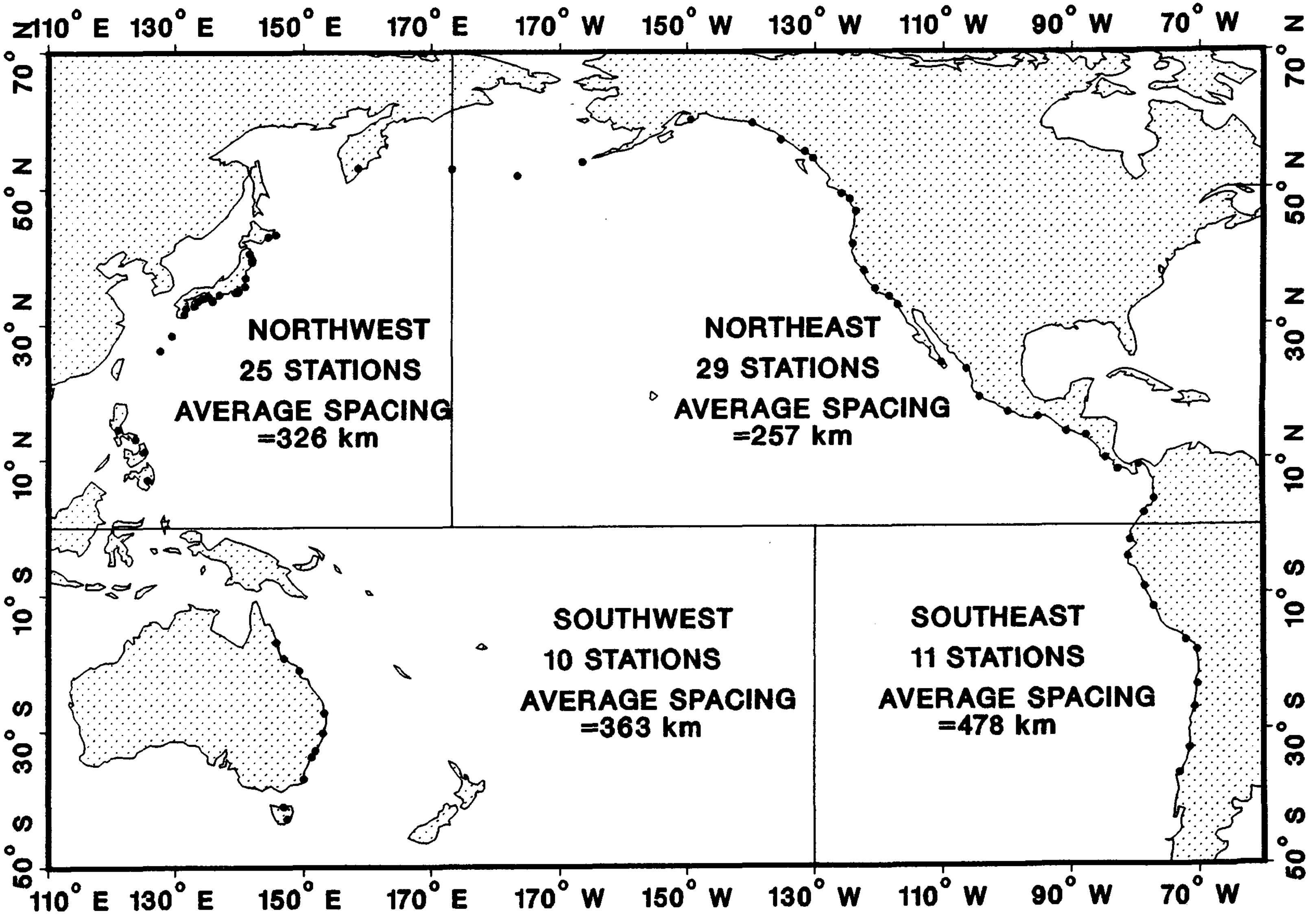

FIG. 1. Locations of sea level stations used in this study, grouping of stations, average intervals on the station lines, and numbers of stations.

2. Procedure

The station names and locations and the average station separations for each group are given in Fig. 1 and Table 1. Except for the Japanese coast, where uniformly dense coverage was possible, only the best record of any two stations within 50 km of each other was selected. Where possible, more exposed locations were favored over sheltered ones. The northeast and the southeast groups have two stations (Tumaco and La Libertad) in common near the equator and Massacre Bay is the end station for both the northeast and northwest groups.

The data were in the form of monthly means collected and archived by the Permanent Service for Mean Sea Level. From all of the station data within a given group, a 20-year interval was selected that included a maximum total number of monthly mean values. The intervals chosen are given in Table 1. Overall, 90% of the possible data is available. The southwest group has 76% of the possible data available and is the only quadrant with less than 90% available. No missing data values were interpolated to fill gaps and no station with less than 10 years of data was included. Where two data segments for a given station had different reference levels, the step was removed by adding a constant to create a smooth 12-month running mean across the junction of the two segments. The mean, linear trend and annual and semiannual harmonics were fit by least squares and subtracted from the raw data to obtain a residual which emphasized the nonseasonal variability. The detrending removes secular trends and attenuates fluctuations with time scales longer than the record length (20 years).

TABLE 1. Stations used in each of the quadrants shown in Fig. 1. In each quadrant the stations are listed from north to south. The range of years given in parentheses is the 20-year period over which correlations were computed in that quadrant.

	Northeast (1950–69)	Northwest (1955–74)	Southwest (1957–76)	Southeast (1951–70)
1	Massacre Bay	Massacre Bay	Cairns	Tumaco
2	Sweeper Cove	Petropavlovsk	Townsville	La Libertad
3	Dutch Harbor	Hanasaki	Mackay	Talara
4	Seward	Kushiro	Brisbane	Chimbote
5	Yakutat	Hachinohe	Coffs Harbour	Callao
6	Sitka	Miyako	Newcastle	Matarani
7	Ketchikan	Kamaisi	Sydney	Arica
8	Prince Rupert	Onahama	Eden	Antofagasta
9	Tofino	Choshi	Georgetown	Caldera
10	Neah Bay	Mera	Hobart	Valparaiso
11	Astoria	Okada		Talcahuano
12	Crescent City	Toba		
13	San Francisco	Kushimoto		
14	Avila	Kainan		
15	Santa Monica	Komatsushima		
16	San Diego	Kochi		
17	La Paz	Tosa Shimizu		
18	Mazatlan	Hosojima		
19	Manzanillo	Aburatsu		
20	Acapulco	Naze		
21	Salina Cruz	Naha		
22	San Jose	Manila		
23	La Union	Legaspi		
24	Puntarenas	Tacloban		
25	Puerto Armuelles	Davao		
26	Balboa			
27	Buenaventura			
28	Tumaco			
29	La Libertad			

Cross correlations between these residuals were computed within each group of stations. Length scales were found by interpolation along the coastline to find distances up and down the coast at which the correlation falls to some particular value. The method is more fully illustrated in the next section. The correlations were computed at zero lag even though larger correlations may occur at nonzero lags (Enfield and Allen 1980). Consequently, the length scales we compute are conservative estimates for the purpose of designing an observing system.

Before proceeding with a presentation of our results, a short discussion of the statistical significance of the correlations is appropriate. The correlations we will present in the next section have all been tested for statistical significance using a normalization of the correlation values (Sciremammano 1979) that is based on the integral time scale for independence defined by Davis (1976). In all but the southwest quadrant a correlation value of 0.5 is significant at the 99% confidence level. In the southwest region it is significant at the 90% level. We did not use correlation values below 0.5 in our analysis. Although it is possible to contour the length scale over which the correlations are significant at a given confidence level, we decided to show the correlations instead. We made this decision because very low correlation values can be statistically significant while only explaining a small amount of the variance in the time series. By restricting our attention to correlation values above 0.5 we are requiring both that the correlations be statistically significant and that a linear relationship between two series explains a reasonable portion of their variance.

3. Results

We will consider each of the four quadrants shown in Fig. 1 separately. The separation of the data into these regions and the order in which we will consider them reflect our assessment of the quality of the data in each quadrant and the resulting confidence we have in the results on the spacing criteria. We will consider the northeast quadrant first because this is where the data coverage is best.

Contours of constant cross correlation values in the northeast quadrant are shown in Fig. 2. This figure is derived directly from the correlation matrix by introducing the appropriate station separations between

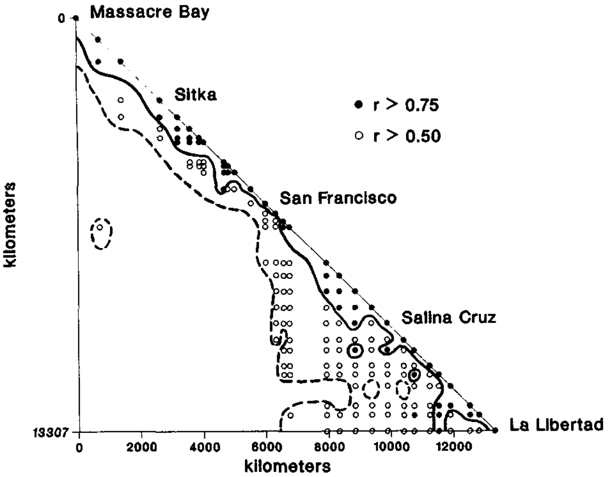

FIG. 2. Correlation contours for the northeast quadrant. The solid line shows $r = 0.75$; the dashed line shows $r = 0.5$.

rows and columns. Such space–space correlation displays have been used previously by Enfield and Allen (1980). Linear interpolation along rows and columns was used to assign length scales, $L(r)$, up and down the coastline from a given station. At Sitka, for example, interpolation is seen to indicate $L(0.5)$ is about 2000 km to the north and 1500 km to the south. Where $L(r)$ did not lie within the contoured boundaries, two techniques are used. Between the northeast and southeast quadrants, correlations with stations across the equator are used in the interpolation. At the other boundaries between quadrants, the diagonal value ($r = 1$) and the boundary value were used for extrapolation. To more clearly depict the values computed this way, results are presented in the form of Fig. 3 where $L(r)$ is plotted as positive to the north and negative to the south. Note that the five lines above and below the horizontal axis correspond to $L(r)$ for r values of 0.9 to 0.5 by steps of 0.1. Although we will often use $L(0.5)$ in our discussion, the reader can easily choose another value.

Two regions with distinct length scales appear in Fig. 3 and are separated by a minimum at about 38°N. Length scales for all r values remain fairly independent of latitude from 53°N (Massacre Bay, Alaska) to 38°N (San Francisco), with the average value of $L(0.5)$ equal to 1300 ± 400 km. The uncertainties attached to values of $L(r)$ are the standard deviations of the values within the stated range of latitude. Within 400 km to the north or the south of San Francisco $L(r)$ reaches a minimum for all r. The average of the northward and southward values of $L(0.5)$ near 38°N is 600 ± 100 km. South of this point, a parallel-sided structure develops which indicates a length scale imposed by some form of cutoff at the boundary of the region at 38°N rather than by physical conditions within it. The average value of $L(0.5)$ within this structure is 3100 ± 1700 km and long length scales persist to the equator. However, there is a weak minimum in length scale for $r = 0.9$ through $r = 0.7$ at about 10°N which may mark another region. Enfield and Allen (1980) have pointed out signals in this area that may be associated with the motions of the intertropical convergence zone.

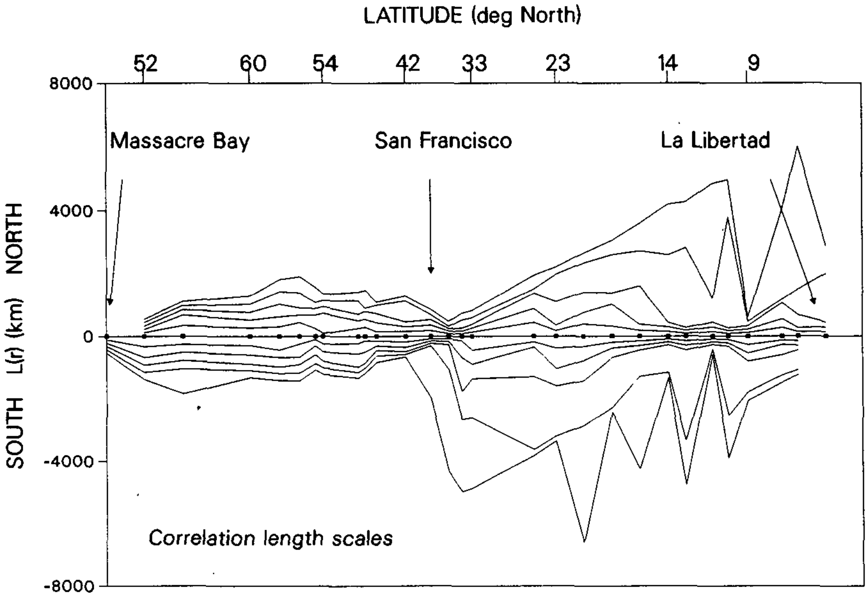

FIG. 3. Correlation length scales, $L(r)$, for the northeast quadrant. Values of $L(r)$ are shown for $r = 0.9$ to 0.5 in steps of 0.1.

The correlation length scales for the northwest quadrant, which extends from Massacre Bay at 53°N to Davao, Philippines at 7°N, are shown in Fig. 4. Although the length scales in this figure are generally smaller than those in the previous figure, two regimes are again apparent with a minimum separating them near 35°N (Mera, Japan). Another structure suggesting cutoff boundaries is evident between 34° and 31°N from approximately Okada to Aburatsu. North of 42°N (Kushiro to Massacre Bay) the average value of $L(0.5)$ is 1100 ± 400 km. For the five stations centered on Mera, the value is 250 ± 150 km, and increases to 800 ± 300 km for stations south of 35°N.

Summarizing to this point, in the Northern Hemisphere we have seen two regimes of correlation length scale. The boundaries along the eastern and western coastlines occur at approximately 38° and 35°N, respectively. The change in the tropical length scales near the equator from 800 km on the western boundary to 3100 km on the eastern boundary is not surprising. Poleward-traveling Kelvin waves along the eastern boundary can carry information away from the equatorial region (Enfield and Allen 1980) and will thus increase the correlation length scales.

Results for the southern hemisphere are shown in Figs. 5 and 6. As discussed above, a correlation of 0.5 is significant at a lower level (90%) in the southwest quadrant (Fig. 5). This change is the result of longer integral time scales, particularly along the northeast coast of Australia inside the Great Barrier Reef. The standard error in r in this quadrant is 0.18, compared to an average of 0.11 for the other three quadrants. Values of $L(r)$ for the southeast quadrant (Fig. 6) are all based on correlation values that are significant at the 99% confidence level.

Note that the stations shown in Fig. 5 cover only 3300 km, from Cairns at 17°S to Hobart at 43°S along the eastern coast of Australia. Values of $L(0.5)$ at the northern end average 1100 ± 300 km and are consistent with the tropical values in the Northern Hemisphere. Continuing south, a minimum of 300 ± 70 km is reached at 30°S (Coffs Harbor) and is followed by a return to larger values of 700 ± 300 km between 34°S (Sydney) and 43°S (Hobart). In order to maintain continuity with the southern current gyre, we will consider Fig. 6 from right to left. Little variability is seen between 37° and 18°S; $L(0.5)$ in this region has an average value (700 ± 300 km) that is similar to that found for southeastern Australia. A transition between 19° and 17°S (near Arica, Chile) leads to higher values (2800 ± 2100 km) that persist to the equator and are comparable to the tropical values in the northeast quadrant (3100 ± 1700 km).

4. Discussion

The length scale results for all quadrants are summarized schematically in Fig. 7. Long length scales of from 800 to 3100 km are found near the equator and are separated from the shorter scales of 700 to 1300 km at higher latitudes by very distinct transitions. Length scales on the eastern equatorial boundary of both hemispheres are found to be about 2 to 4 times longer than those on the western equatorial boundary.

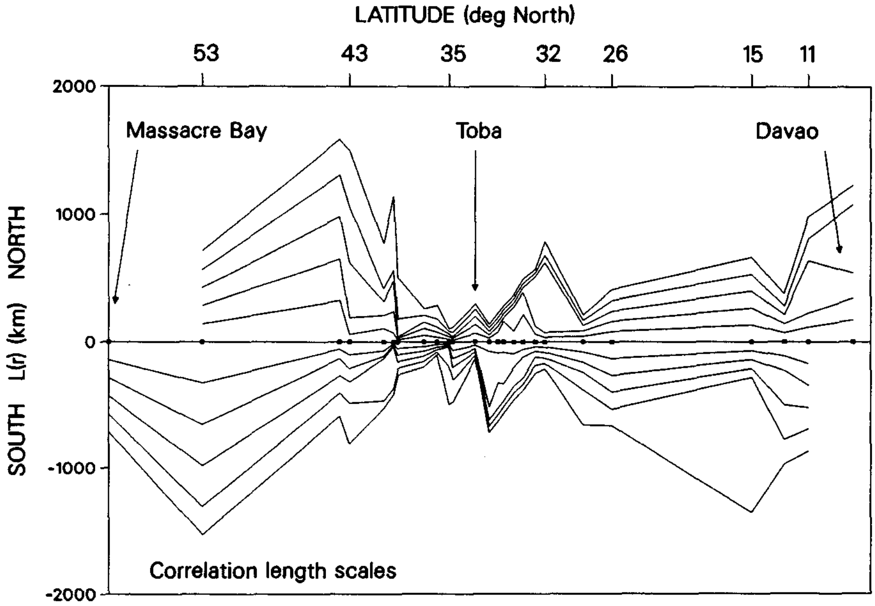

FIG. 4. As in Fig. 3 but for the northwest quadrant. Note the change in scale on the vertical axis.

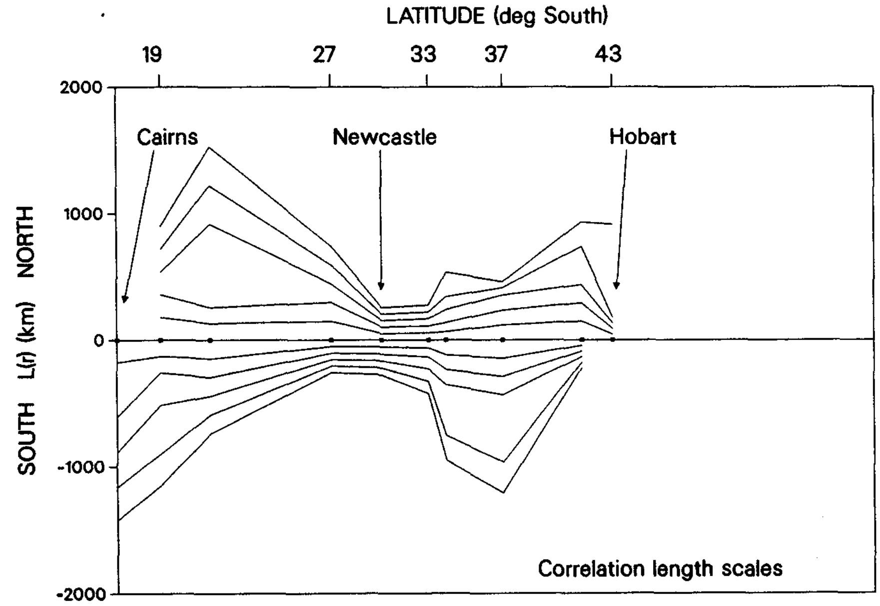

FIG. 5. As in Fig. 3 but for the southwest quadrant. Note the change in scale on the vertical axis.

In the northern Pacific, minima in the length scales are found near transitional points in large-scale wind and current structures. In the northeast, the minimum near San Francisco is coincident with a transition in the mean annual cycle of sea level variation (Wyrtki and Leslie 1980). This area of the coast also corresponds to a transition from a southern regime dominated by remote forcing to a northern region more affected by local atmospheric forcing (Pares-Sierra 1987). Enfield and Allen (1980) also discuss the remotely forced signal along this coastline. In the northwest quadrant, the separation of the Kuroshio from the east coast of Japan appears to coincide with the minimum in correlation length scale. In the southwest, the southernmost extent of the Great Barrier Reef at the easternmost extent of the Australian coast provides a physical transition point. Relative to the other quadrants, the abrupt change in length scale along the South

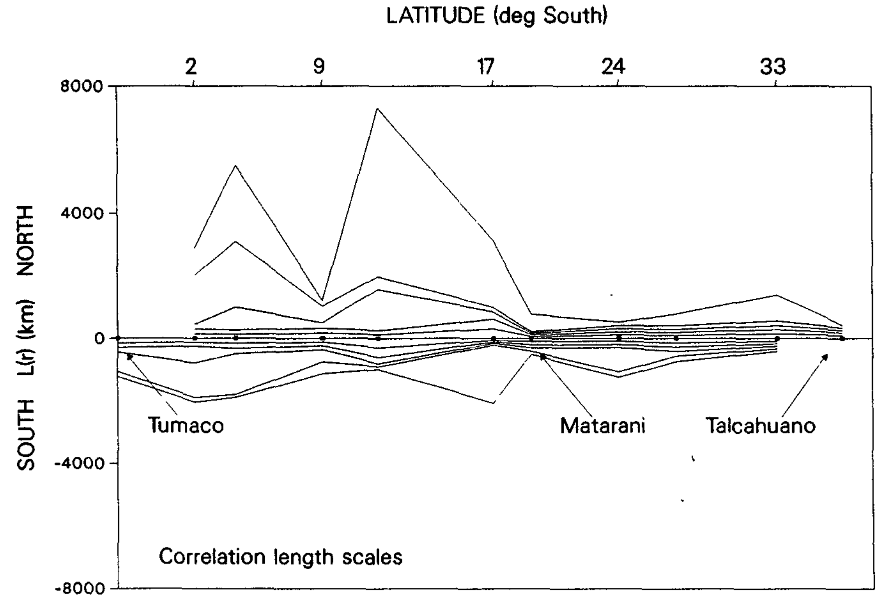

FIG. 6. As in Fig. 3 but for the southeast quadrant.

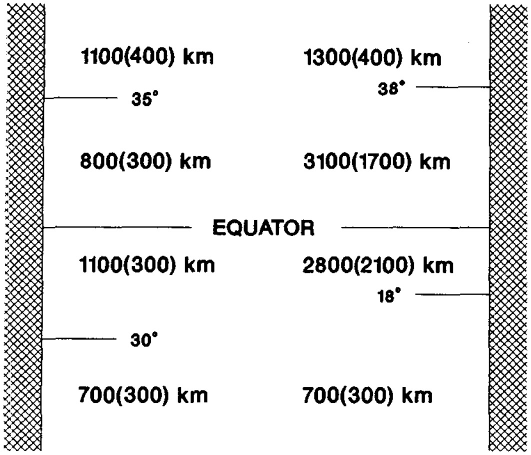

FIG. 7. Schematic of length scale values for each quadrant.

American coast occurs closer to the equator. This transition coincides with a sharp change in the direction of the South American coastline. A minimum in $L(r)$ that is confined to a few degrees of latitude as seen in the previous quadrants is not evident here. However, the limited latitude range in this quadrant may miss a minimum south of 37°S.

Spacing criteria for the placement of sea level stations need to provide for variations in the correlation length scale. The stations used in this study require an interval of 800 ± 300 km to insure a correlation greater than or equal to 0.5 for adjacent records away from transition regions. Transitions can occur for a number of reasons; a few examples have been presented above. Intervals as short as 250 km are needed near the transitions to maintain this level of correlation. However, these values may be somewhat conservative since we have not allowed for higher correlations at nonzero lags. Additional stations on the west coast of South America are needed to provide continuity of coverage from the equator to the Antarctic Circumpolar Current. Three well-located stations presently exist, but as yet insufficient data is available. One or two additional stations in the western Pacific between Davao at 7°N and Cairns at 17°S are needed to provide continuity across the equator.

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