Journal of Marine Research, 41, 113-125, 1983

Westward propagation of short-term climatic anomalies in the western North Pacific Ocean from 1964-1974

by Warren B. White[1]

ABSTRACT

Short-term climatic anomalies in the surface dynamic height (0/400 db) structure of the western North Pacific from 1964-1974 are investigated on a seasonal basis for propagational character. From the equator to 32.5N, negative dynamic height anomalies occurred in 1965, 1969 and 1972, approximately every three years, associated with El Nino events in the eastern tropical Pacific (Wyrtki, 1977). The decorrelation time scale of these short-term climatic anomalies was independent of latitude (i.e., 6-9 months), but the decorrelation longitude scale decreased poleward; i.e., from 10° longitude at 7.5N to 5° longitude at 32.5N. Time/longitude correlation studies find these anomalies to have propagated westward at the speed of baroclinic long (Rossby) waves; i.e., 14 ± 4 cm/sec to the west at 7.5N and 1.5 ± .5 cm/sec to the west at 32.5N, with intermediate speeds in between.

1. Introduction

Recently, White and Hasunuma (1980) investigated interannual variability in the surface dynamic height (0/400 db) structure of the western North Pacific from 1954-74. They found the baroclinic structure over the entire region to undergo short-term climatic variability, with decorrelation scales of 6 months-10 years. The shorter time scales were associated with the "Southern Oscillation" (Wyrtki, 1975) previously thought to be confined in the tropical Pacific. The longer time scales were associated with decadal changes in global atmospheric indices (Namias, 1980). In association with this, the relative strength of each of the major current systems in the region (i.e., the North Equatorial Countercurrent, the North Equatorial Current, the Subtropical Countercurrent and the Kuroshio Current) exhibited fluctuations, principally on the time scale of the Southern Oscillation with magnitudes of up to 25% about the mean, each in phase with the other. This short-term climatic variation in current strength was associated with widespread "spin-up" and "spin-down" of the baroclinic gyre structure over the entire western North Pacific Ocean on these time scales.

In the foregoing study, the modal character of short-term climatic variability

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from 1954-1974 was explored through the use of empirical orthogonal function (EOF) analysis. This expansion of the variability in terms of standing modes was relatively successful, with the first three functions explaining 60% of the total variance. However, careful examination of the EOF spatial patterns suggests now that short-term climate anomalies in the ocean may have had propagational character. According to simple linear theory (e.g., McCreary, 1976) interannual variability in baroclinic structure should behave like forced, baroclinic, long (Rossby) waves. This is also suggested by earlier field studies in the eastern and central North Pacific, both in the subtropical region (e.g., Price and Magaard, 1980; Kang and Magaard, 1980; White and Saur, 1981) and in the tropical region (e.g., White, 1977; Meyers, 1979), where westward phase propagation of thermocline variability (i.e., an alias of surface dynamic height variability) on annual and interannual time scales has been shown to conform to linear, baroclinic, long wave theory.

Recently, this baroclinic long wave hypothesis was supported, indirectly, by White *et al.* (1982) in their analysis of the space/time statistical character of short-term climatic variability in the thermal structure of the western North Pacific. They discovered that short-term climatic anomalies over the entire latitude range, from 5N to 35N, were dominated by a six-month decorrelation scale from 1967-1974, with a zonal decorrelation scale that decreased with latitude, approximately as the internal Rossby radius of deformation.

In the present study, analysis is conducted on ten years (i.e., 1964-1974) of individual seasonal mean maps of dynamic height, constructed from a subset of data used in the investigation by White and Hasunuma (1980). The analysis consists of developing time/longitude correlation matrices, which allow the propagation character of variability to be seen. The results of this analysis confirm the propagational character of short-term climatic anomalies and establishes their similarity to baroclinic (Rossby) long waves. The latter establishes a definite capability for the prediction of short-term climatic variability in dynamic height and heat content in the western North Pacific.

2. Data

In a report by White and Wylie (1977), subsurface temperatures from nearly 45,000 stations (composed of hydrographic, expendable and mechanical bathythermograph observations), taken from 1954-1974, were interpolated onto a regular grid each season (i.e., 2.5° latitude by 5° longitude north of 17.5N and 5° latitude by 10° longitude south of 17.5N). White and Hasunuma (1980) used these gridded temperatures, together with a constant value of salinity (i.e., 34.5‰), in the equation of state to compute specific volume. This allowed dynamic height (0/400 db) to be computed as the vertical integral of specific volume over the upper 400 m of ocean. Earlier, White *et al.* (1978) had conducted a comparison between dynamic height computed in the foregoing manner and dynamic height computed from the knowledge of both temperature and salinity. This comparison was conducted along two meridional hydrographic sections made by the RV *Ryofu Maru* along 137E from the equator to 35N. The difference between the two measures of dynamic height was found to have been smaller than 1.5 dyn. cm. This difference is similar in size to the error (i.e., 1 dyn. cm) attributed to the computation of dynamic height due to errors in temperature, salinity, and pressure (Wooster and Taft, 1958). Therefore, the accuracy of this procedure is considered to be approximately 2.0 dyn. cm.

In the study by White and Hasunuma (1980), investigation into short-term climatic variability was conducted upon 20 individual annual maps of dynamic height (0/400 db) over the period 1954-1974. Each individual annual mean map was produced by averaging the four seasonal maps together. From this earlier work, the long-term annual mean dynamic height (0/400 db) and the interannual RMS differences over this 20-year period are displayed in Figure 1. Inspection of this figure shows the largest interannual variability to have existed at the location of strong horizontal gradients in dynamic height, associated with the Kuroshio Current, the North Equatorial Current, and the North Equatorial Countercurrent. At the location of these currents, White and Hasunuma (1980) found vertical displacements in the structure of the main thermocline to account for most of this interannual variability in surface dynamic height (see Fig. 2). This fact first suggested the hypothesis that short-term climatic anomalies in dynamic height (0/400 db) could be interpreted in terms of internal, baroclinic, long waves propagating along the main thermocline.

In the present study, confirmation of this hypothesis is sought in individual seasonal maps of dynamic height (0/400 db) from 1964-1974. Seasonal resolution is particularly necessary for the detection of phase propagation in the tropical portion of the study. However, the full 20 years of seasonal maps produced by White and Hasunuma (1980) were not adequate for this investigation; rather, only the last ten years from 1964-1974. Earlier seasonal maps relied upon too few data (see White and Wylie, 1977), making them unreliable for present purposes.

Individual seasonal maps of anomalous dynamic height (0/400 db) are shown for the first time in Figure 3, beginning with spring (March, April, May) of 1964 and extending through winter (December, January, February) of 1974. Anomalies of short-term climatic variability were created by subtracting the individual seasonal means from the long-term seasonal means, computed from 1964-1974 (not shown). The contour interval in each is 2 dyn. cm, equal to the estimated interpolation error (White and Hasunuma, 1980). Data coverage in the southeast portion of the study was consistently sparse and did not warrant mapping during most seasons. Information on the distribution of data used to construct these maps is given in White and Wylie (1977).

Inspection of the seasonal maps of anomalous dynamic height (0/400 db) in the

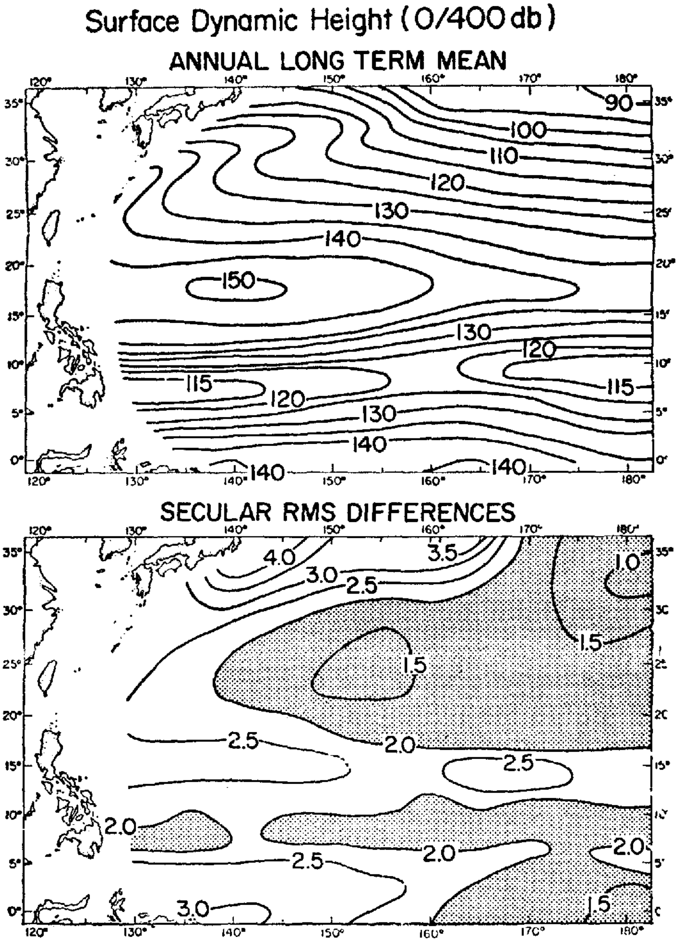

Figure 1. Annual long-term mean horizontal map (1954-1974) of estimated dynamic height (0/400 db) over the western North Pacific. Also shown are the RMS dynamic height differences. Units are dynamic cm. Taken from White and Hasunuma (1980).

western North Pacific finds a tendency for the subtropical region (north of 20N) to have been out of phase with the tropical region, in agreement with the EOF analysis of White and Hasunuma (1980). In the tropical region, the zonal scales of anomalous variability were clearly much larger than those in the subtropical region, in agreement with the statistical anlysis conducted by White *et al.* (1982). Over the ten-year period shown, the western North Pacific experienced approximately three reversals in the sign of anomalous dynamic height, with negative anomaly development in the tropics being the signature for the onset of "El Nino" (Wyrtki, 1977). These occurred in 1965, 1969 and 1972. In both 1969 and 1972, the onset of "El Nino" can be seen to have propagated into the region from the east; this was not

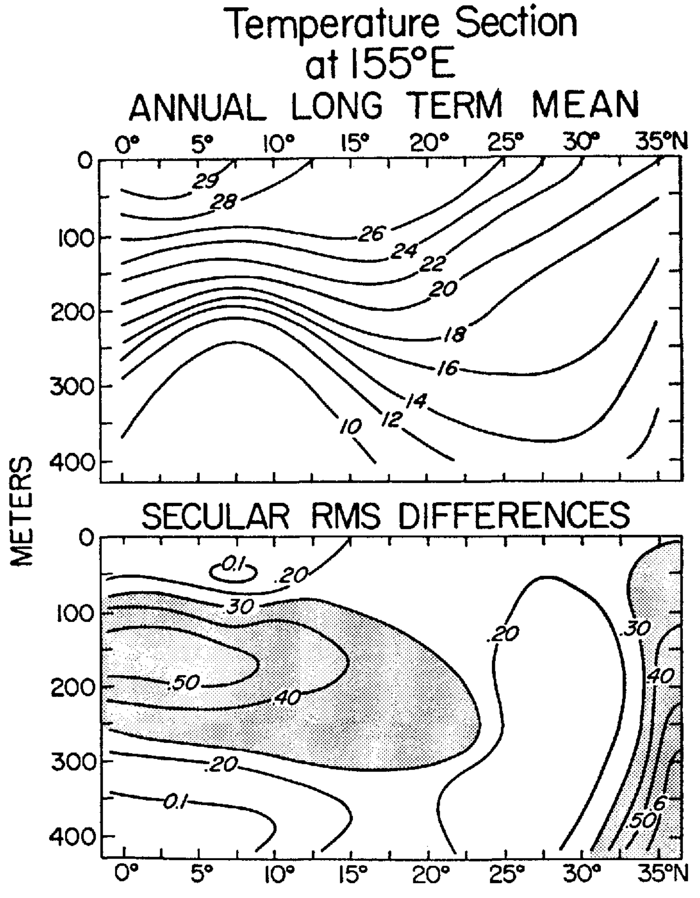

Figure 2. Annual long-term mean meridional section (1954-1974) of temperature (°C) from 0-35N and 0-400 m along 155E. Also shown are the RMS interannual temperature (°C) differences (1954-1974) along this same section. Taken from White and Hasunuma (1980).

true in 1965. In each case, "El Nino" onset occurred as a fall/winter process; hence, the name. In the subtropical region, the propagation character was much less clear and cannot be ascertained from these maps.

3. Westward propagation

From data used to construct the individual seasonal anomaly maps in Figure 3, construction of time/longitude matrices of anomalous dynamic height (0/400 db) visually enhances the search for westward propagation. These matrices are constructed at 5° latitude intervals from 7.5N to 32.5N (Fig. 4). They extend in longitude from 180° (where possible) to the western boundary of the North Pacific (see

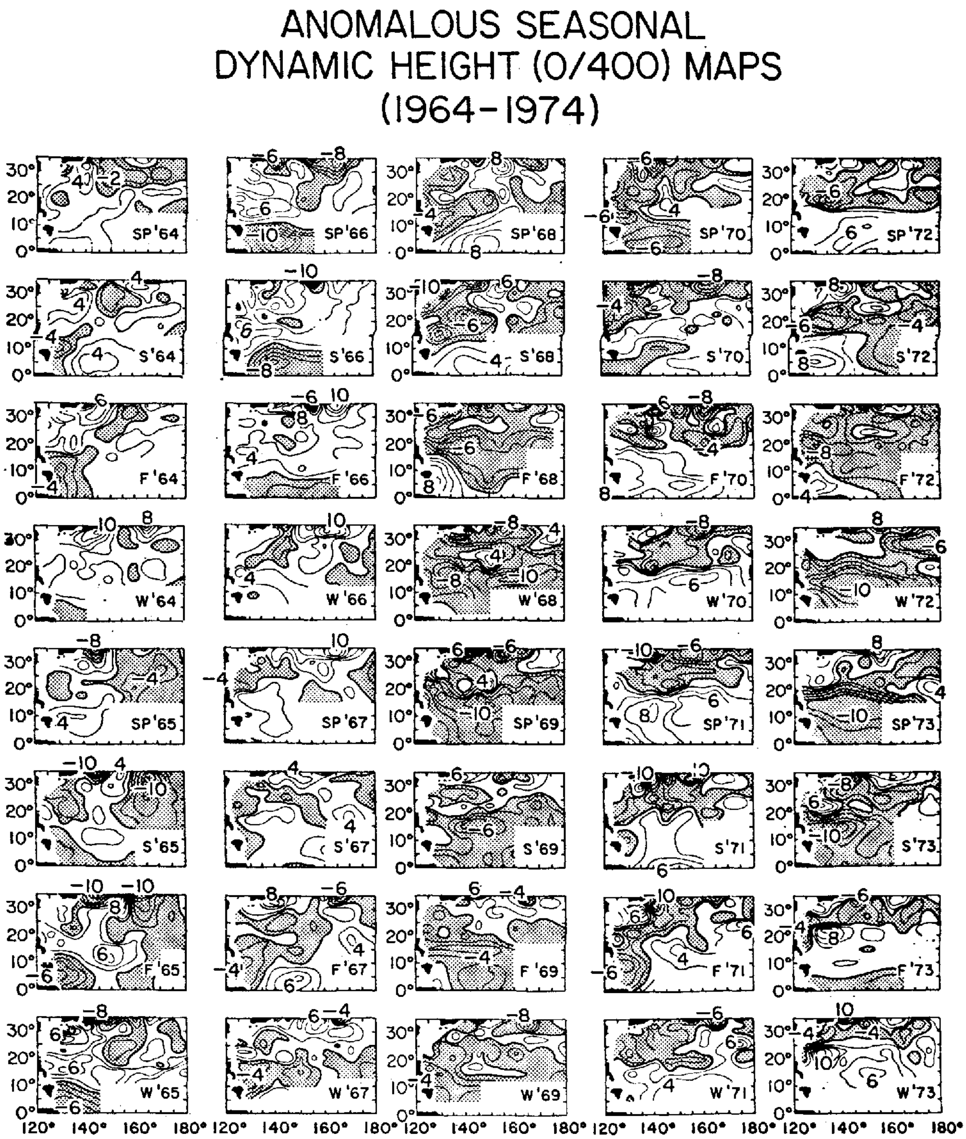

Figure 3. Anomalous distribution of dynamic height (0/400 db) computed for each season from 1964-1974. Units are dynamic cm.

Fig. 1). They indicate a definite westward propagation at most latitudes, with anomalies traveling the entire zonal extent of the region in about six months-two years, depending upon the latitude. For example, at 17.5N, a negative anomaly can be seen to have propagated westward with increasing time in 1972. Also, at 7.5N this same negative anomaly can be seen to have propagated westward with increas-

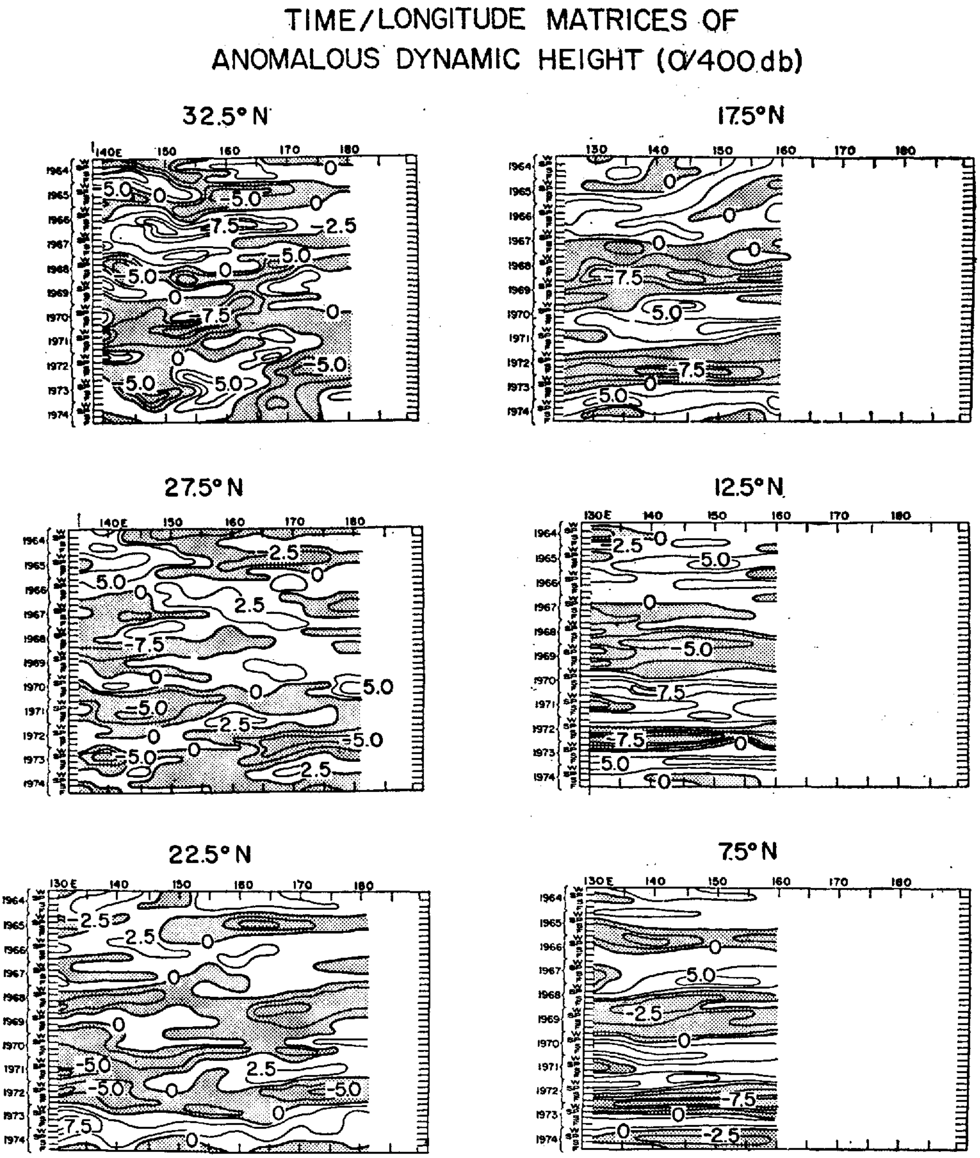

Figure 4. Time/longitude matrices of anomalous dynamic height (0/400 db) computed from 1964-1974 along 7.5N, 12.5N, 17.5N, 22.5N, 27.5N, and 32.5N.

ing time, but at a much faster rate. On the whole, westward speed of propagation seems to have diminished with increasing latitude.

In these time/longitude matrices there is, of course, a certain amount of correlated and uncorrelated noise in the field, which act to obscure westward propagation in

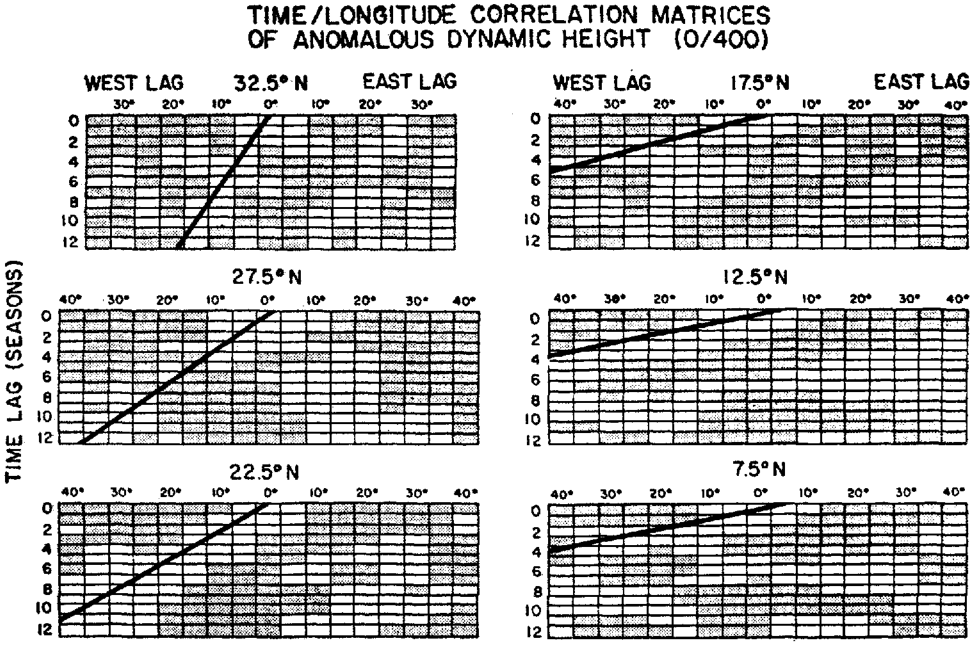

Figure 5. Time/longitude correlation matrices of dynamic height (0/400 db) computed from 1964-1974 along 7.5N, 12.5N, 17.5N, 22.5N, 27.5N, and 32.5N.

some cases. Sources of this noise may be instrumental error, subgrid variability, and local large-scale forcing by the wind. The influence of this noise can be suppressed and the *average propagational speed* at each latitude computed, from considerations of sample correlation matrices (Fig. 5), constructed from the data matrices in Figure 4.

The correlation matrices in Figure 5 show a definite westward propagation to have existed at all latitudes, with positive correlation extending toward west space lag with increasing time lag. Individual correlation values are not necessarily statistically significant; it is the shape of the correlation field that gives confidence to the results. The ability to draw a line through the correlation matrix delineating maximum positive correlation indicates the presence of propagation phase speed. The ratio of space lag to time lag along this line yields magnitude of the phase speed. At 32.5N it was 1.5 ± .5 cm/sec to the west, and at 7.5N it was 14 ± 4 cm/sec to the west. All latitudes in between indicate westward propagation with intermediate speeds. These speeds are given in Table 1. Errors in the speed derive from ambiguities in fitting the line through the maximum positive correlation values.

Evidence exists in these sample correlation matrices for eastward propagation to have existed in the latitude range 25-30N. In the correlation matrix at 27.5N in Figure 5, the baroclinic long (Rossby) wave signature can be seen (with westward

Table 1. The time and longitude lag distances where the sample correlation matrix goes to zero, as a function of latitude. Also, the phase speed of westward propagation is given as a function of latitude.

Latitude	Decorrelation scales Δt (months)	Δx (° longitude)	Zonal phase speed (cm/sec)
7.5N	6	10	-14 ± 4
12.5°	6	10	-12 ± 3
17.5°	7	11	-10 ± 2
22.5°	8	7	-4.5 ± 1.5
27.5°	9	9	-3.5 ± 1.0
32.5N	6	5	$-1.5 \pm .5$

propagation indicated by the black line), but it is linearly superimposed upon a correlation structure that indicates eastward propagation as well. This eastward propagation had a decorrelation space scale of approximately 10° longitude, a decorrelation time scale of approximately 1.5 years, and an indicated speed of approximately 2 cm/sec. The latitude band in which this eastward propagation occurred is, upon inspection of Figures 1 and 2, both the location of minimum interannual variability and the location of an absence in a well-defined main thermocline in the upper 400 m. In this region the Subtropical Mode Water exists (Masazawa, 1969), with temperatures ranging between 14-18°C. The absence of any strong thermocline between 200 m and 400 m depth is indicative of the lack of influence that internal baroclinic long waves had on dynamic height (0/400 db) fluctuations. Most probably, this allowed thermohaline processes occurring in the upper 300 m to become dominant in the determination of interannual variability in surface dynamic height. If true, eastward advection of mixed layer temperature anomalies by the background geostrophic flow (see Fig. 1) would be expected. In fact, the speed of mean background flow at 2.7.2N in Figure 1 was approximately 2 cm/sec, the same as that of eastward propagation found in Figure 5.

The time and longitude decorrelation scales of variability at each latitude are given in Table 1, computed as the first zero crossing of the sample correlation along the time-lag and longitude-lag axes, respectively. Values are interpolated to the nearest whole degree longitude and nearest whole month. The time scale at each location was approximately the same (i.e., six-nine months) in agreement with previous estimates of the temporal statistical structure by White *et al.* (1982). This means that short-term climatic fluctuations went through a cycle every two-three years on average during this ten-year time period (i.e., 1964-1974). This is consistent with inspection of the data matrices themselves (Fig. 4). The zonal scale length of this interannual variability decreased significantly with increasing latitude, again consistent with results discussed previously by White *et al.* (1982). In that study, the decrease in zonal length scale with latitude was shown to be consistent with the decrease in the internal Rossby radius of deformation with latitude.

Comparing the propagation results of Figures 4 and 5 with the long-term mean dynamic height map in Figure 1, one finds westward propagation to have been independent of the mean relative geostrophic zonal current structure. For example, at 22.5N the Subtropical Countercurrent occurs with mean flow to the east; yet, the anomalies of dynamic height of this latitude propagate to the west, upstream. In this case, the anomalies can be said to have propagated in the "retrograde" direction; i.e., in the opposite direction to the background mean flow. These results are consistent with the theory of baroclinic long (Rossby) wave propagation in the presence of mean baroclinic flow (Killworth, 1979), where the principal effect of mean flow upon wave propagation is through the alteration of the internal wave speed, not through the Doppler shift.

4. Comparison with baroclinic long wave theory

Baroclinic long wave theory has been shown by White (1977), Meyers (1979), Price and Magaard (1980), Kang and Magaard (1980), and White and Saur (1981), to explain much of the *annual cycle* of thermocline variability (i.e., an alias of surface dynamic height) in the eastern, central, and tropical North Pacific. This theory is even better suited (i.e., McCreary, 1976) to explain variability on interannual time scales, as are encountered in the present study.

In a two-layer model ocean, which portrays adequately the first mode baroclinic adjustment of the main thermocline, baroclinic long waves derive from consideration of the conservation of potential vorticity; i.e.,

$$\frac{\partial D'}{\partial t} + \left(\frac{-\beta g' H_o}{f^2}\right)\frac{\partial D'}{\partial x} = 0 \tag{4.1}$$

where D' is the dynamic height adjustment to internal fluctuations of the main thermocline, β is the meridional derivative of the Coriolis parameter f, g' is the reduced gravity of a two-layer system, and H_o is the depth scale of the main thermocline. The westward phase speed of these waves; i.e.,

$$C_{px} = \frac{-\beta g' H_o}{f^2} \tag{4.2}$$

is latitude dependent through both f and H_o.

The theoretical zonal phase speed given in (4.2) is shown as a function of latitude in Figure 6. In this calculation, g' is taken as 3 cm sec^{-2}, representing the buoyancy of the surface waters relative to the deeper waters, and H_o is allowed to vary with the mean depth of the main thermocline (i.e., approximately equal to the depth of the 16°C isotherm in Fig. 2). This yields a profile of zonal phase speed that approximates that derived by Meyers (1979) for the central North Pacific. Also displayed in Figure 6 are the observed phase speeds taken from Table 1.

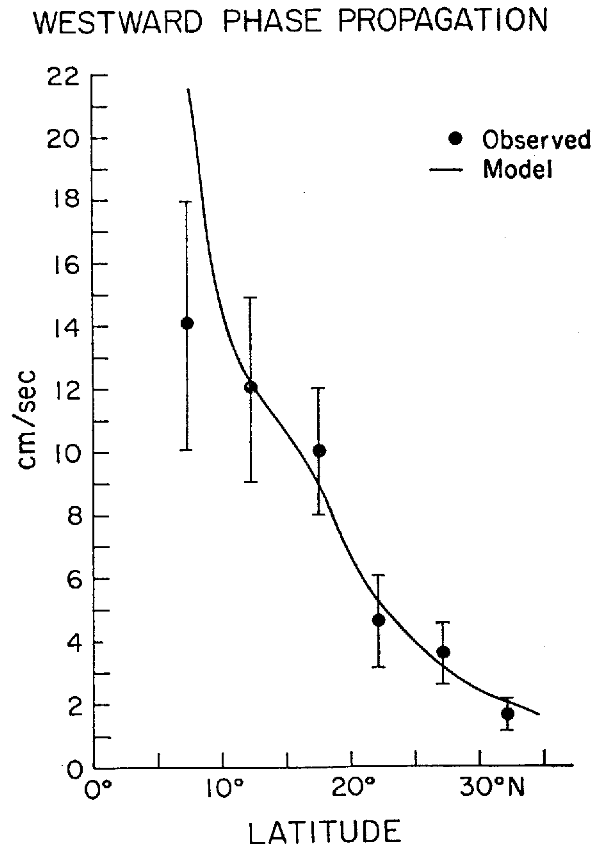

Figure 6. Observed and model westward phase speed as a function of latitude.

The comparison of theory and observation in Figure 6 demonstrates a consistency between the westward propagation of free baroclinic long waves and the westward propagation of short-term climatic anomalies in dynamic height. On an individual basis, climatic anomalies in thermocline depth (i.e., an alias of dynamic height) should not be represented strictly by free waves; i.e., local wind forcing is operating as well. But over the ten-year time period, local anomalous wind forcing apparently had enough of a random nature (averaging to near zero in the correlograms) that the underlying long wave character of anomalous thermocline adjustment could be demonstrated.

5. Summary and discussion

The character of short-term climatic variability in the surface dynamic height (0/400 db) structure of the western North Pacific from 1964-1974 appears consistent with that expected from linear theoretical models of the transient general circulation (e.g., McCreary, 1976). Short-term climatic anomalies propagated from east to west at baroclinic long wave speeds; i.e., 1.5 ± .5 cm/sec at 7.5N increasing monotonically to 14 ± 4 cm/sec at 32.5N.

In the tropics, south of 20N, dynamic height anomalies seem to have propagated into the western North Pacific from the central North Pacific (see Fig. 4), with little or no adjustment or change due to local processes within the study region itself. North of 20N, this propagation of information from the central North Pacific (see Fig. 4) was not as prevalent, with local effects becoming clearly much more important. This can be seen in Figure 4, where much of the westward propagation of these latitudes seems to have begun with events generated locally within the study region itself. Part of the reason for this may have been the relatively long travel times for short-term climatic anomalies in the subtropics, associated with the relatively slow speed of propagation. In this region, it can be hypothesized that anomalous climatic events did not have time enough to travel the entire width of the western North Pacific before the local forcing altered the sign of the anomaly. This region also lacked the strong relationship between variability in main thermocline depth and in surface dynamic height. Much more of the dynamic height fluctuations there were due to thermohaline fluctuations in the deep mixed layer found in this region and, therefore, were apt to be influenced by eastward advection as by internal, baroclinic long wave dynamics.

Acknowledgments. Gratitude is extended to Dr. Keiichi Hasunuma of the Ocean Research Institute at the University of Tokyo for his participation in both the collation of data and the subsequent map construction leading to this study. Appreciation is extended to both Bob Wylie and Ted Walker, who as computer programmers, conducted the analyses contained in this study.

This research was sponsored by the Office of Naval Research under Contract #N00014-80-C-0440 and the University of California, San Diego, Scripps Institution of Oceanography through the Ocean Research Division.

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Received: ***23 March, 1982;*** **revised:** ***2 August, 1982.***