Fluctuations of Sea Level in the Western North Pacific and Inferred Flow of the Kuroshio[1]

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ABSTRACT

Monthly sea-level elevations at Naze and Aburatsu, sites on either side of the Tokara Strait through which the Kuroshio flows, were analyzed for the period 1963–74. The sea-level elevations were adjusted to uniform atmospheric pressure using a barometric factor of 1 cm mb^{-1}. The adjusted elevations are presented as 1) long-term mean seasonal values and 2) deviations from the long-term means. Differences in the elevations between the two sites were then used as indices of the transport of the Kuroshio.

The seasonal amplitude of the elevation differences across the Kuroshio, Naze minus Aburatsu, is ~13% of the mean surface geopotential anomaly difference of 0.6 dyn m (0/1000 db). The phase of this difference signal indicates maximum northward flow in summer. Zonally integrated wind-stress curl at this latitude in the Pacific interior, however, is most anticyclonic during winter. Instead, the seasonal fluctuations of the Kuroshio are more nearly in phase with the fluctuations in the latitudinal gradients of Ekman pumping in the western North Pacific. The seasonal winds between 7 and 15°N drive a westward interior flow to the western boundary, and winds north of 15°N drive flow away from the western boundary. We speculate that this mechanism effects the seasonal fluctuations of the Kuroshio. The seasonal cycle of Ekman pumping, particularly between 11 and 19°N, is not constant across the Pacific, which helps to reconcile seasonal differences in the fluctuations of the Kuroshio and the North Equatorial Current.

Significant interannual variations are observed in the Kuroshio and at sea-level stations within the North Equatorial Current, e.g., at Guam and Legaspi (Philippines). However, there are fluctuations clearly associated with El Niño at Legaspi, Guam and San Diego which do not appear in the Kuroshio during the 12-year period we examined.

1. Introduction

This study examines the variability in monthly tide-gage data within the North Pacific subtropical gyre. Its objective is to obtain information on the fluctuations of the geostrophic flow within the gyre. The sea-level differences between two islands within the same horizontally coherent flow are proportional to the fluctuations of the geostrophic surface current. In particular, we have focused attention upon the elevation differences across the Kuroshio.

In the classical, linear, wind-driven circulation theories of the North Pacific (for example, Munk, 1950) the Kuroshio is the subtropical western boundary current into which at least a portion of the North Equatorial Current flows. The more recent data indicate some differences in detail to the above model. In particular, there is a ridge in the maps of surface geopotential topography (Wyrtki, 1975; Reid and Arthur, 1975) which is most pronounced west of 160°E, and it roughly has an L or a C shape. This ridge indicates that there is a southwestward return flow from the Kuroshio and that, subsequently, the flow turns eastward as a subtropical countercurrent north of the North Equatorial Current. Eventually, all of the eastward flow turns southward to complete the recirculation back to the North Equatorial Current. [Hasunuma and Yoshida (1978) presented data indicating a circulation system in the western North Pacific of even more complexity.] White and Hasunuma (1980) found that the interannual fluctuations of the Kuroshio, the subtropical countercurrent, and the North Equatorial Current west of 170°E are in phase and have magnitudes ±10–20% of their respective means. According to their work, these fluctuations in flow have time scales of 2–5 years and are associated with the coherent fluctuations of the above ridge system.

The analysis of White and Hasunuma (1980) did not resolve phase less than a year. In an earlier comparison of sea-level and geopotential-anomaly differences across the North Equatorial Current, Wyrtki (1974) found a minimum in that flow in spring and a maximum in fall. This phase, upstream of the Kuroshio, may be compared with the long-term averages of monthly and quarterly variations in the Kuroshio presented by Taft (1972). Taft showed the seasonal

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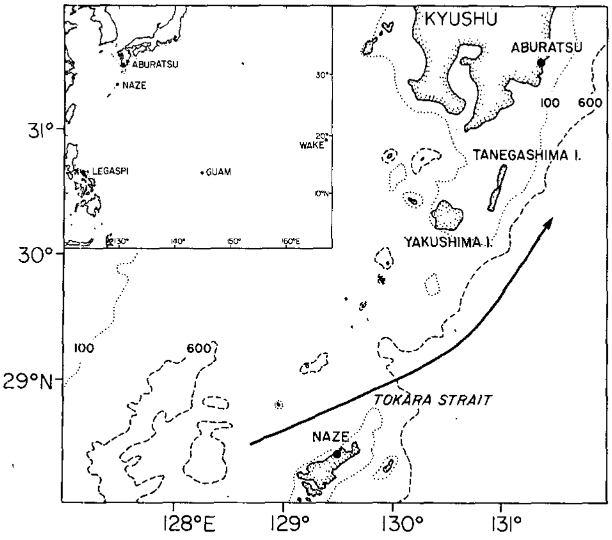

FIG. 1. Locations of the tide gages at Naze and Aburatsu and a schematic of the path of the Kuroshio. The bathymetry in fathoms (1 fm = 1.83 m) is from Scripps Institution of Oceanography (1969). Other tide-gage sites in the western Pacific, from which data were used, are also shown.

variations in three sets of measured or computed flow south of Japan and east of the Ryukyu Islands: 1) geostrophic transports computed from hydrographic data, 2) GEK surface velocities, and 3) velocities inferred from ship drift. The baroclinic transports and GEK velocities were averaged quarterly; both sets show a seasonal maximum during August and September. The more numerous ship-drift data resolve the monthly variability, and they indicate a maximum surface velocity in July or August and a minimum in March or April. One has the impression, however, that the uncertainty in arriving at a seasonal phase based upon the hydrographic and GEK data, at least, can be large. For example, as Taft noted, Uda (1964) determined a GEK velocity maximum during May–August and a second, smaller maximum during January–February, which is at some variance with Taft's own curve. Taft (1972) also noted that the hydrographic data taken off Taiwan and presented by Wyrtki (1961) indicated a maximum in surface flow in May and a minimum in November to January but that the data might be too few to provide reliable averages.

The analyses of the seasonal variations of the Kuroshio transport are not entirely conclusive nor has the phase relationship between the fluctuations of the North Equatorial Current and the Kuroshio been firmly established. Part of the problem has simply been a lack of data. Aliasing in the above data may be a major problem south of Honshu where large lateral excursions occur and the system is rife with eddies. The present study determines the seasonal variations of the Kuroshio by using continuous sea-level data and by examining the flow in a region where the lateral meandering is small.

Niiler and Richardson (1973) showed that direct measurements of the Florida Current transport were maximum in summer, about June, and were minimum in winter. This seasonal fluctuation was found to be largely barotropic. Similar to the confinement of the Florida Current between Florida and the Bahamas, the major flow of the Kuroshio occupies the channel west of the Ryukyu Islands until it reaches Kyushu Island (see, e.g., Nitani, 1972). As shown in Fig. 1, the two tide gages at Naze and Aburatsu should allow the computation of sea-level differences across the Kuroshio. As far as we can determine, Naze is situated on the offshore ridge such that the great majority of northward flow occurs just west of the Ryukyu Island chain. The elevation differences between these gages have advantages over other existing data on the Kuroshio: they are a relatively longer time series, they contain the seasonal barotropic fluctuations, and they have adequate temporal resolution to permit filtering the short-term variability (typically with scales of 2–14 days) in the geostrophic flow.

This study deals essentially with the elevation differences between Naze and Aburatsu, from which the fluctuations in the Kuroshio flow are inferred, and briefly with data from other sites across the North Pacific. We will show that the seasonal fluctuations in the Kuroshio lead the phase of the North Equatorial Current as determined by Wyrtki (1974). We will further show that the seasonal fluctuations in wind forcing at latitudes between 7 and 15°N are in phase with the flow inferred from the sea-level differences and provide a source of westward flow to the Kuroshio.

2. Data

Monthly-mean coastal tide-gage data were taken from the compilation of the Institute of Oceanographic Sciences (1978) from January 1963 to December 1974 at Naze (28°23′N, 129°30′E), Aburatsu (31°35′N, 131°25′E), Legaspi (13°9′N, 123°45′E) [Philippines], Guam (13°26′N, 144°39′E), Wake (19°17′N, 166°37′E), Honolulu (21°19′N, 157°52′W) and San Diego (32°44′N, 117°10′W). About 2½ years of records during this period are absent at Wake. The elevations were adjusted to uniform sea-level pressure using a barometric factor of 1 cm mb^{-1}. The monthly atmospheric-pressure data were usually based upon airport measurements taken near the tide-gage sites and published by the U.S. Department of Commerce (1963–74), but occasionally the pressures were interpolated from monthly maps of sea-level atmospheric pressure.

Individual, linear trends at each site were removed by a least-squares method. The average January,

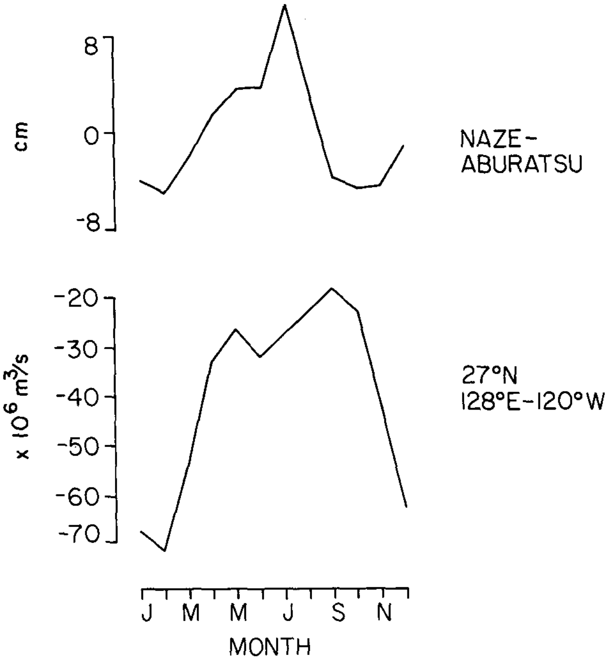

FIG. 2. Seasonal sea-level differences, Naze minus Aburatsu (positive differences indicate stronger than normal Kuroshio flow), 1963–74, and computed Sverdrup interior transports from zonally integrated surface wind-stress curl at 27°N, 1961–70. For reference, but not shown, the mean transports are in 10^6 m^3 s^{-1}: 24 (11°N), 2 (15°N), −17 (19°N), −30 (23°N), −40 (27°N); southward transport is negative.

average February, etc., were then computed at each station to form the mean monthly, or seasonal, signal. The seasonal values were then subtracted from the individual monthly elevations during the 12-year series. These computed deviations will be called the elevation anomalies. The elevation differences between Naze and Aburatsu were computed for both the anomalies and the seasonal values.

The effects from local winds or river runoff are probably insignificant at the island stations. However, the coastal gages at Aburatsu and at San Diego are potentially liable to the effects of wind-driven Ekman divergence at the coast. Shoji (1972) noted that the adjusted daily sea-level data along the south coast of Japan indicated southwestward propagating events. In his Fig. 8, Shoji showed a common time period of sea-level records during which the daily elevations at Aburatsu and Nishinoomote, an inshore gage on Tanegashima Island (see Fig. 1), were visually well correlated. In regard to the effects of alongshore winds, Nishinoomote is a more appropriate location than Aburatsu for our analysis; unfortunately, over the chosen 12-year period, the record at Nishinoomote has numerous gaps which make it unsuitable in this study. The amplitudes of the fluctuations at Nishinoomote over time scales of a few days were relatively smaller than at Aburatsu, but the presence of the same features at Nishinoomote suggests that they are not strongly shelf-trapped and, perhaps, not directly wind-driven either. Extrapolating the results of this comparison to periods greater than a few months, we assume that the elevations at Aburatsu are as representative of the fluctuations in the Kuroshio as a complete record at Nishinoomote would be.

Another, and large, contribution to the elevations is the steric effect of seasonal heating. The Appendix describes our attempts to estimate this effect. Our ability to calculate the spatial gradients of the steric heights is more uncertain than we would like. For example, winter cooling is more intense at Aburatsu than at Naze, but we are unable to resolve the resulting steric differences to better than 2 or 3 dyn cm. Nevertheless, the steric differences which could result from inhomogeneities in surface heating between Naze and Aburatsu are estimated to be no greater than 3 dyn cm. In fact, the measured range in the sea-level differences is ~15 cm (Fig. 2), and the sea-level differences do not have a phase that can be fully explained by seasonal surface heating. Therefore, the latitudinal gradients of local surface heating cannot explain the seasonal variations in the flow through the Tokara Strait.

3. Seasonal sea-level differences

A channel between Naze and Kyushu, the Tokara Strait, confines the lateral movement of the Kuroshio (see Fig. 1). The sea-level differences, Naze minus Aburatsu, are estimates of the average monthly cross-stream pressure gradients. Therefore, the elevation differences are proportional to the average geostrophic surface currents. We shall assume that the surface currents correlate with the geostrophic flow at depth and, therefore, with transport as well. For example, from the data presented by Niiler and Richardson (1973) the elevation differences across the Florida Current that were computed from measured surface speeds were highly correlated (correlation coefficient = 0.8) with the measured transports.

The seasonal elevation differences in Fig. 2 indicate maximum northward flow in summer, which is similar to the findings of Niiler and Richardson (1973) for the Florida Current. The amplitude of nearly 8 cm may be compared with a typical relief across the Kuroshio in the vicinity of these stations of ~0.6 dyn m (0/1000 db), which corresponds to 40×10^6 m^3 s^{-1} [Maritime Safety Agency (1966) and other volumes in this series]. Thus the surface flow variation is 13%, and the inferred transport variation is $\pm 5 \times 10^6$ m^3 s^{-1}. The seasonal variation in the surface flow from ship-drift data, shown in Taft (1972), is 10%, and the ship-drift data agree in phase with the sea-level elevations. For comparison, the respective values for the Florida Current are 14% and ±4.1 × 10^6 m^3 s^{-1} (Niiler and Richardson, 1973).

White (1978) presented the distribution of rms variability of monthly temperatures at 200 m from 25 to 45°N. The intensity of this variability is markedly greater west of 170°E than to the east, and apparently much of the variability can be fit with the 12 month per cycle harmonic. That fit suggested greater eastward flow in the North Pacific Current (the extension of the Kuroshio) during spring and summer than in fall and winter. Because of the "coarseness" of the annual fit, it is unclear that White's results are significantly out of phase with our inferred signal for the Kuroshio.

However, Wyrtki (1974) found that the maximum and minimum westward flow of the North Equatorial Current in the central North Pacific occurred in fall and spring, respectively. The seasonal amplitudes of the North Equatorial Current are ~25% of the mean flow as opposed to 13% for the Kuroshio; however, the amplitude is 6–8 cm across both currents. The separation in phase between the two currents is ~3–5 months and is addressed in Section 5.

4. Interannual sea-level differences

Fig. 3 presents the anomalies in sea-level difference between Naze and Aburatsu. Within the interannual variability, higher-than-normal sea-level differences (relatively large transport) are apparent during 1963, 1965–67, and from 1969 to the end of the record. Sustained lower-than-normal sea-level differences occur during 1964–65 and 1967–69. The interannual variations in the subtropical gyre were first investigated by White (1975); he found periods of larger-than-normal transport during 1955–58 and 1963–68 and smaller-than-normal transport during 1959–62. White found that these fluctuations were reproduced in Nitani's (1972) results from hydrographic sections taken southeast of Yakushima Island if discrepancies in phase of 1–2 years could be explained by the uncertainties in the data. Nitani (1975) extended the transports through 1972 by including additional sections from south of Japan. Our record length does not fully overlap the time periods examined by White (1975) and Nitani (1975). This discrepancy will introduce some uncertainty in the mean value and the placement of the zero line in Fig. 3 for determining a higher- or lower-than-normal transport. Nevertheless, our inferred transports agree satisfactorily with those presented by White and Nitani.

The general agreement between White's (1975) and Nitani's (1972) results indicates that the great majority of the interannual variability is determined by the subtropical ridge at these latitudes. It is the fluctuation of this offshore feature which produces the time-varying gradients of the geopotential topography. We find a similar result in the elevation anomalies shown in Fig. 4 and in Table 1. The interannual fluctuations at Naze (offshore) are larger than they are at Aburatsu (inshore). In addition, according to White and Hasunuma (1980) the variations in the subtropical ridge and the North Equatorial ridge in the western Pacific are in phase, bringing the North Equatorial Current in phase with the

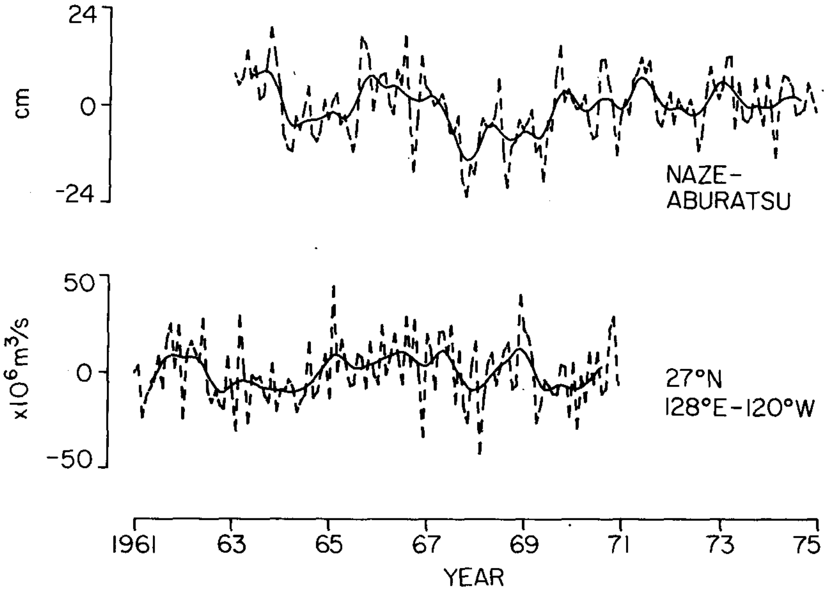

FIG. 3. Anomalies of sea-level differences, Naze minus Aburatsu, and computed Sverdrup interior transports at 27°N. The solid curve is the result of applying a Lanczos filter with a 6-month half-power response. The mean transports have been removed.

Kuroshio. In Fig. 4, a clear effect of the 1972 El Niño appeared in the elevations at Legaspi, Guam and San Diego but does not appear distinguishable from the background fluctuations at Naze[2]. Legaspi and Guam are within the North Equatorial Current, and the event had a magnitude that was at least as large as the mean cross-stream difference, which is ~30 dyn cm (Wyrtki, 1974). In contrast to the results of White and Hasunuma (1980), the sea-level data indicate that a major fluctuation can occur in the North Equatorial Current and not be reproduced in the Kuroshio.

5. Comparisons with wind-stress curl

Stommel (1948) explained the steady, western-boundary current as a necessary result of the basin-wide vorticity balance of wind-driven ocean circulation. Over the ocean interior and according to the Sverdrup (1947) relationship, the curl of the surface wind stress is proportional to the net meridional interior transport. The meridional transports along the western boundary and zonally integrated across the interior must balance along a parallel of latitude. At 28°N, Meyers (1980) computed 40×10^6 m^3 s^{-1} as the mean Sverdrup transport, which is in agreement with the mean baroclinic transport of the Kuroshio (40×10^6 m^3 s^{-1} relative to 1300 db) estimated by Nitani (1972) near this latitude. Theoretically, this comparison is appropriate on time scales long compared to the dynamic adjustment time. The interior barotropic response would require less than a month to adjust to the seasonal fluctuations in the wind-stress curl (see Anderson and Gill, 1975); on the other hand, the baroclinic response far removed from the equator is too slow to adjust to the seasonal forcing.

We have made computations of curl from the wind-stress field presented by Goldenberg and O'Brien (1981). This wind-stress field has been derived from ship observations of wind. The wind-stress values are given every 2°, and our finite differences of stress were made over 4°. A constant drag coefficient of 1.5×10^{-3} was used. We computed monthly curl, 1961–70, at 7, 11, 15, 19, 23 and 27°N.

In Fig. 2, at 27°N, the maximum southward Sverdrup transport occurs in winter. This cycle is ~6 months out of phase with the transport of the Kuroshio. Although the mean transports are in excellent agreement (Meyers, 1980), seasonal variations of the Kuroshio and of the wind-stress curl, zonally integrated across the gyre, are not in phase at approximately the same latitude. In an analogous comparison, but between curl over the Sargasso Sea and

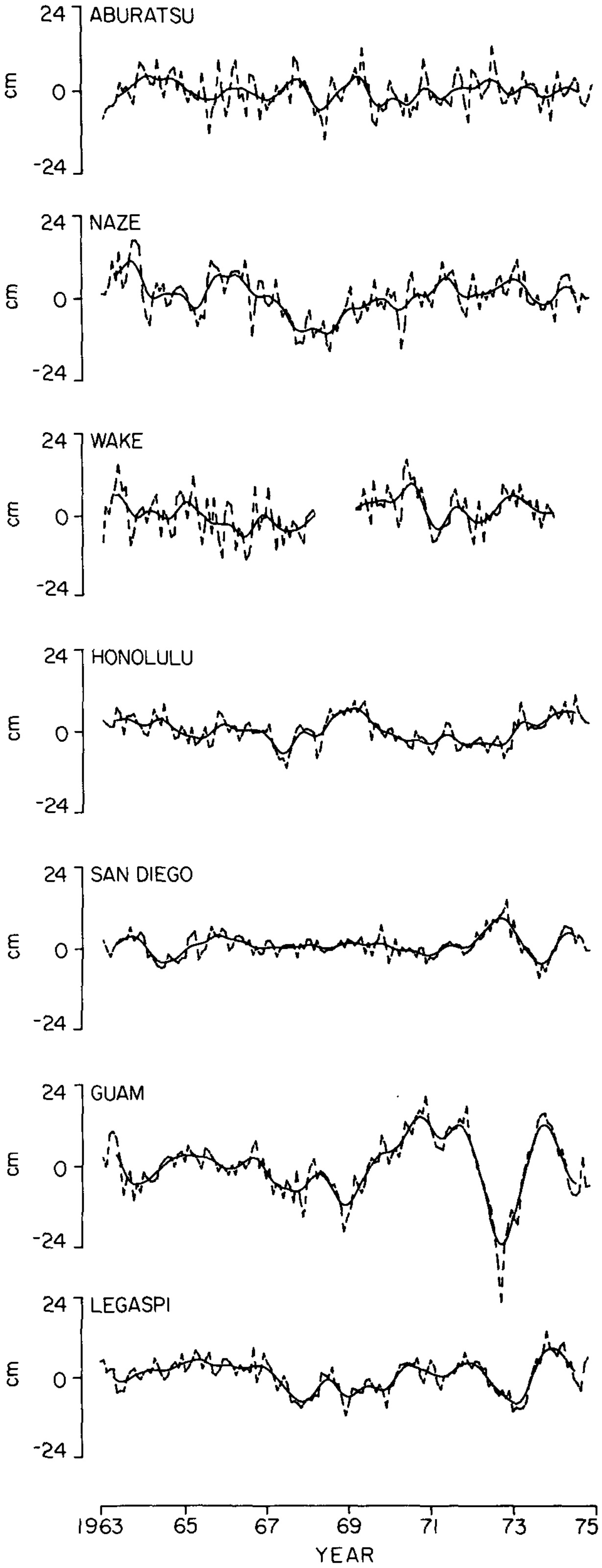

FIG. 4. Anomalies of sea-level elevation adjusted to uniform atmospheric pressure (dashed line). The solid curve is the result of applying a Lanczos filter with a 6-month half-power response.

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[2] Wyrtki (1977) had already shown that the effect of the 1972 El Niño did not appear in the sea level records at Honolulu or Wake.

TABLE 1. The anomaly variance (cm^2) 1963–74. The total variance applies to the dashed-line elevations in Fig. 4. The interannual variance applies to the smoothed elevations in Fig. 4, the result of applying a Lanczos filter with a 6-month half-power response. The eddy variance applies to the difference between the total and smoothed signals. The Wake Island record length is effectively 9½ years. Note that eddy variance generally increases to the west, a result consistent with other analyses (see, e.g., Dantzler, 1976), but that the interannual variance at Naze is also large.

	Guam	Naze	Wake	Aburatsu	Legaspi	Honolulu	San Diego
Total variance	86.5	41.5	38.2	24.3	23.1	17.9	12.7
Interannual variance	63.4	21.7	12.1	5.7	15.0	10.2	6.9
Eddy variance	10.1	14.3	19.8	15.5	4.4	5.0	3.5
Eddy/ interannual	0.16	0.66	1.64	2.71	0.30	0.49	0.51

measured transports of the Florida Current, Niiler and Richardson (1973) found a similar result: the fluctuations in seasonal transport of the western-boundary current could not be explained as a quasi-steady response to the computed Sverdrup flow at the same or nearby latitudes.

Using wind-stress curl, which was computed from data of atmospheric pressure on an alternating 10° grid, White (1975) found no significant correlation between the interannual fluctuations in baroclinic transport and zonally integrated curl. In Fig. 3, we show the anomalies of elevation difference across the Kuroshio and the anomalies of Sverdrup transport at 27°N computed from the above, more recent wind series. Although there appear to be four or five significant interannual events in curl, they seem to lead the Kuroshio by 1–2 years. Unfortunately, the short length of the data series does not allow an adequate determination of the interannual cross-correlations, and the overall results are inconclusive.

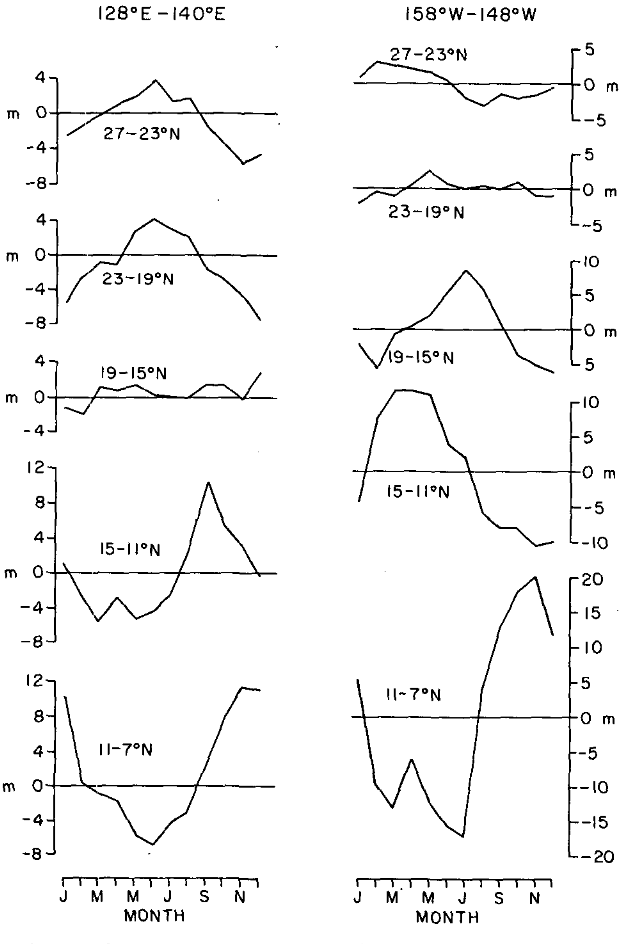

FIG. 5. Seasonal variations of the (north minus south) differences in meters of isopycnal displacement computed from curl$_z(\tau/\rho f)$. Westward flow is inferred from a negative slope. The mean displacements have been removed prior to the time integration.

An alternate hypothesis to the time-varying Sverdrup interior flow may be found in a local effect of winds upon the baroclinic flow field. In this case, divergences in the winds would locally displace the isotherms lying below the mixed layer. Specifically, non-zero divergence of the horizontal Ekman transport (**M**) throughout the surface layer leads to a vertical velocity (W_{Ek}, Ekman "pumping") at the bottom of the surface layer:

$$W_{\mathrm{Ek}} = \nabla\cdot\mathbf{M} = \nabla\cdot\left(\frac{\tau}{\rho f}\times\hat{\mathbf{k}}\right) = \hat{\mathbf{k}}\cdot\nabla\times\frac{\tau}{\rho f},$$

in which τ is the wind stress, f the Coriolis parameter, and ρ the density. Time integration of the velocity W_{Ek} yields the isotherm displacement; the latitudinal gradient in this displacement is proportional to the longitudinal baroclinic flow. For example, Meyers (1975) found that the seasonal variations in the North Equatorial Current could be explained by the latitudinal distribution of Ekman pumping. One can imagine a westward flow that is generated by Ekman pumping impinging upon the western boundary and producing fluctuations in the western-boundary current. How do the seasonal phases of a flow computed from the Ekman pumping in the western Pacific and the inferred flow of the Kuroshio compare?

Goldenberg and O'Brien (1981) presented spectra of zonal and meridional surface wind stress in the Pacific between 29°S and 29°N which show that power at the annual harmonic is concentrated west of ~155°E. The seasonal differences of time-integrated curl$_z(\tau/\rho f)$ per 4° of latitude are shown in Fig. 5 for the segment 128–140°E. The seasonal variations in the isotherm slope between 7 and 15°N imply a maximum westward tendency in the flow in summer, perhaps leading the Kuroshio by a month. The slopes computed north of 15°N, however, indicate a maximum eastward flow in summer, which would be roughly in phase with the outflow from the Kuroshio. North of 15°N the amplitude of the slope is substantially less than at the lower latitudes. In conclusion, there is agreement in phase between the seasonal variations of the Kuroshio and the north-south slopes of the isotherms between 7 and 15°N. This agreement suggests that the region 7–15°N is the source for the seasonal transport fluctuations of the Kuroshio.

Fig. 5 also shows the latitudinal slopes of the isotherms within the segment 158–148°W. The seasonal phase of the curve 11°N minus 7°N is largely constant across the Pacific, but there are significant longitudinal variations in the curves 15°N minus 11°N and 19°N minus 15°N, in which the tendency for maximum westward flow changes from summer in the western Pacific to fall and winter in the central Pacific. (That transition appears at or a few degrees east of the 180° meridian in the wind data.) The longitudinal shift in phase in the effect of local Ekman pumping is consistent with the 3–5 month lag between our signal for the Kuroshio and that for the North Equatorial Current in the central ocean (Wyrtki, 1974; Meyers, 1975). That is, the seasonal cycle of transport of the North Equatorial Current is not constant along its path, but maximum flow of this system in the far western ocean appears to be in summer in agreement with the cycle in the Kuroshio.

Busalacchi and O'Brien (1980) have used this same wind-stress series to compute numerically the seasonal variations in the North Equatorial Current with a linear model. Their results, averaged from 170°E to 140°W, include both the above local effects of Ekman pumping and the non-local effects of propagating Rossby waves. They computed the maximum flow of the North Equatorial Current to be during June and July. Their computations are more nearly in phase with the elevation differences across the Kuroshio than the cycle of fall maximum and spring minimum that was observed by Wyrtki (1974). This disagreement may be a result of the longitudinal changes which are occurring in $\mathrm{curl}_z(\tau/f)$ between 170°E and 140°W.

In Fig. 6, we show the computations of latitudinal slope based upon the anomalies of $\mathrm{curl}_z(\tau/f)$. In this figure one can see, perhaps, a correspondence between the smaller westward flow between 11 and 7°N and smaller transport of the Kuroshio during 1967–70 in Fig. 3, but these results are inconclusive. The interannual variability is pronounced in Fig. 6, but one can imagine a number of serious difficulties with these values. In addition to errors in the data, mixing over interannual time scales is likely to produce major effects on the vertical transfer of water properties. Fig. 6 shows only the contribution of vertical advection to the isotherm distribution; the effect of mixing is unknown. Both anomaly series also suffer from their short lengths in this comparison.

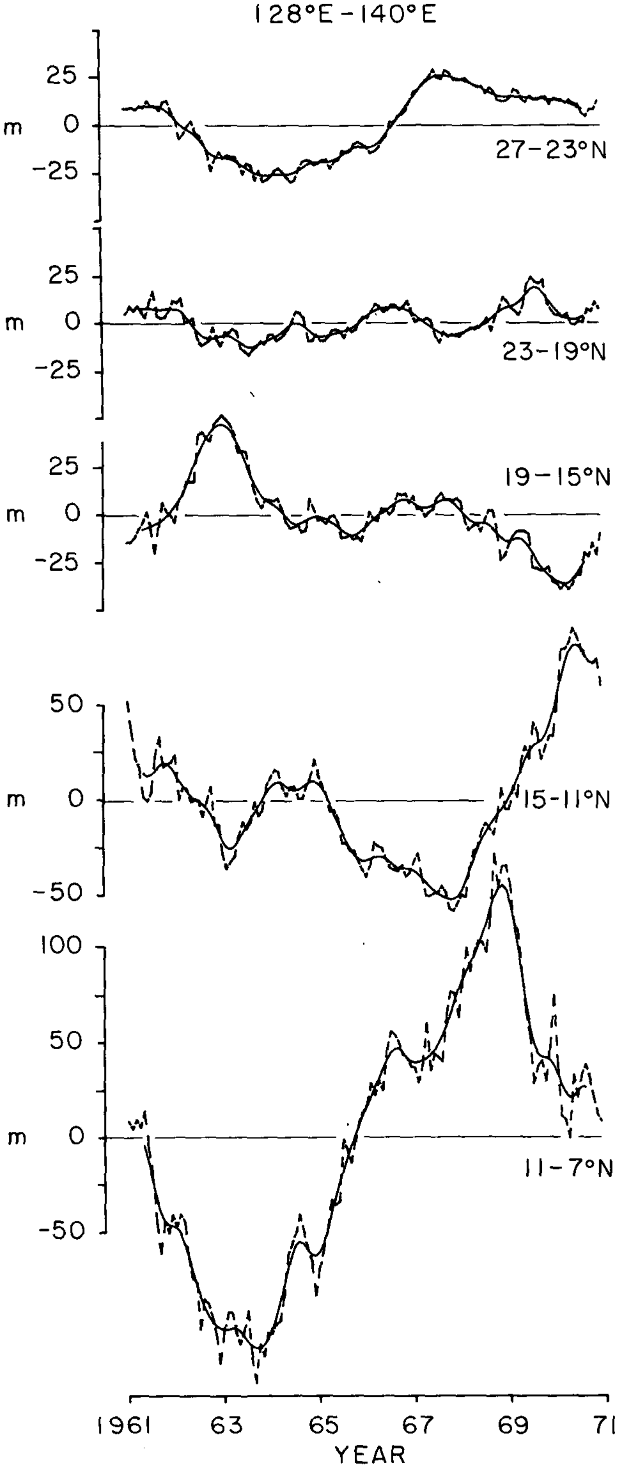

FIG. 6. Same as Fig. 5 except for the anomalies of $\mathrm{curl}_z(\tau/\rho f)$, 1961–70. Again, the mean displacements have been removed prior to the time integration.

6. Discussion

White (1975) found that the interannual variations in transport of the subtropical gyre are primarily caused by changes in the geopotential maximum southeast of Kyushu. Our data seem to be consistent with White's observations; Naze is situated in the vicinity of the ridge and displays appreciably more interannual variance than at Aburatsu or other sites that we examined in the subtropical region. However, our data also indicate that, at least on one occasion, the large interannual fluctuations at Guam, a site within the North Equatorial Current, do not appear as far north as Naze. We believe that more complete data are required to determine the role of the interannual variations of the North Equatorial Current on the subtropical circulation.

The seasonal fluctuations in the sea-level slope across the Kuroshio at about 30°N do not agree with the transports computed by zonally integrating wind-stress curl at any latitude between 15 and 28°N. This disagreement near the same latitude band is a negative result based upon established dynamics. Yoshida and Kidokoro (1967) have presented maps of the mean and seasonal (upper layer) interior flow computed from the observed distribution of winds and the Sverdrup (1947) balance. Our sea-level data do not allow any comment on their computations for the mean interior flow. However, our data do not support a quasi-steady extension of the Sverdrup computations to the seasonal variability.

Rather, we would propose that the maps of the seasonal interior flow in the Pacific be based upon the formulations of vertical velocity that are given by Yoshida and Mao (1957) and Meyers (1975) and from which one could compute the time-varying, local displacement of the isotherms. In the western Pacific, this latter effect agrees with the seasonal fluctuations of the Kuroshio. Specifically, it indicates that wind-driven flow from the interior could feed the Kuroshio within the band 7 to 15°N. We also found that the phase of the wind-induced isopycnal slopes varies with longitude, which resolved a difference between the seasonal transport maximum of the Kuroshio and that of the North Equatorial Current in the central Pacific. On the other hand, we have not presented a specific dynamical model which would describe the response of the Kuroshio to this particular interior forcing. For example, why would the flow through the Tokara Strait respond to the proposed westward flow, which is ~1500 km to the south? Is there an inertial downstream overshoot, similar to that found by Veronis (1966, 1970), which carries the flow northward of the latitude of forcing? Or, is the seasonal flow through the Tokara Strait simply a reflection of the gradients in Ekman pumping in the far western Pacific north of 15°N, which produce a tendency for maximum eastward flow also in summer?

We would like to note that White (1978), who attempted to model the annual temperature variability at 200 m as a response to wind forcing, found qualitative agreement in phase, but not in amplitude, between the observed and modeled isotherm displacements in the western Pacific. White used wind-stress curl from monthly sea-level pressures on a 5° latitude by 5° longitude grid. He proposed that one factor leading to the disagreement in the amplitudes was that the wind-stress curl was being underestimated in these data. Our data only marginally overlap the region examined by White (25–45°N and 150°E–130°W). However, from Fig. 5, the seasonal range of slope from 27 to 19°N for the western Pacific is ~20m $(800 \text{ km})^{-1}$. Unlike White's modeled results, this value is large enough to be consistent with the observed temperature variability near 200 m displayed in his Fig. 7. We believe that the wind data are the limiting factor in White's (1978) computations and recommend that such a modeling effort be repeated using a wind field with sufficiently greater spatial resolution.

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Note added in press: Kawabe (1980, *J. Oceanogr. Soc. Japan,* **36**, 227–235) used some of the same data sets analyzed in our paper to examine transport through Tokara Strait. He did not examine seasonal variability, but focused on transport fluctuations as related to the large meander in the Kuroshio south of Japan. The fluctuations in sea level at Naze were visually well correlated with those at Naha, Okinawa (~300 km south of Naze). His conclusion that the sea level difference across the Kuroshio is largely determined by variations at Naze is identical to our own result.

APPENDIX

Steric Heating

We briefly discuss the effect of local heating and cooling across the surface on the adjusted sea-level elevations in Fig. 7. Steric heights representing the effect of seasonal heating were computed 1) from maps on a 5° grid of surface heat flux by Weare *et al.* (1980), and 2) from compilations of bathythermograph data by Robinson and Bauer (1976). The data bases possess different advantages. The steric heights from heat flux do not contain the contaminating effects of eddies and Rossby waves, which can

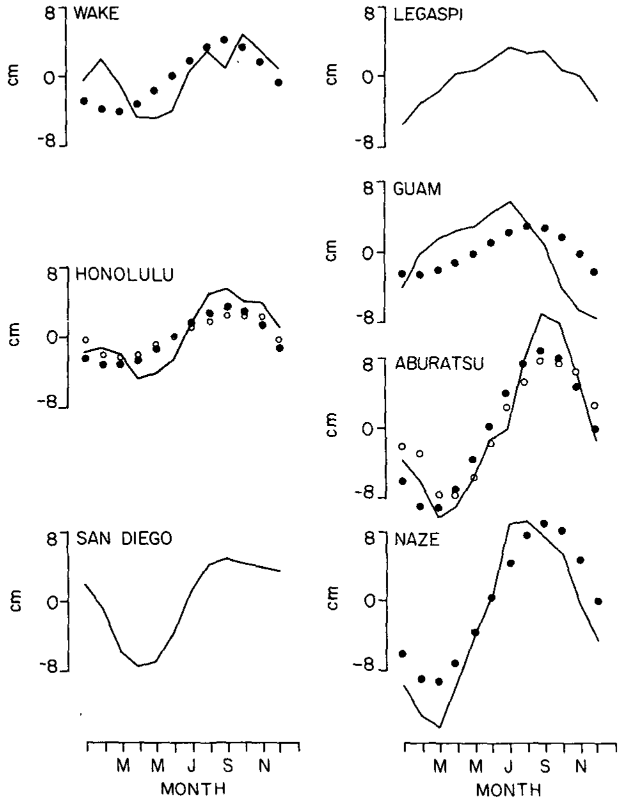

FIG. 7. Average seasonal sea-level elevation, 1963–74, based upon monthly values adjusted to uniform atmospheric pressure. Overplotted are steric heights computed from the surface heat flux (solid circles) taken from Weare *et al.* (1980) and the seasonal temperatures in the surface layer (open circles) taken from Robinson and Bauer (1976). The mean heat flux was removed, and the coefficient of thermal expansion needed to compute the steric heights from the temperatures was chosen as 3×10^{-4} °C^{-1}. A variable coefficient of thermal expansion was used with the subsurface temperatures. The same steric signal is used to represent surface heating and cooling at Naze and Aburatsu. The temperatures near Guam appear "noisy", and we do not show them.

appear in the directly measured temperatures. In our computations using the surface heat flux, the coefficient of thermal expansion was assumed constant (actually it might vary here as much as ±20%), and the net flux over a year, which in the ocean is removed by advection or vertical mixing, was approximated as an annual mean flux which was removed prior to integrating the flux.

The sea-level elevations at Aburatsu appear significantly larger than the steric heights by 3–4 cm. This result also appears in Masuzawa (1972, Fig. 22), in which he compared the sea-level elevations, adjusted for atmospheric pressure, along southern Japan with the dynamic height signal (0/200 db) at Ocean Station *Tango* (29°N, 135°E). The seasonal cycle of temperatures within the coastal surface layer may explain this discrepancy; however, fluctuations in the alongshore geostrophic flow could also have an effect. Naze and Aburatsu are separated by nearly 400 km, which is smaller than the grid spacing provided by Weare *et al.* (1980). Our best estimate of the maximum difference in steric heating between these two sites from the maps of Weare *et al.* (1980) is 3 cm. This number is in agreement with the results of Masuzawa (1972) if one can assume that the steric heights at Ocean Station *Tango* are equally representative of the heating effect at Naze.

Although the differences between sea level and the steric heights at Wake, Honolulu and San Diego are small in magnitude, the relative error can be nearly 50%. The sampling periods of the sea-level elevations and the steric heights are not identical, but this factor is probably not the sole source of disagreement. A typical standard error is 10–20%; the differences during winter and spring between measured sea level and the steric heights appear larger than this uncertainty. The relative contribution from local heating is small in the signals at Guam and Legaspi. The greatest effect of surface heating and cooling is west of Wake.

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