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Relations Between Sea Level, Thermocline Depth, Heat Content, and Dynamic Height in the Tropical Pacific Ocean

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The use of combined information from expendable bathythermograph and sea level observations for ocean monitoring requires the establishment of relations between sea level, thermocline depth, heat content, and dynamic height. Sea level fluctuations are a good measure of thermocline depth fluctuations in the tropical Pacific between about 15°N and 15°S and allow the determination of changes of upper-layer volume. Sea level is also a good measure of heat content, and useful correlations extend to higher latitudes. Dynamic height and sea level fluctuations agree only in those areas where the thermal structure resembles a two-layer system very well, and good correlations are restricted to a narrower area. The combination of bathythermograph and sea level observations will allow a better mapping of the changes of thermocline topography, heat content, and dynamic height for the monitoring of climatic changes in the tropical Pacific.

1. INTRODUCTION

It has been repeatedly claimed that sea level, isotherm depth, heat content, and dynamic height of the upper ocean are related, but statistically significant evidence backed by good observations is difficult to find. The literature containing such claims is much too voluminous to be quoted, and therefore only a few representative examples are given. *Shoji* [1972] related sea level and dynamic height in the Kuroshio and found an excellent linear relation over a wide range of 1 meter. *Saur* [1972] investigated the sea level difference between Honolulu and San Francisco and obtained correlation coefficients of 0.65 and 0.54, respectively, between sea level and dynamic height at the two locations. *Wunsch* [1972] found that low-frequency variations of sea level at Bermuda are reflected in the density structure and in dynamic height. *Chaen and Wyrtki* [1981] related sea level and isotherm depth at Truk and found a correlation of 0.92 for monthly mean values. Comparing daily mean sea level and dynamic height at Fanning Island, *Wyrtki* [1980] found a correlation of 0.70. We are not aware of studies documenting a relation between sea level and heat content in the open ocean, although such a relation was strongly suggested by *Pattullo et al.* [1955]. For shallow seas, *Dietrich* [1954] analyzed the relations between sea level, heat content, and other oceanographic and meteorological influences.

The apparent relation between the slope of isotherms and the slope of the sea surface has been used frequently to estimate geostrophic flow, but a systematic documentation of this relationship is lacking. *Wyrtki and Kendall* [1967] used a two-layer system to approximate geostrophic flow of the North Equatorial Countercurrent in the Pacific and obtained a good correlation of these estimates with geostrophic flow computed from hydrographic stations. *O'Brien et al.* [1980] successfully used a two-layer system to model the dynamic response of the equatorial Pacific Ocean to variations in wind stress without investigating to what degree the two-layer approximation is actually fulfilled.

This study is an attempt to document the relations between sea level, isotherm depth, heat content, and dynamic height at selected locations in the tropical Pacific Ocean and to determine the size of the region over which a relationship between these parameters exists that would be useful for ocean monitoring.

2. THE TWO-LAYER SYSTEM AND ITS LIMITATIONS

The tropical ocean is characterized by a stable density structure consisting of a warm upper layer and a cold deep layer, which are separated by a more or less steep thermocline. Temporal changes or horizontal differences in this basic structure are largely associated with changes in the depth of the thermocline and the steepness of the temperature gradient. The topography of the thermocline is also related to the geostrophic flow and thus provides a first-order description of both the structure and the circulation of the tropical ocean.

In an ideal two-layer system with an upper layer of depth D, density ρ_1, and temperature T_1 and a motionless lower layer of density $\rho_2 = \rho_1 + \Delta\rho$ and temperature T_2, changes in sea level Δh and changes in the upper-layer depth ΔD are related by $\Delta h = \Delta D \cdot \Delta\rho/\rho$ [*Wyrtki and Kendall*, 1967]. Heat content H and dynamic height d are proportional to the upper-layer depth D and are given by the relations

$$H \sim D(T_1 - T_2)$$

and

$$d \sim D(\rho_2 - \rho_1)/\rho_1$$

These relations are still valid in a system with a thermocline between the two layers as long as the vertical gradients of density and temperature remain constant in time. These conditions imply that the thermocline has to move up and down as a slab and that the vertical displacements of all isotherms must be perfectly correlated. It can be shown that a linear relation should exist between heat content and dynamic height, regardless of the shape of the vertical temperature pro-

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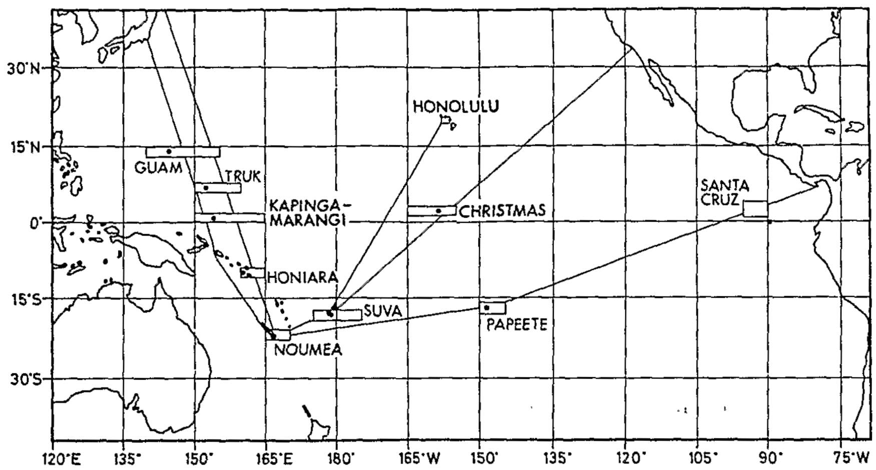

Fig. 1. Shipping routes with XBT observations, sea level stations (solid dots), and areas used to compare sea level and XBT data (rectangles).

file, if the specific volume were a linear function of temperature. However, in reality the relation between specific volume and temperature is not linear over the observed range of temperatures, and the influence of salinity is also important, and consequently, such a relation does not exist for an arbitrary temperature profile.

The relations between sea level, thermocline depth, heat content, and dynamic height in the tropical ocean will consequently depend on how closely the ocean resembles a two-layer system. The steeper the thermocline, the better the relations will be. Variations in the steepness of the thermocline will adversely affect the relations, and so will changes in the temperature and salinity of the surface layer. An ideal two-layer system has only one internal mode of oscillation, namely, the first baroclinic mode, which has a maximum of vertical velocity at the interface. Deviations from an ideal two-layer system will allow other vertical modes to become important, and the relations between the four observed parameters will be less pronounced. In the following we will try to document these relations on the basis of observed data.

3. DATA

Temperature profiles from expendable bathythermograph (XBT) drops taken from ships of opportunity along the shipping routes in the Pacific between 1979 and 1983 [*Meyers and Donguy*, 1980] in the vicinity of each sea level station, usually within 2 degrees of latitude and several degrees of longitude, have been used for the analysis. The sea level stations and the shipping routes are shown in Figure 1. Data from the years 1979 to 1983 were used. The number of XBT drops near each location ranges between 70 and 160, and data from between 30 and 48 months are available, giving an average of only two to three XBT observations per month. For each temperature profile the depth of the 20°C isotherm, the mean temperature of the upper 300 m, and the dynamic height relative to 400 m were determined. All values for each parameter were averaged for each month of the 4-year period, giving at each location between one and seven observations per month. The average vertical profiles of temperature near the 10 sea level stations are shown in Figure 2.

A much more comprehensive data set was used near Honolulu. It consisted of 2930 XBT observations taken within 100 km from Honolulu during the period 1970–1980, resulting in an average of 22 observations per month. Only two months were without observations during this period. The same computations were performed for the data near Honolulu as for the other stations, except that dynamic heights were computed only to a depth of 300 m.

An analysis of the data set shows that the typical deviation of the 20°C isotherm from its monthly mean was between 8 and 15 m, which is a measure of the ambient noise of thermocline depth in the general vicinity of a sea level station during a month. It is larger than the instrumental error, which is quoted as ± 5 m [*Seaver and Kuleshov*, 1982], but small compared to the total range of isotherm depth variation, which is between 60 and 100 m, depending on the location.

For the computation of dynamic height, standard temperature-salinity (*TS*) curves were used as they are given by *Emery and Wert* [1976]. To avoid extrapolation, we have chosen a depth of 300 m for the computation of heat content because some XBT profiles do not penetrate below this depth. Dynamic height was computed relative to 400 m, and consequently, the number of XBT traces used for this analysis is slightly smaller.

Sea level measurements obtained by the Pacific sea level network [*Wyrtki*, 1979] have been used for comparison with

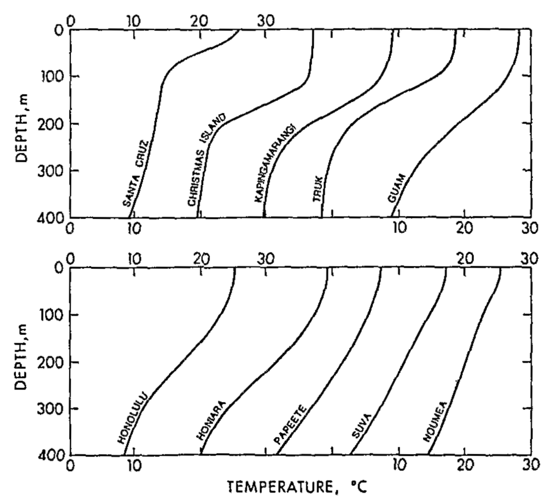

Fig. 2. Average vertical profiles of temperature in centigrade between the surface and 400 m at the 10 locations shown in Figure 1. Each profile is offset by 10°C.

TABLE 1. Linear Regressions Between Monthly Means of Sea Level, Depth of the 20°C Isotherm (m), Heat Content (Mean Temperature of the Upper 300 m in °C), and dynamic height (dyn cm Relative to 400 dbar) Near Islands in the Pacific Ocean

Station	ϕ	n	Sea Level vs. 20°C Isotherm r	a	$\bar{D}$	Sea Level vs. Heat Content r	b	$\bar{H}$	Sea Level vs. Dynamic Height r	c	$\bar{d}$
Santa Cruz	0	34	0.93	160	64	0.92	8	16.6	0.92	0.77	91
Truk	7°N	48	0.90	190	125	0.91	12	18.4	0.92	0.93	112
Christmas	2°N	39	0.80	200	140	0.85	11	19.4	0.87	0.82	115
Guam	14°N	43	0.73	190	186	0.79	10	21.9	0.70	0.73	139
Honiara	9°S	40	0.69	200	186	0.75	9	22.0	0.80	1.03	122
Kapingamarangi	1°N	37	0.56	170	160	0.68	12	20.9	0.78	0.93	126
Noumea	22°S	29	0.32	350	194	0.68	7	21.2	0.31	0.63	121
Suva	18°S	34	0.30	300	220	0.38	10	22.5	0.33	1.14	125
Papeete	18°S	37	0.39	380	232	0.40	13	23.1	0.37	0.99	121
Honolulu	21°N	132	0.41	220	156	0.64	11	19.8	0.69	0.66	103*

Listed are latitude ϕ; number of months with observations n; correlation coefficients r; the slopes of the regression a, b, and c; and the mean values $\bar{D}$, $\bar{H}$, and $\bar{d}$.
*Relative 300 dbar.

the XBT data. Although daily values of sea level were available for all stations, we have based our analysis on comparison of monthly means. The accuracy of a monthly mean value of sea level from a well-maintained station is usually better than ± 2 cm. The values of sea level have not been corrected for fluctuations of atmospheric pressure because in the area and spectral range of interest the two parameters are poorly correlated [*Luther*, 1982]. Only at the fringes of the area of interest, at Noumea and Hawaii, would a correction of sea level for atmospheric pressure be meaningful but small.

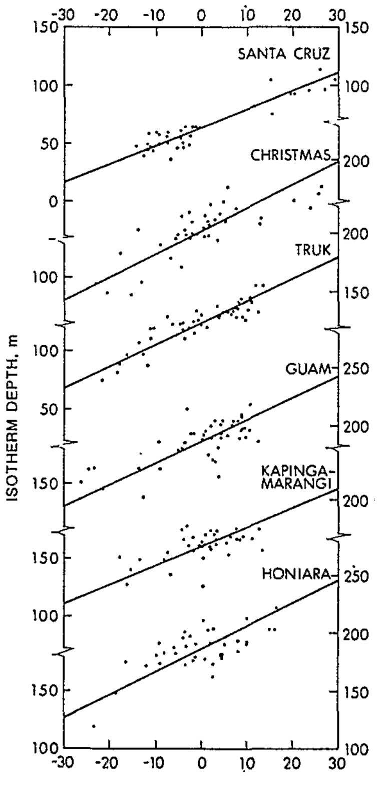

Fig. 3. Relations between monthly means of the depth (m) of the 20°C isotherm and sea level (cm) near six islands in the tropical Pacific.

Because of the different nature of the two data sets, comparison is not a simple task. Sea level is recorded continuously at a fixed station and shows, even after removal of the tides, a spectrum of high-frequency variability in the range of days [*Luther*, 1982]. Temperature profiles, on the other hand, are spot measurements at a given instant within several hundred kilometers of the sea level station. Consequently, the variability of sea level in the time domain and the variability of the thermal structure in the space domain must be considered when making comparisons. A comparison of daily mean sea level with individual XBT profiles would not be advisable because of the high ambient noise in the depths of isotherms and because much of the variability of sea level in the range of a few days is barotropic and should not be reflected in fluctuations of the thermal structure. If daily temperature profiles were available, one would probably compare 10-day averages or low-pass-filtered records, but since only a few temperature profiles are available in each month, a comparison of monthly means is the most appropriate procedure, and all subsequent discussion refers to monthly mean values.

4. SEA LEVEL AND THERMOCLINE DEPTH

The depth of the thermocline as represented by the depth of a selected isotherm or density surface is a measure of the amount of upper-layer water present at a location. If variations of the thermocline are related to variations in sea level, fluctuations in upper-layer volume can be monitored continuously by sea level observations. This would allow a monitoring of the volume of the tropical warm water pools, which are of interest in climate studies [*Niiler and Stevenson*, 1982]. A horizontal integration of upper-layer volume allows the determination of the water budget of the upper layer and an analysis of water displacements [*Wyrtki*, 1985].

The correlations between sea level and the depths of the 20°C isotherm are summarized in Table 1. Highest correlations are found at Santa Cruz and Christmas Island near the equator and at Truk near the countercurrent trough. In the western Pacific, good correlations extend as far as Guam to the north and Honiara to the south. The relation breaks down at latitudes between 15° and 20°, as demonstrated by the poor correlation at Papeete, Suva, Noumea, and Honolulu. At these locations the 20°C isotherm is also much deeper than in the equatorial belt, and the thermocline is weaker and no longer

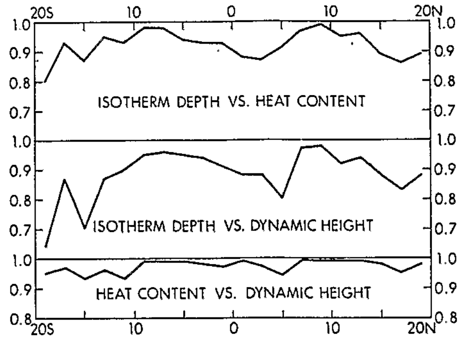

Fig. 4. Correlation coefficients between monthly means of isotherm depth and heat content, isotherm depth and dynamic height, and heat content and dynamic height determined from XBT observations along the route from Noumea to Japan as a function of latitude.

resembles a two-layer system (Figure 2). A shallower isotherm cannot be used for a similar analysis because surface temperatures in winter are not much greater than 20°C, and deeper isotherms are often below the reach of the XBT. There is a direct relationship between the correlation coefficient and the mean depth of the 20°C isotherm. The shallower the thermocline, the better is the relation between its fluctuations and those of sea level. Because a shallower thermocline usually implies a steeper thermocline, and a better approximation of an ideal two-layer system, the best correlations between thermocline depth and sea level are found where the two-layer system is most pronounced, as can be seen from a comparison between Figure 2 and Table 1.

The theoretical relationship between changes of sea level Δh and changes of isotherm depth ΔD in a two-layer system with the lower layer at rest is $\Delta D = \Delta h \cdot \rho/\rho\Delta$. The regression lines according to the relation $D = \bar{D} + a(h - \bar{h})$, shown in Figure 3, and their slopes $a = \Delta D/\Delta h$, listed in Table 1, give values of $a = \rho/\Delta\rho$ between 160 and 380. Values around 200 are typical for the equatorial belt and all the locations with a high correlation coefficient, whereas the larger values of a are found at locations away from the equator, where the correlation is less pronounced. A value of a 200 means that thermocline depth changes of 20 m correspond to sea level changes of 10 cm.

In summary, sea level is a good indicator of vertical movements of the thermocline in the tropical Pacific between about 15°N and 15°S and can be used with a high degree of confidence to monitor the fluctuations of upper-layer volume.

It is difficult to assess the significance of the correlation coefficients accurately because the data do not exhibit a Gaussian but a bimodal distribution (Figure 3). The data also contain a pronounced low-frequency signal, which implies that the monthly means are not statistically independent and therefore questions arise as to the number of degrees of freedom of the data set. Most stations have about 40 months of observations, and if the data were statistically independent and Gaussian distributed, a correlation coefficient of 0.3 would be significant at the 95% level and a coefficient of 0.4 at the 99% level.

On the other hand one can argue that both data sets are subject to considerable ambient noise and that the true values of the parameters are known only with a random error. It is well known that in such a case the correlation of the true values is larger than that of the observed values. In any case, correlation coefficients in excess of 0.7 indicate that variations of one parameter explain 50% of the variance of the other parameter, and if the correlation coefficient is 0.9, 80% of the variance is explained.

5. SEA LEVEL AND HEAT CONTENT

A knowledge of the changes of ocean heat content is part of the basic information needed for climate studies. It can be determined from vertical profiles of temperature as given by XBT traces or other temperature profiles by vertical integration of temperature. We have used an integration to a constant depth of 300 m and have given heat content H as the mean temperature of the upper 300 m of the ocean. If heat content is related to sea level and its changes can be monitored by sea level observations, the direct observations of heat content along XBT routes could be supplemented by indirect determinations of heat content at sea level stations. Such a procedure might considerably improve the spacial coverage in maps of heat content, which might be limited otherwise to routes with XBT observations. It is therefore worthwhile to document the relation between sea level and heat content.

Correlations between sea level h and heat content H, as given by the average temperature of the upper 300 m, are slightly better at most stations than the correlations between sea level and isotherm depth D (Table 1). This is not surprising, since the integration of temperature results in a less noisy set of values than the set given by single isotherm depths. Good correlations are found over the entire tropical Pacific from the Galapagos Islands to Guam in the north and Noumea in the south. Near Noumea, sea level is well correlated to heat content but not to isotherm depth; this is not the case for Suva and Papeete, where correlations are weak for both parameters.

The slopes b of the regression lines between sea level h and heat content H, according to the relation $H = \bar{H} + b(h - \bar{h})$, are rather uniform between 7° and 13°C per meter of sea level change. The regression lines and data distributions are not shown because they are very similar to those shown in Figure 3. The computed values of b imply that a change of 1°C in the average temperature between the sea surface and 300 m is approximately equivalent to a change of 10 cm in sea level. Because sea level can be measured confidently to within 2 cm, changes in the average temperature of 0.2° can be monitored. A change of 0.2°C over a depth of 300 m is equivalent to a change in heat storage of 6000 cal cm^{-2} or 25×10^7 J m^{-2}. Such a value is of the same magnitude as the inaccuracies in the computation of heat storage from XBT data [*Wyrtki and Uhrich*, 1982] but more than an order of magnitude smaller than the mean annual cycle of heat storage in the tropical and subtropical oceans [*Levitus*, 1984].

6. SEA LEVEL AND DYNAMIC HEIGHT

Computations of dynamic height allow the determination of the topography of the sea surface relative to a selected reference surface and the calculations of geostrophic currents and transports relative to that surface. Therefore a knowledge of the time variations of dynamic topographies would be a tool in monitoring ocean circulation. Unfortunately, dynamic topographies are difficult and expensive to monitor, and substitute measurements, like temperature profiles and standard temperature-salinity relations, have to be used for their estimation in a monitoring program.

Sea level and dynamic height should correspond, but not on all time scales. Dynamic height is a measure of the baroclinic structure of the ocean, which varies only slowly, and is computed relative to a reference surface, which may vary with

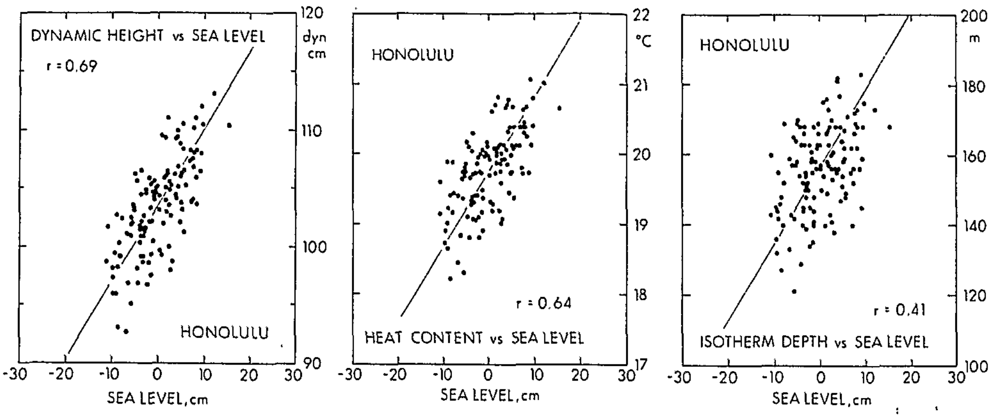

Fig. 5. Relations between monthly means of sea level (cm), the depth of the 20°C isotherm (m), heat content (average temperature in the upper 300 m, in degrees Celsius), and dynamic height relative to 300 m (dyn cm) near Honolulu.

time. Sea level, on the other hand, contains barotropic effects, which are most energetic in the short periods from hours to days. Consequently, the two parameters can only be compared meaningfully at the low frequencies. Such a comparison is attempted here for monthly mean values.

If definite relations between sea level and dynamic height can be established, both parameters can be used jointly in a monitoring scheme that combines time series of sea level at selected spots with spatial information along certain shipping routes obtained at specific times. Such a combination would greatly improve the coverage obtained by a monitoring system.

The correlations between sea level h and dynamic height d listed in Table 1 show values similar to those for thermocline depth or heat content, except at Kapingamarangi and Honiara, where the correlation with dynamic height is better. It should also be noted that the slope c of the regression line according to the relation $d = \bar{d} + c(h - \bar{h})$ is not one at all stations. Whereas values between 0.9 and 1.1 may not be significantly different from 1.0, the values at Guam, Honolulu and Noumea of around 0.7 are definitely smaller than 1. This means that fluctuations in dynamic height are smaller than corresponding fluctuations in sea level, which is probably because the reference surface at 400 m is too shallow for these stations. At the equatorial stations, sea level fluctuations seem to reflect density changes above 400 m, whereas farther from the equator toward the subtropical gyres, sea level can only be compared with changes in the density structure over a deeper layer. This effect was noted by *Wyrtki and Kilonsky* [1984] when they evaluated geostrophic flows observed during the Hawaii to Tahiti Shuttle Experiment.

A comparison of the shapes of the vertical temperature profiles in Figure 2 with the correlation coefficients between sea level and dynamic height in Table 1 demonstrates more than anything else that the goodness of the correlation between sea level and dynamic height depends on the degree to which the thermal structure approaches a two-layer system.

7. Relations Between Thermocline Depth, Heat Content, and Dynamic Height

A single vertical temperature profile allows the determination of three basic oceanographic parameters of interest to ocean monitoring: the depth of the thermocline, as given by the depth of a selected isotherm D; the heat content H of the upper layer as given by the vertical average temperature above a selected depth; and the dynamic height d relative to a chosen reference depth and integrated with the use of a standard temperature-salinity relationship. In addition, other parameters like mixed-layer depth and mixed-layer temperature could be obtained, but they are not of interest in this study.

Any relations between these three parameters should be useful for the interpretation of synoptic maps prepared for ocean monitoring, like those by *White et al.* [1985]. For this reason we have correlated thermocline depth D, heat content H, and dynamic height d along the XBT section from New Caledonia to Japan (Figure 1). Only XBT traces that reached at least 400 m were used, and heat content and dynamic height were calculated to 400 m for each of the 3599 XBT traces. The data were averaged by month and over intervals of 2° of latitude, and correlation coefficients between the three parameters were computed for each location. They are shown in Figure 4 as a function of latitude between 20°N and 20°S.

The best correlation is found between heat content and dynamic height and is better than 0.93 along the entire section. This good correlation is not surprising, as heat content is a straight integral of temperature with depth, whereas in the computation of dynamic height, temperature is modified by the use of a temperature-salinity relation but remains still an integral of this modified temperature with depth. The two integrals should correlate well as long as the temperature-salinity relation remains stable in time.

The thermocline depth as given by the depth of the 20°C isotherm is correlated well with both the heat content and the dynamic height, but the correlations are slightly better for heat content. The best correlations along the section are found between 6° and 14°N and between 2° and 10°S, coinciding with the countercurrent trough in the northern hemisphere and with the South Equatorial Countercurrent. The correlations decrease rapidly poleward because of an increasing thickness of the thermocline and seasonal variations of temperature and salinity in the surface layer. More surprising is the intermediate minimum of the correlation between 3° and 5°N, which coincides with the southern boundary of the countercurrent. This area has a deeper position of the thermocline, a higher average heat content, and probably a larger variability of surface layer salinity. It is also characterized by a minimum of variability of these three parameters during the 1979–1983 period. There is no simple, obvious explanation for the reduced correlations in this location.

8. Relationships Near Honolulu

A much larger and longer data set can be used in the vicinity of Honolulu, Hawaii, as mentioned in section 3 on data. The relations between monthly means of sea level on the one

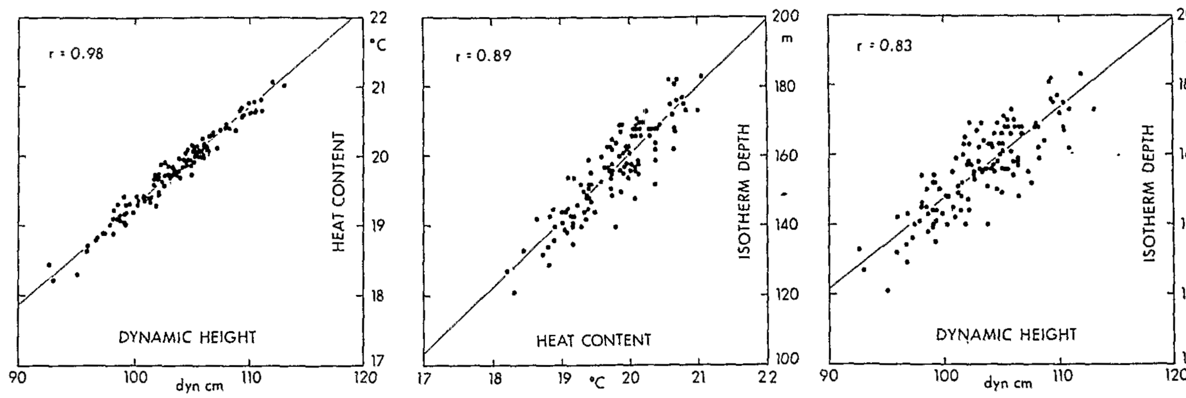

Fig. 6. Relations between monthly means of the depth of the 20°C isotherm (m), heat content (°C), and dynamic height (dyn cm relative to 300 m) derived from XBT profiles near Honolulu.

hand and isotherm depth, heat content, and dynamic height on the other hand are shown in Figure 5. Reasonably good correlations are found between sea level, dynamic height, and heat content, explaining 48% and 41% of the variance, respectively. This is not much compared with correlations at the equatorial stations, but it is better than at Suva, Papeete, and Noumea, where correlations with dynamic height are particularly weak. The reason may be the shallower position of the thermocline near Hawaii. Heat content is equally well monitored by sea level near Honolulu or Noumea but very badly monitored near Suva and Papeete, where average temperatures are highest and the 20°C isotherm is below 200 m. The correlation between isotherm depth and sea level is poor near Honolulu, as is obvious from the large scatter of dots in Figure 5. It is not very useful for monitoring purposes.

The three parameters derived from XBT observations—isotherm depth, heat content, and dynamic height—relate well with each other (Figure 6). The best correlation is between dynamic height and heat content, for the reasons stated in section 7. The correlation between isotherm depth and heat content is also highly useful for ocean monitoring, although an average temperature can only be determined with a standard error of 0.3°C from an observed isotherm depth. The correlation between isotherm depth and dynamic height of 0.83 is sufficiently high to use one set of data as a proxy for the other. It is a known fact that isotherm topographies and dynamic height maps in the Hawaiian waters resemble each other very well [*Patzert*, 1969]. From a given isotherm depth, dynamic height can be inferred with a standard error of only 2.5 dyn cm.

9. Discussion and Conclusions

An analysis of the relations between sea level, isotherm depth, heat content, and dynamic height has been made for the tropical Pacific Ocean to determine the usefulness of these relations for ocean monitoring. It has been found that relations are best where the ocean resembles a two-layer system most closely. The reason for this agreement lies in the fact that an ideal two-layer system has only one vertical baroclinic mode with maximum vertical displacements at the interface. The relations were derived for monthly means and are valid in the low-frequency domain, but certainly not on time scales of a few days. From the analysis of the observations the following statements can be made:

1. Sea level is a good indicator of vertical movements of the thermocline in the tropical Pacific between about 15°N and 15°S. It can be used to monitor fluctuations of upper-layer volume. Away from the tropics, the relation deteriorates rapidly.

2. Sea level is an even better measure of heat content, which is an integral over the thermal structure. It should, however, be noted that fluctuations in heat content are chiefly determined by fluctuations in the depth of the thermocline rather than by changes in the temperature of the mixed layer. Good relations extend to Honolulu and Noumea but not to Suva and Tahiti.

3. Sea level and dynamic height agree well in the tropics, where major horizontal flows are concentrated above 400 m, the reference depth of the computations. In the tropics the relation between changes in sea level and dynamic height is near unity, but outside the tropics it is less than 1 because a deeper reference surface should be used.

4. The combined use of sea level at discrete locations and of XBT observations along selected shipping routes will lead to a better mapping of thermocline topography, heat content, and dynamic height for ocean monitoring.

This analysis is, unfortunately, still based on a rather small data base, but a larger data set is simply not available for the tropical Pacific. Therefore, the results must be considered preliminary, and the analysis will have to be repeated after a larger data set has been accumulated like the one for Honolulu. It would also be advisable to conduct a systematic experiment near an oceanic island to determine the relation between sea level, density structure, atmospheric pressure, and bottom pressure in the entire spectral range from tides to several years so that these relations could be based on a systematic data set. Such experiments have been proposed in the past but have never been funded.

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