POTENTIAL OCEANOGRAPHIC APPLICATIONS OF SATELLITE ALTIMETRY FOR INFERRING SUBSURFACE THERMAL STRUCTURE

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Abstract

A unique data set consisting of expendable bathythermograph (XBT) observations from repeated Gulf Stream crossings was used to provide ground-truth for GEOS-3 altimeter measurements of temporal sea height variability. The XBT data were obtained by NAVOCEANO using ocean liners travelling between New York and Bermuda as observation platforms. Approximately 120 crossings, each consisting of 50-60 XBTs, were made between October 1969 and November 1974. Dynamic heights were calculated using XBT profiles and temperature/salinity relationships from historical data. Results were then compared to sea height variability measured from the differences in altimeter profiles between pairs of collinear GEOS-3 passes. The comparison shows that the satellite measurements are in good agreement with the conventional shipboard observations. Additionally, it is shown that dynamic height variability correlates very highly with temperature variability at depths between 100 and 450 meters. This relationship indicates that in the Gulf Stream region, the sea surface topography in conjunction with historical data could be used to infer subsurface thermal structure.

Introduction

Satellite altimetry has been shown to be an effective tool for determining dynamic height anomaly and temporal sea height variability. To compute the dynamic height it is necessary to remove from the altimeter profile effects of atmospheric pressure, wind, tides, ephemeris error, and most significantly, gravity. A precise gravimetric geoid is required for these computations. Several geoid-independent techniques are also available for measuring temporal sea height variability as shown by Douglas and Cheney,[1] Menard,[2] Cheney, et al.,[3] and Douglas, et al.[4] Generally these techniques consist of calculating the differences between altimeter readings at cross-over points of ascending and descending orbits or between pairs of collinear or repeat ground tracks. In these methods the spatial variations due to geoid are cancelled out, and the differences represent temporal sea height variability. Because a precise gravimetric geoid is not available except for a few select regions, the main thrust of satellite altimetry has been towards geoid-independent techniques.

Altimetric analyses have in the past been compared to conventional determinations from expendable bathythermographs (XBTs), ship drift and surface drifters. However, these independent observations are not always compatible with satellite altimetric analysis. The reason for the discrepancy as explained by Wyrtki,[5] Ebbesmeyer and Taft,[6] and Douglas, et al.[4] is principally due to the way in which the variability statistics are derived. The altimeter measures variability at the same point but at different times, providing temporal variability. The oceanographic observations, however, are taken at different times but seldom at the same point. The variability statistics must therefore be generated by averaging the data within a 100km to 200km square region. This yields variability which includes the spatial as well as temporal components. In the open ocean, spatial variability in a 200km square region may be negligible, but in the vicinity of western boundary currents, the spatial component can dominate.

One oceanographic data set does exist which can provide temporal variability unbiased by the spatial variability component. Between 1969 and 1974 the Naval Oceanographic Office (NAVOCEANO) conducted a program for collecting XBT data along a track between New York and Bermuda using ocean liners as observation platforms. These observations resulted in 120 collinear sections across the Gulf Stream. Model T-7 XBT probes extending to 760m depth were used whenever water depth exceeded 450m. This is important in the Sargasso Sea where the main thermocline is generally found between 600 and 1100m. In contrast, historical XBT files consist predominantly of T-4 XBT (450m) probes. Using XBT temperatures and salinities from historical temperature/salinity (T/S) relationships, we could calculate temporal dynamic height variability along the New York - Bermuda track which is analogous to measurements from collinear satellite altimeter data.

In addition to providing valid ground-truth for altimetric analysis, this data set provided a unique opportunity to determine the relationship between temporal sea height variability and the variability of sub-surface thermal structure. Traditionally, oceanographers use in situ temperature and salinity measurements to calculate dynamic heights or sound velocities. With the advent of satellite altimeters, we have the capability to measure sea height variability directly. It is important to know what inferences can be made from these measurements about sub-surface thermal structure which has many practical applications in oceanography and underwater acoustics.

Data

Figure (1) shows the location of XBTs used in this study. The observations were taken from the shelf break at 73.5°W to the Bermuda rise at 65°W. Approximately 50 to 60 XBTs were taken on each survey with spacing varying from about 10km in the Gulf Stream to 20km-40km elsewhere. The duration of each cruise was about 36 hours. Observations were taken during the southbound transit from New York to Bermuda and during the return trip four days later; the survey was then repeated in two weeks. In order to produce a more uniformly spaced time series, only the southbound sections at two week intervals were used in this

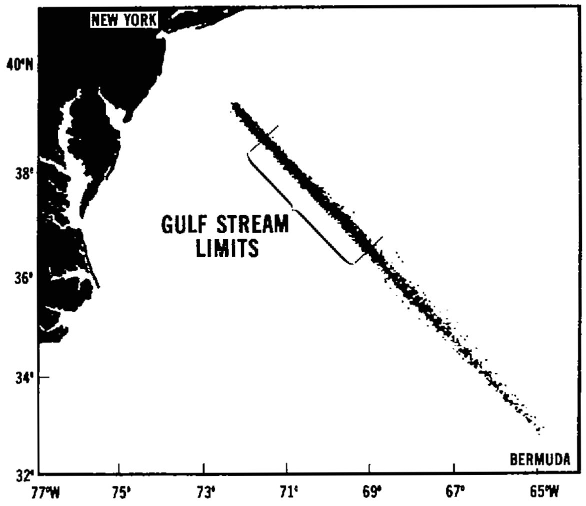

Fig. 1. Location of XBT observations based on the 61 cross sections, and historical limits of surface Gulf Stream positions along the New York to Bermuda track. Data were obtained between 1969 and 1974.

study. Data were not collected during winter months because ocean liners altered their routes from December to March. However, one winter crossing by a Coast Guard cutter, which collected identical data, was also included. This resulted in a total of 61 sections which were used in variability computations. (During 1972 the cruises originated in Norfolk rather than New York. These data were excluded from the present study.)

method

Dynamic Height Computation from Shipboard Data

Dynamic heights were calculated from XBT temperatures using the T/S relationships from NAVOCEANO's Generalized Digital Environmental Model (GDEM). The model is a synthesized data base with temperature, salinity, and sound speed profiles at every 30 minutes of latitude and longitude. It is based on all available historical data including Nansen casts, salinity/temperature/depth (STD) stations, and XBTs. A description and evaluation of the model is given in Locklin et al.[7] The T/S curve shown in figure (2a) was used for determining salinities in Sargasso water and the Gulf Stream. This T/S curve did not show any significant seasonal variability. In the slope water, there was considerable scatter in the T/S relationship. This scatter was reduced by using seasonal T/S curves as shown in figure (2b). The water mass type was determined for each XBT profile based on the temperature at 200m depth. If the temperature was below 15°C, the slope water salinity was used for dynamic height calculations; if the 200m temperature was 15°C or warmer, the Sargasso water salinity was used. Dynamic heights were calculated relative to a 700 decibar (dbar) level. When an occasional XBT profile did not extend to that depth, it was extrapolated using the average temperature gradient for the appropriate water mass.

Figure (3) shows composite plots of dynamic height for 61 sections between New York and Bermuda, the mean profile, and its standard deviation. Gulf Stream meanders, warm rings, and cold rings are clearly discernible in the cluster of lines. The mean

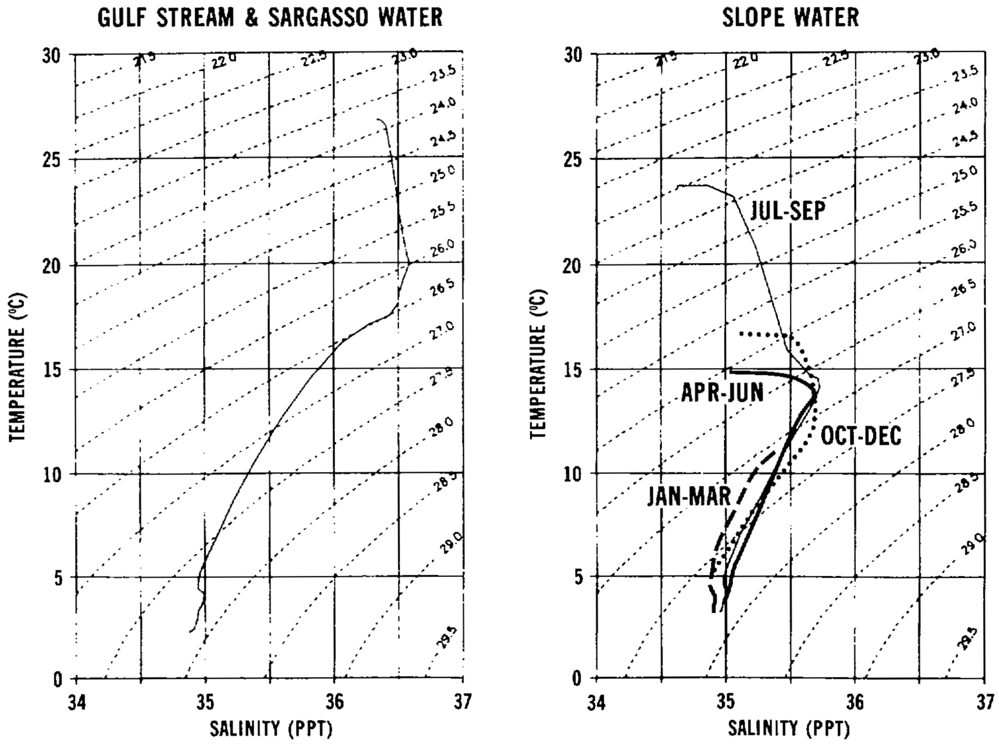

Fig. 2a. Fig. 2b.

Fig. 2. Temperature/Salinity/Sigma T computed from the NAVOCEANO GDEM model. One profile (Fig. 2a) was used for the T/S relationship for the Gulf Stream and Sargasso water. Seasonal T/S relationships (Fig. 2b) were used in slope water to reduce the scatter.

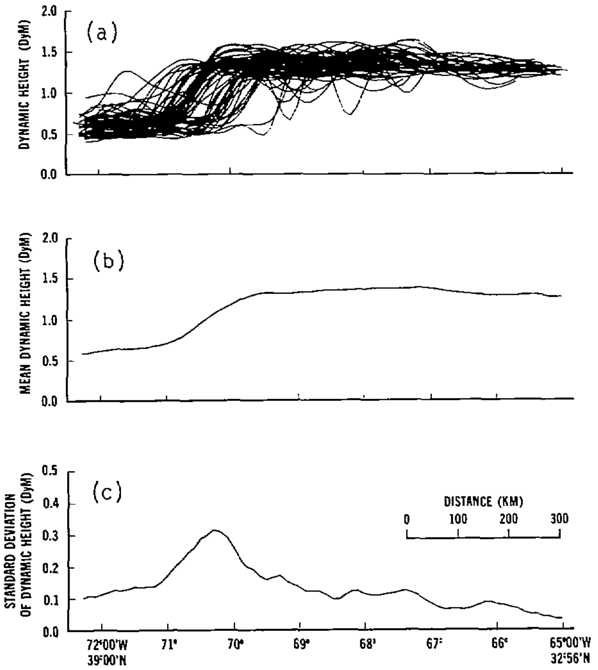

Fig. 3. Dynamic height anomaly (relative to 700 dbar) between New York and Bermuda. Fig. 3a shows composite plots for the 61 cross sections (cubic spline smoothing was applied along each track). The mean and standard deviations are shown in Figs. 3b and 3c.

Gulf Stream, located 70-71°W along this section, appears as an 80cm step between the slope water and Sargasso Sea. It is here that we see the peak sea height variability, approximately 30cm rms. On either side of the Stream, variability gradually drops to 10cm.

Sea Height Variability Computation from Satellite Altimeter

Figure (4) from Douglas, et al.[4] shows mesoscale sea height variability in the western North Atlantic, and Gulf of Mexico computed from GEOS-3 altimeter data. The satellite was operational from May 1975 to October 1978 and produced over 1000 pairs of collinear profiles in the region.

The altimeter data were edited and smoothed using a seven-point (7 second) trimmed mean filter, effectively reducing the noise level of the GEOS-3 data to about 10 cm. Corresponding sea surface heights along the tracks of each pair members were then differenced and linear trends removed from the complete profile difference. Trend removal is necessary to eliminate long wavelength errors in the altitude of the satellite. After trend removal, rms variations were computed for each 1.5° geographic square. Since the profile differences reflect the sum of mesoscale variability in both passes, a reduction by the square root of two was required for results to be equivalent to computing variations about the mean. Finally these values were contoured to produce a map of variability shown in figure (4).

The minimum time separation between repeat tracks for GEOS-3 data was 38 days. This means that each track can be considered to be an independent observation, and the computed variabilities can be compared to long-term oceanographic surveys.

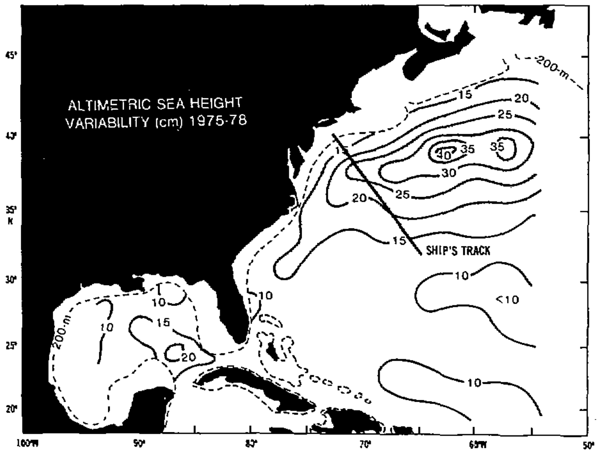

Fig. 4. Sea surface height mesoscale variability computed from repeated pairs of GEOS-3 altimeter profiles (from Douglas, et al.[4]), and the location of ship tracks.

Results

Comparison of XBT and Altimetric Sea Height Variability

For direct comparison of XBT and altimeter derived sea height variability between New York and Bermuda, some rescaling of XBT data was necessary. First, the values had to be averaged over 1.5° of longitude along the track to simulate the averaging process used in altimeter data. Then, an adjustment had to be made because the XBT dynamic heights were computed relative to a 700 dbar level of no motion, while the satellite measures the total signal. Deep hydrographic stations show that dynamic height relative to the 700 dbar level accounts for about 75% of the total dynamic height (Cheney[8]). The XBT values therefore had to be increased by one third. A direct quantitative comparison could then be made between temporal sea height variability as measured by the altimeter and the temporal dynamic height variability computed from XBTs. This is shown in figure (5).

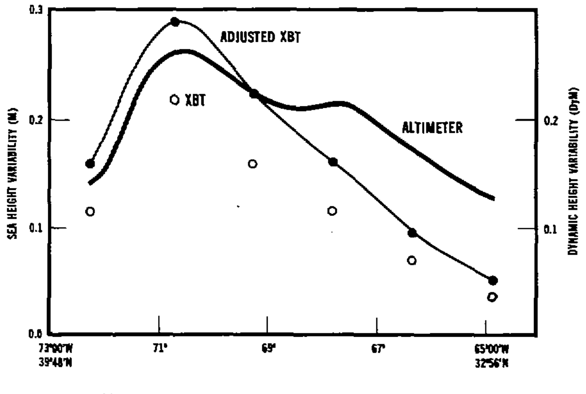

Fig. 5. Temporal sea height variability and dynamic height variability along a section between New York and Bermuda. Altimeter profile was taken from Fig. 4. Shipboard data (relative to 700 dbar) were rescaled for direct comparison.

Both methods show the maximum variability occurring between 70°-71°W with a maximum magnitude of 25-30 cm. Southeast of the Stream, in the area of cold eddy formation, the altimeter shows higher variability than XBTs. One possible explanation for this discrepancy is that the observations covered different time periods. The XBT observations were made between October 1969 and November 1974 whereas the GEOS-3 data were collected between May 1975 and October 1978. These two time periods may have had different levels of eddy activity which would result in different sea height variability. The discrepancy could also be attributed to the noise floor of the altimeter.

Correlation Between Sea Surface Topography and Sub-Surface Thermal Structure

Cheney[8] has shown that there is a high correlation between dynamic height and the depths of 15°C isotherm, 17.5°C isotherm, and the temperature at 350m. The relationships can be explained by the fact that dynamic height is largely a function of the thermocline depth. Collinear XBT data offer an opportunity to examine the relationship between temporal dynamic height variability (a parameter that can be determined from satellite altimetry) and the sub-surface thermal structure.

Figure (6) shows the mean temperatures at the sea surface, 50m, 100m, 200m, 450m, and 700m depths. At the sea surface, and at 50m there is a gradual increase in temperature from the shelf break at approximately 73°W to the eastern Gulf Stream boundary at 69.5°W. At greater depths, the main increase in temperatures of approximately 8°-10°C occurs between 71°-69.5°W coinciding with the envelope of Gulf Stream positions along this cross section. Note that between 100m and 700m depths the mean temperature curves are very similar to the mean dynamic height curve shown in figure (3b) suggesting that mean temperatures could be expressed as a function of dynamic height with high accuracy.

Figure (7) shows the standard deviations of temperatures between New York and Bermuda at several depths. Sea surface temperature shows the maximum variability of approximately 7°C at 73°W. It decreases gradually to about 3°C at 70°W which is the southern limit of the Gulf Stream location and stays at that level in the Sargasso water. At 50m depth the maximum variability of 5.5°C occurs at approximately 70.5°W, which is the mean Gulf Stream position. With increasing depths, the location of maximum variability is gradually shifted to the east and at 700m depth it occurs at approximately 70°W. The gradual shift to the east is consistent with the vertical slope of the Gulf Stream North Wall. Maximum variability therefore is always at the same location relative to the Gulf Stream North Wall. At 700m depth, there is also a marked increase in variability southeast of the Gulf Stream when compared to the 450m depth. This is probably caused by the increased vertical gradient below the limits of 18°C water[9]. During 1969-1974 the 18°C water was observed between 200m and 500m in this region.

The temperature standard deviation curves between 100 and 450 meters are very similar to the dynamic height standard deviation shown in figure (3c), indicating that high correlations exist between these parameters. Cross correlation coefficients along the track for the mean values and for the standard deviations have been computed for the following parameters: dynamic height anomalies (DH), depth of 15°C isotherm (DEP15), sea surface temperatures (SST), 50m temperature (T50), 100m temperature (T100), 200m temperature (T200), 450m temperature (T450) and 700m temperature (T700). Table 1 shows the cross correlation of mean values. The high correlation coefficients indicate strong linear relationships between mean dynamic heights and mean temperatures at all depth levels.

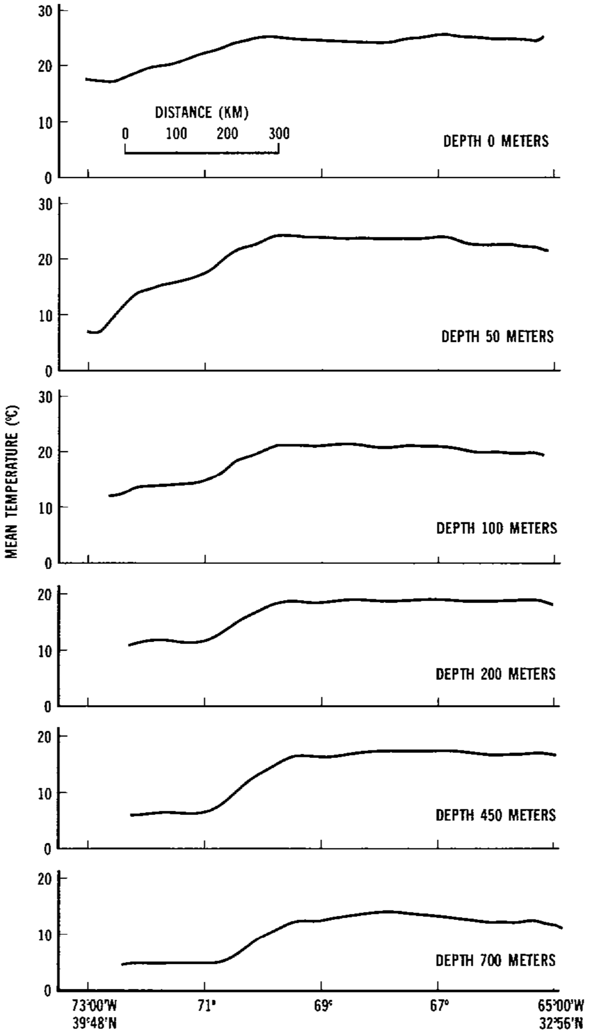

Fig. 6. Mean temperatures along New York to Bermuda section. Gulf Stream limits are evident at all depths below 100m.

The cross correlation coefficients of variabilities are shown in table 2. It can be seen that between the 100m and 450m depths the dynamic height correlation with temperature is very high (0.95-0.98) indicating a strong linear relationship. This implies that at these depths, dynamic height variability could be used to infer temperature variability with high accuracy. Table 2 also shows that sea surface temperature variability does not correlate with any other parameter, indicating that it cannot be used to predict subsurface thermal structure variability.

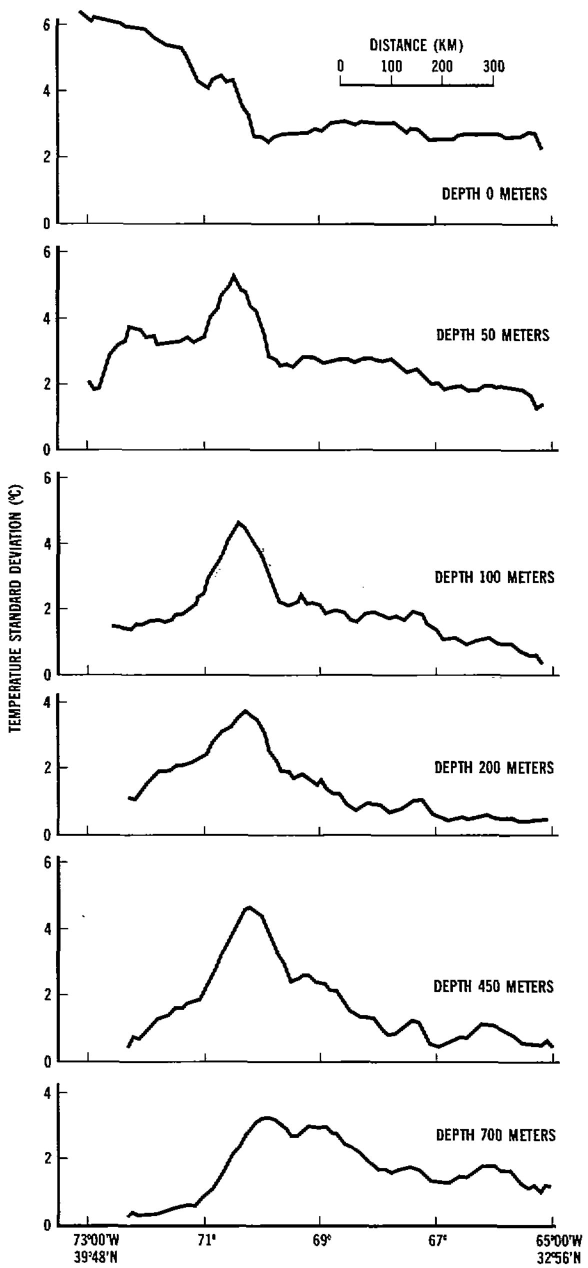

Fig. 7. Standard deviation of temperatures along New York to Bermuda section. Maximum variability coincides with the mean Gulf Stream location.

Inferring Sub-Surface Thermal Structure from Sea Surface Topography

Although high correlation coefficients imply a strong linear relationship between two variables, they do not quantify the value of one variable as a function of the other. For this objective, regression plots and computation of standard error of estimate of y on x (σ) and the coefficient of determination (r^2) which measures the "goodness of fit" is a more appropriate approach. Note that $0 \le r^2 \le 1$, and if $r^2=1$, we have a perfect fit.

Figure (8) shows mean 200m temperature ($\overline{T}200$) computed along the track as a function of mean dynamic height ($\overline{DH}$). In equation form, it can be expressed as:

$$\overline{T}200 = 10.63\ (\overline{DH}) + 4.63.$$

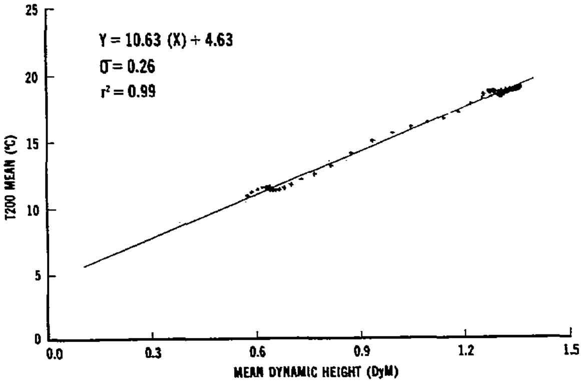

Fig. 8. Relationship between mean dynamic height anomaly (relative to 700 dbar) and mean 200m temperature.

The least square linear fit shows a standard error of 0.26°C and r^2 of 0.99. This indicates that if the mean dynamic height is known, the mean temperature at 200m could be computed with surprisingly high accuracy. Similar relationships were derived for mean temperatures at other depths as a function of $\overline{DH}$. In equation form these are:

$\overline{SST} = 6.18(\overline{DH})+16.7$	$\sigma=0.77$	$r^2=0.84$
$\overline{T}50 = 10.83(\overline{DH})+8.97$	$\sigma=0.94$	$r^2=0.91$
$\overline{T}100 = 9.63(\overline{DH})+8.02$	$\sigma=0.48$	$r^2= .97$
$\overline{T}450 = 15.93(\overline{DH})-4.18$	$\sigma=0.51$	$r^2=0.99$
$\overline{T}700 = 12.64(\overline{DH})-3.77$	$\sigma=0.82$	$r^2=0.95$

The above equations show that between 100m and 450m depths, mean temperatures can be derived from mean dynamic heights with very high accuracy.

Linear relationships along the track between dynamic height variability and temperature variability have also been determined. Figure (9) shows the plot of dynamic height variability (DH_v) vs 200m temperature variability ($T200_v$). In equation form:

$$T200_v = 13.52(DH_v) - 0.34.$$

The least squares fit indicates a standard error of 0.29°C and r^2 of 0.91. Similar equations for other depths are:

$SST_v = 2.86(DH_v)+3.07$	$\sigma=1.08$	$r^2=0.03$
$T50_v = 11.41(DH_v)+1.35$	$\sigma=0.47$	$r^2=0.73$
$T100_v = 14.27(DH_v)+0.07$	$\sigma=0.19$	$r^2=0.96$
$T450_v = 16.54(DH_v)-0.47$	$\sigma=0.38$	$r^2=0.90$
$T700_v = 5.90(DH_v)+0.93$	$\sigma=0.79$	$r^2=0.20$
$DEP15_v = 637(DH_v)+20.3$	$\sigma=25.6$	$r^2=0.74$

Table 1. Cross Correlations of Means

	DH	SST	T50	T100	T200	T450	T700	DEP15
DH	1.00	.91	.95	.98	.99	.99	.97	.99
SST	.91	1.00	.97	.93	.91	.88	.82	.87
T50	.95	.97	1.00	.98	.94	.92	.87	.91
T100	.98	.93	.98	1.00	.98	.96	.93	.96
T200	.99	.91	.94	.98	1.00	.99	.97	.99
T450	.99	.88	.92	.96	.99	1.00	.99	.99
T700	.97	.82	.87	.93	.97	.99	1.00	.99
DEP15	.99	.87	.91	.96	.99	.99	.99	1.00

Table 2. Cross Correlations of Variabilities

	DH	SST	T50	T100	T200	T450	T700	DEP15
DH	1.00	.18	.85	.98	.95	.95	.45	.86
SST	.18	1.00	.59	.19	.38	-.01	-.65	-.22
T50	.85	.59	1.00	.89	.89	.70	.04	.55
T100	.98	.19	.89	1.00	.93	.91	.42	.83
T200	.95	.38	.89	.93	1.00	.89	.25	.75
T450	.95	-.01	.70	.91	.89	1.00	.64	.96
T700	.45	-.65	.04	.42	.25	.64	1.00	.81
DEP15	.86	-.22	.55	.83	.75	.96	.81	1.00

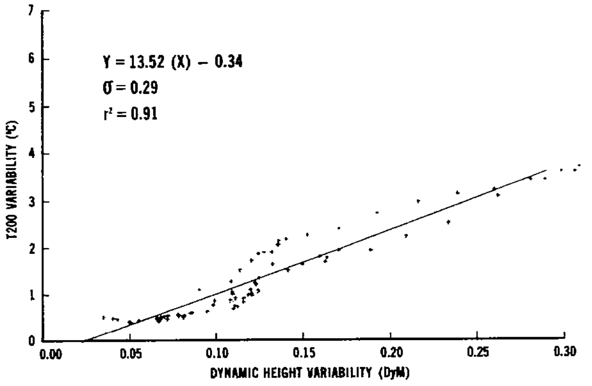

Fig. 9. Relationship between dynamic height (relative to 700 dbar) temporal variability and 200m temperature temporal variability. Least square fit has a standard error of 0.29°C.

These results indicate that between 100m and 450m depths, temperature variability can be estimated from dynamic height variability with standard error of 0.38°C or less. Therefore, if temperatures at these depths are known from historical data or a survey, their variability could be predicted from sea surface height variability.

Additional regression curves were computed using individual values of temperatures (in contrast to mean values) as a function of dynamic heights. Figure (10) shows the plot of T200 vs DH computed at 68°W along the New York to Bermuda track. At this location all

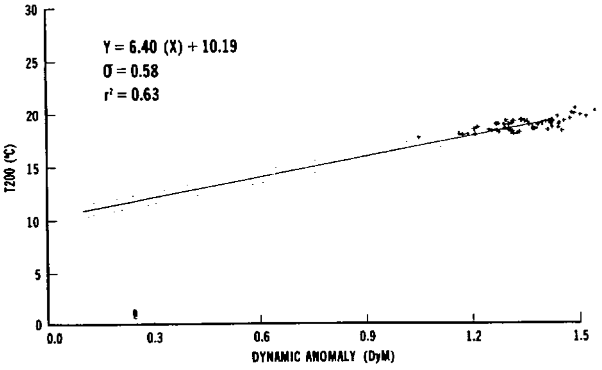

Fig. 10. Relationship between dynamic height anomaly and 200m temperature based on 61 observations in the Sargasso Sea. Least square fit has a standard error of 0.58°C.

the observations are in Sargasso water. The equation for the regression line is:

$T = 6.40(DH) + 10.19 \qquad \sigma=0.58 \qquad r^2=0.63.$

Similar computations for 200m temperatures at different locations along the track yielded the following results:

At 72^{o}W (Slope water)
$T200= 9.48(DH)+5.62 \qquad \sigma=1.09 \qquad r^2=0.50$

At 71^{o}W (Gulf Stream)
$T200=12.23(DH)+3.14 \qquad \sigma=1.22 \qquad r^2=0.75$

At 70^{o}W (Gulf Stream)
$T200=10.95(DH)+4.17 \qquad \sigma=1.14 \qquad r^2=0.87$

At 69^{o}W (Sargasso Water)
$T200=10.50(DH)+4.62 \qquad \sigma= .93 \qquad r^2=0.70$

These results show relatively large values of σ and smaller r^2 values. Therefore, inferring T200 from individual values of dynamic heights in pure water masses (Slope and Sargasso) is not practical since climatological models such as GDEM can predict the temperatures with considerably smaller standard deviations. Within the Gulf Stream an improvement over statistical models can be expected. Similar computations for other depths also resulted in large standard errors and low r^2 values confirming that direct inference of sub-surface temperatures from dynamic heights without the a priori knowledge of the thermal structure is not practical.

Summary and Conclusions

1. Sea height variability between New York and Bermuda computed from GEOS-3 altimeter collinear tracks is in good agreement with analogous measurements from collinear XBT measurements.

2. Between 100m and 450m depths, mean temperatures can be computed from mean dynamic heights with a standard error of 0.51°C or less.

3. Between 50m and 450m depths, temporal variability of temperatures can be determined from temporal dynamic height variability, with a standard error of 0.47°C or less.

Acknowledgements

The authors acknowledge the contributions of Mr. M. K. Shank and Mr. A. Lewando for initiating and administering the ocean liner program; Dr. T. Davis, Dr. J. Blaha and Mr. C. Horton for technical and editorial advice; Ms. L. A. Stanley for preparation of the manuscript.

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