# COMPUTING DYNAMIC HEIGHT FROM TEMPERATURE PROFILES NORTH OF 30°N IN THE PACIFIC OCEAN

A Thesis

by

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ABSTRACT

Computing Dynamic Height from Temperature Profiles North of 30°N in the Pacific Ocean. (May 1978)

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Mean temperature-salinity (TS) and salinity-depth (SZ) curves are computed for 5° squares from all available hydrogaphic data in the Pacific Ocean between 30°-70°N. A comparison is made between methods of inferring salinity from each curve for use in computation of dyanmic height. The root mean square (RMS) difference between observed dynamic height and salinity inferred dynamic height indicates where a mean TS or SZ curve should be used to compute dynamic height from temperature profiles. The boundaries between regions where SZ curves should be used to infer salinity rather than TS curves coincide with temperature and salinity fronts above 30°N in the Pacific Ocean.

## ACKNOWLEDGMENTS

The author wishes to thank Dr. William J. Emery for providing necessary funds and especially for his patient guidance and support throughout all phases of this research.

The author also wishes to thank committee member Dr. Steven Slinker for reviewing the manuscript and committee chairman Dr. Thomas Spence for his meticulous examination and constructive criticisms.

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## 1. Introduction

It is common in oceanography to use the temperature-salinity (TS) relationship to identify water masses. This application of TS curves to describe water mass distribution stems from the observation by Helland-Hansen in 1916 that TS curves are similar over large areas of the ocean. In 1947, Stommel explored the idea of using mean TS curves to infer salinity from temperature observations for the computation of dynamic height. Using a few hydrographic stations in the Atlantic, Stommel found a mean difference between the true or observed dynamic height (computed from observed temperature and observed salinity) and dynamic height computed from observed temperature and salinity inferred from a mean TS curve to be about 5 dyn cm. Yasui (1955, 1957) found a similar difference of 5 dyn cm using salinities inferred from TS curves near Japan. Following these early efforts relatively little use has been made of TS relationships to infer salinity for dynamic height computations.

Recently, the use of the XBT (expendable bathythermograph) in collecting inexpensive temperature profiles has stimulated interest in the computation of dynamic height from temperature profiles. Since the XBT can be deployed by ships other than research vessels methods which combine existing temperature and salinity data with XBT profiles could greatly reduce the cost of computing dynamic height.

In 1975, Emery found good agreement between observed dynamic

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height and dynamic height computed using salinity inferred from a mean TS curve (called "TS dynamic height") at two weather stations (ocean weather station "Victor" (39°N, 164°E), ocean weather station "November" (30°N, 140°W)) in the North Pacific Ocean. At a third weather station, "Papa" (50°N, 145°W), the mean difference between true and TS dynamic height was found to be on the order of 10 dyn cm. Emery suggested that this high value resulted from temperature inversions. Temperature inversions cause several different salinity values to correspond to the same temperature value within the inversion layer thus increasing the salinity standard deviation in the TS relationship. Tabata (1961) and Roden (1975) have found temperature inversions common in the subarctic water masses above 40°N in the Pacific. Emery and Wert (1976) restricted further investigation of the method of TS dynamic height to latitudes below 40°N where temperature inversions do not occur.

Another method must then be devised for inferring salinity in those areas north of 40°N in the Pacific where a mean TS curve should not be used. Such a method is limited to data given by the XBT, hence, one must reexamine the basic information which is provided in a temperature profile measured by an XBT.

The XBT measures temperature as a function of depth in the upper layer (∿500-700 m). Therefore, corresponding salinity values must be inferred from either the temperature data or depth. Although Flierl (1978) has shown that in some cases TS dynamic height can be improved considering temperature-salinity-pressure relationships, in regions where salinity should not be inferred from a TS relationship the only other possibility is to infer the salinity using the observed depth. The relationship between salinity and depth can be described by a mean salinity versus depth profile (SZ curve). Tabata (1960,1961,1965) has shown that at station "Papa" the variations of salinity at all depths are less pronounced than the temperature variations and below the 200 m level salinity variations approach a magnitude attributable to observational error (<.02 °/₀₀). In light of Tabata's findings a new method of inferring salinity for computation of dynamic height can be explored using the SZ relationship. This method, called SZ dynamic height, will be shown to be effective for computing dynamic height from temperature profiles in areas, such as station "Papa," where the TS method should not be used and there is a "tight" (small standard deviation in salinity) salinity-depth relationship.

## 2. Area of study

The region north of 30°N in the Pacific Ocean was chosen for this investigation because it contains areas where the TS method of dynamic height should and should not be used. Also there exists a sufficiently large number of hydrographic stations so that errors resulting from poor sampling are reduced.

In 1975, Roden described three major temperature and salinity fronts associated with the general surface circulation above 30°N in the Pacific (Fig. 1). Since these fronts have a bearing on the discussion of the results presented later, a brief summary of Roden's findings will be presented here.

The Kuroshio front can be found at about 155°E between 37° and 39°N but the actual location of the front is variable due to meandering of the Kuroshio. Associated with this front are strong horizontal temperature gradients (on the order of 6°C per 60 km) that can be traced several thousand kilometers seaward from Japan. The Oyashio front (∿145°E and 40°N) shows both strong horizontal temperature and salinity gradients as a result of the warm, high salinity water of the Kuroshio contacting the cold, low salinity Oyashio water from the Arctic. Evidence has been found for the existence of multiple fronts spaced about 60-70 km apart along a 400 km section at 40°N between Japan and 147°E.

Stretching nearly across the entire Pacific between 40°-45°N, the subarctic front is also a region of sharp contrasts in temperature and salinity. This is an area which Roden (1970) has previously

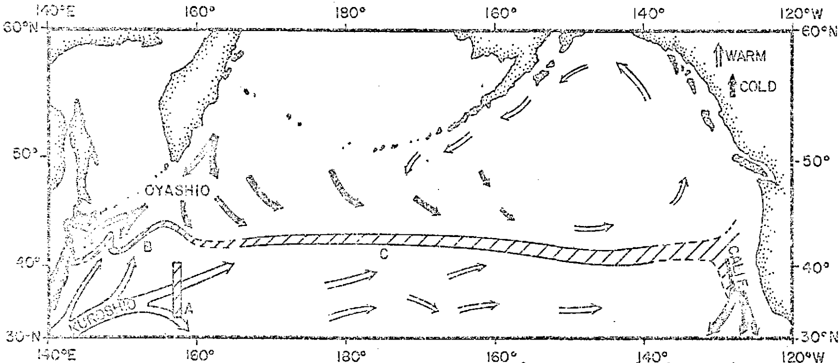


FIG. 1. Schematic map of the fronts and currents above 30°N in the Pacific Ocean. Arrows indicate prevailing current directions. Letters refer to fronts; A, Kuroshio front; B, Oyashio front; C, subarctic front. (After Roden, 1975).

found to be the northern edge of the Mid-Pacific transition zone and is typified by horizontal thermal gradients on the order of 8°C per 60 km and salinity gradient of about 1.2 °/₀₀ per 60 km. Roden has noted that the mixed layer extends to the top of the halocline (∿100 m) north of the front and found no halocline to the south. These strong contrasts were also found to contain seasonal variations with the most severe contrasts occurring in winter and spring.

## 3. Data

The data for this study were taken from the NODC hydrographic station data file. For both TS and SZ computations, data were used at observed depth levels. Where actual observations were not available at a depth a 2-point linear interpolation scheme was used.

The location of weather ship "Papa" is defined by the two degree square centered at (50°N, 145°W) and the measurements are considered to be a long time series of data at that point. The large number of hydrographic casts taken at station "Papa" provides an adequate sample and so it was chosen a primary test site.

In all other areas north of 30°N in the Pacific Ocean the data is spatially averaged over a 5° square so that a large number of hydrographic stations can be complied and TS and SZ dynamic height can be computed.

## 4. Application of methods to ocean weather station "Papa"

The method of SZ dynamic height was initially tested at station "Papa" so that the results could be compared with the previous findings of Emery (1975). This region has shown poor agreement between true and TS dynamic height.

At station "Papa" a mean SZ curve (Fig. 2) is constructed from salinity values averaged at 66 specific depth levels; surface to 150 m by 5 m intervals and 160 to 500 m by 10 m intervals. The SZ method then uses the depths of the observed temperatures to determine the corresponding salinity values from the mean SZ curve. The observed temperatures and SZ inferred salinities are combined to define a density profile using the algorithm for sigma-t presented in the *User's Guide to NODC's Services* (1974) from which SZ dynamic height is computed. For comparison the "true" or observed dynamic height is also computed using the temperatures and salinities observed at the 66 depth levels.

A histogram of d-d' difference at station "Papa" is given in Fig. 3, where d is the true dynamic height (relative to 500 m) and d' is the inferred dynamic height. The histogram graphically represents the number of stations which exhibit a given d-d' difference. Each d-d' difference is rounded to the nearest whole dynamic centimeter and displayed at integer intervals on the abscissa. The root mean square (RMS) d-d' value is computed to indicate the average difference between true and salinity inferred dynamic height. The RMS d-d' difference using the annual mean SZ curve at station

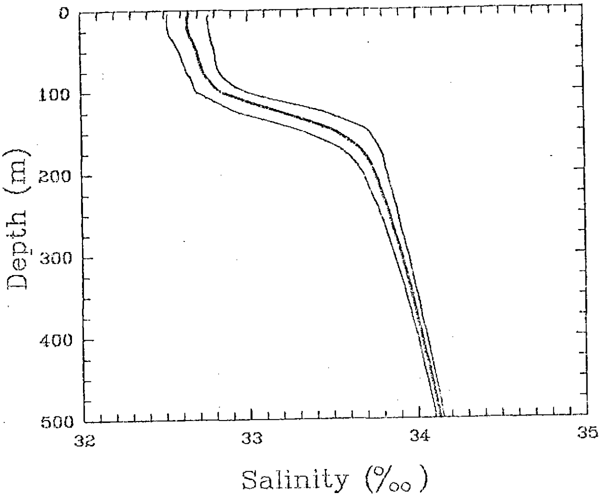


FIG. 2. Mean annual SZ curve at station "Papa" (50°N, 145°W). The dark center line is the mean SZ curve and the lighter outer lines show the standard deviation.

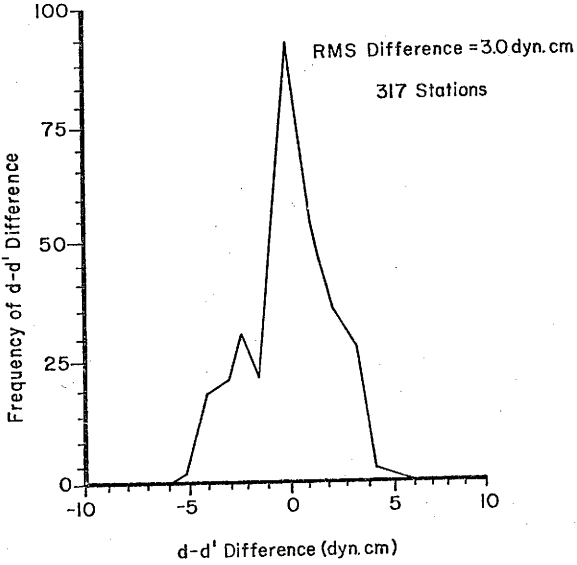


FIG. 3. Annual histogram of SZ d-d' difference at station "Papa."

"Papa" was 3.0 dyn cm. This value is much lower than that found by Emery (1975) using the annual mean TS curve and lower than the observed uncertainty in true dynamic height (~4.2 dyn cm; Emery, 1975). The observed uncertainty in dynamic height is a combined result of possible errors and fluctuations in dynamic height and serves as an upper limit to the accuracy of a dynamic height value. The reduced RMS d-d' difference for the SZ method might have been expected since the "tight" mean SZ curve (Fig.2, p. 9) makes it more likely that a salinity value from the mean SZ curve will be very near the observed salinity so that the SZ method should produce dynamic height which corresponds closely to the true dynamic height. Also neither the temperature inversions (Emery, 1975; Tabata, 1961) nor the large temperature variations (Tabata, 1965), strongly affecting TS dynamic height, have any effect on the salinity-depth relation used in the SZ method of dynamic height (discussed later).

In areas where strong seasonal fluctuations are present, their signal can be masked in the mean annual curve as a result of long term averaging. The mean annual curve, hence, would not represent the true salinity-depth relationship and SZ dynamic height would not be in good agreement with true dynamic height. Therefore, a large salinity standard deviation in the mean annual SZ curve could indicate an area where the seasonal fluctuations are strong and the necessity for mean seasonal SZ curves.

In order to determine whether or not a strong seasonal signal is present within the mean annual SZ curve at station "Papa" four seasonal curves were computed (Figs. 4-7). The seasonal curves show little or no difference below about 200 m agreeing with Tabata's (1960, 1961) findings. The largest variations from season to season are seen in the surface layer (<100 m) which will not greatly alter SZ dynamic height computations. The histogram (Fig. 8) for mean seasonal SZ dynamic height exhibits little deviation from the annual histogram in Fig. 3 (p.10). Moreover, the RMS d-d' difference remains constant at 3.0 dyn cm.

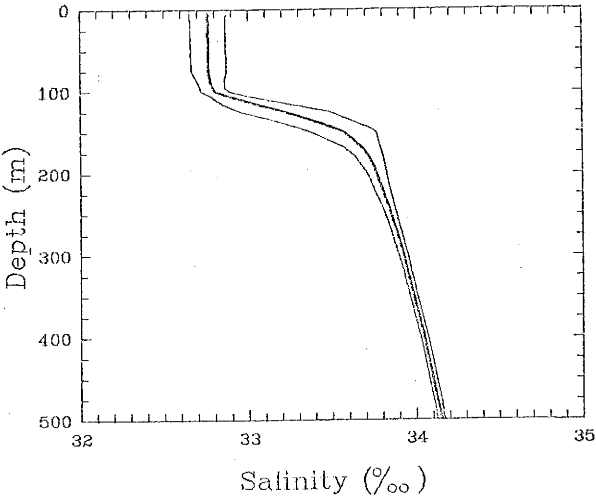


FIG. 4. Mean SZ curve for months February through April at station "Papa". Lines are as in Fig. 2.

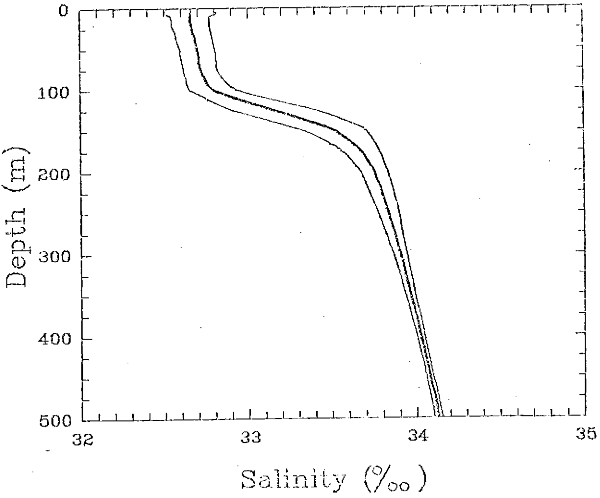


FIG. 5. Mean SZ curve for months May through July at station "Papa." Lines are as in Fig. 2.

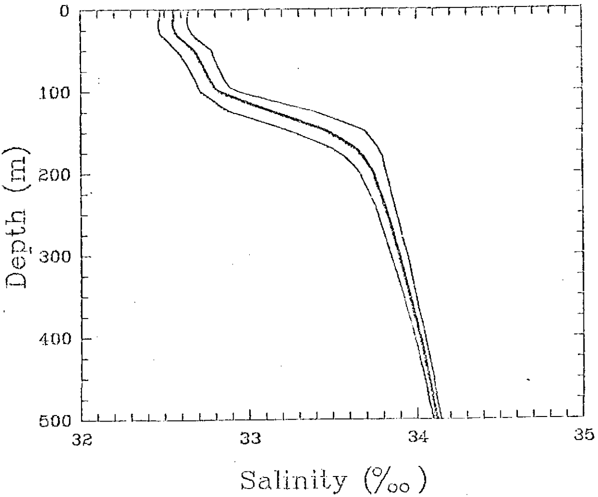


FIG. 6. Mean SZ curve for months August through October at station "Papa." Lines are as in Fig. 2.

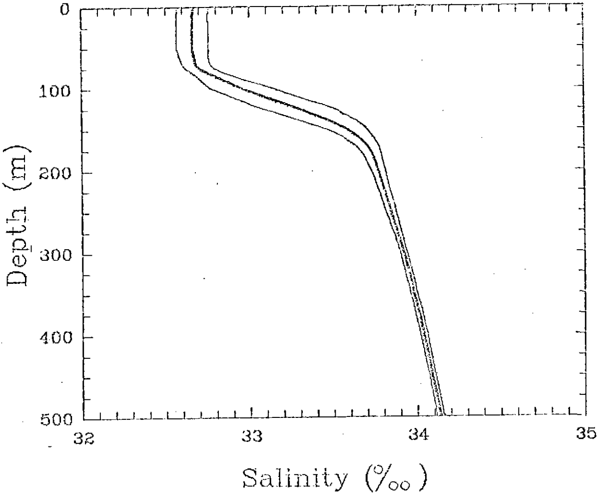


FIG. 7. Mean SZ curve for months November through January at station "Papa." Lines are as in Fig. 2.

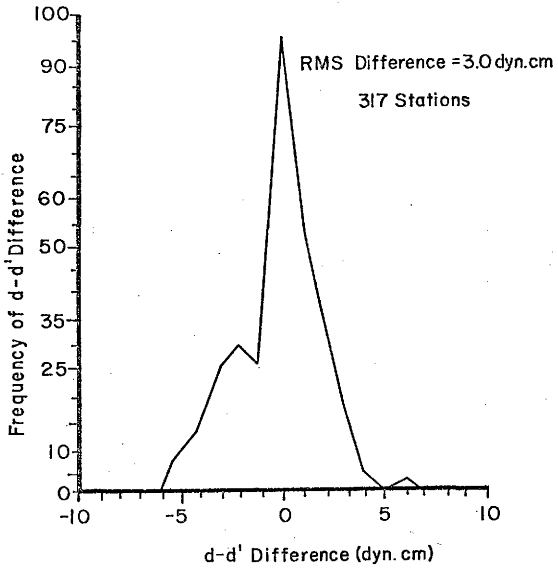


FIG. 8. Seasonal histogram of SZ d-d' difference at station "Papa."

## 5. Application of the TS method (30°-70°N)

The mean TS curves for the Pacific are computed from salinities averaged at .1°C intervals of temperature and then smoothed once using a 5-point mixing average to reduce noise (Fig. 9).

Using the mean TS curve for each square TS dynamic height and RMS d-d' difference were computed for all stations. The RMS d-d' difference and the number of stations for each 5° square are shown in Fig. 10. In general, the low RMS d-d' difference and "tight" TS curves are in the central north Pacific between 30°-40°N. This agrees with the results of Emery and Wert (1976). Above 40°N the difference between true and TS dynamic height increases. The North American west coastal regions are areas of high RMS d-d' difference due to the influx of fresh water from rivers introducing variability into the coastal salinities.

Farther off shore the RMS d-d' difference for TS dynamic height remains generally high (>4.0 dyn cm). These central areas, described by Roden (1970), are part of the Mid-Pacific transition zone and contain the characteristic temperature inversions. Since the TS dynamic height results at station "Papa" (Emery, 1975) were strongly affected by temperature inversions a similar consequence would be expected in the transition zone.

The area of poorest agreeement between true and TS dynamic height is located between 45-50°N and 140-170°W. The exact cause of these very high RMS d-d' differences is unknown. It is suspected that temperature inversions and strong temperature variations have

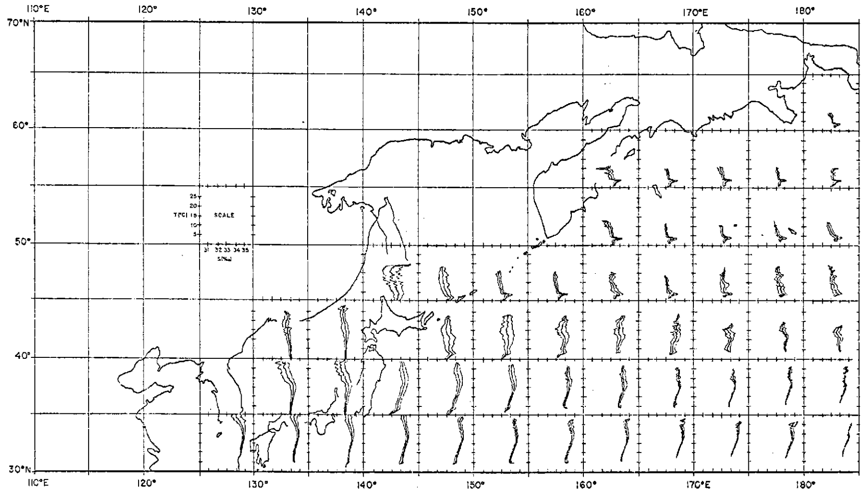


FIG. 9a. Mean TS curves for 5° squares above 30°N in the Pacific Ocean. The center line is the mean TS curve and the outer lines show the standard deviation.

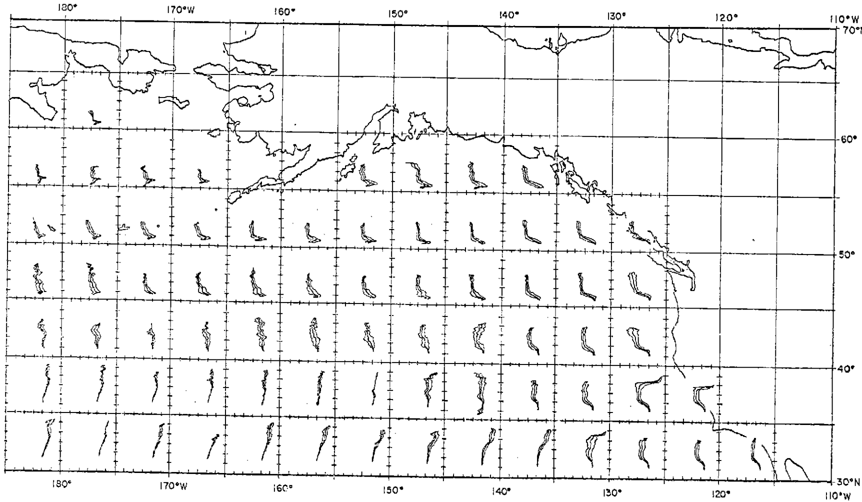


FIG. 9b. Mean TS curves above 30°N (continued).

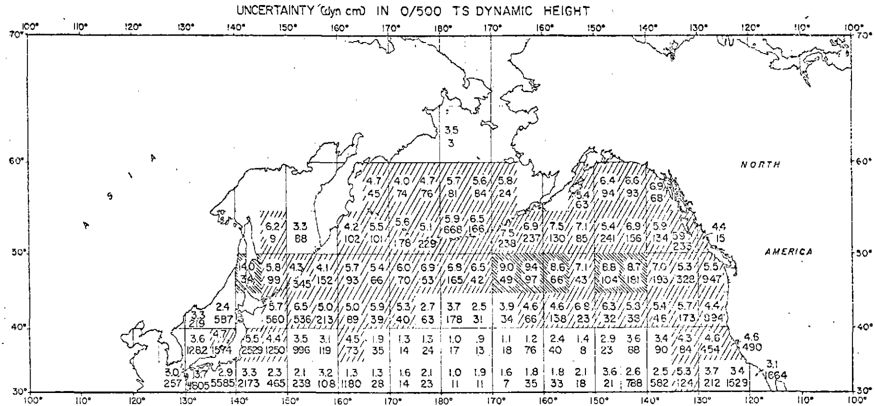


FIG. 10. TS dynamic height uncertainty (dyn cm) for 5° squares. The number of hydrostations used in each square are also shown.

played a major role since this area is a site of cold, low salinity waters of arctic origin mixing with the warmer waters of the Alaska Gyre (Roden, 1975).

For areas of high RMS d-d' difference the standard deviations in salinity in the mean TS curves (Figs. 9a and b, pp. 19 and 20) are significantly larger than the salinity standard deviations below 40°N where the mean TS curves yielded small RMS differences. As expected, there is a correlation between the magnitude of the salinity standard deviation in the mean TS curve and the relative effectiveness of the method of TS dynamic height. A large standard deviation indicates a large uncertainty in the mean TS salinity information and consequently poorer agreement between true and TS dynamic height. Generally, the mean TS curves for the high d-d' RMS central north Pacific and coastal regions are not considered "tight" with respect to salinity variations and so higher RMS values are not surprising.

## 6. Application of the SZ method (30°–70°N)

The mean SZ profiles used in computation of SZ dynamic height are shown in Fig. 11 (a and b). As with the TS method, an RMS d-d' difference was computed for each location (Fig. 12).

Generally, the SZ method of dynamic height is seen to give better agreement with true dynamic height in many of the areas where the TS method yielded poorer agreement. Above 40°N in the central North Pacific the SZ method yielded RMS d-d' differences that were consistantly 2-4 dyn cm less than the TS method. The SZ curves in this area are fairly "tight" and the results suggest that there is less variability in salinity with respect to depth than there is with respect to temperature. The temperature inversions, which were seen to strongly effect the TS method in this region and at station "Papa," do not enter into SZ computations. The higher latitude water masses have salinity increasing to the bottom and a stable density configuration can be maintained when the temperature inversion is balanced by a change in the slope of the SZ curve at the depth of the halocline. In an area where temperature inversions are common the mean SZ curve contains the average slope change, hence, a fairly "tight" SZ relationship can still be expected.

In the North American coastal regions the SZ method again is seen to give RMS d-d' differences less than those given by the TS method. This is an area of water mass formation due to lateral mixing of Subarctic and Equatorial water types. Since the SZ method has shown the salinity variations to be small in this area it

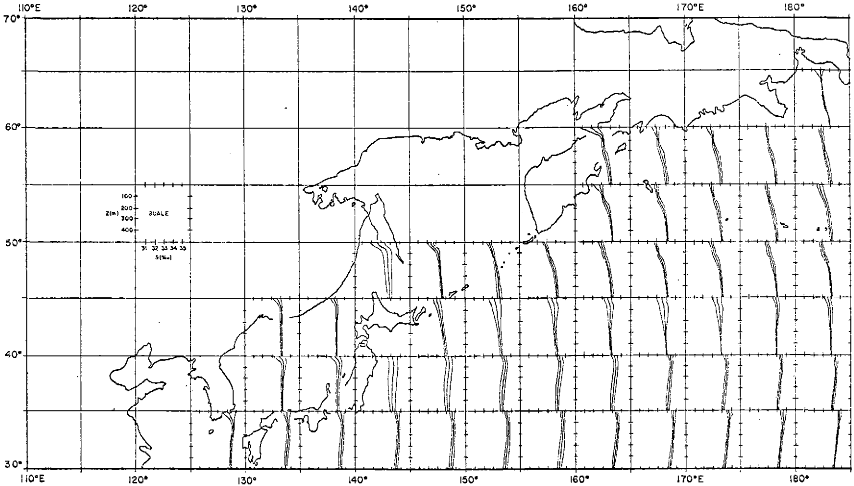


FIG. 11a. Mean SZ curves for 5° squares above 30°N in the Pacific Ocean. The center line is the mean SZ curve and the outer lines show the standard deviation.

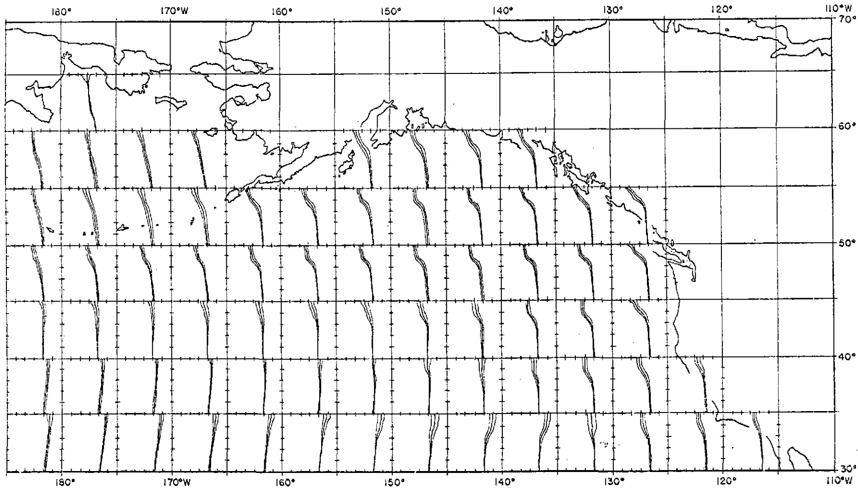


FIG. 11b. Mean SZ curves above 30°N (continued).

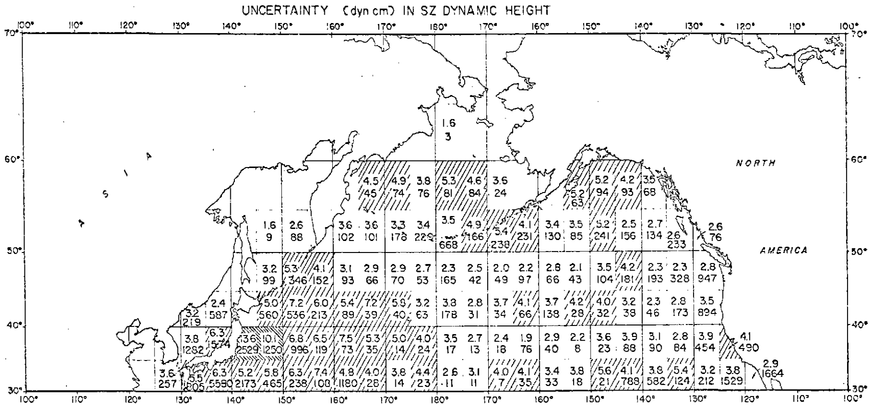


FIG. 12. SZ dynamic height uncertainty (dyn cm) for 5° squares. The number of hydrostations used in each square are also shown.

appears that salinity is the controlling factor for density structure resulting from mixing along sigma-t surfaces (Sverdrup *et al*, 1942).

The poorest agreement of SZ dynamic height with true dynamic height is found in the extreme western portion of the area presented in Fig. 12 (p.26). In this area, previously described as the site of the Kuroshio and multiple Oyashio fronts, the higher SZ RMS d-d' differences are not surprising. The area is subject to large variability in salinity as a result of the meandering of the fronts which separate water masses of different salinities. As the fronts meander across 5° square boundaries the salinity profiles taken over time would show the change of the salinity-depth relationship with the changing water mass. This produces a large standard deviation in salinity on the mean SZ curves for that area resulting in SZ dynamic height that differs widely from the true dynamic height. The multiple Oyashio fronts would produce a similar effect as a result of averaging salinity-depth curves spatially across the fronts.

In the next section three particular 5° squares are examined to further illustrate the contrasts of the TS and SZ methods of dynamic height.

## 7. Selected areas applying TS and SZ methods

The square bounded by 30°-35°N, 160°-165°E is a location where the TS method results in a fairly small RMS difference between TS and true dynamic heights. A histogram of d-d' difference appears gaussian in shape with an RMS value of 1.3 dyn cm (Fig. 13). This low RMS d-d' difference, compared to the observed uncertainty in dynamic height (∿13.6 dyn cm), and gaussian histogram are considered to be highly indicative of a conservative TS relationship which is well resolved by the large number of stations (∿1180). The reliability of TS dynamic height could be predicted from the mean TS curve (Fig. 14). The curve shows a small salinity deviation over a large portion of the curve with the expected higher salinity variation in the surface layer (<100 m).

The histogram for this square using the SZ method is shown in Fig. 15. The histogram is very much wider over the bottom half of the curve and the RMS d-d' difference is greatly increased (∿4.8 dyn cm) over the TS value. The number of stations contributing to the peak of the histogram is about five times larger in the TS histogram (Fig. 13, p.29). The mean SZ curve for this square (Fig. 16) shows a standard deviation in salinity on the order of .2 ‰ over the entire curve, hence the reduced peak and larger RMS d-d' difference is not surprising.

In the area 40°-45°N, 175°-180°E the TS and SZ methods yield about the same RMS d-d' difference (∿3 dyn cm) which is below the 3.9 dyn cm value of observed uncertainty in dynamic height. Both

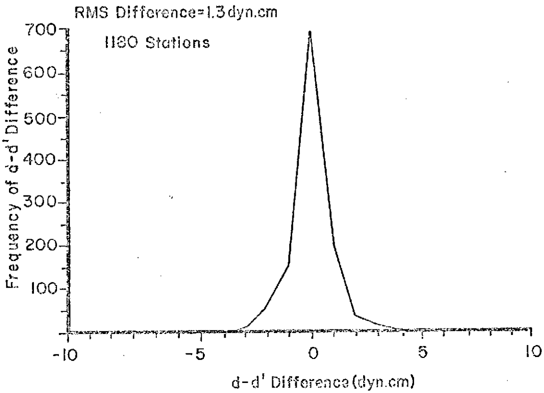


FIG. 13. Histogram of TS d-d' difference for (30°-35°N, 160°-165°E).

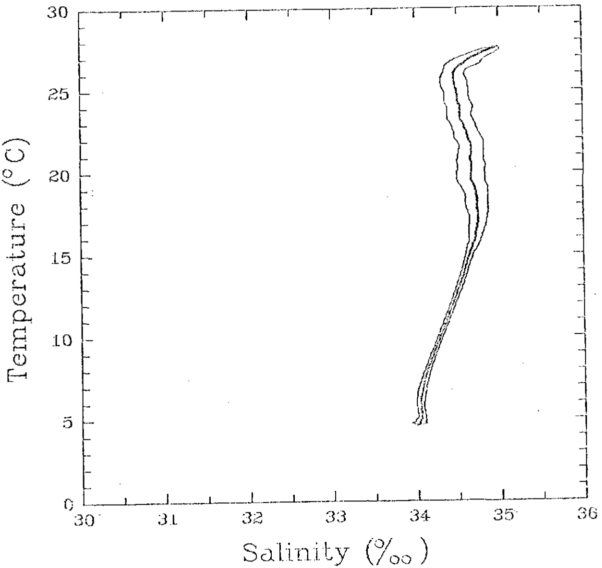


FIG. 14. Mean TS curve for (30°-35°N, 160°-165°E). The dark center line is the mean TS curve and the lighter outer lines show the standard deviation.

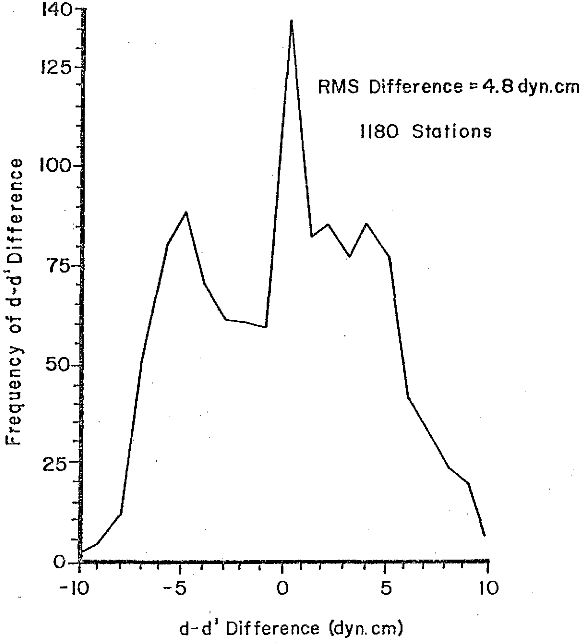


FIG. 15. Histogram of SZ d-d' difference for (30°-35°N, 160°-165°E).

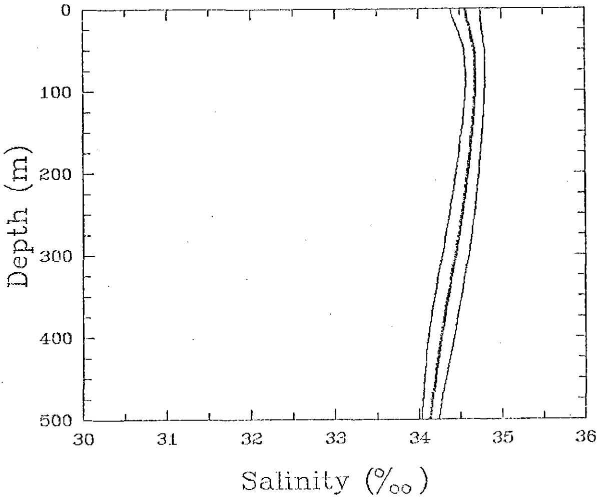


FIG. 16. Mean SZ curve for (30°-35°N, 160°-165°E). The dark center line is the mean SZ curve and the lighter outer lines show the standard deviation.

histograms (Figs. 17 and 18) are seen to be gaussian in shape. The variations in salinity for the TS (Fig. 19) and SZ (Fig. 20) curves are generally large (∿.1 °/₀₀) and Fig. 1 (p.5) shows that the subarctic front passes directly through this square. Therefore, averaged TS or SZ curves will contain information from the two distinct water masses separated by the front. The effects of averaging over this front can be seen in the d-d' histograms. The peaks in both the TS and SZ histograms (Figs. 17 and 18, pp. 34 and 35) are at d-d' = -1 dyn cm, offset from zero. This is due to the low salinity water north of the subarctic front shifting the mean curves (TS and SZ) lower on the salinity scale. The observed salinity values used in computing true dynamic height are then generally larger than the mean curve values. In most cases the difference was enough to produce a d-d' difference less than -.5 dyn cm and hence fell into the d-d' = -1 dyn cm range. This test site has shown that when both temperature and salinity are subject to strong variability, as the subarctic frontal motion produces, neither the TS nor the SZ method of dynamic height will give significantly better agreement with true dynamic height.

In the square bounded by 45°-50°N, 165°-170°W the SZ dynamic height compared much better with true dynamic height than did TS dynamic height. The RMS d-d' difference using the TS method was found to be 9.0 dyn cm while using the SZ method the RMS value was reduced to 2.0 dyn cm. In this square only the SZ RMS value is below the 3.1 dyn cm value of observed uncertainty in

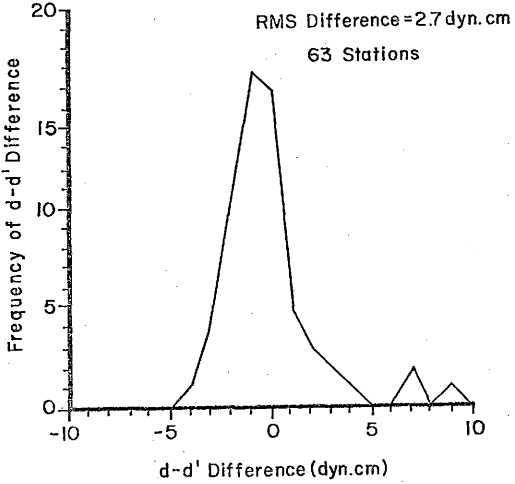


FIG. 17. Histogram of TS d-d' difference for (40°-45°N, 175°-180°E).

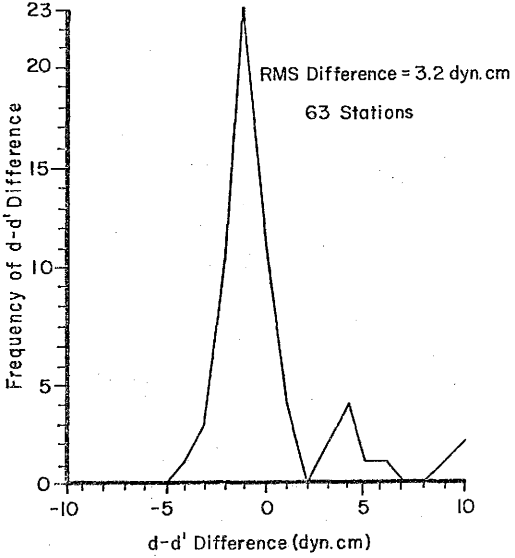


FIG. 18. Histogram of SZ d-d' difference for (40°-45°N, 175°-180°E).

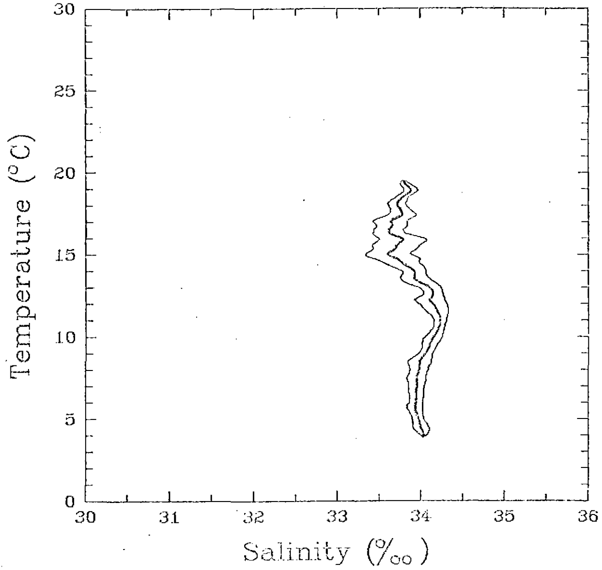


FIG. 19. Mean TS curve for (40°-45°N, 175°-180°E). Lines are as in Fig. 14.

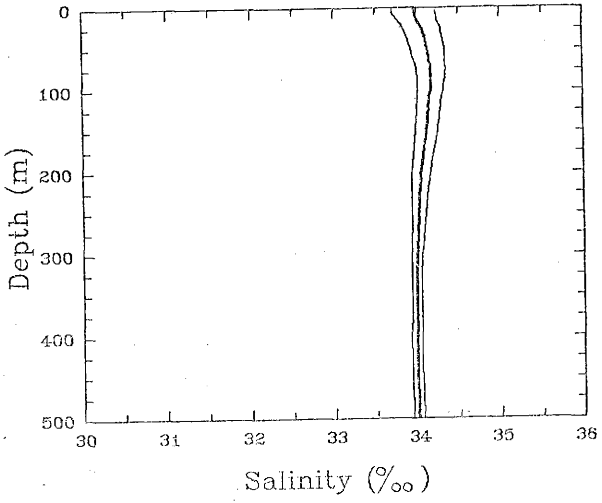


FIG. 20. Mean SZ curve for (40°-45°N, 175°-180°E). Lines are as in Fig. 16.

dynamic height. Also, the SZ d-d' histogram, shown in Fig. 21, is much more gaussian than the bi-modal TS histogram (Fig. 22). The mean TS and SZ curves for this square are in Figs. 23 and 24. The large RMS value from the TS method could have been foreseen as a result of the large salinity standard deviation over the entire curve (Fig. 23, p.41). The area is located within an arctic water type (Sverdrup *et al.*, 1942) and is subject to the effects of northern Pacific temperature inversions (Roden, 1970). Also, the strong dependence on salinity in the formation of water masses in this region has resulted in a greater correspondence of salinity to depth and not to temperature. The SZ curve for the square shows this much smaller variation of salinity with respect to depth (Fig. 24, p.42).

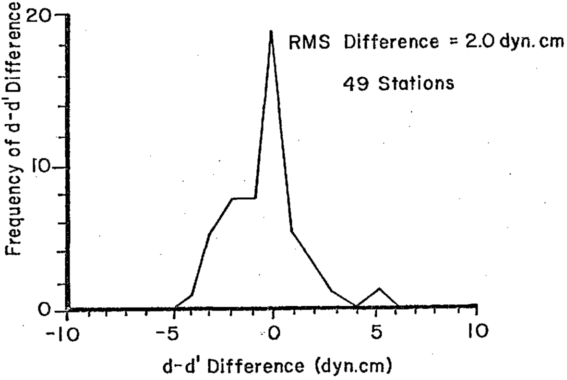


FIG. 21. Histogram of SZ d-d' difference for (45°-50°N, 165°-170°W).

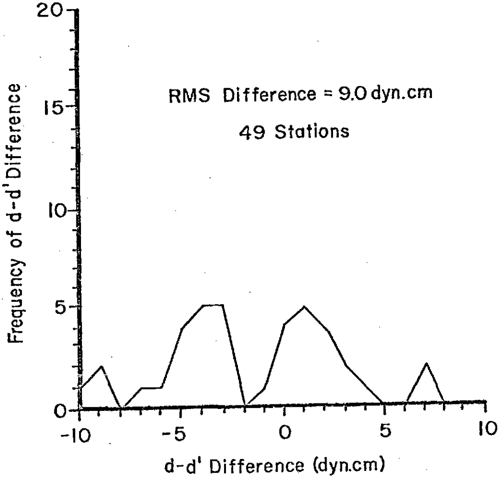


FIG. 22. Histogram of TS d-d' difference for (45°-50°N, 165°-170°W). Eleven stations have a d-d' difference that is beyond ± 10 dyn cm.

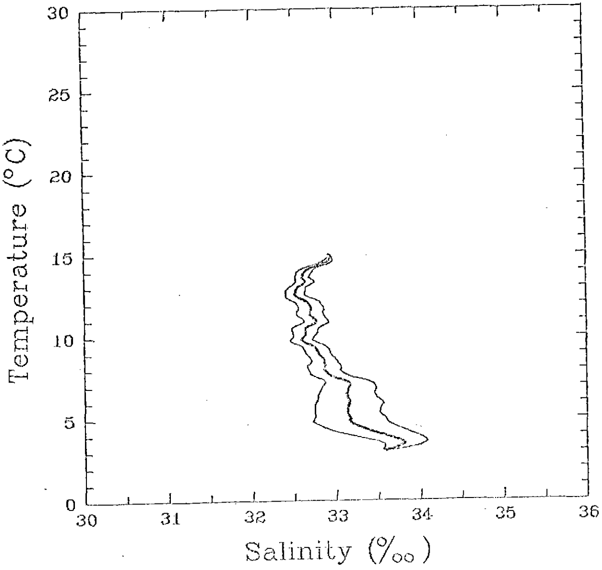


FIG. 23. Mean TS curve for (45°-50°N, 165°-170°W). Lines are as in Fig. 14.

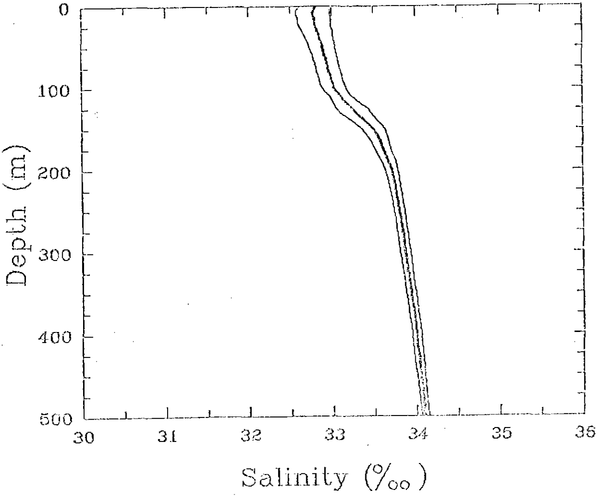


FIG. 24. Mean SZ curve for (45°-50°N, 165°-170°W). Lines are as in Fig. 16.

## 8. Discussion

The effectiveness of the TS and SZ methods are closely associated with the temperature and salinity fronts of the North Pacific Ocean. The subarctic front (Fig. 1, p.5) acts as a boundary south of which the TS method should generally be used and the SZ method to the north. To the north of this front, water mass formation creates a density structure strongly dependent on salinity. As the density structure becomes more dependent on salinity and less on temperature, as is true in the higher latitudes, the SZ method yields better agreement with dynamic height than does the TS method. Also in this northern region, temperature inversions directly affect the TS dynamic height computations which increases the RMS d-d' difference.

In the western North Pacific neither method provides an accurate estimate of dynamic height. The strong contrasts in salinity and temperature between Oyashio and Kuroshio water masses lead to the formation of oceanic fronts between them. These fronts are not stationary and so large changes in temperature or salinity can occur at any point through displacements of the fronts. Since, under this condition, neither the TS nor the SZ relationship could be said to be conserved the poor results for both TS and SZ dynamic heights are not surprising.

The basis for either the TS or the SZ method is the "tight" relationship of the respective parameters, hence, any process which tends to increase the variations in salinity will cause poorer agreement between true and inferred dynamic height. This study has shown that, in most cases, the processes that vary the temperature-salinity relationship are independent of those that vary the salinity-depth relationship. For example, internal waves would cause greater salinity variation in the mean SZ curve than the mean TS curve since the depth parameter is independent of the vertical displacement of the interface between water parcels of differing salinities. As the wave passes, the salinity observed at depths within the influence of the wave would show the changes in salinity at those depth thus increasing the standard deviation in salinity. The TS relationship, though, may not be affected since it is independent of depth. The water parcels sampled above and within the wave would still have the same respective temperature-salinity relationship.

Exploring the small salinity variation of the SZ curve should be continued. Other areas should be tested with both the TS and SZ method to determine if small SZ standard deviations are found to be common and if use of the SZ method is restricted to regions above mid-latitudes.

## 9. Conclusion

Computation of dynamic height using mean SZ curves is found to be more effective than the method of TS dynamic height in most areas north of 40°N. The higher latitude salinities are seen to be less variable with respect to depth than with respect to temperature shown by the standard deviations of salinity for mean SZ and TS curves. For either method to be useful the standard deviation in salinity must be on the order of .1 °/₀₀.

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