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Estimation of Salinity Profiles in the Southeastern Mediterranean off the Egyptian Coast

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Abstract. The main objective of the present study is the estimation of salinity profiles in the upper 500 m from measurements of temperature profiles and surface salinity in the southeastern Mediterranean off the Egyptian coast. 291 Temperature and salinity profiles were selected for this study, taken from expeditions carried out by Egypt and different countries during the period 1963-1990. Six methods were used for estimating salinity profiles in the present study. The results obtained from the climatological salinity-profile data were slightly better than the methods which were obtained by using the traditional mean salinity method. Estimated salinity profiles are able to characterize barrier layers, and regions formed by a halocline within the thermal mixed layer.

Keywords: Surface Salinity, Temperature profile, Regression, Mediterranean, Egypt.

Introduction

The Egyptian Mediterranean coast lies between Longitudes 25°E and 34°E and from Latitude 31°N to Latitude of 34°N. Striking features of this area are the presence of different water masses, which converge and mix. These are the surface water masses of high salinity; the subsurface water mass of minimum salinity and maximum oxygen which is of Atlantic origin and extends between 50-150 m; the intermediate water mass of maximum salinity extends below 150 m to about 300-400 m depth and deep waters which are of the Eastern Mediterranean origin (Said, 1993a). Most of the known characteristics of these water masses have been obtained by constructing T-S diagrams and section of horizontal and vertical distribution of some physical and chemical properties of sea water such as salinity, temperature and oxygen (Morcos and Hassan, 1973 & 1976; Gerges, 1976; Sharaf El Din and Karam, 1976; Maiyza, 1979; Saad, 1984; Abdel-Moati and Said, 1987; Said, 1993b; Said *et al*., 2007; and Said *et al.*, 2009). Salinity and temperature profiles have been also used historically for characterizing ecosystems and for calculating ocean currents by the geostrophic method and could be used in the ocean circulation (Ji and Leetmaa, 1997).

The technology for economical measurements has been developed only for sea temperature (why?) because, sea surface temperature is the most important for air-sea interaction variable and also the subsurface temperature is the dominant variable for sound speed determination. Many of temperature profiles are being measured in the Egyptian Mediterranean waters and used in the present analysis. However, density or specific volume is the important dynamic variable in the ocean, and density is determined by both temperature and salinity. In this paper we represent approaches or schemes to estimate salinity profiles for assimilation into numerical circulation models or for such other applications, as they may be needed. The main objective is to estimate salinity profiles (in the upper 500 m) from measurements of temperature profiles and sea surface salinity in the southeastern Mediterranean off the Egyptian coast.

Methods of Analysis

The most frequently used method for estimating salinity has been the climatological average, so numerical models of oceanic circulation are usually initialized in this way (Chassignet *et al*., 1996; and Ji *et al.*, 1995], and this approach has also been used for updating model runs in which other variables are being assimilated from observations (Carton and Hackert, 1990). Although this procedure suppresses the effects of salinity anomalies, the results of Sprintall and Tomczak (1992) indicate that it can capture at least part of the barrier layer phenomenon. Stommel (1947) proposed use of the statistical relationship between salinity and temperature (*T-S*) to estimate salinity from more plentiful temperature-profile data: $\hat{S}(z) = \acute{S}[T(z)]$. (An over slash is used to indicate average at fixed temperature, while angular brackets will be used to indicate average at fixed depth. $\hat{S}(z)$ denotes the estimated value for salinity at the depth z). Stommel (1947) concludes, this method can be used in regions having a well-defined temperature-salinity (*T*-*S*) relation, *i.e.*, in regions of sufficiently uniform water mass characteristics. Emery and O'Brien (1978) found that using the mean salinity profile $\hat{S}(z) = \langle S(z) \rangle$ gives more accurate estimates of geopotential height than does Stommel's method at latitudes higher than about 35°N in the Pacific.

Donguy *et al.* (1986) introduced modification of the basic method for a data set in which temperature profiles were complemented by measurements of surface salinity. Vossepoel *et al.* (1999) have introduced a hybrid scheme that estimates salinity below the bottom of the thermally mixed layer by the *T*-*S* method and within the isothermal layer by linear interpolation to measured sea-surface salinity. This method frequently will yield fictitious barrier layers beginning right at the surface in tropical regions. Where surface salinity is anomalously high, it also can produce fictitious density inversions beginning at the surface.

Hansen and Thacker (1999) have improved upon use of the mean salinity profile by exploiting correlations of salinity at a given depth z with other observables such as temperature at that depth, surface salinity, and latitude. The algorithm can be stated concisely as a generic regression equation:

$$\hat{S}(z) = \langle S(z) \rangle + \sum_i a_i(z) \left(P_i - \langle P_i \rangle\right)$$

Where angle brackets denote climatological averages, P_i represents the variables that are used as predictors, and the values of the coefficients a_i are derived from regressions for each depth z. Estimates are modifications of the climatological salinity profile by deviations of the observed predictors from their climatological means.

This method has been applied in the present work for estimating salinity profiles in the 3°×9° area in the southeastern Mediterranean between Longitudes 25° and 34°E and Latitudes 31° to 34°N, Fig. 1.

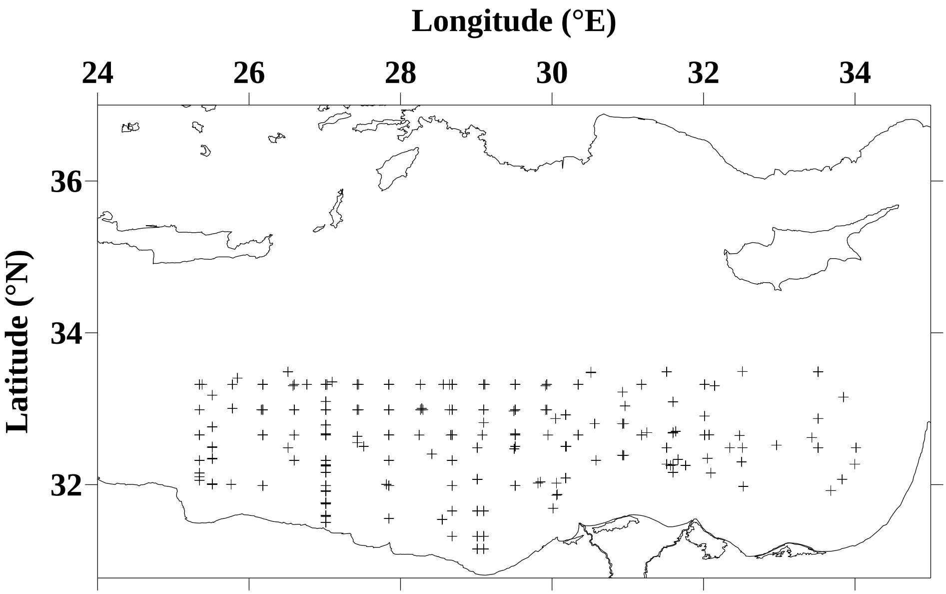

Fig. 1. Region of the study area and spatial distribution of selected data profiles.

The data used in this study have been taken from several expeditions carried out by Egypt and different countries during the period 1963-1990. Figure 2, shows the spatial and temporal distribution of the 291 selected profiles. The profiles had data listed in different intervals (0, 10, 20, 30 50, 75, 100, 150, 200, 250, 300, 400 and 500 m). Only the data for the upper 500 m were used, because that range are the most available profiles and also it facilitates comparisons with other studies. The salinity and temperature profiles and T-S curves for these data are shown in Fig. 3. The salinity profiles reveal some variability in the surface mixed layer commonly reaches nearly 1.79 psu. The haline mixed layer commonly reaches 30 meter or more, indicating that surface salinity is a useful indicators of upper salinity in this region. Below a depth about 250 m the scatter among the profiles becomes small. The temperature profiles exhibit much less variability in the surface mixed layer and relatively little scatter below the thermocline. The T-S relationship is well defined for temperatures less than 16 °C but becomes increasingly ill defined from the bottom of the thermocline to the surface.

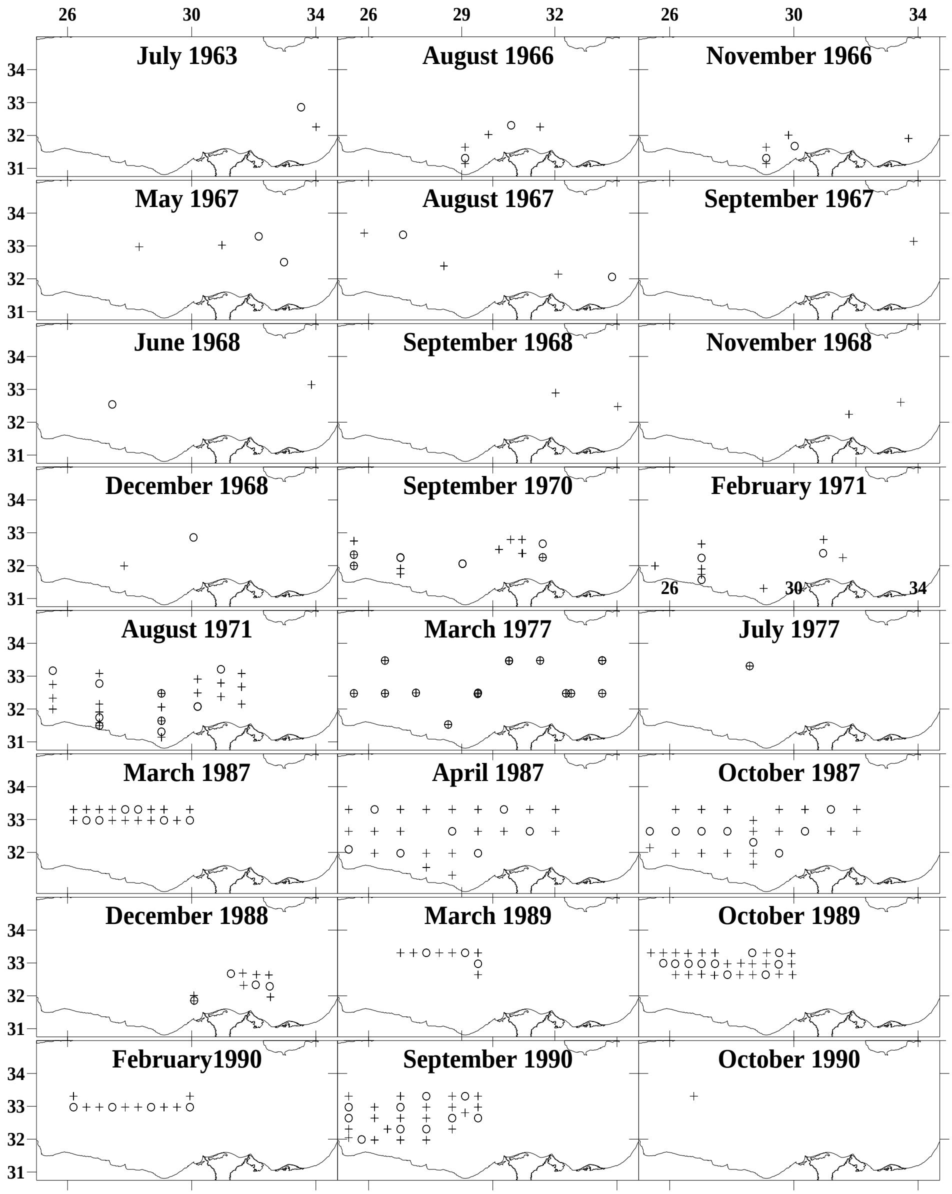

Fig. 2. Time-space distribution of data casts used in the present study (circle indicates verification data; plus denotes training data).

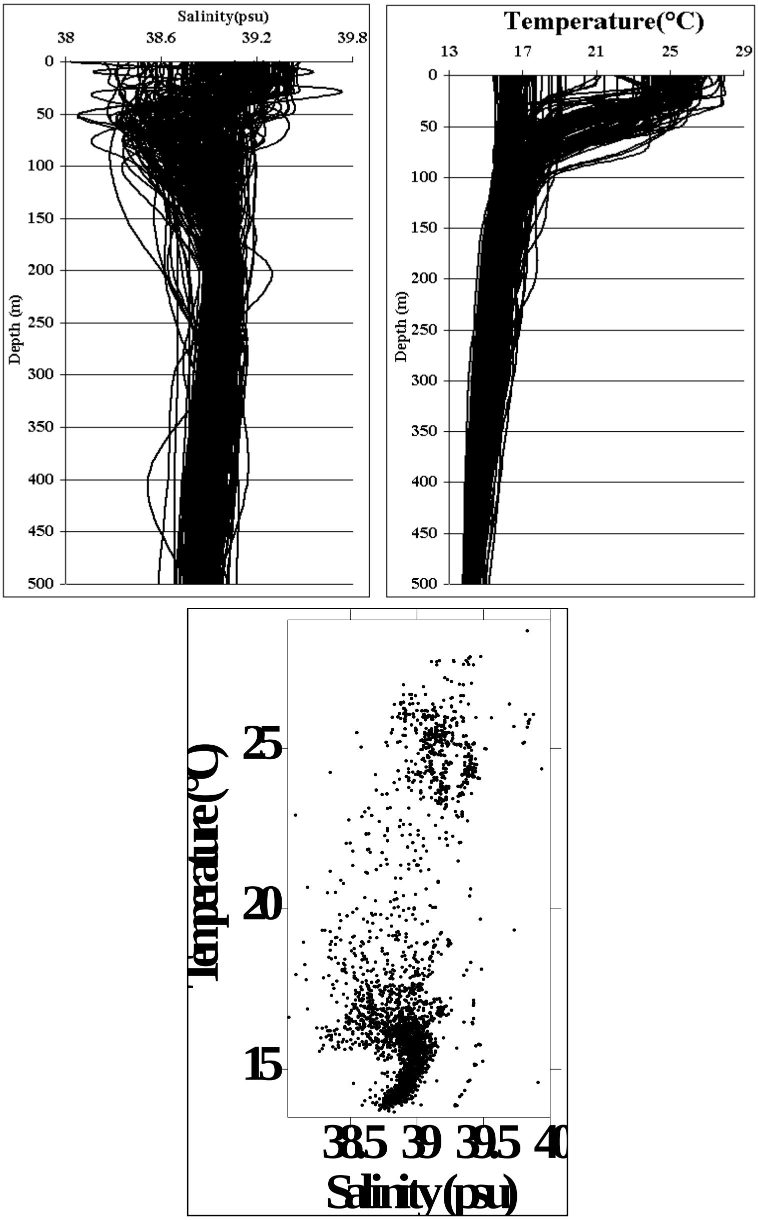

Fig. 3. Profiles of (left) salinity-depth and (middle) temperature-depth and (right) temperature-salinity for the 291 data sets used in this study.

The mean profiles <S(z)> and <T(z)> are shown in Fig. 4 together with their standard deviations. Correlation coefficients between salinity S(z) and temperature T(z) and between S(z) and surface salinity S(0), which are central to the regression models discussed below, are shown in Fig. 5. Correlation with temperature is nearly high and positive in the upper 50 m, nearly zero in 50 m, small and negative between about 50 m and 250 m, and positive below 250 m depth. The reversal sign of these correlations near 250 m reflects the presence of the salinity maximum *i.e.*, vertical displacements causing changes in S and T to have opposite signs. Correlation with surface salinity is strong in the above 50 m, where correlation with temperature is nearly high and negligible elsewhere. The complementary nature of these correlations suggests that their joint use should be advantageous. The 291 temperature and salinity profiles were separated into two sets, 198 profiles comprising the training data to be used for model fitting (indicated by plus in Fig. 2 and 93 profiles for independent verification (represented by circles).

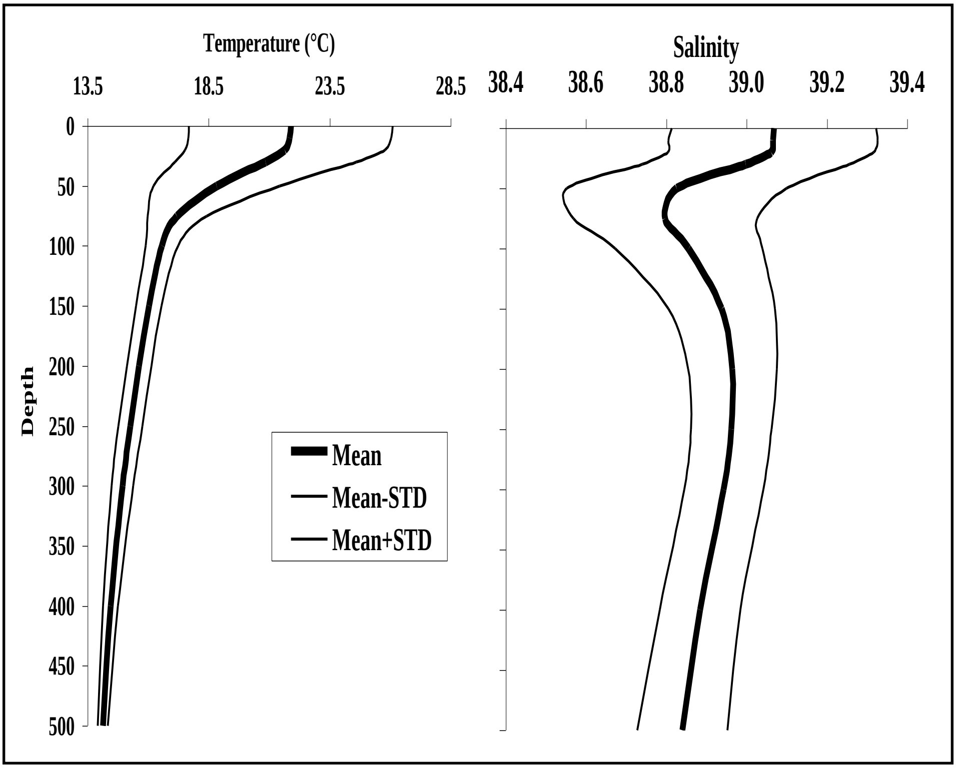

Fig. 4. Mean values of (left) temperature and (right) salinity shown by thick curves for the 291 data sets used in this study, and standard deviations from means shown by thin curves.

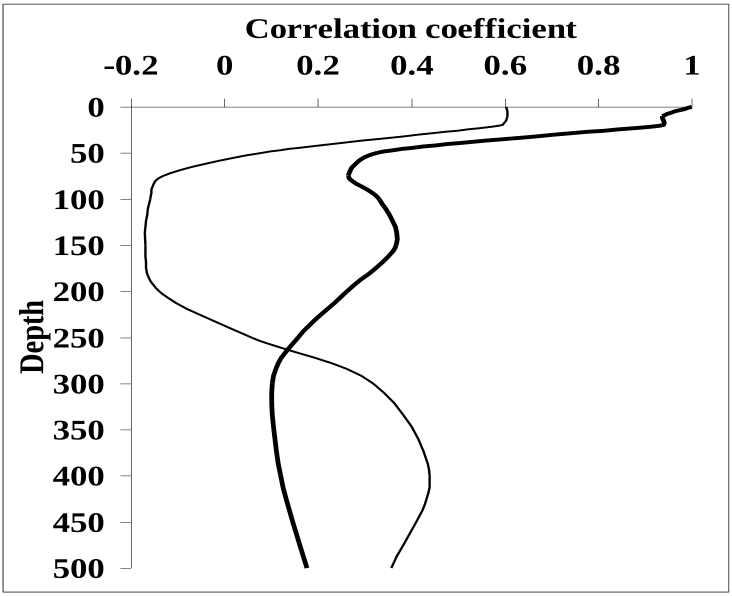

Fig. 5. Thick line represents correlation coefficient between surface salinity S(0) and S(z); and Thin line between S(z) and T(z) at different depth interval.

Results and Discussions

Estimated Salinity Profiles from Six Methods

Salinity profiles were estimated for the upper 500 m using the mean salinity profile, and five variants of the regression procedure for the 93 profiles of the verification data set. The root mean square (RMS) differences between the estimated and measured salinities for the verification profiles were then computed and are shown in Fig. (6).

The Mean Salinity Method

This method examines the estimation of salinity by its climatologically mean:

$$\hat{S}(z) = \langle S(z) \rangle \quad (1)$$

The RMS errors for this method were labeled “mean salinity”; and appear as the rightmost profile in Fig. 6 left. This method captures more variability at 200 m depth but small variability at 500m. Near the surface, errors slightly exceed the variability because of the difference between the training and verification data.

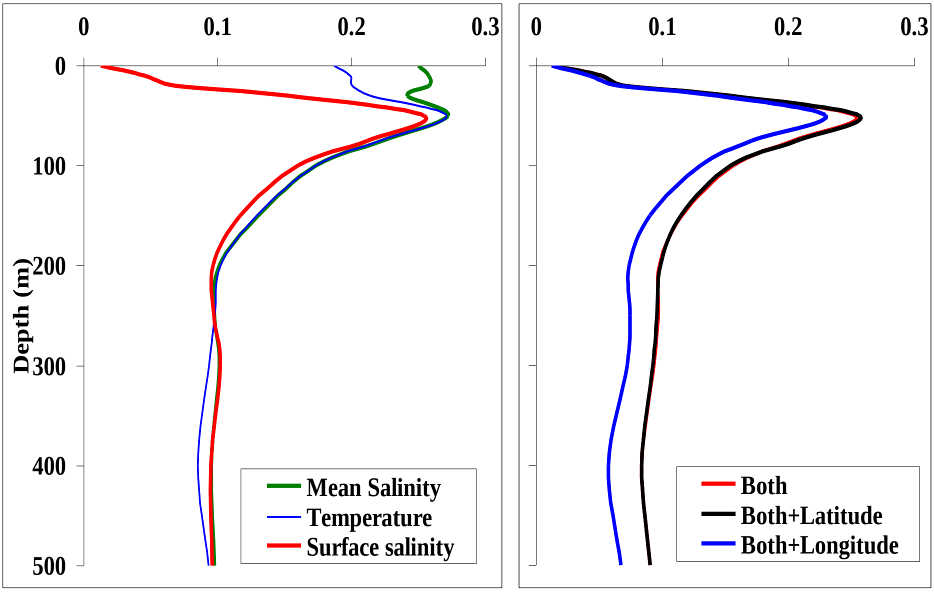

Fig. 6. Root mean square errors for various methods of estimating salinity profiles of verification data. (Left) errors for mean salinity profile, regression on temperature and regression on surface salinity. (Right) errors for regression on both surface salinity and temperature, surface salinity, temperature and latitude and surface salinity, temperature and longitude.

The Temperature Method

The complementary of depths at which the T-S and climatological mean methods perform best suggests merger of these methods, using observed temperature to improve upon the climatological mean salinity in a regression model (Hansen and Thacker 1999):

$$\hat{S}(z) = \langle S(z) \rangle + aT(z)\,[T(z) - \langle T(z) \rangle] \qquad (2)$$

This method and those discussed below were fitted to the training data. Although the model was fitted independently at each level of the selected interval, the coefficients varied smoothly with depth. The RMS errors, labeled "temperature" in Fig. 6, left; show that this approach realizes better than the mean salinity method in the upper 50m and down 250m; and in the depth interval 75 to 250 m the two methods are equivalent. These results are supported by the correlation theme in Fig. 5, which represents the existence of a high correlation between salinity and temperature for the upper 50 m layer and below the 250 m depth and low correlation in the depth interval 50 to 250 m.

The Surface Salinity Method

We turn now to the issue of using measurements of surface salinity to capture some of the variability that characterizes the upper several tens of meters. First, we consider their use in the absence of an observed temperature profile. At each depth z a regression equation establishes how deviations of the observed surface salinity from its mean modify the estimates based on the mean salinity profile:

$$\hat{S}(z) = \langle S(z) \rangle + as(z)\,[S(0) - \langle S(0) \rangle] \quad (3)$$

Owing to the strong correlation of S(z) with S(0) in the upper 50 m of the water column, the RMS estimation error, labeled "surface salinity" in Fig. 6 left, is reduced to 0.15 psu in the upper 30m. Deeper than 50 m, surface salinity provides no information, the regression coefficient $a_s(z)$ is essentially zero, and the "surface salinity" curve of Fig. 6 left, becomes coincident with the "mean salinity" curve.

The Surface Salinity and Temperature

It is straightforward to include deviations of both surface salinity and temperature profile from their means to estimate deviations of salinity:

$$\hat{S}(z) = \langle S(z) \rangle + aT(z)\,[T(z) - \langle T(z) \rangle] + as(z)\,[S(0) - \langle S(0) \rangle] \quad (4)$$

The values of the coefficients a_T and a_s are not the same as those for equations (2) and (3); they must be determined by fitting equation (4) to the training data. However, at depths where surface salinity carries no information about the subsurface salinity, it turns out that, a_s (z) decrease to nearly zero and $a_T(z)$ is the same as that found for equation (2). The curve labeled "both" in Fig. 6 right, indicates that near the surface this extension yields no improvement over use of surface salinity, but it further reduces errors in all depths deeper than 250 m.

All the methods we have described above are expected to do best in application to homogenous water mass. However, for reliable statistics, data must be drawn from sizable region, *e.g.*, our 3°×9° region, over which horizontal gradients of water properties may contribute significantly to the variances about the mean profiles. To test the possibility of capturing part of this variability as those discussed below, the Latitude ϕ and Longitude φ would be added to the other predictors, because the climatologically structure in the Mediterranean Sea is primarily zonal.

The Surface Salinity and Temperature Plus Latitude

In this method, the latitude was added to the set of predictor as shown in equation (5). The results were indistinguishable from those obtained using both Surface salinity and temperature method.

$$\hat{S}(z)=\langle S(z)\rangle+aT(z)[T(z)-\langle T(z)\rangle]+as(z)[S(0)-\langle S(0)\rangle]+a\phi(z)[\phi-\langle\phi\rangle] \tag{5}$$

The Surface Salinity and Temperature Plus Longitude

The use of Longitude was surprisingly beneficial, yielding (left most curve in Fig. 6, (right) some further reduction of errors in the troublesome interval from 50 m to 100 m and also at all depths greater than 150 m. Above 50 m, the errors are nearly coincident with those from other methods using surface salinity. The coefficients are functions with z (6) reducing to the simpler models when predictors offer no information.

$$\hat{S}(z)=\langle S(z)\rangle+aT(z)[T(z)-\langle T(z)\rangle]+as(z)[S(0)-\langle S(0)\rangle]+a\varphi(z)[\varphi-\langle\varphi\rangle] \tag{6}$$

Results from six methods of estimating salinity profiles have been presented in the present work, including one conventional procedure using mean salinity. The curves had shown in Fig. 6 sorting themselves into three classes in the near surface and three different classes in deep waters. The first five methods are nearly indistinguishable near 250 m depth. Near surface, the largest errors are associated with mean salinity method. However the mean salinity with addition of temperature data, are slightly better. The use of salinity only as predictors substantially reduces the RMS estimation error. Additional of surface salinity information to the climatologically profiles reduces the estimation errors to 0.15 psu in the upper 30 m.

At depth 50 to 200 m, inclusion of temperature information by regression is more benefitial than mean salinity. At depths greater than 200 m, all methods of using temperature provide equivalent results, reducing the errors to 0.09 psu or less. Surface salinity provides no improvement at 50m depths. Latitude provides no improvement than both of surface salinity and temperature. Inclusion of Longitude gives further improvement in lower than 50m, yielding the smallest errors at nearly all depths. The model (6) performs best in all depth ranges. To illustrate the ability of the model (6) to replicate individual salinity profiles, all 93 observed and estimated salinity profiles at each selected interval of the verification data set are displayed in Fig. 7. In addition, 32 samples of these observed and estimated salinity profiles are displayed in Fig. 8; the associated temperature profiles of these samples are shown in Fig. 9.

Conclusion

Six methods were used for estimating salinity profiles in the southeastern Mediterranean off the Egyptian coast. Only 291 temperature and salinity profiles were selected for this study, taken from expeditions carried out by Egypt and different countries during the period 1963-1990. The profiles were separated into two sets, 198 profiles comprising the training data are used for model fitting and 93 profiles for independent verification. The skills of the used methods were demonstrated for the experimental area for its apparent difficulty. Sea surface salinity provides additional information relevant to the part of the salinity profile where the uncertainty otherwise is greatest. Results obtained from the climatologically salinity-profile data were slightly better than the methods which were obtained by using the traditional mean salinity method.

Extensive use of equation (6) in support of Sea analyses based on assimilation of observation into circulation models will require enhancement of surface salinity observations and compilation of the climatologically means. Application of model (2) to regional analyses for which the T-S method has been used previously in many years is obvious and straightforward and can be improved by including location data.

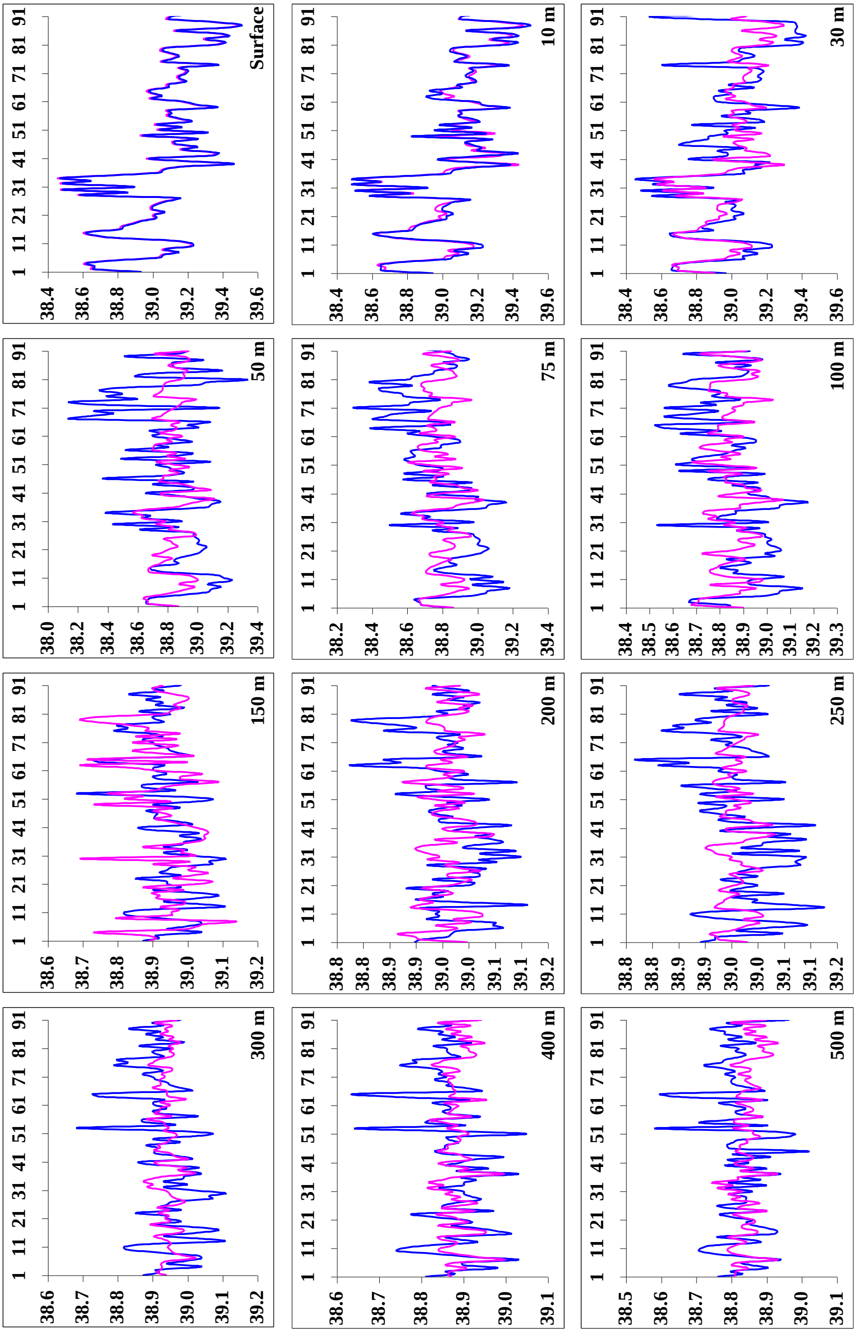

Fig. 7. Measured (blue) and estimated (pink) salinity for verification data in some of selected data levels.

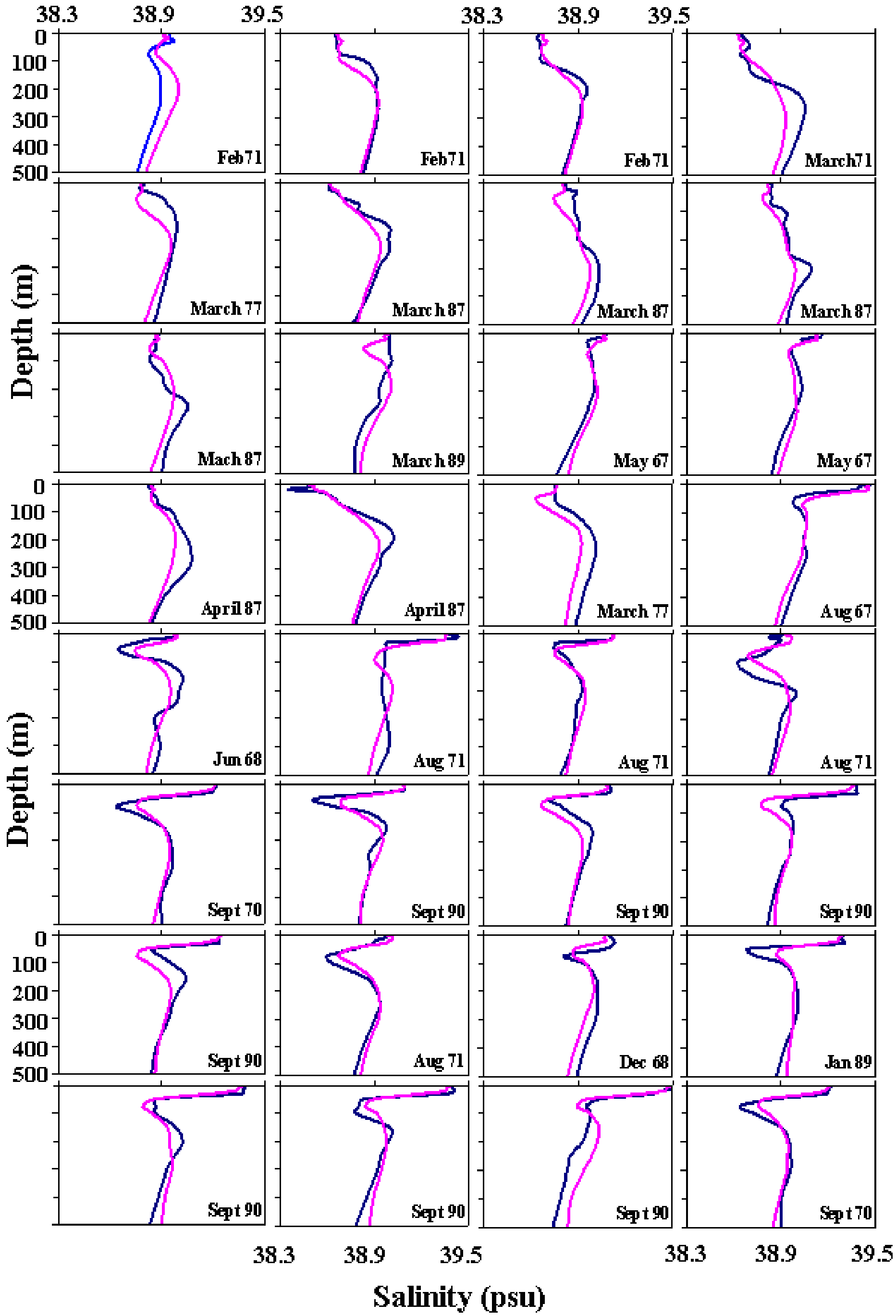

Fig. 8. Estimated (pink) and observed (blue) profiles of salinity for the 32 casts that were not used in establishing statistical relationships.

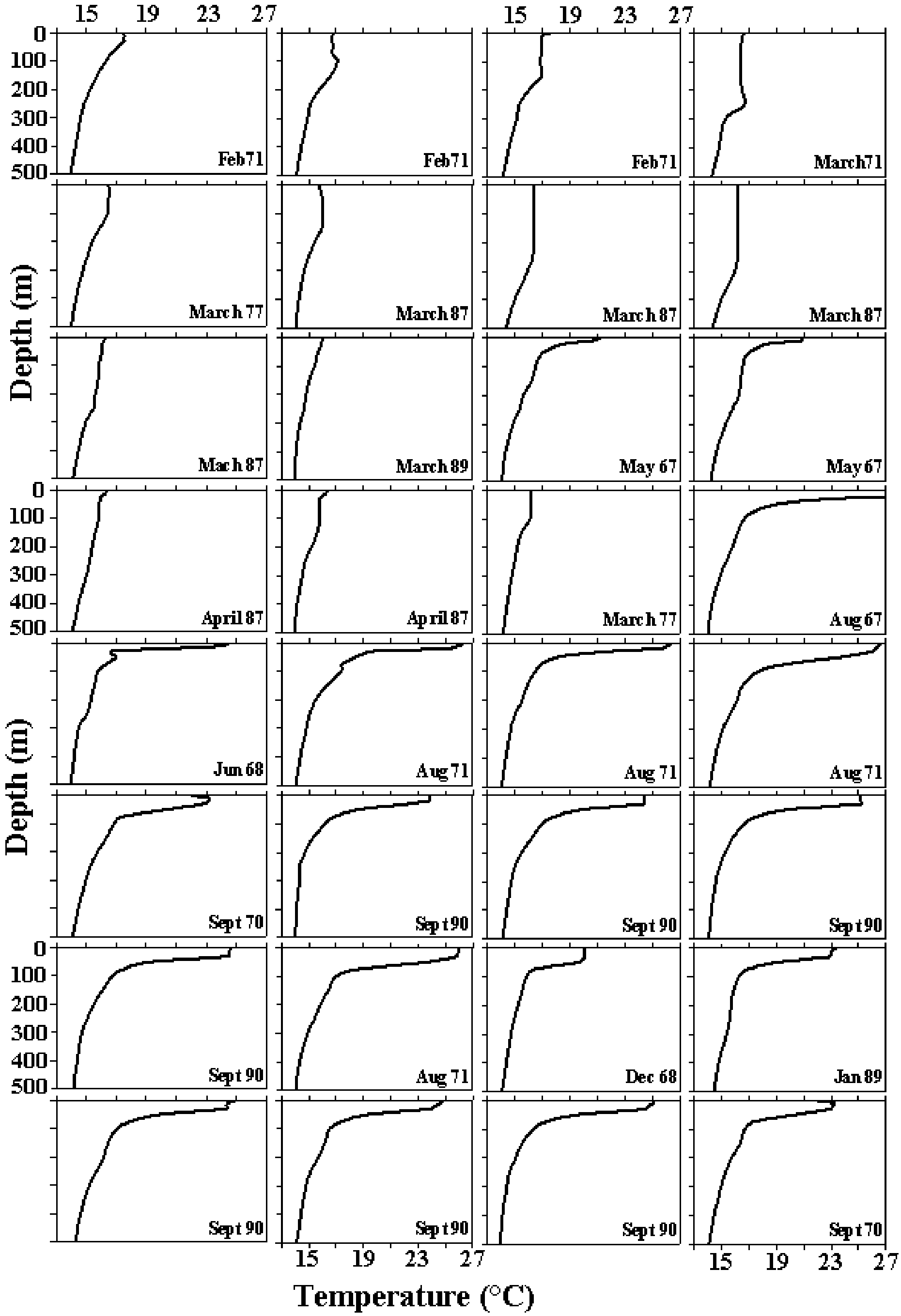

Fig. 9. Observed profiles of temperature that were used in estimating the salinity profiles in Fig. 8.

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استنتاج قيم الملوحة أمام الساحل المصرى جنوب شرق البحر المتوسط

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المستخلص. الهدف الرئيسي من هذه الدراسة هو استنتاج قيم الملوحة في الجزء العلوي من مياه البحر (حتى عمق 500 متر) من قياسات درجات الحرارة (عند نفس العمق)، والملوحة السطحية في جنوب شرق البحر الأبيض المتوسط أمام السواحل المصرية. وقد تم اختيار 291 عينة فقط من درجات الحرارة والملوحة لهذه الدراسة، تلك العينات جمعت بواسطة رحلات قامت بها مصر وبلدان مختلفة خلال الفترة 1963–1990. وتم فصل العينات إلى مجموعتين: المجموعة الأولى وبها 198 عينة استخدمت بياناتها فى التدريب المناسب للنموذج، والمجموعة الثانية بها 93 عينة آستخدمت بياناتها فى عملية التحقق من دقة البيانات المستنتجة من النموذج. استخدمت ست نماذج مختلفة لاستنتاج قيم الملوحة لعمود المياه (المحدد سابقاً في هذه الدراسة). وكانت النتائج التي تم الحصول عليها لقيم الملوحة المستنتجة افضل من تلك النتائج التي يتم الحصول عليها باستخدام الأسلوب التقليدي (متوسط قيم الملوحة). كما أن هذه الطرق غير التقليدية كان لها القدرة على تمييزالحد الفاصل بين الطبقات، والتى تتكون بواسطة الخط الحراري الفاصل للطبقة العلوية المختلطة الحرارة من البحروالطبقات التى أسفل منها. بذلك يمكننا أن نستنتج قيم الملوحة لعمود المياه، حتى 500 متر عمق باستخدام قيم الملوحة السطحية، ودرجات الحرارة و خط الطول للعينة.