Research Article

Hydrographic Measurements in the North Western Coastal Area of Malta

Aldo F. Drago
Malta Council for Science and Technology, Valletta, Malta.

Summary. *The first synoptic CTD data set obtained during summer 1992 in the coastal waters of the Maltese Islands is presented. The nature of the summer water structure in the upper 50m depth reveals a strong water column stratification with significant horizontal gradients in both temperature (T) and salinity (S). A diurnal vertical oscillation of the thermocline is confirmed by comparison with subsurface temperature time series recorded at an open sea station in the area of study. The T,S profiles are characterised by very sharp salinity reversals at the subsurface layer where a stepwise micro-structure is developed.*

Keywords: CTD, coastal, double diffusion, salinity, salt fingering, temperature, micro-structure

Physical oceanographic data in the nearshore and coastal waters of the Maltese Islands is generally lacking. Before 1991, the only published measurements (Havard, 1978) are those carried out in the framework of the IOC/UNEP (Intergovernmental Oceanographic Commission/United Nations Environment Programme) co-ordinated pilot project MED-VI. Within this project several mechanical bathythermograph (BT) measurements were made between April-July 1976. The abrupt interruption of this work in 1980 resulted in the loss of these unarchived and unprocessed data.

Later, data from this work together with BT, XBT (expendable bathythermo-graphs) and hydrographic data extracted from data banks were reviewed in the paper presented at the CERP (Coastal Environment Research Project) Workshop in 1991, (Drago, 1991). Although these data include only few hydrographic stations in the close vicinity of the Maltese Islands, it can be inferred that the nearshore summer water column structure is dominated by a solar heated upper water mixed layer, averaging 20m in depth. Sustained sea surface evaporation rates increase the salinity which reaches maximum values of S=38.0 to the south of Malta. The high surface temperatures between 20-26°C formed a well stratified surface layer above the cooler and relatively fresher Modified Atlantic Water (MAW). In the underlying layer, the water mass has a characteristic temperature of 15°C and a salinity of S=38.4, which indicates the influence of the modified Levantine Intermediate Water (LIW). The winter mixing processes result in the homogenization of the water column up to depths in excess of 100m, and with temperatures on average 0.5°C higher to the south of Malta.

The CTD data set

The first physical oceanographic campaign in the Maltese coastal waters was carried out as part of the CERP programme, during August 1992. This two-week long survey aimed to obtain valuable information on the circulation and water column structure in the North Western coastal area of Malta, comprising Mellieha Bay and St. Paul's Bay. The data were acquired from the 20-foot boat *Sabrina* by means of a profiling ICTD (Conductivity-Temperature-Depth) probe from Falmouth Scientific Inc. (FSI). The ICTD carried both a platinum thermometer and a fast thermometer which enabled very precise determination of sea water temperatures at the rate of 25 scans per second down to a depth of about 50m. The ICTD was calibrated at FSI three months before the survey. The location of the 26 CTD stations shown in Fig. 1 covers an area of approximately 12 square nautical miles. The CTD casts were made over a period of 3 successive days (16-19 August 1992).

A 1200Khz RD Instruments shipborne Acoustic Doppler Current Profiler (ADCP) was also utilised for vertical profiles of water currents at 1m depth bins up to a depth of 30m and at 30 second intervals along selected transects. In addition, a subsurface current meter mooring was deployed at a location approximately mid-way between Dahlet-ix-Xilep on the Mellieha Bay western headland, and the White Bank to the northeast. This location is situated between the CTD stations 11, 13 and 14. Two RCM4 Aanderaa current meters were used at 23m and 6m from the seabed respectively, and in a total water depth of 35m.

Processing of CTD data

The pre-processing of the station raw data files consisted in the detection and auto-correction of salinity spikes according to prescribed allowed levels of fluctuation. After converting pressure data into engineering units, pressure averages of the unscaled temperature and conductivity values at pressure intervals of 2 decibars were then calculated. In this process a correction was applied to eliminate the effect of time lags between the temperature and conductivity sensors. An exponential recursive filter was used by means of the following algorithm:

$$C(t)=C(t-dt)\exp[-dt*\tau_c/\tau_f] + C_{raw}(t)\,(1-\exp[-dt*\tau_c/\tau_f]$$

$P(t)=P(t-dt) \exp[-dt*\tau_c/\tau_f] + P_{raw}(t) (1 - \exp[-dt*\tau_c/\tau_f]$

where C(t), P(t)=lagged Conductivity/Pressure value at time t
$C_{raw}(t)$, $P_{raw}(t)$=raw Conductivity/Pressure value at time t
dt=CTD sampling interval in seconds;
τ_c, τ_f=time constants of conductivity cell/fast thermistor.

The fast thermistor temperature was then added to the Pt thermometer temperature to give the summed temperature T(t) as follows:

$F(t)=F(t-dt) \exp[-dt*\tau_f/\tau_{pt}] + F_{raw}(t)(1 - \exp[-dt*\tau_f/\tau_{pt}])$
$F'(t)=Fraw(t) - F(t)$
$T(t)=Tpt(t) + F'(t)$

where $F_{raw}(t)$=raw thermistor temperature at time t;
$T_{pt}(t)$=raw Pt thermometer temperature;
τ_{pt}=time constant of platinum thermometer.

In the pressure averaging process, values in air were flagged and ignored; the lowering rate dP/dt was calculated in order to detect pressure reversals. At such reversals the last previously good data value was substituted in order to keep the time sequence in the averaging.

The pressure averaged temperature and conductivity values were finally converted into engineering units. In this process, values of conductivity were adjusted for cell distortions by temperature and pressure. The location in time of the temperature and conductivity averages may not necessarily coincide with the centre of the pressure interval; in order to ensure a uniform pressure series, temperature/salinity gradients with pressure were thus used to calculate interpolated values in synchronisation with the central pressure.

Salinity was computed from the averaged P, T and C values using the PSS-78 algorithm. The pressure averaged values were also used to calculate other parameters treated in the study. A special Fortran code was developed in order to prepare files of the studied parameters at selected depths. Horizontal contour plots were made by means of SURFER, a PC product by Golden Software Inc.

Water column structure
The T/S profiles in Fig. 2 show the summer stratified structure of the water column that characterises the study area. A surface thermally heated and more saline mixed layer extends to an average thickness of 16m. This surface layer is separated from the underlying Modified Atlantic Water by a very sharp halocline that overlies some remarkable salinity reversals at depths between 15-30m. These reversals occur at depths coinciding with a monotonic temperature and density profile. The composite T-S diagram (Fig. 3) confirms an extensive range of mixing between the surface mixed layer with average values of T=27.5°C, S=37.74 and the underlying water mass of MAW origin characterised by T=16°C, S=37.45.

The water column in the bays is homogeneous due to the intense surface heating. The profiles in Fig. 4 show the temperature and density horizontal structure in St.Paul's Bay. The water body in this bay is greatly dominated by the salinity with a consistent along-axis gradient of the order of 0.025 Km^{-1}. This is an indication that the water in the bay has a relatively long retention time while at the same time it is undergoing vertical mixing.

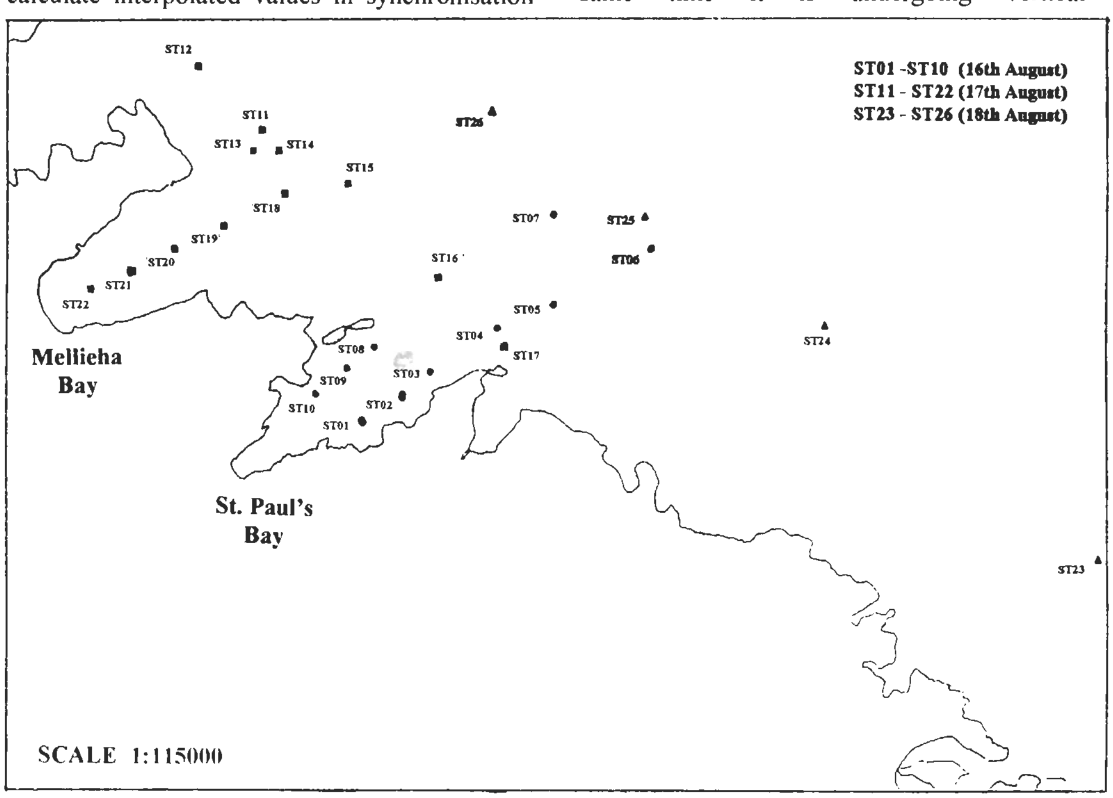

Figure 1. CTD stations in the NW coastal waters of Malta.

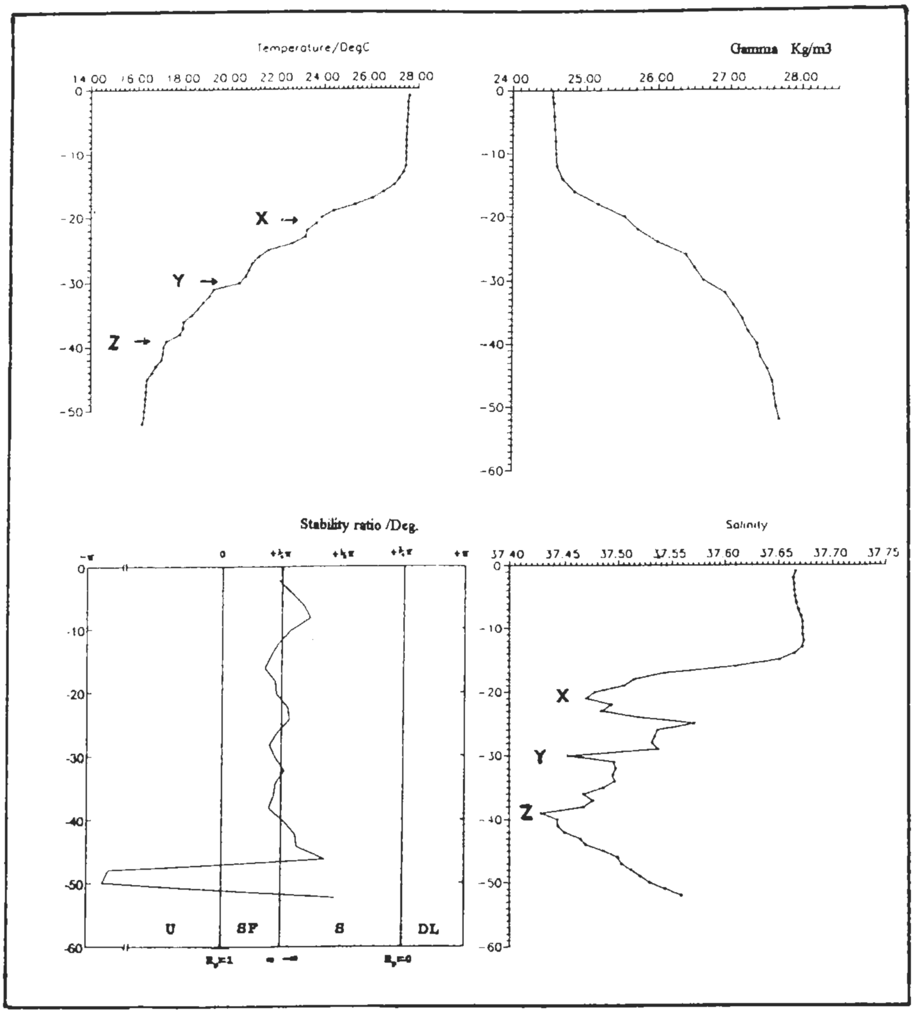

Figure 2. Temperature, salinity, density and stability angle profiles at station 25 (Position 35° 58.93'N 14° 27.21'E Depth 55m).

The CTD data and the temperature data time series, recorded by the thermistor probes of the two current meters, reveal an oscillation of the thermocline. The position of the current meters, with respect to the thermocline (Fig. 7), indicates that the vertical movement of the thermocline is followed very precisely from the recorded temperature variations. The upward movement of the thermocline results in a decrease of the temperature at the upper current meter when it becomes immersed in the thermocline and is exposed to cold water. Moreover, when the thermocline is moving downwards the temperature at the lower current meter increases as it is exposed to warm water carried from the water layers above it. These temperature fluctuations occurred for a few days in the second half of August and reached average values of 8°C. By early September, the mixed layer engulfed completely the upper current meter and the temperature variations disappeared. The CTD casts at nearby stations carried out on the 17th of August, show that the average temperature gradient along the thermocline is $0.5^{o}Cm^{-1}$. The magnitude of the vertical oscillation of the thermocline was thus quantified to be of the order of 4m.

STATION NUMBER	MIXED LAYER THICKNESS	TIME OF CAST (GMT)	DAY
4	16	07H40	
5	19	08H06	
6	19	08H55	AUG 16
7	16	09H40	
8	16	10H40	
11	10	06H14	
12	9	06H37	
13	9	07H08	
14	9	07H50	
15	11	08H25	
16	10	08H42	AUG 17
17	12	09H08	
18	10	09H50	
19	11	10H10	
20	11	10H30	
21	13	10H42	
23	15	06H27	
24	15	07H14	AUG 18
25	13	07H48	
26	11	08H25	

Table 1: Variation of thermocline depth.

On the basis of the vertical extent of the mixed layer (Table 1), these CTD casts carried out in the open sea area can be grouped into three sets, that coincide with the respective days of measurement. Considering that these CTD data sets were collected over a short period during each day, this grouping can be related to the phasing of the thermocline oscillation. The variation in the thickness

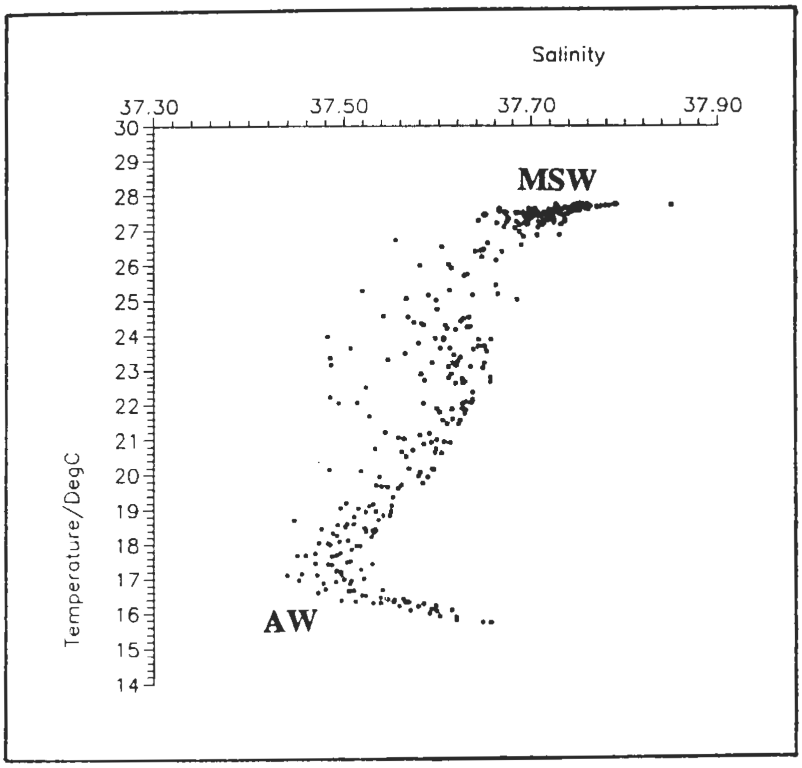

Figure 3. Composite T-S Diagram (16-19 August 1992).

of the mixed layer (Fig. 6), observed during different days by the CTD casts ST06 and ST25 agrees with the phase of the temperature time series recorded at the nearby current meter station.

Fig. 5 shows the contours of temperature, salinity and density at three depths, in the mixed layer (8m), on the pycnocline (20m) and below (30m) respectively. A positive salinity gradient exists towards the coast, and a negative gradient for temperature. The latter parameter is dominant on the water density. The disposition of the temperature and density isolines in the mixed layer suggests an anticyclonic residual flow around the White Bank. An opposite return flow outside Mellieha Bay proceeds further downcoast towards southeast. The horizontal distribution of temperature below the surface mixed layer is affected by the vertical movement of the thermocline. This may be aliased into fictitious horizontal gradients. The reversal of the thermocline gradients in the deeper layer with respect to those in the mixed layer may be artificial, especially in the areas closer to the shore.

Salinity gradient reversals

At the bottom of the sharp halocline, salinity gradient reversals are observed. This salinity neutrally buoyant tongue is associated with step-like fine structure in temperature and density and is present in the whole area outside the bays. It is exemplified by the CTD plots at ST25 at the eastern extremity of the area of study (Fig. 2), and at ST14 (Fig. 8) close to the current meter station. Reviewing older data, collected in 1976, a striking sequence of steps and layers is also noted in the summer bathythermograph profiles to the north of the Grand Harbour and in the southern Comino Channel. This phenomenon appears to exist in the whole northern coastal area of the Islands. The small scale structure of the thermohaline fluctuations consists of successive 'layers' of nearly uniform density that are separated by thin interfaces or 'sheets' where the gradients are large. This type of microstructure in the water column has been observed in much of the central waters of the world's oceans and especially in the Mediterranean Outflow by Tait and Howe (1968), Howe and Tait (1970), Magnell (1970) and more recently by Washburn and Kase (1986). In the Tyrrhenian Sea, the deepest recorded stepped structure was found at depths below 600 dbars and down to 2800 dbars (Zodiatis and Gasparini, 1996). Fine thermohaline formation associated to lens formation in the SE Ionian Sea, at a depth of 400 dbars, has also been reported by Zodiatis (1992). The occurrence of this type of T, S structure in coastal shallow areas has been recently reported in the Arabian Gulf by Sultan and Elghribi (1996). The fine structure in the coastal waters of the Maltese Islands is considered to result from the convergence of cool and less saline MAW with the warm and saline surface coastal water. This gives rise to situations where variations of one property alone determines the density and the interfaces that are unstable to double-diffusive processes.

A controlling parameter in the fluxes of heat and salt between two well-mixed layers is the density ratio R_p, defined as:

$$R_p = aT_z/bS_z$$

where T_z and S_z are the vertical in situ temperature and salinity gradients, a is the coefficient of thermal expansion (a>>0), and b is the coefficient of haline contraction. Following the laboratory experiments by Schmitt (1979), McDougall and Taylor (1984) have found a rapid

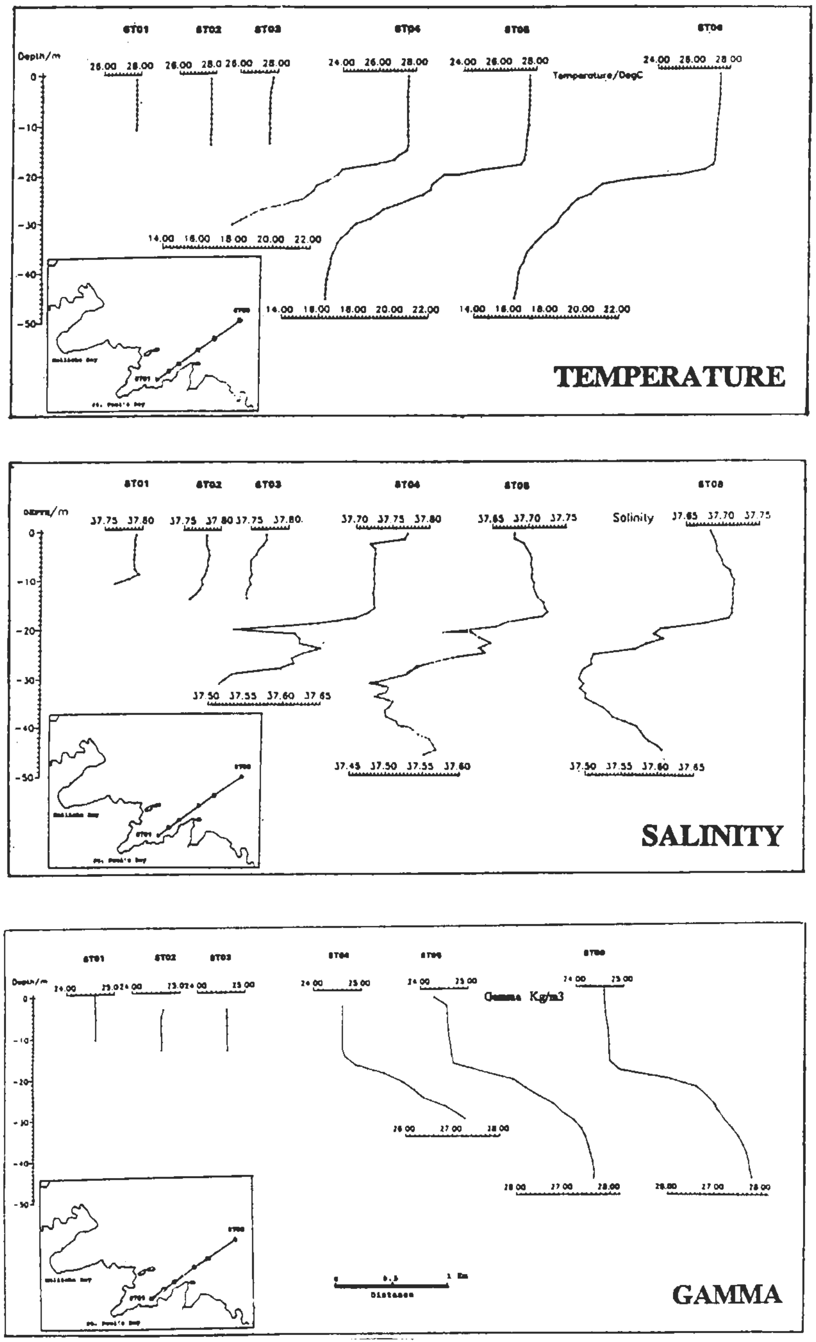

Figure 4. Composite T, S, gamma profiles along St. Paul's Bay.

increase in salt flux between two layers as R_p decreases to 1.2. Following Washburn and Kase (1986), the stability properties of the local stratification in the water column are studied by the stability ratio T_u instead of directly from R_p. T_u is defined as:

$$T_u = \mathrm{Tan}^{-1}[(R_p - 1)/(R_p + 1)]$$

so that it removes some ambiguities in R_p plots, and replaces the infinite scale of R_p by a finite one running from +180° to -180°. Taking the z-axis as positive downward, the stabilizing contributions to vertical density gradients are $aT_z << 0$ and $bS_z >> 0$. The vertical distribution of T_u allows portions of the profile to be grouped into four stability regimes: S denotes a stable region of the profile, U a region with density inversions (resulting from instrument errors or potentially due to overturning), SF a region that is diffusively unstable to salt fingering, and DL a region that is unstable to double diffusive layering. The profiles of the stability angle (Fig. 2c and Fig. 8c) at two representative CTD stations, show that diffusive layering regions are excluded at all depths.

The section of the water column underneath the mixed layer is found to consist of alternate layers of relative stability, which coincide with the 'layers' of moderate temperature gradient. These are separated by 'sheets' of potential salt fingering activity and which coincide with the higher gradients of the temperature profile. Close to the thermocline, the temperature step across 'sheets' is of the order of 2°C. At the deeper parts of the water column it decreases to 1°C. The vertical position of these 'sheets' coincides with impressive precision to the salinity minima such as at A and B for ST14, and X,Y and Z for ST25. Brunt-Vaisala frequencies along

TEMPERATURE **SALINITY** **GAMMA**

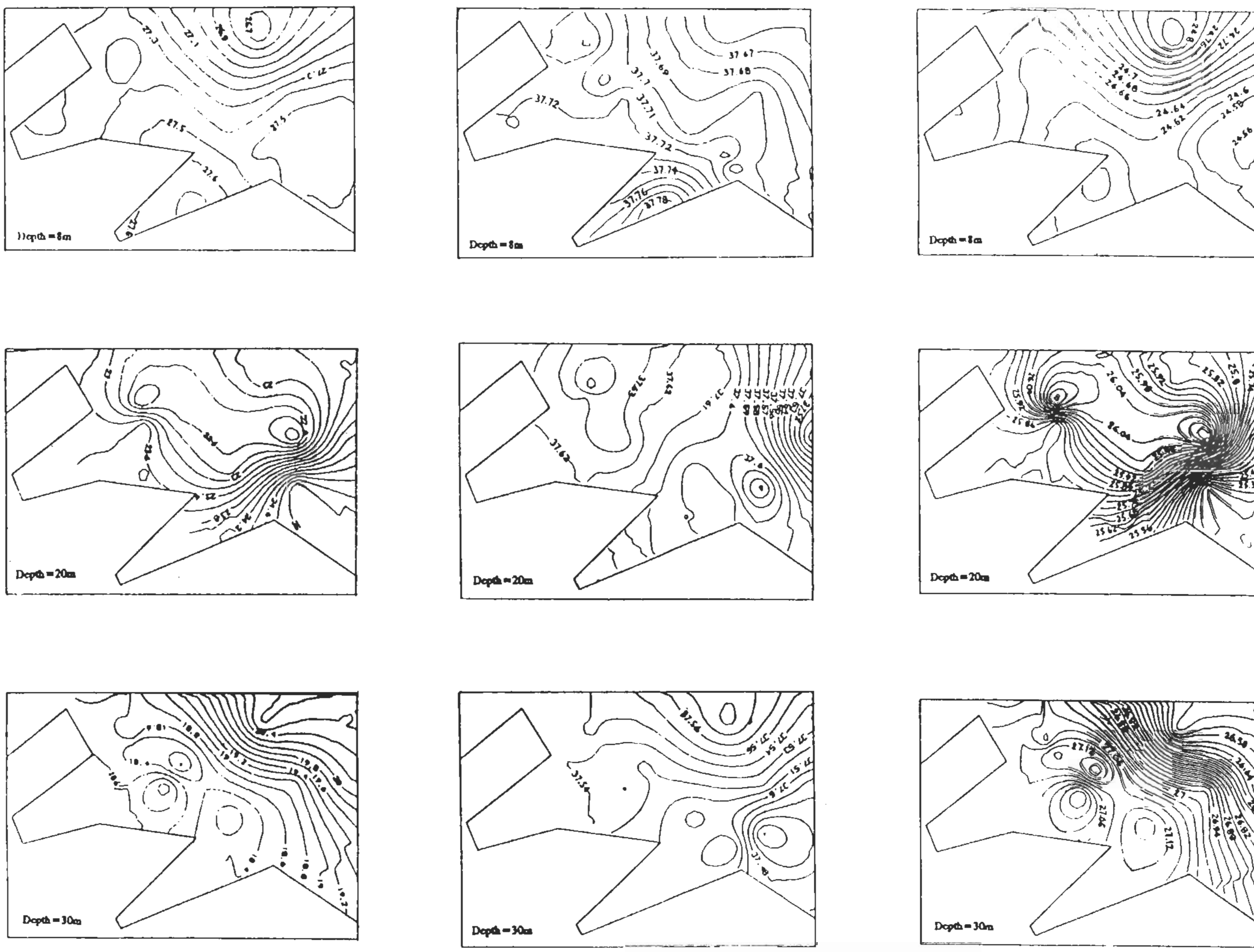

Figure 5. Level plots of Temperature, Salinity and Density at three depths.

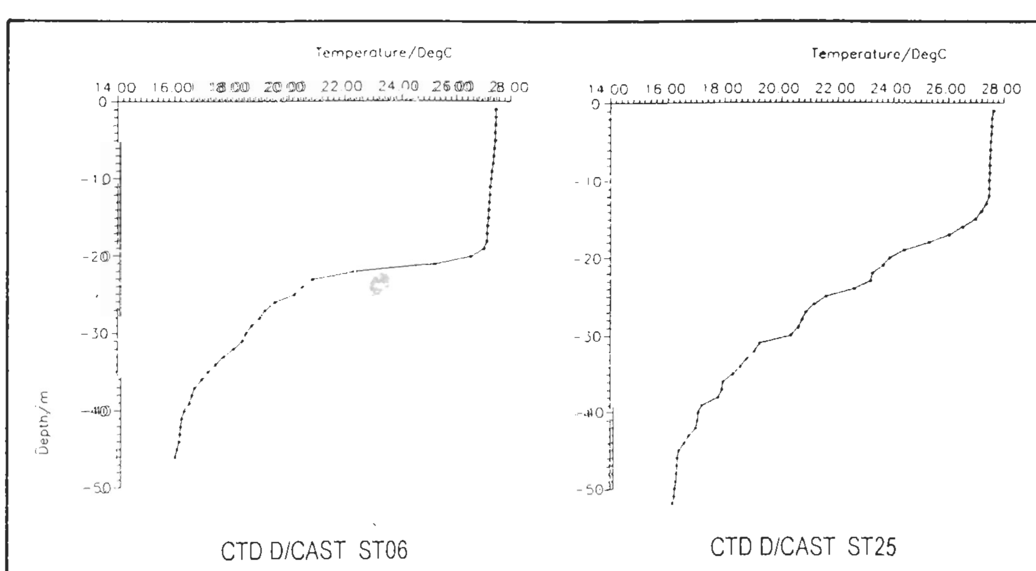

Figure 6. Comparison of temperature plots ST06 and ST25.

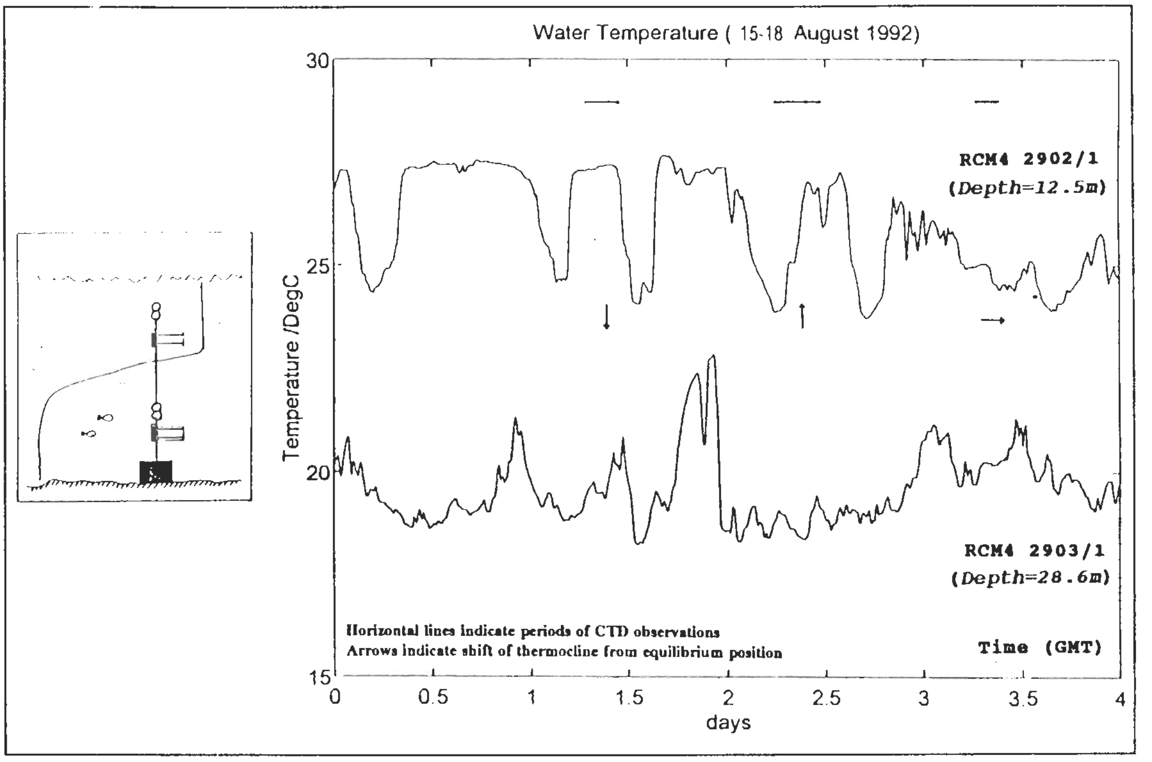

Figure 7. Temperature time series at two depths measured at Ahrax Station

'sheets' reach values close to 30 c/hr, which is two to three times higher than in the neighbouring 'layers'. The examination of the S and T profiles reveals the coincidence of the local minima of salinity and temperature at these points.

The multiple salinity inversions and the associated irregular T-S relationship suggest that in addition to vertical salt fingering, intrusive activity sustained by the strong horizontal salinity and temperature gradients could also be a responsible agent. The intrusive nature of these inversions is further supported by their stable nature and by the associated closed contours of temperature and salinity. Further in-situ CTD measurements can quantify the extent to which these fine-scale inversions are transient phenomena, and confirm their relation to tongues of interleaving water.

Conclusion

The horizontal and vertical distribution of sea water parameters such as temperature and salinity provide information about water movement in the sea. The seasonal and annual variability can be examined by regular in-situ hydrographic observations. Knowledge on the T-S fields are furthermore essential for assimilation in hydrodynamical numerical models.

This kind of baseline data is unfortunately lacking for the coastal areas of the Maltese Islands. A set of CTD casts obtained during a research study in a small area on the NW coast of Malta, comprising two embayments, has provided the first near-synoptic hydrographic data set. The results obtained from this study have revealed some aspects of the coastal oceanographic regime in the region of the islands.

The Maltese Islands constitute an obstacle to the main vein of Atlantic water moving across the Sicilian Channel towards the Eastern Mediterranean, and wake-like streaks have been observed to trail towards the east behind the westernmost tip of Gozo, following well-defined swerving paths downcoast, capturing surface garbage and debris along their way. This area of the Mediterranean is very prolific in mesoscale phenomena that give rise to a system of intertwining frontal structures which pervade the offshore areas around the islands. These phenomena have been also synthesised by satellite views notably from the Coastal Zone Colour Scanner (CSCZ) and the Along Track Scanning Radiometer on ERS-1. The phenomenology of the T-S field in the coastal seas of the Maltese Islands needs a dense grid of hydrographic stations in both time and space in order to be studied properly.

The coastal water in the area of study is dominated by the effect of both salinity and temperature. The salinity shows a consistent horizontal gradient especially beyond the entrance of the embayments. The along-axis salinity gradients and homogeneity in temperature of the embayment waters during this period of the year indicates that the retention time is relatively long and that vertical mixing processes are in action. The SSE main Atlantic Water flow close to the islands is greatly influenced by bottom topography. The White Bank to the North of Mellieha Bay is a source of negative vorticity which results in a reversal of the residual flow closer to the coast and at the entrance of the embayments. The vortex circulation in the top homogeneous layer outside Mellieha Bay is reinforced by the coastal configuration and the seabed topography. This inhibits flushing of the inner bay waters with the open sea.

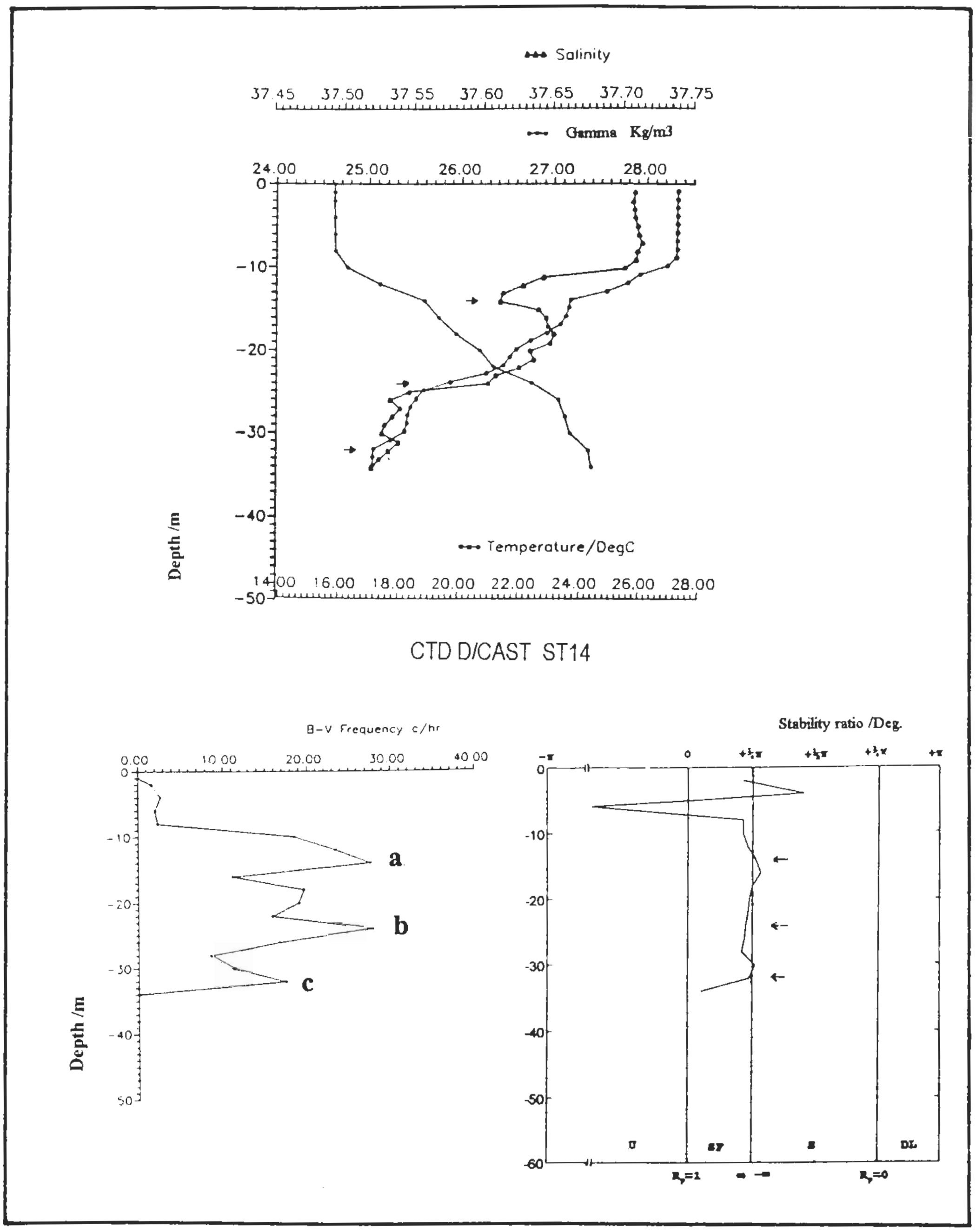

Figure 8. Temperature, Salinity and Density anomaly profiles, Brunt-Vaisala Frequency and Stability Angle close to Ahrax Stattion (35° 59.48'N 14° 23.50'E, 17 August, 1992).

A fine thermohaline structure exists in the summer thermocline layer with vertical scales of a few meters. It is notable that these T,S inversions are very similar to those observed by Armi and Zenk (1984) and Washburn and Kase (1986) in the regions around the salt lenses of the Mediterranean Water outflow into the Atlantic, at depths of 1400 decibars.

These hydrographic measurements were not originally intended to investigate microstructure. Future studies shall focus on the identification of the mechanisms generating the observed fine structure steppiness.

Acknowledgments

This work was jointly financed by the Marine Resources Network of the Malta Council for Science and Technology, and by the Euro-Med Centre on Insular Coastal Dynamics. Helpful discussions and comments on the data analysis have been enjoyed with Dr. Paolo Scarazzato from the Osservatorio Geofisico Sperimentale, Trieste, Italy, and Dr. George Zodiatis from the Laboratory of Physical Oceanography, Department of Fisheries, Centre of Marine Research, Cyprus.

I am also grateful to Dr. Simon Boxall from the Department of Oceanography, Southampton Oceanography Centre, UK, for supervising the preparations of the marine survey, and to Dr. Rhu Nash and Dr. Paul Forster for their support during the field measurements. I would also like to thank Mr. Anton Micallef for logistic support and Dr. Alan Fougere of Falmouth Scientific Inc., MA for lending me his personal CTD probe.

References

Armi L and Zenk W (1984) Large lenses of of highly saline Mediterranean Water. *Journal of Physical Oceanography*, **14**, 1560-1576.

Drago AF (1991) Physical Oceanography in the Coastal Waters of the Maltese Islands, Malta CERP Workshop, October 1991, *MRN Technical Report Series*, No. **1**, pp 24.

Gregg MC (1975) Microstructure and intrusions in the California Current. *Journal of Physical Oceanography*, **5**, 253-278.

Havard DA (1978) The Study of the Problems of the coastal Transport of Pollutants in Maltese Coastal Waters. *4th Journees Etudes Pollutions* 555-557 Antalya, C.I.E.S.M.

Howe MR and Tait RI (1970) Further observations of thermohaline stratification in the deep ocean. *Deep Sea Research*, **17**, 963-972.

Magnell B (1976) Salt fingers observed in the Mediterranean Outflow region (34°N 11°W) using a towed sensor. *Journal of Physical Oceanography*, **6** 523-551.

McDougall TJ and Taylor JR (1984) Flux measurements across a finger interface at low values of the stability ratio. *Journal of Marine Research*, **42**, 1-14.

Schmitt RW (1979) The growth rate of super-critical salt fingers. *Deep Sea Research*, **26**, 23-40.

Schmitt RW (1981) Form of the temperature-salinity relationship in the Central Water; evidence for double-diffusive mixing. *Journal of Physical Oceanography*, **11**, 1015-1026.

Sultan SAR and Elghribi NM (1996) Temperature inversion in the Arabian Gulf and the Gulf of Oman. *Continental Shelf Research*, **16**,1521-1544.

Tait RI and Howe MR (1968) Some observations of thermohaline stratification in the deep ocean. *Deep Sea Res*earch, **15**, 275-280.

Washburn L and Kase RH (1987) Double diffusion and the distribution of the density ratio in the Mediterranean waterfront southeast of the Azores. *Journal of Physical Oceanography*, **17**, 12-25.

Zodiatis G (1992) Lens formation in the SE Ionian Sea and double diffusion. *Annales Geophysicae*, **10**, 935-942.

Zodiatis G and Gasparini GP (1996) Thermohaline staircase formation in the Tyrrhenian Sea. *Deep Sea Research*, **43**, 655-678.