ON THE FORMATION OF LEVANTINE INTERMEDIATE WATER

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Résumé - Abstract

Atmospheric factors favourable to the formation of Levantine intermediate water are shown to exist within a meso-scale region of the north eastern Levant. Evaporation rates are computed and utilized in a simple box-model. These computations are in agreement with the measured annual trend of salinity until sinking of the surface waters begins in early spring.

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Introduction

The northeastern Mediterranean region to the south of Asia Minor is known to be one of the possible sources of the Levantine Intermediate Water (LIW); a water mass identified in the whole Mediterranean basin at depths of 200-400 m. This distinct water mass is a product of the thermohaline circulation caused by the excessive evaporation in the Mediterranean (LACOMBE and TCHERNIA,1960, 1974; WÜST,1960; GERGES,1972; MORCOS,1972). The sources and spreading of this water mass have been investigated using the core method of Wüst (1960) and with limited evaluations of the atmospheric conditions favorable for the formation of LIW (MORCOS,1972). According to Lacombe and Tchernia (1960) and Wüst (1960), the primary source region is the area between Rhodes and Cyprus, while Morcos (1972) concludes that there are probably three different source regions: around Rhodes, to the north of Cyprus and a secondary source region at the Egyptian coast; only after reaching the Ionian basin does the LIW become more uniform. The northeastern part of the Levantine Basin (area between Turkey and Cyprus) is shown to contribute large amounts of the LIW by Moskalenko and Ovchinnikov (1965) and has also been claimed to be a possible source of even deep water masses (PLAKHIN,1970).
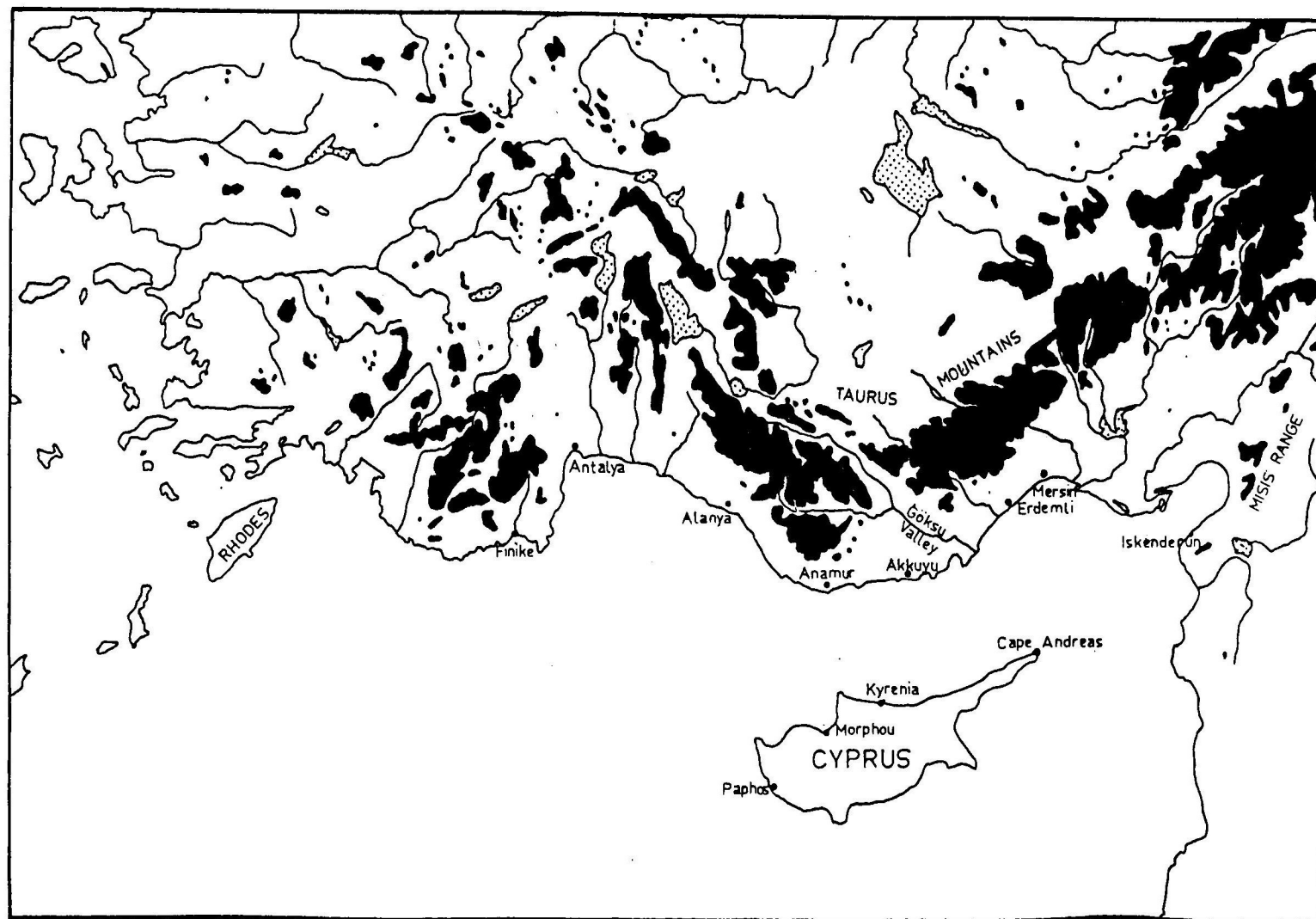
Fig.1: Location of Coastal Stations and Topographic Relief of the Southern Turkish Coast.
(Shaded Areas Represent Elevations Above 1500m).

An examination of the meteorological factors along the Turkish coast points to the predominance of evaporation rates at two regions: the Gulf of Antalya and the area between Anamur and Silifke, while the latter is shown to be much more important. Annual variation of salinity, temperature and density obtained in this region show the evidences of LIW formation and indicate the time scales of evolution.

Evaporation and Rainfall

a. Evaporation: Evaporation rates in units of $gm\ cm^{-2}\ day^{-2}$ ($\simeq cm\ day^{-1}$ of sea water) are computed using the following bulk formula (BUDYKO, 1963, BUNKER, 1972):

$$E = C\ (0.98\ q_w - q_a)\ W \tag{1}$$

where W is the wind speed in units of cm/sec, q_w the saturation value of specific humidity at the air-sea interface, q_a the specific humidity at a given elevation (10m) above the sea surface, and C is an empirical coefficient. A value of C = 0.216 is adopted when monthly mean values are used in the calculation, and a value of C = 0.194 is taken when using daily means (BUNKER, 1972).

Evaporation has been calculated at the coastal stations Finike, Antalya, Alanya, Anamur, Akkuyu, Mersin and Iskenderun, the locations of which are shown in Fig.1. With the exception of Akkuyu, monthly mean data were obtained from the Turkish Meteorological Office. At Akkuyu, where previous measurements were not available, an oceanographic measurement programme carried out during August 1977-June 1978 has yielded the meteorological and oceanographical information. In order to summarize part of the data base used in the evaporation calculations, the annual variations of wind speed, air temperature, and sea surface temperature at the coastal stations are given in Fig.2. The mean sea and air temperatures do not show significant variations from one station to the other, but the winds are seen to be highest at Akkuyu, followed next by Antalya and the other stations.
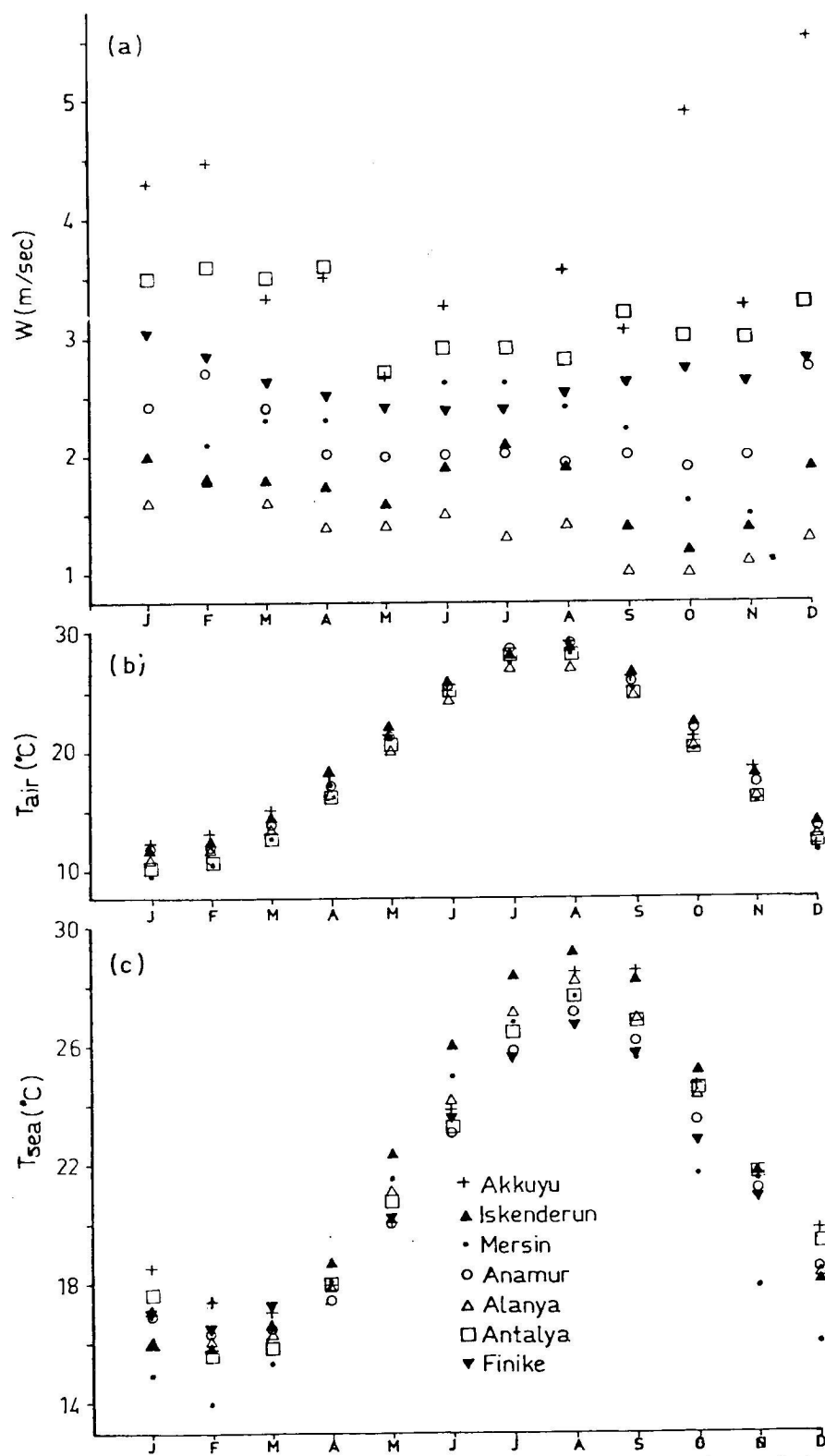
Fig. 2 : Annual Variation of Mean Monthly Wind Speed (a)
Air Temperature (b) and Sea Surface Temperature (c).

Monthly evaporation values E computed via Eq.(1) and the measured rainfall R are given in Table I. For comparison, pan evaporation values, when available, are also provided in the same table. It is seen in Table I that the annual evaporation in Akkuyu area has the largest magnitude accompanied by a relatively small rainfall. In fact, during the cooling period extending from October to February, Akkuyu has the largest evaporation rates among the seven coastal stations. The only serious competitor to Akkuyu in evaporation is Antalya where the rainfall is also larger.

_ The relatively large rate of evaporation in Akkuyu can be attributed to a wind system that is referred to locally as the Poyraz, a northerly wind that frequently blows through the Göksu Valley, which forms the largest opening in the east-west oriented Taurus mountain chain (Fig.1). The width of the Poyraz wind system is approximately 100 km. In summer (August) the Poyraz is triggered by thermal gradients. In cooler months (October-February) the wind system is driven by extratropical cyclones which frequent Anatolia and the eastern Mediterranean (PALMEN and NEWTON,1966). The Taurus mountains form an obstruction to the descending motions of the northerly flow behind low pressure areas (PALMEN and NEWTON,1966), except in the segment of mountain chain lying between Silifke and Anamur. The result is locally intensified mesoscale northerly flow that often transports the dry air from the upper air layers over central Anatolia as seen from the relative humidity plots in Fig.3.b. The situation is very reminiscent of the Mistral in the western Mediterranean (BUNKER, 1972), and the Bora in the Adriatic coast (CROWE, 1971).

Typical Poyraz events have durations of 1-10 days and contain diurnal fluctuations due to radiational heating/cooling. Wind speeds may reach up to 35 m/sec (hourly averages) and relative humidity often falls below 10%. These extreme values are not shown in Fig.4 since 10 day averages have been plotted. As a result of the mixing and evaporation caused by Poyraz, the water temperature (Fig.3) drops significantly during winter months. The variation in water temperatures occurs in a series of stepwise drops during Poyraz dates (not
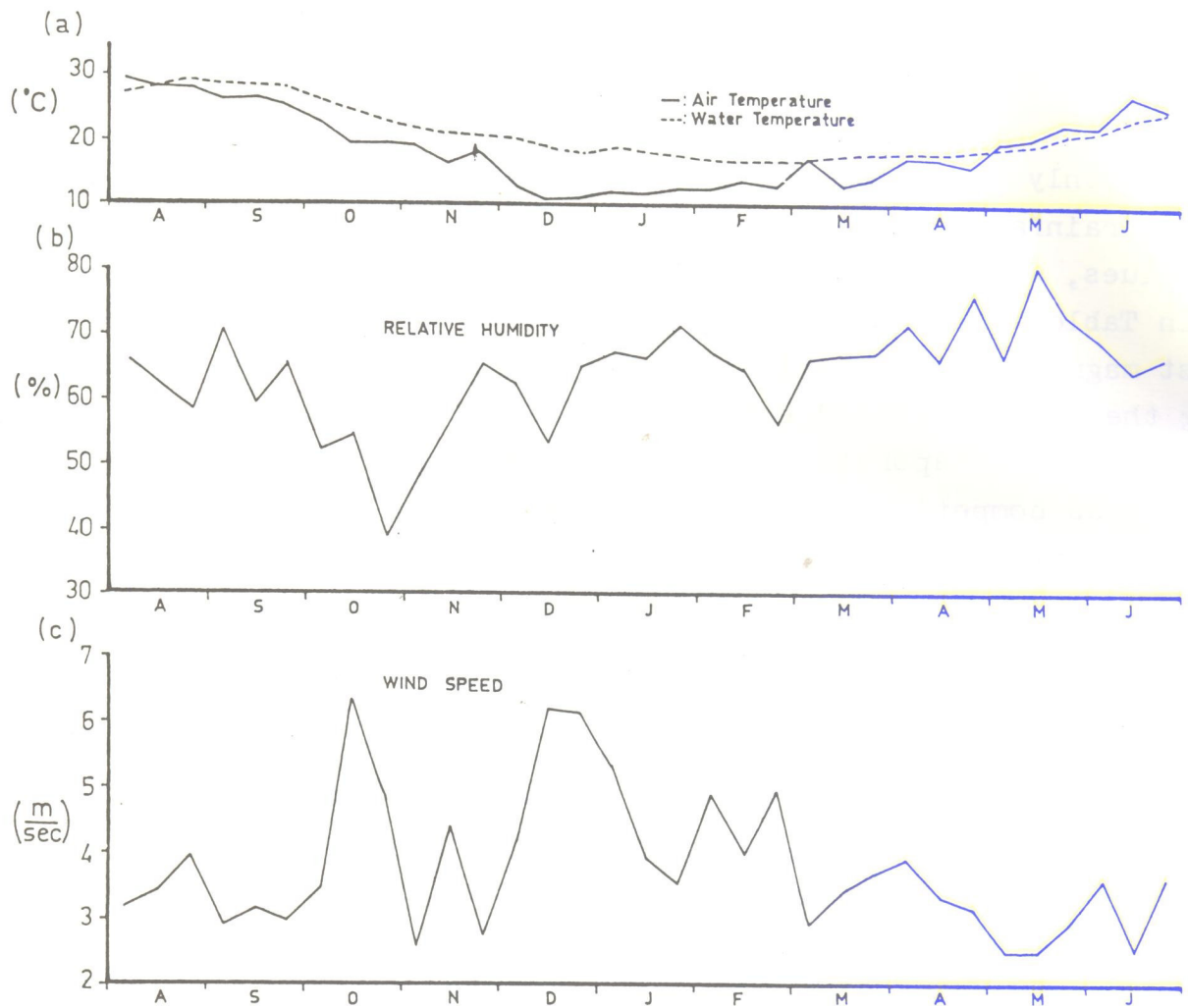
(a)

(b)

(c)

Fig.3: Air Temperature Water Temperature (a) Relative Humidity (b) and
Wind Speed (c) Variations at Akkuyu for the Period September 1977–June 1978.
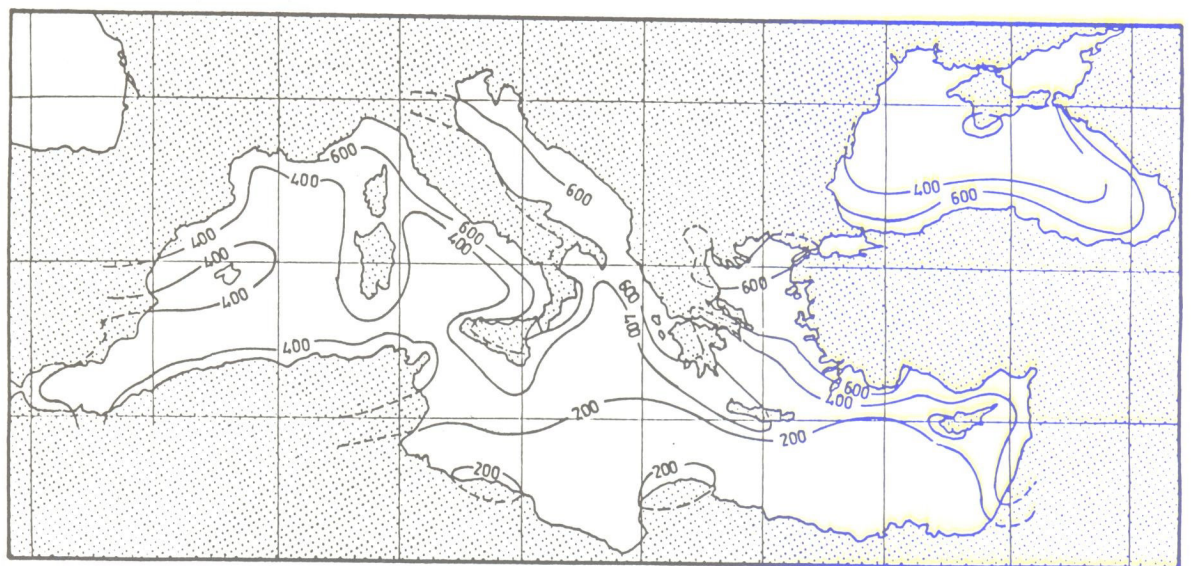

Fig. 4: Annual Rainfall Distribution Over the Mediterranean Sea (after
Tixeront 1970).

shown here due to 10 day averaging). However, the sea water is still about 8°C warmer than the air during January, which favors further evaporation.

An examination of the topographical features of the Taurus mountain chain reveals that there are several narrow valleys which also cause channelization of the northerly winds driven by the large-scale cyclonic disturbances. However, the extent of such a channelization is by no means as large as that found in the Akkuyu area. It appears nonetheless that winds at Antalya are sufficiently high to cause considerable evaporation (Table I and Fig.3). It is also worthy of note that the relative humidity in Antalya does not show the minima found in Akkuyu (Figure 3). Northerly winds are also found at Finike but their intensity is not as high as those found in Antalya. This yields lower evaporation rates in the Finike area.

- The rate of evaporation for the eastern Mediterranean during February have been computed by Bunker (1972), using SSMO data. The region of the northern Levant lying between Rhodes and Cyprus is found to have February evaporation rate of 0.52 gm cm^{-2} day^{-1}. The coastal stations Finike, Antalya and Alanya are in this region, and it is inferred from Table I that the evaporation rates for these stations are, 0.39, 0.49, and 0.22 gm cm^{-2} day^{-1}, respectively. Consequently, our evaporation estimates for Antalya and, to some extent, for Finike is close to Bunker's while the value for Alanya is considerably smaller. This is attributed to orography, for Alanya is well protected from the northerlies. On the other hand, the February evaporation rate calculated by Bunker for the northeastern Levant lying between Turkey and Cyprus is 0.44 gm cm^{-2} day^{-1}. The evaporation rates for the stations Anamur, Akkuyu, Mersin, and Iskenderun located in this region are 0.31, 0.61, 0.28 and 0.26 gm cm^{-2} day^{-1} respectively.

It is seen that our estimate for Akkuyu exceeds Bunker's, while the rates for Anamur, Mersin and Iskenderun are underestimated. The average evaporation rate of these four stations is 0.37 gm cm^{-2} day^{-1}. It is expected that the orographic effects should yield

Table I.
Evaporation E(mm) and Rainfall R(mm). Numbers in
parentheses refer to pan evaporation values.

	Finike		Antalya		Alanya		Anamur		Akkuyu		Mersin		Iskenderun	
	E	R	E	R	E	R	E	R	E	R	E	R	E	R
Jan.	114	279	155 (66)	264	63 (116)	244	90 (887)	218	177	137	81 (39)	115	76 (62)	124
Feb.	95	130	141 (70)	156	66 (101)	174	96 (87)	189	164	179	69 (41)	105	62 (70)	99
March	79	92	129 (93)	93	51 (126)	81	81 (107)	110	107	74	78 (60)	50	58 (76)	92
April	76	36	111 (91)	44	45 (107)	34	57 (128)	30	84	38	78 (66)	33	52 (82)	65
May	70	22	85 (107)	31	39 (106)	32	54 (116)	25	42	3	87 (73)	23	57 (99)	53
June	94	6	114 (157)	10	51 (148)	4	63 (152)	5	100	2	102 (87)	11	84 (87)	18
July	109	3	146 (202)	2	63 (148)	2	81 (192)	0	150	0	105 (99)	9	106 (106)	4
Aug.	133	1	166 (196)	3	81 (198)	0	96 (227)	0	213	0	132 (103)	5	107 (104)	16
Sept.	156	10	218 (174)	14	63 (132)	24	117 (180)	10	187	1	147 (98)	11	92 (92)	38
Oct.	136	69	189 (137)	58	69 (179)	74	102 (142)	77	311	8	99 (89)	41	74 (83)	92
Nov.	123	78	165 (85)	111	54 (104)	131	96 (101)	114	179	14	66 (59)	75	75 (73)	77
Dec.	112	262	162 (68)	284	51 (97)	244	102 (84)	236	305	111	81 (43)	124	84 (92)	107
Total (cm)	130	99	178	107	69	104	104	101	202	57	113	60	93	79
E-R(cm)	31		71		-35		3		145		53		14	

ifferent values for these stations. Although the underlying reasons for the differences found between Bunker's estimates and those given here is difficult to ascertain, the details of the air-land interactions are probably lacking in the SSMO data.

b. Rainfall: The rainfall values given in Table I for various coastal stations should be viewed with care when applying these values to the sea, since the measurements at mountainous areas generally reflect the orographic precipitation in the immediate environment. The effect of orography is demonstrated by the variation of annual rainfall recorded over 90 cm. in Finike, Antalya, Alanya and Anamur to lower values around 60 cm. towards Akkuyu and Mersin. Large scale disturbances moving into the eastern Mediterranean from the Aegean region (Mediterranean Pilot,1976) generally follow the Taurus mountain range. The associated low level fronts are usually intercepted by the southwest Anatolian mountains which are aligned in a SW-NE direction (Fig.1), and leave much of their moisture in this region as orographic precipitation. Therefore the cyclones which are rejuvenated in the Cyprus area do not bring much rain to the Akkuyu-Mersin coastal region, where the Taurus range lies parallel to the coast. A relative increase in rainfall is observed at Iskenderun (80 cm) due to the Misis mountain range, which lies in the direction perpendicular to the paths of the cyclones.

The orographic influences on precipitation in coastal areas make the estimation of rainfall over the northern Levantine sea (area between Rhodes and Cyprus) a difficult task. Tixeront (1970) has compiled the distribution of rainfall over the Mediterranean from observations at coastal stations on islands and from limited ship observations. The corresponding distribution of annual rainfall in the western coastal stations seem to be much in excess, whereas the values near Akkuyu and Mersin seem to be more representative of the rainfall over the sea. In order to obtain corrected rainfall values over the northern Levantine sea, averages of the rainfall recorded at coastal
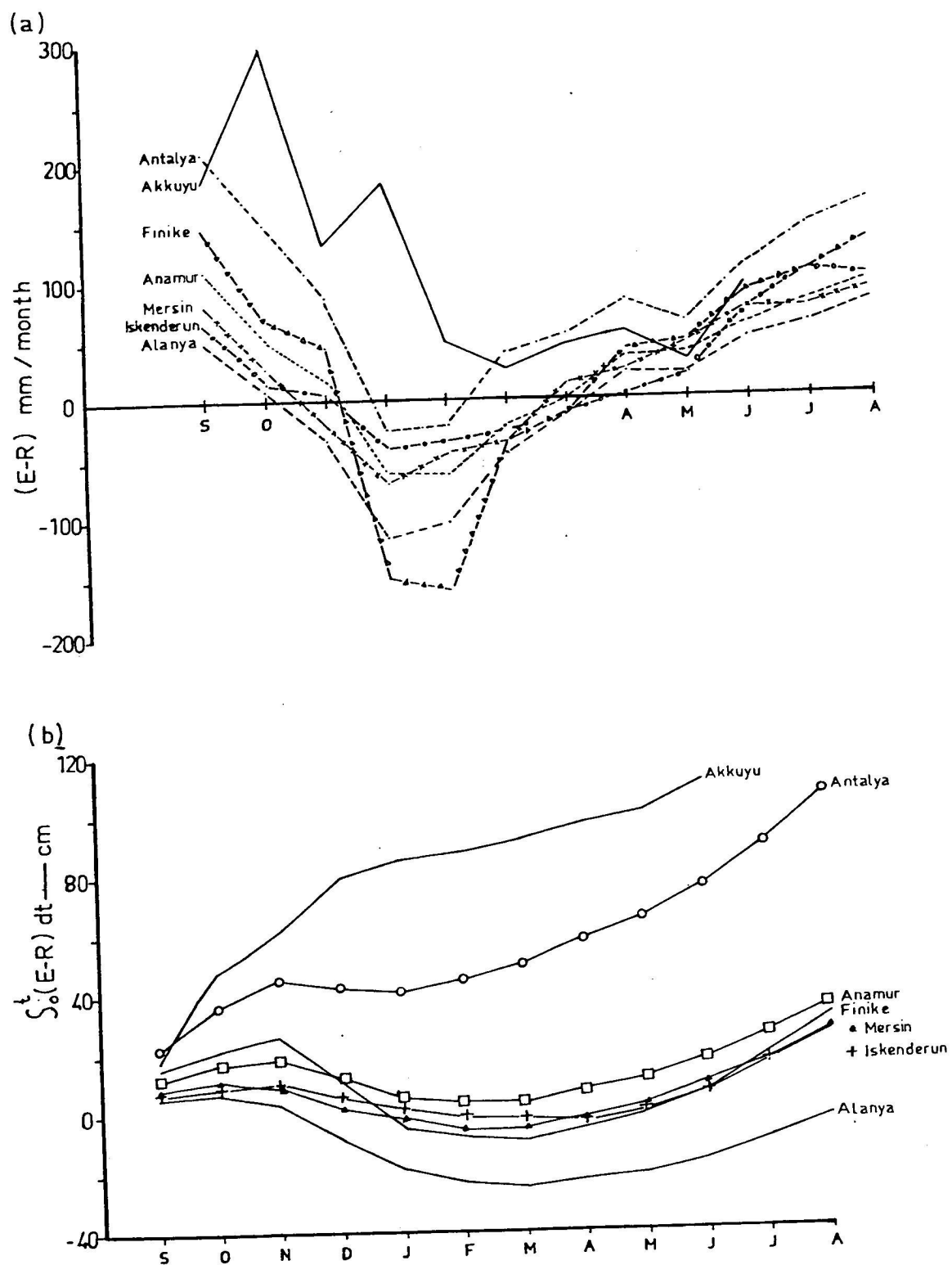
(a)

(b)

Fig 5: E-R (a) and Cumulative E-R (b) at Coastal Stations.

stations and those across from these stations on Cyprus were formed. The rainfall was thus estimated by taking the averages Antalya-Paphos (annual average rainfall:76 cm), Finike-Paphos (78 cm), Anamur-Morphou (69 cm), Akkuyu-Kyrenia (56 cm), Mersin-C.Andreas (56 cm), and Iskenderun-C.Andreas (65 cm). Cyprus data were obtained from the Mediterranean Pilot (1976). The averaged values of annual rainfall compare better with Tixeront's (1970) estimates (see Fig. 4).

  c. (E-R) and Salinity Changes: The values of E-R calculated from the evaporation values in Table I and the corrected rainfall values described in section 2.b are shown in Fig.5.a. The highest two peaks occur in Akkuyu during the months of October and December when strong and dry Poyraz winds are effective in the region (see Fig.). The next highest values of E-R are encountered in Antalya, with values slightly higher than that of Akkuyu during the spring months. However, the much higher evaporative losses at Akkuyu between September and February are significant in aiding water mass formation. The other coastal stations display much smaller values of E-R as compared to these two stations.

  The salinity of the surface layers of the sea is influenced by the water losses and the mixing of this newly formed water mass over the surface mixed layer. A simple box model accounting for salinity changes in the mixed layer due to the surface mass flux component is expressed as (KRAUS,1977):

$$\frac{dS}{dt} = \frac{1}{h} (E\text{-}R) \, S \tag{2}$$

where S is the salinity, and h is the mixed layer depth. In the solution to Eq.(2):

$$S = S_o \exp \int_0^t \left(\frac{E\text{-}R}{h} \right) dt, \tag{3}$$

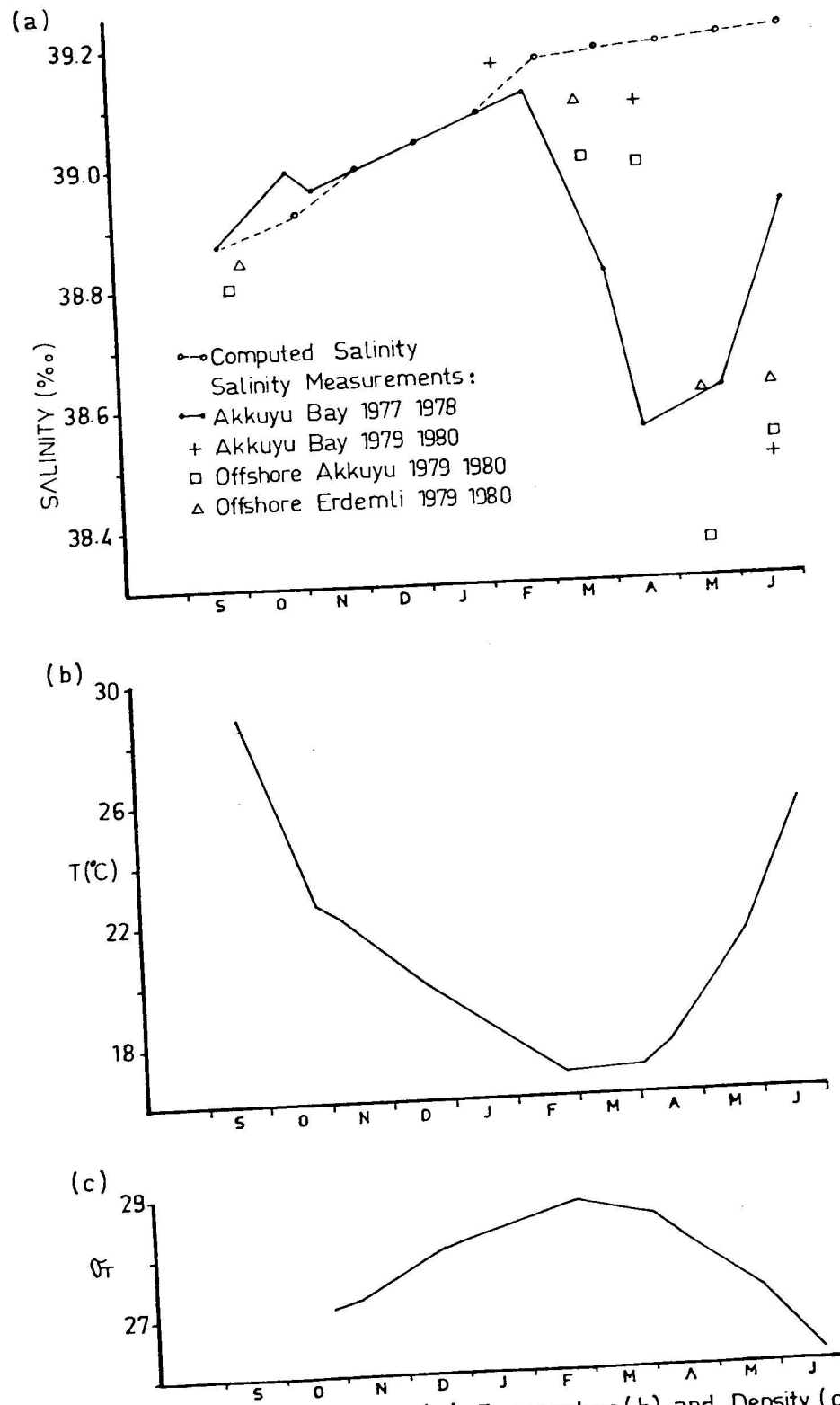the salinity evolves from an initial value S_o in proportion to the

(a)

(b)

(c)

Fig. 6: Salinity (a), Temperature (b) and Density (c) Variations at Akkuyu for the Period September 1977 - June 1978.

cumulative values of (E-R)/h. Since accurate information on the annual march of salinity and mixed layer depth at each station is lacking, a most simple estimation of the cumulative effects of evaporative fluxes has been made by assuming the mixed layer depth to be constant and comparing the cumulative E-R curves for each station. These curves shown in Fig.5.b indicate the largest contribution to the salinity evolution at Akkuyu, followed by Antalya and the other stations.

LIW Formation

The annual variation of salinity, temperature, and density at Akkuyu are shown in Fig.6. The measurements have been done in Akkuyu Bay, where an oceanographic monitoring programme has been carried out on a monthly basis. Data from four profiling stations within Akkuyu Bay have been averaged to obtain the values presented in Fig.6. Akkuyu Bay is a small (radius=2 km) and deep bay with a continuous connection with the narrow Turkish continental shelf; the depth at the bay entrance is about 30 m. and it increases linearly further offshore.

The annual march of salinity in Fig.6.a has an absolute maximum of 39.1 ^{o}/oo in the month of February, at which time the temperature reaches its mimimum value of 16.8^{o}C and a maximum density value σ_t = 28.7 is observed. During the following months, the salinity first drops to 38.6 ^{o}/oo, then continues increasing in a new period of evolution. The total length of this period is about four months. The calculation of salinity at Akkuyu based on Eq.(3) and a constant mixed layer depth of 150 m. is in agreement with the measurements during September - February, but fails to produce the sharp drop after February. This remarkable evolutionary phase signifies the period of formation of the Levantine Intermediate Water (LIW).

Continuous monitoring of the annual variability (Fig.6) has not been made available earlier. The surface waters reach salinity sub-maxima and temperature maxima during summer. After this pre-transformation phase, the cold and dry outbreaks of continental polar air masses enhance evaporation and the resulting instability mechanisms

cause water mass formation (LACOMBE and TCHERNIA,1974). The high
salinity and low temperature waters during winter form the LIW which
is identified with S = 39.1 ^{O}/oo, T = 15.5^{O}C and σ_t = 29.0 (MORCOS,
1972). In Fig.6.a. a water mass with values close to these are seen
to be formed in February. The temperature is slightly higher than
that for the core of the LIW, in agreement with Morcos' observations.
The dense waters formed at the surface are mixed to much greater depths
after February. In November, there is an Atlantic water of minimum
salinity ($\sim$38.6 ^{O}/oo) underlying the seasonal thermocline at 60 -
100 m. and above the intermediate salinity maximum at 250 - 300 m. ob-
served from oceanographic profiles in the northern Levantine region
(MILLER et al,1970). After the sinking of the dense surface waters
and the mixing with this Atlantic water mass, salinity in the region
drops considerably during February - April. The uniformity of salinity
profiles up to depths of 300 m. during these months as a result of the
joining of surface and intermediate waters has also been reported by
Lacombe and Tchernia (1974) and Morcos (1972). Measurements obtained
during 1979-1980 at Akkuyu and also offshore of Erdemli (Fig.6.a)
indicate a repetition of the sinking process with a delay of about one
month due to the excessive amounts of rainfall (return period 30 years)
received during this year.

Summary and Discussion

The review of climatological and oceanographic data shows that
the northern Levantine is a possible source region for the LIW . In
particular, the area between Anamur and Silifke on the Turkish coast
channelizes cold outbreaks reaching the region from the north.
Different water masses of the Mediterranean are formed at the Gulf
of Genoa, the Adriatic Sea and near Cyprus, all of which are regions
of cyclogenesis. An analogy also exists between these areas in that
behind the depressions passing from these areas, violent northerly
winds (Mistral and Tremontana in the Gulf of Lions, Bora in the north-
ern Adriatic coast, and Poyraz on the Turkish coast to the north of

Cyprus) are formed due to channelization of the flow of valleys
(LACOMBE and TCHERNIA,1974; BUNKER,1972). The Poyraz winds deepen
the mixed layer during August-February and cause large evaporation
rates as a result of which the pre-sinking transformation of the
surface waters takes place. The further mixing of these dense
waters through sinking motions contributes to the core of the LIW.

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