JED. JOUR. MAR. RES., Vol. 1., 1981.

# EVAPORATION FROM THE COASTAL WATER IN FRONT OF JEDDAH

**A.K.A. Behairy, M.M. Osman and A.H. Meshal**
Marine science Institute,
King Abdulaziz University

## ABSTRACT

Monthly evaporation from the coastal water of the Red Sea in front of Jeddah was estimated by the aerodynamic method. Computations were performed using monthly mean values of sea surface temperature and surface meteorological data.

Results reveal that monthly mean evaporation is greatest in spring and summer and least in autumn and winter. The annual evaporation was found to be 205 cm. Comparison with published values of evaporation for the Red Sea indicates that the present value lies within the limits given by previous investigators.

## INTRODUCTION

The Red Sea loses much more water through evaporation than it gains by precipitation and runoff owing to its position in an arid zone between two great deserts. Evaporation is then the principal factor in forming the high salinity water of the Red Sea However, the effect of evaporation as a controlling factor for water circulation and sea level variations is still a controvercial subject (Patzert, 1972; Bogdanova, 1974). Much of the confusion is ascribed to the lack and inconsistency of evaporation data.

The existing information about evaporation from the Red Sea is not solidly based on representative data due to the great variability in the meteorological and oceanic conditions. There are many gaps in the available information regarding temporal and spatial distribution of evaporation Therefore the demand for reliable determinations of evaporation from the different regions of the Red Sea during the seasons of the year is self evident.

The present work is an attempt to determine monthly mean evaporation from the coastal water of the Red Sea in front of Jeddah for the year 1973. The aerodynamic method is applied here to compute evaporation using sea surface temperature and surface meteorological parameters. No work has been published so far to estimate evaporation along the Eastern Coast of the Red Sea.

Throughout 1973, surface water temperature was recorded continuously at Jeddah Coastal Laboratory of Marine Research Centre (Morley, 1974). The temperature recording instrument was installed at a distance of 40 m from Ras-el-Qahaz head near Jeddah. Wind velocity, atmospheric pressure and humidity were recorded at Jeddah Meteorological Station (lat. 21° 30′ N, long 39° 12′ E, elev. 17 m).

## METHOD OF ESTIMATION OF EVAPORATION

Formulae for the determination of evaporation were proposed by different authors among them are Sverdrup (1937), Millar (1937), Norris (1948) and Sutton (1949). These formulae were built up on the same bases but involving different assumptions about the details of the Prandtl layer. Detailed discussions of the relative merits of these equations were given by Anderson, Anderson and Marciano (1950) and Sverdrup (1951).

Marciano and Harbeck (1954), and Meshal (1973) found that only Sverdrup's (1937) and Sutton's (1949) formulae gave results in good agreement with observations and non of those of the same type were satisfactory.

In the present work Sverdrup's (1937) formula was applied. In his equation, Sverdrup (1937) considered the sea surface rough at all times and characterized by a constant roughness length independent of wind speed. He assumed that a laminar layer exists between the surface and the turbulent layers. Sverdrup's (1937) equation can be written as:

$$E = 0.623 \frac{\rho D (e_o - e_z) u_*}{P \left( \frac{D}{K} \ln \frac{z + z_o}{d + z} + du \right)} \qquad (1)$$

where,

E is the rate of evaporation per unit area cm/s,

$\rho$ the density of air $= 1.2 \times 10^{-3}$ g/cm$^3$,

D the diffusion coefficient of water vapour $= 0.235$ cm$^2$/s,

k the dimensionless von Karman's constant $= 0.4$,

$z_o$ the roughness length $= 0.6$ cm,

d the thickness of the laminar layer cm.

$u_*$ the friction velocity $= \dfrac{K u_z}{\ln \dfrac{z + z_o}{z_o}}$ cm/s,

$u_z$ the wind speed at height z above the surface cm/s,

$e_z$ the vapour pressure at height z mb,

$e_o$ the saturation vapour pressure at sea surface temperature mb, and

P the atmospheric pressure mb.

The thickness of the laminar layer d was adopted according to von Karman (1934) as:

$$d = \frac{30 v}{u_*} \qquad (2)$$

Where v is the kinematic viscosity of the air $= 0.15$ cm$^2$/s.

Equation (2) was based on extensive measurements and gave satisfactory results (Marciano and Harbeck, 1954). Values of $e_o$ were corrected for the salinity effect. The obtained values of E (equation 1) were multiplied by the number of seconds in the given month to get the monthly mean values of evaporation. It is believed that no serious error is introduced when applying equation (1) over a period of a day or longer (Jacobs, 1942).

## RESULTS AND DISCUSSION

Monthly mean values of sea surface temperature, vapour pressure, wind velocity and atmospheric pressure taken during the year 1973 are graphically represented in figures 1-4.

The lowest value of surface water temperature (fig. 1) occurred in January (25.8 C). The surface temperature increased from March through August when it reached its maximum value of 34.8 C and then decreased. The annual amplitude was 9 C which is greater than the corresponding value for the Red Sea proper (6.9 C) at the same latitude (Morcos, 1970). This difference reflects the continental influence on surface temperature of coastal water which undergoes larger daily and seasonal fluctuations than those of the open sea at the same latitude.

The monthly mean values of vapour pressure varied between a minimum of 17.4 mb in January and a maximum of 32.4 mb in September (fig.2). The large annual amplitude of vapour pressure (15 mb) reflects the continental influence and the effects of coastal winds.

Figure (3-a) indicates that month to month variations in wind speed showed no regular trend. Relatively stronger winds were generally found in mid winter ad spring. The maximum value of 10 knots occured in January, while the minimum (5 knots) - in July and October. Fig. (3-b) shows that for most months the prevailing wind direction was from the north and only in February and September were the winds from NNE and NNW respectively. It is to be noted that along the coasts of the Red Sea the variations in wind characteristics are much more complicated than those over the open sea. Along the sea proper winds are mainly directed along the central axis with minor lateral variations (Patzert, 1972). Coastal winds, however, alternate daily between a nocturnal land breeze and daytime sea breeze (Flohn, 1965). This well developed daily pattern, which occurs almost in all months, is due to large diurnal differences in local heating (Flohn, 1969). Therefore, coastal winds are the approximate sums of the broad scale flow and the diurnal component (Pedgley, 1974).

The monthly values of atmospheric pressure (fig. 4) were high in winter and low in summer. The maximum value of 1014.5 mb occurred in January, while the minimum (1002.9 mb) in July.

The reliability of the meteorological parameters of the year 1973 was examined by comparing the monthly mean values with those averaged over thirteen years (1966 - 1978). In a climatological sense, this available 13 year period may not be enough, but it provides an adequate base for judgement on the deviation of the used meteorological data from their long term averages (fig. 2 - 4). Comparison reveals that the trend of variation of vapour pressure throughout 1973 was the same as that for the long-term average. However, the monthly values of vapour pressure of 1973 were slightly greater than the provisional normals (fig. 2). The most apparent anomaly (4.1 mb) took place in February. The monthly values of wind speed for 1973 fluctuated around their average values with maximum deviation of 2 knots in January and July (fig. 3). Close agreement between the atmospheric pressure for 1973 and for the long-term average is evident from fig. 4.

From the previous discussion, it appears that during the year 1973, the meteorological elements used for the computation of evaporation showed no significant discrepancies from the long-term averages. Unfortunately such comparison could not be done for surface water temperature due to the shortage of data.

Table (1) shows that monthly evaporation was generally greatest in spring and summer (from March to August) and least in autumn and winter (from September to February). The maximum value (7.6 mm/day) was found in May and a secondary maximum (7.1 mm/day) in August. The minimum value (4.0 mm/day) occured in September/October and a secondary minimum (4.1 mm/day) in February. The numerical values of evaporation reflected the combined effects of both vapour pressure deficit and wind speeds. For Jeddah coastal waters, the annual evaporation was found to be 205 cm.

In a previous work (Behairy, Meshal, and Osman, 1981) we estimated evaporation from the central zone of the Red Sea between (21° - 22°N) using data measured simultaneously over the open sea during 1977/1978. The annual evaporation value was 144 cm which constitutes only about 70% of the value presented here. The difference between these two values reflects the variation in meteorological and oceanic conditions in the open sea and near the coast.

Evaporation from the Red Sea and its coasts was summaized by Vercilli (1925) and Morcos (1970). Vercilli (1925) made pan measurements on board the ship and on three coastal stations namely Tor, Port-Sudan and Suakin. Tor station lies on the Eastern Coast of the Gulf of Suez, while Port-Sudan and Suakin stations are located on the Western Coast of the Red Sea at latitudes 19° 40' N and 19° 03' N respectively.

Table (2) shows that evaporation values for Port-Sudan are greater than those of Suakin, although both stations lie close to each other. The monthly evaporation values for Suakin constitute 62% and 95% of those for Port-Sudan in winter and summer respectively. The three coastal stations exhibit maximum evaporation in summer and minimum in winter.

From tables (1) and (2) it is clear that Vercilli's evaporation data for Tor, Port-Sudan and Suakin are higher than the estimated values for Jeddah coastal waters This is because Vercilli's values were based on pan measurements. It is well established that evaporation from pans is much higher than that from a natural water body due to many factors and an empirical reduction factor is usually recommended (Kohler, 1954; Wust, 1954)to pan measurements.

The evaporation values given for the Red Sea as a whole (table 3) show great differences (183-350 cm/year). Krummel (1911), and Vercilli (1925) reported evaporation from the whole Red Sea as 250 cm/year and 350 cm/year respectively.Interpretation of the basic data with a critical evaluation of the applied methods and the assumptions done by Krummel (1911) and Vercilli (1925) reveals that their estimates cannot be regarded as a truly representative of the Red Sea. The more recent estimates of Yegorov (1950), Neumann 1952 (cited by Morcos, 1970) and Privett (1959) vary by about 50 cm/year (table 3).

On the other hand evaporation from the latitudinal regions 25° N and 15° N indicate close agreements in the annual values (table 3) and in the seasons of maximum and minimum. If both Yegorov's and Neumann's evaporation values are interpolated to latitude 21°30' N we get 220 cm/year and 219 cm/year respectively. Although these values represent evaporation from the open sea, they are 7% higher than the annual evaporation for Jeddah coastal waters

It is to be noted that both Yegorov (1950) and Neumann - 1952 (cited by Morcos, 1970) used average data obtained from different meteorological atlases, tables and from published refrences which introduced errors in the estimated values of evapoation (Behairy, Meshal and Osman, 1981).

## SUMMARY AND CONCLUSIONS

Monthly evaporation from the coastal water in front of Jeddah, was estimated using the aerodynamic method. Although the basic data used for the computation of evaporation represents 1973 calender year, it was clear that they showed no considerable individuality compared with the climatological normals. The continental influence was obviously reflected on the marine and meteorological characteristics of the coastal water compared with those for the open sea; with subsequent effect on the estimated value of evaporation (205 cm/year)

Because of the simple boundary conditions of the Red Sea (no river discharge, low rainfall and little heat advection through narrow and shallow openings) the heat budget can be used to check the bulk aerodynamic formulae to be used for the determination of evaporation. This needs surface synoptic observations of the marine-meteorological elements both from coastal and open sea waters.

## REFERENCES

Anderson, E.R., Anderson, L J., and Marciano, J.J., 1950. A review of evaporation theory and development of instrumentation. Rep. No. 159, San Diego. U.S. Navy Electronics Laboratory: 1-37.

Behairy, A.K.A., Meshal, A.H., and Osman, M.M., 1981. Evaporation from the central zone of the Red Sea. Jed. J. Mar. Res., 1 1 - 6.

Bogdanova, A.K., 1974. Indirect estimation of the seasonal variation of the water exchange through Bab-el-Mandeb. L'Oceanographie physique de la Mer Rouge. CNEXO Publications. Serie-Actes de Colloques., No. 2., Paris: 253-265.

Flohn, H., 1965. Klimaprobleme am Roten Meer. Erdkunde 19 (3): 179-191.

Flohn, H., 1969. Local wind systems. World Survey of Climatology. Vol. 2, New York., Elsevier Pub. Comp., 142-144.

Jacobs, W.C., 1942. On the energy exchange between Sea and Atmophere. J. Mar. Res., 5: 37-66.

Karman, V.Th., 1934. Turbulence and skin friction. J. Aeronaut. Sci., 1: 1-20.

Kohler, M.A., 1954. Lake and pan evaporation. Prof. Papers No. 269. Washington., U.S. Geological Survey; 127-148.

Krummel, O., 1911. Handbuch der Ozeanographie. Bd. 2. J. Engelhorn, Stuttgrat : 525 pp.

Marciano, J.J., and Harbeck, G.E., 1954. Mass transfer studies. Prof. papers No. 269. Washington, U.S. Geological Survey: 46-70.

Meshal, A.H., 1973. Water and salt budgets of Lake Qarun, Faiyum, Egypt. Ph.D. thesis, Alexandria University: 278 pp.

Millar, F.G., 1937. Evaporation from free water surface. Department of Transport, Division of Meteorological Services, Canada, Canadian Meteorological Memoirs, 1 : 39-45.

Morcos, S.A., 1970. Physical and Chemical Oceanography of the Red Sea. Oceanogr. Mar. Biol. Ann. Rev.; 8-72.

Morley, N.J. 1974. Sea water temperature, salinity and chlorinity in the vicinity of the proposed New Jeddah power station. Int. Rep No. 6. Jeddah, Marine Research Centre: 1-4.

Norris, R., 1948. Evaporation from extensive surface of water roughened by waves. Quart. J. Roy. Meteorol. Soc., 74: 1-12.

Patzert, W.C. 1972. Seasonal variations in the structure and circulation in the Red Sea. Ph.D. thesis, University of Hawaii: 58 pp.

Pedgley, D.E. 1974. An outline of the weather and climate of the Red Sea. L'Oceanographie physique de la Mer Rouge. CNEXO Publications., Serie-Actes de Colloques, No. 2, Paris: 9-27.

Privett, D.W. 1959. Monthly charts of evaporation from the Norht Indian Ocean, including the Red Sea and Persian Gulf. Quart. J. Roy. Meteorol. Soc., 85: 424-428.

Sutton, O.G., 1949. The application to micrometeorology of the theory of turbulent flow over rough surface. Quart. J. Roy. Meteorol. Soc., 75: 335-350.

Sverdrup, H.U., 1937. On the evaporation from the oceans. J. Mer. Res., 1: 3-14.

Sverdrup, H.U., 1951. Evaporation from the oceans. Compendium of Meteorology. Boston, Amer. Met. Soc. : 1071-1081.

Vercilli, F., 1925. Richerche di oceanografic fisica eseguite della R. Nave AMMIRAGLIO MAGNAGHI (1923-1924). Part I. Correntie maree. Annali Idrografici., 11: 1-188.

Wust, G., 1954. Gesetzmaessige Wechselbeziehungen Zwischen Ozean und Atmosphaere in der zonalen Verteilung von Oberflaechensalgehalt. Verdunstung und Niederschlag. Arch. Meteorol., Geophys., Bioklim., A., 7, Wien. Defant Festschr., 305-328.

Yegorov, N.I., 1950. Calculation of the heat balance of the Red Sea. Meteorologiia i Gidrologiia, 3: 49-56 (in Russian).

TABLE 1

MONTHLY MEAN VALUES OF EVAPORATION FOR JEDDAH COASTAL WATER OF THE RED SEA

| Month | $e_0 - e_Z$ (mb) | $u_*$ (cm/s) | P (mb) | E (cm) |
|---|---|---|---|---|
| January | 15.23 | 25.75 | 1014.5 | 20.2 |
| February | 13.59 | 18.03 | 1012.3 | 11.5 |
| March | 14.60 | 23.18 | 1011.2 | 17.5 |
| April | 15.81 | 23.18 | 1008.1 | 18.4 |
| May | 18.93 | 23.18 | 1006.6 | 22.8 |
| June | 17.87 | 20.60 | 1003.8 | 18.6 |
| July | 24.13 | 12.88 | 1002.9 | 16.4 |
| August | 23.19 | 18.03 | 1003.5 | 21.9 |
| September | 15.33 | 15.45 | 1003.7 | 12.0 |
| October | 17.70 | 12.88 | 1009.2 | 12.0 |
| November | 19.25 | 18.03 | 1012.7 | 17.4 |
| December | 19.89 | 15.45 | 1014.5 | 16.0 |
| Annual | | | | 205 |

TABLE 2

MONTHLY AND ANNUAL VALUES OF EVAPORATION (CM) FROM COASTAL STATIONS OF THE RED SEA (AFTER VERCELLI, 1925)

| Month | Tor | Port-Sudan | Suakin |
|---|---|---|---|
| January | 19.4 | 22.0 | 13.6 |
| February | 19.2 | 17.0 | 13.2 |
| March | 25.1 | 23.6 | 15.1 |
| April | 26.5 | 26.0 | 15.8 |
| May | 28.5 | 30.9 | 20.7 |
| June | 32.7 | 39.2 | 31.1 |
| July | 31.3 | 41.1 | 39.6 |
| August | 30.0 | 39.4 | 36.0 |
| September | 26.5 | 31.4 | 23.4 |
| October | 21.5 | 20.8 | 14.5 |
| November | 20.2 | 21.4 | 14.1 |
| December | 25.5 | 22.9 | 14.3 |
| Annual | 306 | 336 | 251 |

TABLE 3

SUMMARY OF PUBLISHED DATA ON EVAPORATION OF THE RED SEA
ANNUAL AVERAGE; CM YEAR
(AFTER MORCOS, 1970)

| METHOD OF ESTIMATION | WATER BUDGET | DIRECT OBSERVATION BY PAN MEASUREMENTS | | HEAT BALANCE EQUATION | BULK AERODYNAMIC METHOD | | |
|---|---|---|---|---|---|---|---|
| REGION | KRUMMEL (1911) | VERCILLI (1925) | CORRECTED ACCORDING TO Wust (1954) | NEUMANN (1952) | YOGOROV (1950) | NEUMANN (1952) | PRIVETT (1959) |
| Whole Sea | 250 | 350 | 192.5 | 211 | 230 | 215 | 183 |
| 27 30' N | | | | | 237 | | |
| 25 N | | | | 211 | 208 | 215 | 204 |
| 20 N | | | | 225 | | | |
| 15 N | | | | 235 | 234 | | |

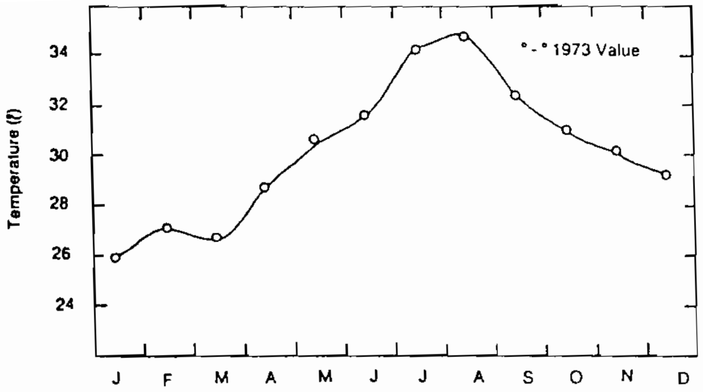


Fig. 1. Monthly mean values of surface water temperature

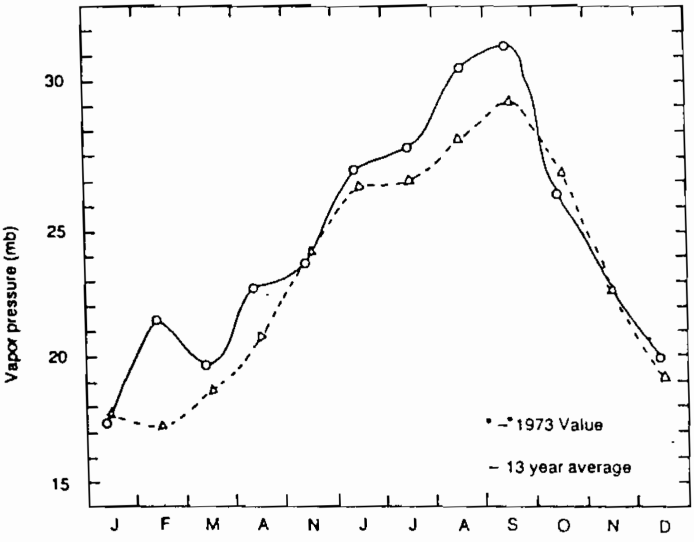
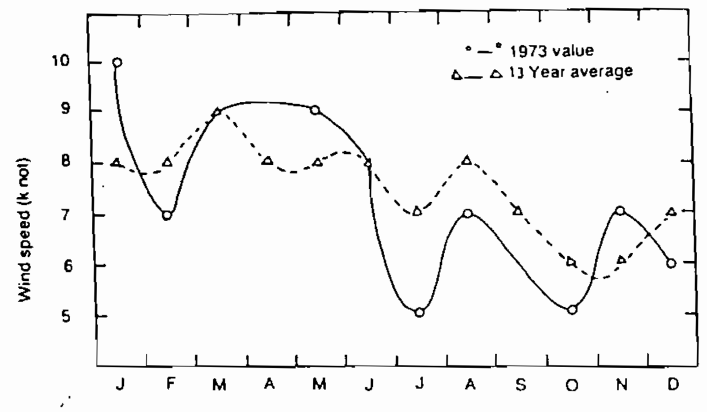


Fig. 2. Monthly mean values of vapor pressure

(a) Wind speed



(b) wind direction

| Month | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1973 | N | NNE | N | N | N | N | N | N | NNW | N | N | N |
| 1966-1978 | N | N | N | N | N | NNW | NNW | NW | N | N | N | N |

Fig. 3. Monthly mean wind speed (a) and wind direction (b)

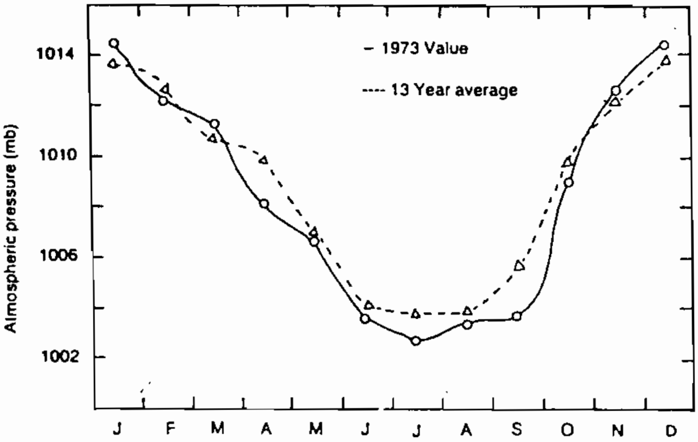


Fig. 4. Monthly mean values of atmospheric pressure

# البخر من المياه الساحلية أمام جده

عبد القادر على بحيرى . محمد محسن عثمان . أمين حامد مشعل
كلية علوم البحار – جامعة الملك عبد العزيز

تم حساب القيم الشهرية للبخر من المياه الساحلية امام جده بتطبيق الطريقة الأيروديناميكية . ولقد تم اجراء الحسابات باستخدام المتوسطات الشهرية لدرجة الحرارة السطحية لمياه جدة الساحلية علاوة على بيانات العناصر الجوية السطحية لنفس المنطقة .

وقد اظهرت النتائج ان اعلى قيم للبخر الشهرى تكون في فصلى الربيع والصيف وأقلها في فصلى الشتاء والخريف . كما وجد ان البخر السنوى من منطقة البحث يعدل ٢٠٥سم .

وباستعراض البيانات المتاحة عن البخر من البحر الاحمر وجد أن النتائج التى تم التوصل اليها تقع في الحدود المعقولة لقيم البخر في منطقة [illegible] .

JED. JOUR. MAR. RES., Vol. I., 1981.

# EVAPORATION FROM THE CENTRAL ZONE OF THE RED SEA

**A.K.A. Behairy, A.H. Meshal and M.M. Osman**
Faculty of Marine Science,
King Abdulaziz University.

## ABSTRACT

The aerodynamic method was used to estimate daily and monthly evaporation from the central zone of the Red Sea between the parallels 21°N and 22° N. Evaporation was calculated from surface meteorological parameters and sea surface temperature observed simultaneously for a whole year over this region. Standard instruments mounted on board the R/V SOELA were used to collect observations at 21 stations well distributed in the investigated area.

Close agreement occurred between evaporation vaules estimated from parameters averaged over a day and over a month. The total annual evaporation was 144 cm with its highest and lowest values in November and September respectively. Evaporation values presented here are much lower than those estimated by previous investigators, but still higher than evaporation from corresponding latitudes of other oceans.

## INTRODUCTION

This paper presents an attempt to estimate evaporation from the central zone of the Red Sea which includes the hot brine region. The investigated area extends between the parallels 21°N and 22 N and covers the whole width of the Red Sea between the Sudanese and Saudi Coasts (Fig. 1). Observations were made on board the R/V SOELA as part of an environmental survey in the region of the hot brines. This survey was organized and funded by the Saudi Sudanese Commission for the Development of the Red Sea Resources. Surface meteorological parameters and sea surface temperature were observed at 21 stations distributed in four longitudinal sections covering the western, central and eastern parts of the area under investigation.

Field measurements were taken on board the vessel in the period from June 14, 1977 through June 15, 1978. Standard instruments for measuring humidity, atmospheric pressure and air temperature were placed inside a special shelter above the bridge at a height of 22 m above sea surface. Wind sensors were placed at a height of 24 m above sea surface and two graphic recorders ( Chauvin - Arnous) plotted continuously the relative speed and direction of the wind .The meterological parameters as well as sea surface temperature were observed daily at 3-hourly intervals. Measurements were not taken when the vessel was under the lee of the shore and during the call at ports. The number of actual observations was 2259 for wind and 2285 for other parameters which represents about 75% and 76% respectively of the theoretical number of observations (2928). Details of position determination at sea, of field measurements and equipment used are given in the " Environmental Survey" -1977- 1978, Final Report, vol. 1 and 2, Atlantis II Project, Red Sea Commission, Jeddah, Saudi Arabia ( unpublished ).

Daily and monthly evaporation is estimated here by the aerodynamic approach using parameters averaged over a day and over a month. The present investigation is distinguished by the fact that all the meteorological parameters as well as sea surface surface temperatures were observed simultaneously over sea for a whole year. This represents an ideal condition for estimating evaporation from a water body.

## METHOD OF ESTIMATION OF EVAPORATION

The aerodynamic approach allows evaporation to be computed from measurements of meteorological parameters as well as sea surface temperature. Some assumptions are required to relate the transfer mechanism for water vapour to that of either momentum or heat. Several evaporation equations based on the aerodynamic approach were developed by different authors among them are Sverdrup (1937) Millar (1937), Norris (1948) and Sutton (1949). The relative merits of these formulae were discussed by Sverdrup (1951) and by Anderson, Anderson and Marciano (1950). Reliable experimental evaluation of these equations were made by Marciano and Harbeck (1954) and by Meshal (1973). They found that only Sverdrup's (1937) and Sutton's (1949) formulae gave results in close agreement with the observations. Sverdrup's (1937) formula will be used here to estimate evaporation. This formula is based on the existence of laminar and turbulent layers and is given as:

$$F = \frac{\rho k u_* (q_0 - q)}{\ln \frac{z + z_0}{d + z_0} + \frac{k u_*}{D}}$$

where F is the rate of evaporation per unit area ($g\ cm^{-2} s^{-1}$).
S is the density of air = $1.2 \cdot 10^{-3} g\ cm^{-3}$,
k is von Karman's constant = 0.4,
q and $q_0$ are the specific humidities at height z and the saturation value respectively,
D is the coefficient of vapour diffusion = $0.24\ cm^2\ s^{-1}$,
$u_*$ is the friction velocity ($cm\ s^{1}$),
$z_0$ is roughness length cm, and
d is the thickness of the laminar layer (cm) defined as,

$$d = 30\ v/u_* \quad \ldots \quad \ldots \qquad (2)$$

where v is the kinematic viscosity of the air = $0.15\ cm^2\ s^{1}$.
Sometimes it is more convenient to use the vapour pressure stet. instead of the specific humidity q and their relation is given by an equation of the form, ( Mc Lellan, 1965 ),

$$q = 0.622\ e / (p - 0.378\ e) \qquad 0.622\ e/p \quad \ldots \qquad (3)$$

where p is the atmospheric pressure in milli bars. Rearranging Sverdrup's (1937) symbols, replacing q by e using equation (3) and substituting the physical constants by their numerical values, equation (*i*) becomes,

$$F = \frac{29.9\ u \cdot (e_0 - e).\ 10^{-5}}{P\left(\ln \frac{z + 0.6}{d + 0.6} + 7.2\right)} \qquad (4)$$

where e is the vapour pressure at height z and $e_0$ is the corrected saturation vapour pressure at sea surface temperature. Equation (4) can be used to estimate daily and monthly evaporation in cm by taking the density of pure water as 1 g $cm^{-3}$ and by multiplying by the number of seconds in a day or month. The daily evaporation E′ is estimated from,

$$E' = \frac{25.83\ u \cdot (e_0 - e)}{P\left(\ln \frac{z + 0.6}{d + 0.6} + 7.2\right)} \qquad (5)$$

and the monthly evaporation E is estimated from,

$$E = \frac{29.9\ u \cdot (e_0 - e).\ 10^{-5}\ N}{P\left(\ln \frac{z + 0.6}{d + 0.6} + 7.2\right)} \qquad (6)$$

where N is the number of seconds in the concernd month.

## RESULTS AND ANALYSIS

During the period of investigation the monthly mean values of wind speed were fluctuating around 5 m $s^{-1}$. The speed was stronger in late winter and during spring than in summer and autumn. Wind direction was mainly from the north in autumn and winter while in spring it was from the north and north west. In summer the wind had variable directions but the north western direction prevailed. The mean atmospheric pressure fluctuated between 1001 mb and 1014 mb during summer and winter respectively. It increased continuously from August to January and then decreased again. The mean relative humidity reached its highest value in September and lowest in November/December. The average extreme values of air temperatures occurred in July and January. The variation of sea surface temperature followed that of the air with a lag of about one month (Fig. 2). The parameters used in estimating evaporation from the central zone of the Red Sea are given in Table (1). It can be concluded from this table that evaporation values estimated on daily and monthly bases are very close. The average difference between these values is about 0.1% with a maximum of 3% which is much smaller than the expected error in the field observations. The standard deviation for the daily averages calculated over a month was small (0.04). This indicates that there was almost no difference between evaporation calculated from the monthly mean data and that calculated from the daily mean and then averaged over a month. This may be due to the small daily variations in the meteorological parameters and in sea surface tmperature. When rapid and significant daily variations occurred in one or more of these parameters, the standard deviation became large (as in June). However, the difference between daily and monthly evaporations in this case remained small and did not exceed 3%.

The total annual evaporation from the central zone of the Red Sea was 144 cm with its highest value in November and lowest in September which coincided with the periods of extreme values of humidity.

Several attempts have been made to estimate evaporation from different zones of the Red Sea using different techniques (Table 2). Maury (1855) gave an estimation of about 450 cm/year which is considered too high. Krummel (1911) used the water budget method to estimate evaporation from the Red Sea as 250 cm/year from the difference between volumes of inflowing and outflowing water at Dumeira. These volumes were computed from the cross-section area and from measurements of current velocities taken for a short period. He assumed that the average velocities of the inflowing and outflowing currents are of equal and constant magnitude throughout the year. The validity of these assumptions are doubtful and the expected error in the calculated volumes of transported water would be very high. If this error is taken as ± 10%, which is very reasonable, the expected error in the calculated evaporation is about 90%. Although the water budget is the most direct method for computing evaporation, it should be applied with extreme care. Table (2) illustrates the uncertainity in the estimation of the inflowing and the outflowing water to and from the Red Sea made by different authors. Errors in estimating the terms of the water budget equation may be of larger magnitude than evaporation.

Vercelli (1925) used pan measurements at Port Sudan as an index to evaporation from the Red Sea and concluded that it is 350 cm/year. It is misleading to assume that evaporation at port Sudan represents that from the whole Red sea due to differences in the meteorological conditions. Moreover it is certain that evaporation from pans is much higher than that from natural water bodies due to numerous factors influencing pan measurements. This lead many authors to use an empirical reduction factors to convert evaporation from pans to evaporation from sea (Wust, 1954 and Kohler, 1954).

Neumann used the heat balance equation to estimate evaporation from some regions of the Red Sea (Morcos, 1970) and his values are given in Table (2). Evaporation from the region between latitudes 21° N and 22° N can be inferred from Neumann's results as 220.8 cm/year which is much higher than the value estimated here. These high values may be ascribed to the fact that his data were collected at a single meteorological station located at 70 km from the western coast of the Red Sea. He also made use of average data obtained from atlases and tables which may not represent the actual conditions in the region. The use of these average data that are not measured simultaneously may introduce errors in calculating the terms of the heat balance equation especially Bowen's ratio which is sensitive to the difference between air and sea surface temperatures.

Yegorov (1950), Neumann (in Morcos, 1970) and Privett (1959) estimated evaporation from some regione of the Red Sea using the aerodynamic method. The first two authors made use of average data obtained from meteorologicl atlases, tables and from published refernces. Again, the use of such average data may introduce errors in the estimation of evaporation. Privett's data can be considered as an improvement on earlier ones. It consisted of simultaneous observations taken with standard instruments at fixed hours aboard British ships during the period (1921 - 1950). Privett's value represents the evaporation along the main axis of the Red Sea where the ships took their observations.

Krummel, Vercelli, Neumann and Yegorov found that the highest evaporation from the Red Sea was in summer and the lowest in winter. On the other hand, Privett's results show that evaporation was highest in autumn ( November ) and lowest in spring ( May ). However, this does not apply to every zone in the Red Sea. Published data on evaporation from the Red Sea is given in Table (2) which indicates that all of them are much higher than that from the corresponding latitudes from the oceans (120-130 cm/year accordimg to Wust, 1954). Evaporation estimated here is much lower than any of the values estimated by other authors. However, our value is still higher than that from latitudes 21° N 22° N of other oceans ( 130 cm/year ),

## CONCLUSIONS

Sverdrup's ( 1937 ) formula can be used to estimate monthly evaporation from daily measurements of meteorological parameters and sea surface temperature averaged over a month. This facilitates the calculations to a great deal without introducing any unacceptable error since the difference between evaporation estimated on daily and monthly basis did not exceed 3%. It can also be concluded from the above discussion that when the aerodynamic and the heat balance approaches are used to estimate evaporation from the whole Red Sea, the sea should be divided into regions according to meteorological conditions. Evaporation from each of these regions should be estimated from simultaneous measurements taken over the sea surface. Evaporation from the sea as a whole is then obtained by combining the evaporation values from these regions.

## ACKNOWLEDGEMENTS

The Saudi Sudanese Commission for the Development of the Red Sea Resources is sincerely acknowledged for providing the data used here.

## REFERENCES

Anderson, E .R ., Anderson, L .J. and Marciano, J.J., 1950.
A review of evaporation theory and development of instrumentation, Lake Mead water loss investigations. Interim Report, 19159: 1-37.

Bogdanova, A.K. 1966. The hydrological conditions in the Red Sea and Gulf of Aden on observations by R/C ACADEMIC A. KOVALEVSKY. Okeanolohioheskie Issledovanija, 15 ''Nauka, M. (in Russian).

Grasshoff, k., 1969. Zur Chemie des Roten Meeres und des Inneren Golfs von Aden. METEOR Forschungsergebnisse Reihe A, 6, 76 pp.

Kohler, M. a., 1954. Lake and pan evaporatioin. U. S. Geol. Surv Prof Papers. 269 . 127-148.

Krummel, 0., 1911. Handbuch der Ozeanographie. Bd . 2 . J . Engelhorn, Stuttgart, 525 pp.

Marciano, J. J. and Harbeck, G . E ., 1954. Mass-transfer in water- loss investigations. Vol. 1, Lake Hefner studies.Tech . Rep . U.S. Geol. Surv. Prof. Papers, 269. 46-70

Maury, M .F., 1855. The physical geography of the sea and its meteorology.
Edited by J. Leighly, The Harward Library, Cambridge, Mass. (1966), 432 pp.

Mc Lellan, 1965, Elements of Physical Oceanography.
Pergamon Press Inc. Oxford., 151 pp.

Meshal, A.H., 1973. Water and Salt budgets of Lake Qarun, Faiyum. Egypt. Ph .D . thesis, Alexandria University, 278 pp.

Millar, F . G ., 1937. Evaporation fron free water surface. Department of Transport, Division of Meteorological Services, Canada, Canadian Meteorological Memoirs, 1. 39-45.

Morcos., S . A . 1970. Physical and chemical oceanography of the Red Sea. Mar. Biol. Ann. Rev., 8:73.-202

Norris, R., 1948. Evaporation from extensive surface of water roughened by waves. Quart. J. Roy. Meteorol. Soc., 74:1-12.

Privett, D . W . 1959. Monthly charts of evaporation from the North Indian Ocean, including the Red Sea and Persian Gulf. Quart. J. Roy.Meteorol. Soc., 85: 424-428.

Sutton, O . G ., 1949. The application to micrometeorology of the theory of turbulent flow over rough surface. Quart J. Roy.Meteorol. Soc., 75: 335-350.

Sverdrup, H. U., 1937. On the evaporation from the oceans.J. Mar Res., 1 : 3-14 .

Sverdrup, H. U., 1951 . Evaporation from the oceans . In T. F. Malone compedium of Meteorology . Boston .

Vercilli, F. 1925 . Richerche di oceanografic fisica eseguite della R. Nave AMMIRAGLIO MIAGNAGHI ( 1923 - 24 ), Part I, Correntie maree.Annali Idrografici, II : 1-188.

Wust, G. 1954 . Gesetzmässige Wechselbeziehungen zwischen Ozean und Atmosphäre in der zonalen Verteilung von Oberflachensalzgehalt. Verdunstung und Niederschlag . Arch. Meteorol., Geophys ., Bioklim ., A., 1 : 305-328 . Wien . Defant Festschr .

Yegorov, N. I., 1950 . Calculation of the heat balance of the Red Sea. Meteorologiia i Gidrologiia, 3 : 49-56 ( in Russian ).

TABLE 1. Monthly mean values of parameters used in estimating evaporation from the Central Zone of the Red Sea .

| Month | $e_w$ (mb) | e (mb) | u (cm/s) | $u_*$ (cm/s) | P (mb) | E (cm) | E′ (cm) | SD |
|---|---|---|---|---|---|---|---|---|
| January | 30.65 | 21.68 | 455 | 21.94 | 1013.8 | 10.2 | 0.33 | 0.03 |
| February | 30.26 | 22.59 | 554 | 26.72 | 1012.2 | 9.6 | 0.34 | 0.04 |
| March | 31.92 | 24.58 | 707 | 34.10 | 1010.2 | 13.0 | 0.42 | 0.04 |
| April | 34.64 | 27.55 | 674 | 32.51 | 1007.9 | 11.6 | 0.39 | 0.03 |
| May | 37.98 | 30.77 | 565 | 27.25 | 1006.0 | 10.3 | 0.33 | 0.03 |
| June | 39.92 | 32.52 | 545 | 26.27 | 1002.7 | 9.9 | 0.34 | 0.13 |
| July | 42.74 | 32 75 | 451 | 21.75 | 1001.7 | 11 4 | 0.37 | 0.04 |
| August | 43.52 | 34.10 | 525 | 25.32 | 1002.7 | 12.5 | 0.40 | 0.02 |
| September | 40.85 | 33.63 | 544 | 26.24 | 1005.0 | 9.6* | 0.32* | 0.02 |
| October | 38.53 | 29 35 | 537 | 25.90 | 1008.6 | 12 4 | 0.40 | 0.04 |
| November | 36.24 | 23.91 | 585 | 28.21 | 1011.1 | 17.5 | 0 58 | 0.03 |
| December | 33.52 | 21.60 | 525 | 25.32 | 1013.0 | 15.7 | 0.51 | 0.07 |

$e_w$ = Corrected saturated vapour pressure at sea surface temperature .
e = Vapour pressure of the air
u = Wind speed
$u_*$ = Friction velocity
P = Atmospheric pressure

E = Evaporation per month
E' = Evaporation per day
SD = Standard deviation of E'

maximum values of evaporation are underlined and minimum values are designated by.

TABLE 2 . Published data on evaporation from some regions and from the whole Red Sea as well as volumes of inflow and outflow to and from the Red Sea .

| Evaporation (C) | | | | Water balance of Red Sea | | |
|---|---|---|---|---|---|---|
| Region | Value | Red Sea | Author | Inflow $(10^{3} m^{3}/s)$ | Outflow $(10^{3} m^{3}/s)$ | Author |
| | | 250 | Krummel(1) (1911) | 358 | 330 | Morcos (1970) |
| | | 350 | Vercelli(2) (1925) | 730 | 692 | Bogdanova (1966) |
| 25 N | 211 | 211 | Neumann(3)(in Morcos, 1970) | 290 | 260 | Grasshoff ( 1969 ) |
| 20 N | 225 | | | 461 | 424 | Krummel (1911) |
| 15 N | 235 | | ,, | 579 | 486 | Vercelli (1925) |
| 27.5 N | 237 | 230 | Yegorov(4) (1950) | | | |
| 25 N | 208 | | ,, | | | |
| 15 N | 234 | | ,, | | | |
| 25 N | 215 | 215 | Neumann(4) (in Morcos, 1970) | | | |
| 25 N | 204 | 183 | Privett(4) (1959) | | | |

( 1 ) From water budget method
( 2 ) From pan measurements
( 3 ) From heat balance method
( 4 ) From aerodynamic method

# البخر من الجزء الأوسط من البحر الأحمر

عبد القادر على بحيرى ، أمين حامد مشعل ، محمد محسن عثمان

كلية علوم البحار – جامعة الملك عبد العزيز

حسبت قيم البخر اليومي والشهري من الجزء الأوسط من البحر الأحمر فيما بين خطي عرض ٢١° ، ٢٢° شمالا وهذه المنطقة تمثل الاجواء حارة . واستعملت طريقة انتقال الكتلة لحساب البخر من بيانات الأرصاد الجوية ودرجة حرارة سطح البحر التي جمعت في نفس الوقت مدة عام كامل على ظهر سفينة البحوث «سولا» عند ٢١ محطة هيدروجرافية موزعة توزيعا ماسحا في المنطقة المدروسة .

وقد وجد أن نتائج البخر اليومي تتفق مع نتائج البخر المحسوب من متوسطات البيانات الشهرية للأرصاد الجوية ودرجة حرارة سطح البحر .

ونستنتج من البحث أن مقدار البخر السنوي من المنطقة يبلغ ١٤٤سم . وأن أعلى قيمة للبخر حدثت خلال شهر نوفمبر وأقل قيمة خلال شهر سبتمبر . وبمقارنة النتائج التي حصلنا عليها مع نتائج الباحثين السابقين وجد أن القيم التي حصلنا عليها للبخر أقل بكثير من النتائج السابقة وقد بين في البحث أسباب ذلك .