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"Meteorologically Forced Subinertial Flows Through the Strait of Gibraltar"

J. CANDELA
Centro de Investigacion Cientifica
Y Educacion Superior de Ensenada (Cicese)
Ensenada
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Exchange through the Strait of Gibraltar

HARRY L. BRYDEN[1], JULIO CANDELA[2] and THOMAS H. KINDER[3]

[1]*James Rennell Centre for Ocean Circulation, Chilworth Research Centre, Chilworth, Southampton SO1 7NS, UK*
[2]*Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA*
[3]*United States Naval Academy, Annapolis, Maryland 21402, USA*

Abstract – To measure the exchange between the Atlantic and Mediterranean through the Strait of Gibraltar, an array of current meter moorings was deployed for a year in the Strait during 1985-86. A novel aspect of these measurements is the inclusion of conductivity as well as temperature and pressure sensors on each current meter so that the salinity of the flows could be monitored continuously. These salinity measurements determine the water mass characteristics of the flows crossing the sill; they allow definition of the 37psu isohaline as the interface between inflowing fresher Atlantic water and outflowing saltier Mediterranean water; and they enable time series to be developed for the depth of this interface, for the upper layer inflow, and for the lower layer outflow.

From these measurements, the time-averaged outflow of Mediterranean water is estimated to be -0.68Sv (1Sv = 1 x $10^6 m^3 s^{-1}$) and the outflow salinity transport, defined to be the outflow times the salinity excess above a basic Atlantic water salinity of 36.1psu, is estimated to be -1.50 x $10^3 m^3 s^{-1}$ (1Sv x 1psu = 1 x $10^3 m^3 s^{-1}$) equivalent to a net evaporation over the Mediterranean basin of 52cm y^{-1}. Extrapolated measurements of the inflow from current meters generally deployed below 100m depth yield an estimate for the time-averaged inflow of 0.93Sv, which is believed to be unrealistically high in view of the better measured outflow and net evaporation. Thus, a more realistic estimate of the inflow is 0.72Sv, equal to the sum of the outflow and net evaporation as required by the mass budget for the Mediterranean Sea. Such estimates of the exchange are smaller by almost a factor of 2 than previous values for the exchange by LACOMBE and RICHEZ (1982).

The exchange across the Gibraltar sill is found to be due in nearly equal parts to the mean currents and to the tidal fluctuations. The mean currents are smaller than had been expected reaching a peak value of only about -60cm s^{-1} in the deep outflow over the sill. The tidal exchange is due to a strong correlation over the tidal period between the depth of the interface and the strength of the inflowing currents. For the M_2-tide at the sill, the amplitude of the interface depth is 51m and the amplitude of the tidal currents is 1.2m s^{-1}; furthermore, the inflow and interface depth have similar phases. As a consequence, the upper layer is deep on the inflowing tide so that a large slug of Atlantic water crosses the sill into the Mediterranean; on the outflowing tide, the interface is shallow so that a large slug of Mediterranean water crosses the sill into the Atlantic. Similar processes occur for the S_2, O_1 and K_1 tides, though the amplitudes are smaller. In this manner, tidal oscillations lead to a time-averaged exchange of water masses across the Gibraltar sill.

The inflow and outflow, defined to be the instantaneous transports above and below the 37psu isohaline interface, exhibit M_2-tidal amplitudes of 2.3Sv and 1.3Sv respectively. Thus, the tides are large enough to reverse the mean upper layer inflow and lower layer outflow. Daily averaged inflow and outflow transports exhibit low-frequency fluctuations with standard deviations of 0.37Sv and 0.22Sv respectively. Such low frequency fluctuations have been shown previously to be associated with barotropic flows through the Strait of Gibraltar compensating for sea level variations over the Mediterranean due to atmospheric pressure fluctuations (CANDELA, WINANT and BRYDEN, 1989). Finally, from these measurements there appear to be little fortnightly or annual period fluctuations in the exchange through the Strait of Gibraltar.

CONTENTS

1. INTRODUCTION

Observing and modelling the exchange between the Atlantic and Mediterranean basins through the Strait of Gibraltar stimulated many of the early advances in oceanography (DEACON, 1971). The perpetual inflowing surface currents through the Strait of Gibraltar combined with river inputs and even surface waters flowing through the Bosporus into the Mediterranean basin raised the mystery of how the water budget could be maintained when evaporation was clearly not large enough to balance all the inflows. MARSIGLI's (1681) remarkable laboratory experiment demonstrating the two-layer exchange between two basins of different densities combined with his field observations in the Bosporus of a subsurface countercurrent established that the water budget of the Mediterranean must be maintained by a subsurface outflow through the Strait of Gibraltar. Confirmation of this subsurface outflow awaited nearly two centuries until CARPENTER and JEFFREYS (1870), as part of Mediterranean field work in preparation for the upcoming *Challenger* expedition, established the existence of a deep outflow by deploying a drogue at 300m depth from a small boat south of the rock of Gibraltar and observing the boat to drift westward against the wind and the surface currents. This outflow of Mediterranean water over the Gibraltar sill not only aspirates the deep waters of the Mediterranean basin (STOMMEL, BRYDEN and MANGELSDORF, 1973; KINDER and BRYDEN, 1990) but also provides a source of high salinity waters for the intermediate and deep water circulation of the North Atlantic (REID, 1979; PRICE and BARINGER, 1994).

Although NIELSEN (1912) is often cited for first determining the inflow and outflow through the Strait of Gibraltar by applying the Knudsen relations, BUCHANAN (1877) actually applied mass and salt conservation statements for the Mediterranean basin to early values for the salinities of the upper inflow of Atlantic water and of the lower outflow of Mediterranean water derived from specific gravity determinations in the Strait. Combining the salinity values with estimates of the net evaporation (evaporation minus precipitation and river runoff, E-P-R) over the Mediterranean basin, BUCHANAN made surprisingly accurate estimates for the inflow and outflow transports. For the next 100 years, a succession of scientists have made different estimates of the exchange through the Strait using 'improved' values for the net evaporation and for the salinities of Atlantic and Mediterranean waters in the Strait of Gibraltar (Table 1).

LACOMBE (1961) summarised early measurements of the currents in the Strait and concluded that the widely cited inflow transport value of 1.75Sv ($1\text{Sv} = 1 \times 10^6 \text{m}^3\text{s}^{-1}$) by SCHOTT (1915) had little basis in measurement. From analysis of historical current measurements over periods shorter than a day (particularly an estimate by his colleague Lizeray using measurements in 1910), LACOMBE suggested that the inflow and outflow transports were likely to be about 1.0Sv. During a series of cruises in the Strait beginning in 1958 and extending through the 1960s in an international field programme called Projet Gibraltar, LACOMBE (1971, and for a more accessible summary see LACOMBE and RICHEZ, 1982) made the first direct current measurements to determine the tidally averaged inflow of Atlantic water and outflow of Mediterranean water across the Gibraotar sill. These current measurements consisted primarily of current meter lowerings from an anchored ship and the major problem was to take a series of measurements at each depth over a tidal period so that the substantial tidal currents could be averaged out to determine the mean inflow and outflow. The resulting estimates of about 1.2Sv for both the inflow and outflow have been the standard values for the exchange between the Atlantic and Mediterranean basin across the Gibraltar sill for the past 20 years.

TABLE 1. Estimates of net evaporation over the Mediterranean basin, outflow salinity transport, salinity difference between the inflow and outflow transport.

Source	Net Evaporation (cm y^{-1})	Outflow Salinity Transport (x10^{3}m^{3}s^{-1})	Salinity Difference S_M-S_A (psu)	Outflow Transport (Sv)
BUCHANAN 1877	55	1.61	2.60	0.62
NIELSEN 1912	117	3.38	1.91	1.78
SCHOTT 1915	131	3.78	2.31	1.64
SVERDRUP, JOHNSON and FLEMING 1942	87	2.52	1.51	1.68
WÜST 1952	96	2.76		
CARTER 1956	47	1.38	1.50	0.91
TIXERONT 1970	56	1.61		
LACOMBE and TCHERNIA 1972	69	2.00	1.71	1.15
BETHOUX 1979	95	2.75	1.72	1.60
LACOMBE and RICHEZ 1982	75	2.01	1.75	1.15
BRYDEN, CANDELA and KINDER (this paper)	52	1.50	2.20	0.68

The values attributed to NEILSON, SCHOTT, SVERDRUP *et al*, WÜST, CARTER, TIXERONT, and LACOMBE and TCHERNIA are adaptations from Table 2 of HOPKINS (1978). The BRYDEN, CANDELA and KINDER values are those described in this paper from the 1985-86 Gibraltar Experiment measurements.

In the mid 1980s, a group of oceanographers organised an international field programme in the Strait of Gibraltar, called the Gibraltar Experiment, with an overall hypothesis that the amount of exchange between the Atlantic and Mediterranean was determined by the physical configuration of the Strait of Gibraltar, that is by the width and depth of the Strait (BRYDEN and KINDER, 1986). The principal goals of the Gibraltar Experiment were to develop realistic models for the exchange through a strait, to measure the amount of exchange across the Gibraltar sill, and to develop a long-term monitoring strategy to make long time series measurements of the exchange. The field programme and some of the early results of the Gibraltar Experiment are described by KINDER and BRYDEN (1987, 1988).

During the Gibraltar Experiment field programme, remarkable progress was made in developing hydraulic control models for two-layer flow through a strait and sill region like Gibraltar (BRYDEN and KINDER, 1991a). BRYDEN and STOMMEL (1984) put forward an initial model with a single control point at the sill that stimulated ARMI (1986) to publish the results from his 1975 PhD thesis on two-layer flow over obstacles which demonstrated there are in fact two control points of critical flow. ARMI and FARMER (1985) reanalysed the 1960s measurements in the Strait of Gibraltar to suggest that the two control points appeared to be at the sill section and at the narrowest section. Then ARMI and FARMER (1986) and FARMER and ARMI (1986) formulated and solved the maximal exchange problem of steady, two-layer flow through a strait and sill region like Gibraltar for a given density contrast between Mediterranean and Atlantic waters. Furthermore, in analysis of their own observations in the Strait, ARMI and FARMER (1988) found confirmation of the hydraulic control concepts during a three-week shipboard survey of the exchange processes. DALZIEL (1990, 1991, 1992) refined the formulation, re-solved the Gibraltar problem, and studied rotational effects as well as parabolic configurations for the cross-sections of the Strait. BORMANS and GARRETT (1989a,b) also solved the maximal two-layer Gibraltar exchange and studied rotational and frictional effects as well as triangular configurations for the cross-sections; but they stressed the differences between maximal and submaximal exchange solutions and argued that the Gibraltar exchange switches between maximal and submaximal states over the course of a year (BORMANS, GARRETT and THOMPSON, 1986; GARRETT, BORMANS and THOMPSON, 1990). Finally, BRYDEN and KINDER (1991b) solved the steady, two-layer flow using triangular cross-sections, summarised the other models, and emphasized how the maximal exchange solution determined not only the size of the exchange but also the salinity difference between the Mediterranean and Atlantic waters for a given net evaporation over the Mediterranean basin. For a net evaporation of 60cm y^{-1}, BRYDEN and KINDER found that the predicted maximal exchange through the Strait of Gibraltar consists of 0.92Sv Atlantic water inflow, 0.88Sv Mediterranean water outflow with a salinity difference of 1.98psu.

The second goal of the Gibraltar Experiment to measure the exchange through the Strait was also carried out through an extensive programme of moored current meter measurements (PILLSBURY, BARSTOW, BOTTERO, MILLEIRO, MOORE, PITTOCK, ROOT, SIMPKINS, STILL and BRYDEN (1987). Preliminary estimates of the observed exchange from these current meter measurements have so far been presented in a series of limited papers at conferences (BRYDEN, BRADY and PILLSBURY, 1989; BRYDEN and PILLSBURY, 1990; BRYDEN, 1993). The principal purposes of this present paper are to describe these current measurements at the Gibraltar sill during 1985-86, to present various methods for estimating the mean exchange across the sill and to show that the different methods yield consistent estimates for the inflow of Atlantic water and outflow of Mediterranean water through the Strait of Gibraltar, and to investigate the temporal variability of the exchange over time-scales ranging from semi-diurnal tides to the seasonal cycle.

2. DATA AND METHODS

An array of 8 moorings was set in the Strait of Gibraltar during October 1985 (Fig.1a) from the Spanish naval vessel *Tofino* as part of the Gibraltar Experiment (BRYDEN and KINDER, 1986). This array with 3 moorings across the sill section of smallest cross-sectional area (Fig.1b, moorings 1, 2, 3) and with 6 moorings along the central axis of the Strait (Fig.1c, moorings 4, 8, 2, 5, 6, 7) was scheduled for a 6-month deployment and then for replacement to provide a year-long time series of the inflow and outflow through the Strait of Gibraltar. To reduce drag in the high current environment of the Strait, the mooring line was faired above 230m nominal depth and large buoyancy spheres rather than vertically distributed buoyancy were utilized at the tops of the moorings. Two novel techniques were used: new S4 electromagnetic current meters were deployed at the tops of moorings 1, 2, 3, 5 for their first operational use; and all of the current meters measured conductivity as well as current speed and direction, temperature and pressure so that time series of salinity could be obtained.

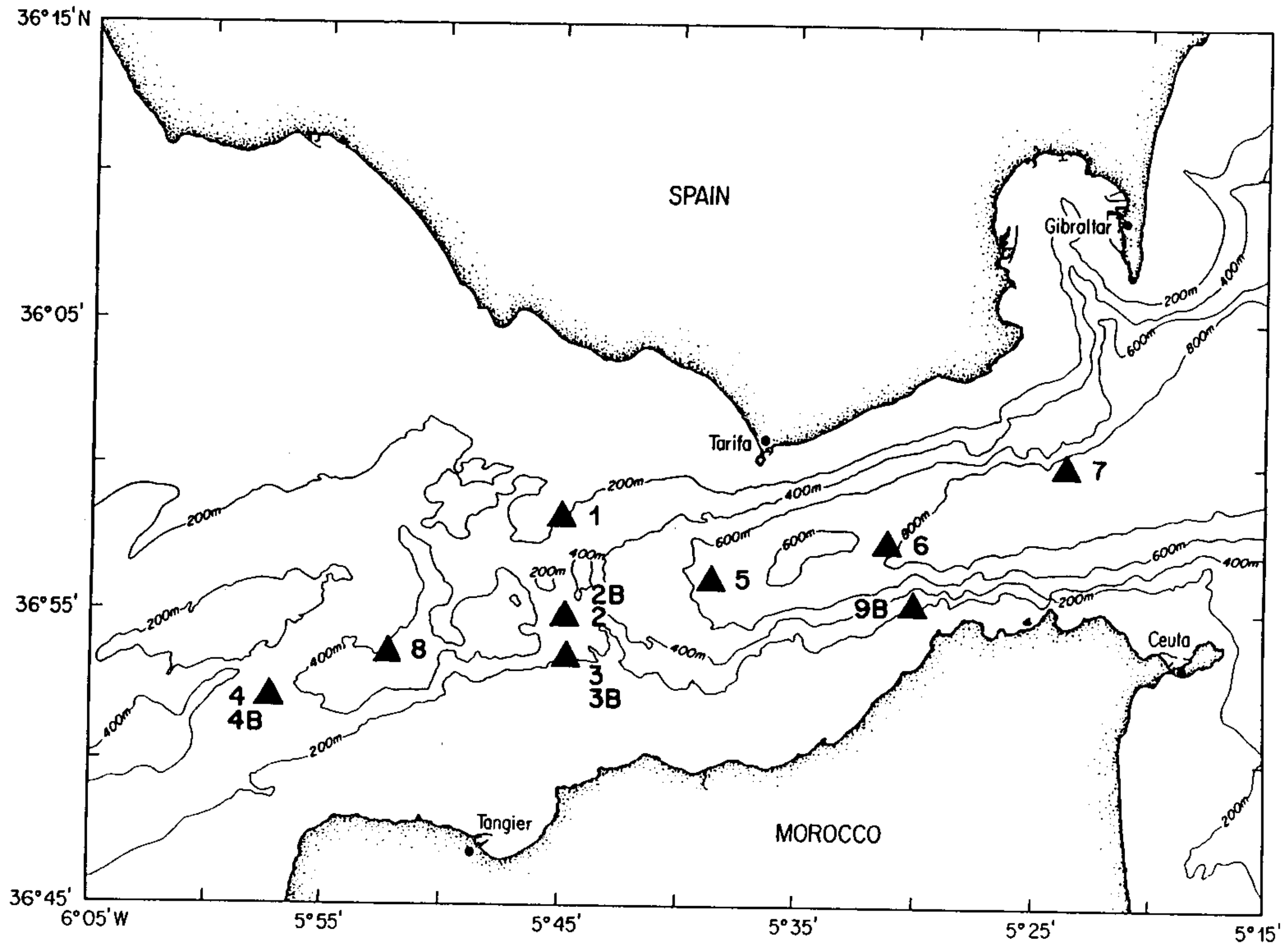


FIG. 1a. Configuration of moorings deployed in the Strait of Gibraltar during 1985-86. Moorings 1 through 8 were deployed for the period October 1985 to May 1986 and moorings 2B, 3B, 4B and 9B were deployed for the period May 1986 to October 1986. Moorings 1, 2 and 3 were deployed across the sill section, that is the section with minimum cross-sectional area, and moorings 2 and 2B were deployed at the sill, that is the location of greatest depth on the sill section.

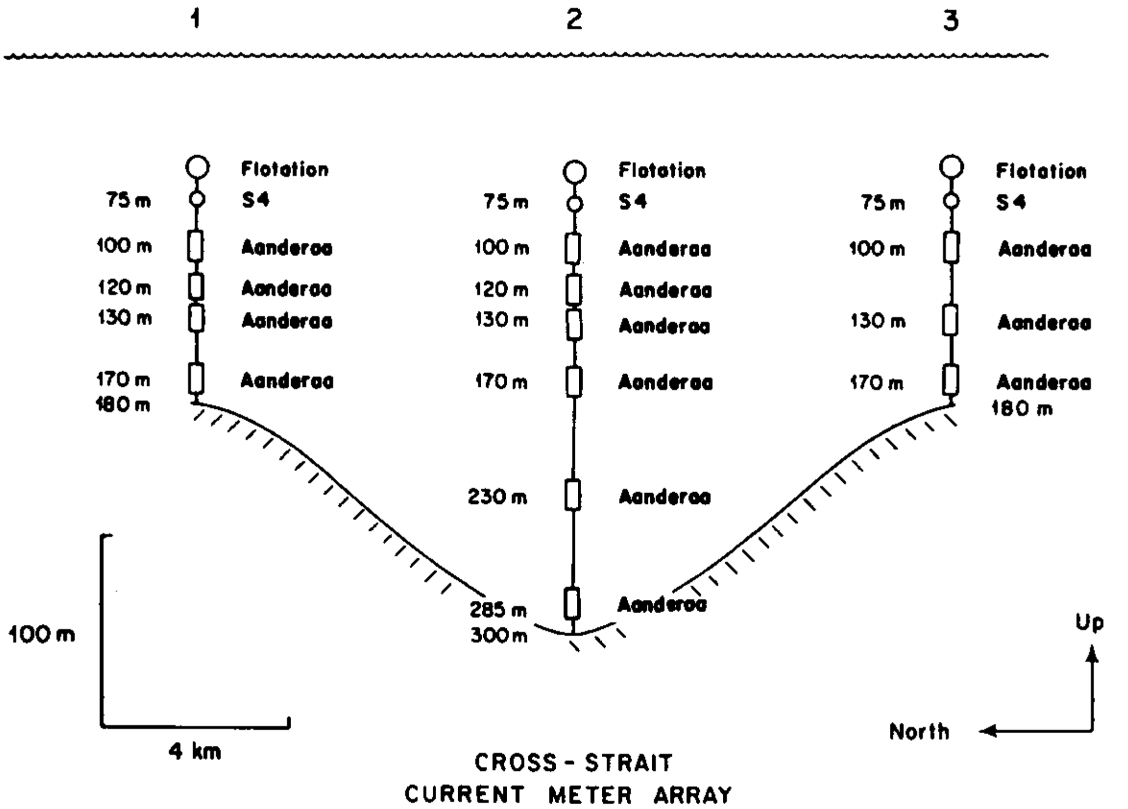


FIG. 1b. Design configuration for the moored current meters deployed across the sill section during October 1985.

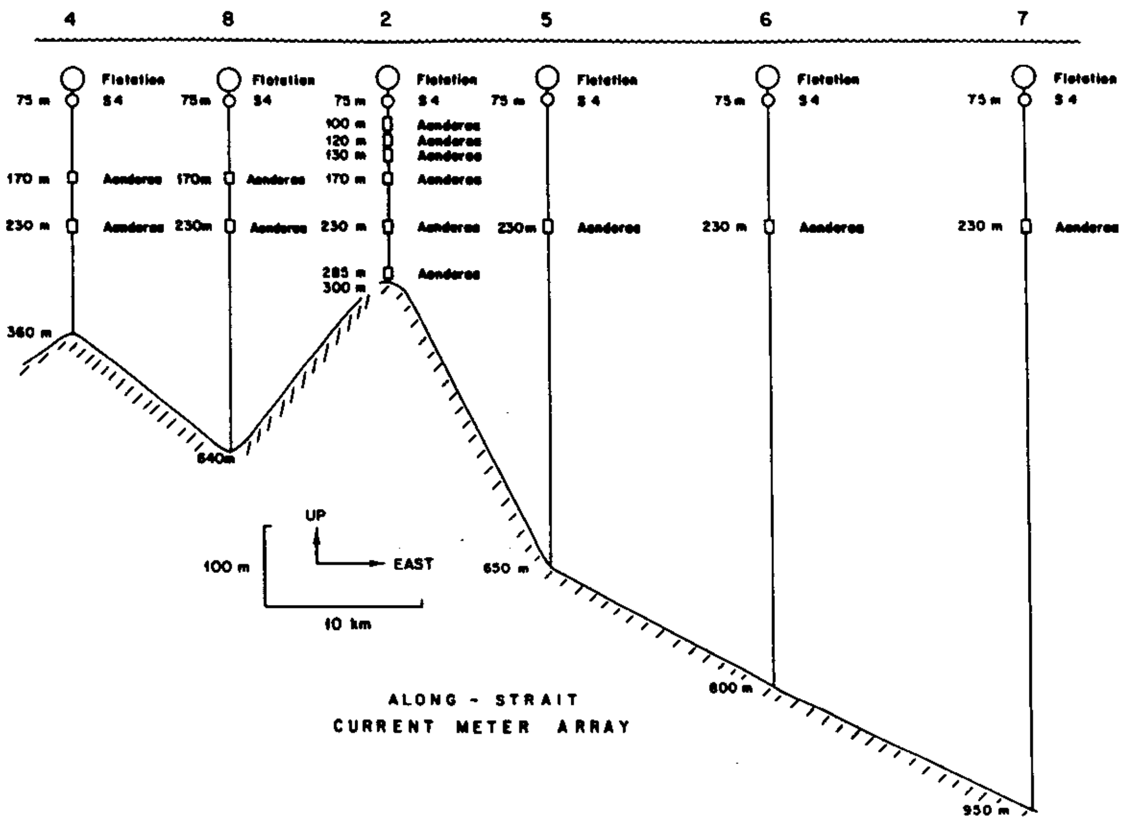


FIG. 1c. Design configuration for the moored current meters deployed along the axis of the strait during October 1985.

There were several technical problems in this first deployment. First, the S4 current meters were improperly programmed for too high a sampling rate so that the instruments ran out of power during the first 36 hours in the water. Secondly, moorings 2, 4, 5, 6, 7, 8 all broke apart at various times during the deployment period so that complete 6-month records were not obtained at these sites. The problem appears to have been that the wire below 230m depth on these moorings was bare, not covered with fairing because of the lengthy time required for fairing installation during deployment and not jacketed because of the effort to keep the wire diameter as small as possible to reduce drag. Although the wire was galvanized, we believe that the currents caused high frequency vibration, or strumming, in the mooring wire which gradually flaked off the galvanizing material. Once the galvanizing material was gone, a battery action was set up and the wire corroded rapidly until it parted. Moroccan and Spanish fishermen recovered the upper parts of moorings 2, 4, 7 and 8 and returned the equipment to the Spanish Navy. At the end of the initial 6-month deployment period, moorings 1 and 3 were recovered intact and the bottom portions of moorings 2 and 5 were also recovered aboard US naval vessel *Lynch*.

The data from the first deployment then consists of complete 6-month records from moorings 1 and 3 on the northern and southern sides of the sill section, one-month records from mooring 2 on the sill and from mooring 4 at the Spartel sill, a 4-month record from mooring 8 in Tangier Basin, and 5-month records from mooring 7 at the eastern entrance of the Strait (Fig.2).

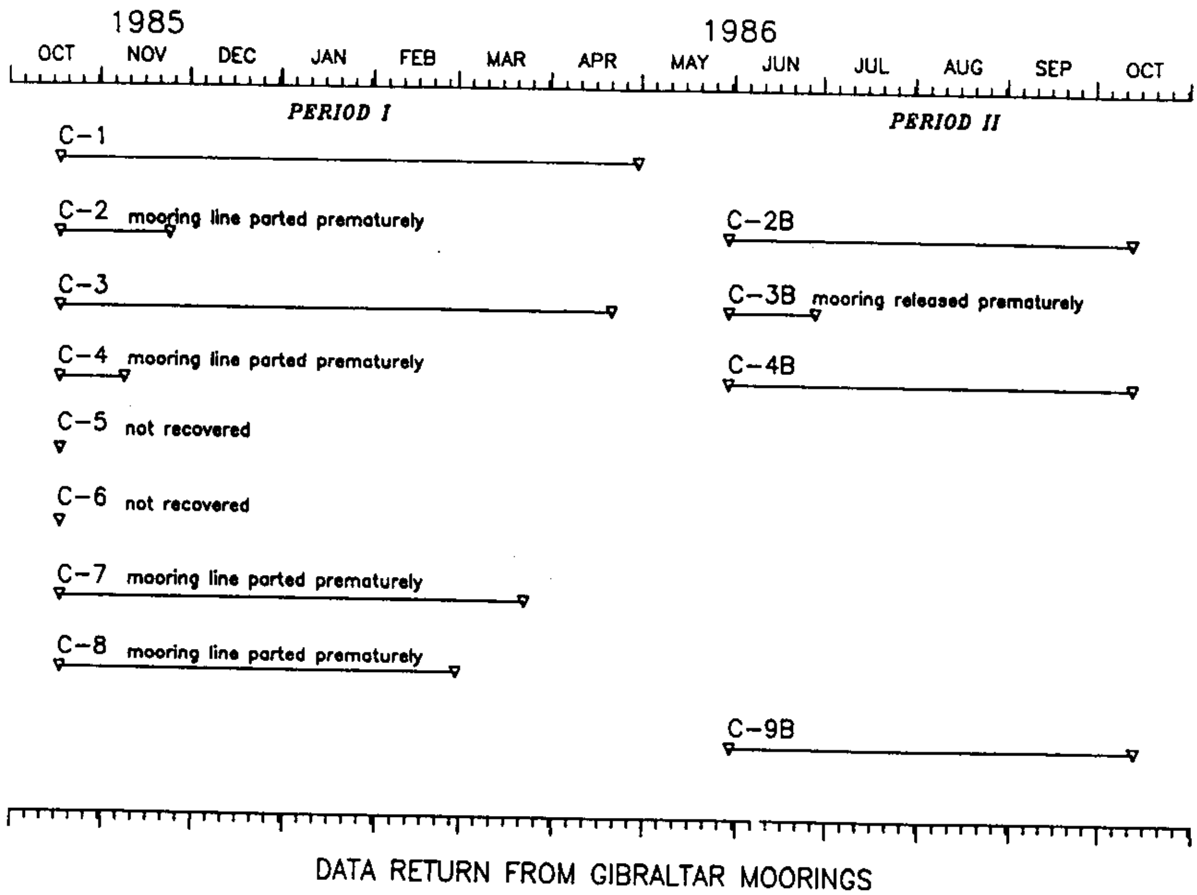


Fig.2. Maximum data length for each mooring deployed during the Gibraltar Experiment.

After the magnitude of the corrosion problem became apparent during the recovery cruise, the array for the second 6-month deployment was redesigned with thicker, jacketed wire throughout each mooring. Fairing was not used on the second deployment because it would not fit over the thicker wire. Because of the limited number of recovered current meters from the first setting, only 4 moorings were redeployed in the Strait from Spanish Naval Vessel *Malaspina*, moorings 2B, 3B, 4B and 9B (Fig.1a). To provide additional measurements, this array was coordinated with the deployment of two Doppler Acoustic profiling current meter (DAPCM) moorings by Dr Neal Pettigrew on the northern side of the sill section (near the location of mooring 1) and on the northern side of the narrowest cross-section (across the Strait from mooring 9). Unfortunately, these 2 DAPCMs did not return any usable data. In mid-October 1986, these moorings were recovered aboard US naval vessel *Lynch*. Of the 4 moorings during the second deployment, only mooring 3B parted prematurely after a month, where the tension bar on the uppermost S4 current meter broke. Each of the other 3 moorings, however, suffered extreme vibration so that some of the current meter sensors failed during their deployment period.

The data from the second deployment then consists of 5-month records at mooring 2B on the sill, mooring 4B at the Spartel sill, and mooring 9B on the southern side of the narrowest cross-section, and one-month records at mooring 3B on the southern side of the sill (Fig.2).

In all, there are 31 current meter records on 10 moorings in the Strait of Gibraltar during the period October 1985 to October 1986. The maximum data length for each mooring is shown in Fig.2 and the time-averaged east and north currents, temperature and salinity and principal axis direction of the current fluctuations for each record are given in Table 2. Current speed and direction, pressure, temperature, and conductivity were measured on each instrument at 30-minute intervals. Presure, temperature and conductivity values are then put into the algorithm given by FOFONOFF and MILLARD (1983) to determine salinity at 30-minute intervals. The data are more fully described by PILLSBURY *et al* (1987).

Because conductivity drifts slowly with time due to cell contamination, each basic salinity time series is corrected for any drift by using the fact that Mediterranean water in the Strait has a maximum salinity of 38.4 to 38.5psu. For each basic salinity time series, the maximum salinity observed over successive four-day intervals was fitted with a least-squares technique to a second order polynomial in time. At each point in the salinity series, the difference between this fit and 38.4psu was subtracted from the salinity. The resulting corrected salinity time series then have a maximum salinity of about 38.4psu which remains relatively constant over the entire data period. As an example of the correction process, the basic and corrected salinity time series are shown in Fig.3 for the current meter at 254m depth on mooring 2.

The character of the current meter data is most easily shown by the time series from mooring 2 at the sill during October-November 1985 (Fig.4). Because the Strait of Gibraltar is oriented in a westsouthwest-eastnortheast direction, the measured currents have been rotated into a coordinate system with the along-strait direction 13° north of east and the cross-strait direction 13° west of north. This rotation was selected by averaging the principal axis directions for all 9 moorings (Table 1) and it is consonant with the general orientation of the Strait. The most striking feature of the along-strait currents (Fig.4a) is the large semidiurnal tidal signal. CANDELA, WINANT and RUIZ (1990) determined that the M_2 tidal currents have an amplitude of 112cm s^{-1} at 123m depth on mooring 2, decreasing to 79cm s^{-1} at 254m depth and that the S_2 tidal currents have an amplitude of 40cm s^{-1} at 123m decreasing to 28cm s^{-1} at 254m. The beating of the M_2 and S_2 tidal signals can be seen in the fortnightly cycle of the amplitude of the semidiurnal tidal currents (Fig.4a). The tidal currents have a similar phase throughout the water column but with a tendency for earlier phase towards the bottom. In the deeper part of the water column, there is a strong mean outflow (negative

TABLE 2. Record-length averaged currents, temperature, salinity and pressure for 31 current meters moored in the Strait of Gibraltar during the period October 1985 to October 1986. Values in parentheses indicate sensor failure during the deployment period so that the averages are over periods shorter than the indicated data length. For the exact time periods of individual sensors, refer to PILLSBURY *et al* (1987).

Mooring	Minimum Pressure (dbars)	Data Length (days)	East Current (cm s^{-1})	Northward Current (cm s^{-1})	Principal Axis Direction (°T)	Temperature (°C)	Salinity (psu)	Pressure (dbars)
1	144	194	-12.58	-9.25	98	13.39	37.93	147
	158	194	-16.69	-8.51	98	13.26	38.01	166
	169	194	-17.70	-10.19	100	13.22	38.03	172
	217	194	-11.21	2.36	107	13.14	(38.23)	218
2	124	32	-3.35	-9.27	78	14.29	36.94	127
	144	32	-14.06	-8.19	78	13.94	37.18	149
	155	32	-22.69	-14.76	75	13.83	37.33	158
	192	32				13.34	37.86	196
	256	32	-46.35	-27.98	61	13.03	38.26	261
	309	32	-26.63	-28.67	49	12.96	38.35	312
2B	91	82	-14.03	-1.94	81	14.43	36.63	102
	113	137	(-1.64)	(0.24)	76	13.92	36.95	123
	136	137	(-26.56)	(-13.37)	74	13.55	37.41	151
	183	137	(-47.27)	(-19.36)	70	13.20	37.91	192
	239	137	(-56.94)	(-21.25)	64	12.98	38.28	247
	302	137	-38.94	-25.51	50	12.95	38.33	306
3	111	182	8.61	10.26	82	14.83	36.85	113
	135	182	-4.66	4.12	80	14.29	37.21	143
	181	182	-22.69	-9.68	69	13.56	37.78	182
3B	103	26	13.20	9.54	86	14.54	36.54	106
	128	23	9.14	6.73	82	14.15	36.87	133
	173	29	-6.55	-2.28	75	13.59	37.52	175
4	68	22	23.96	8.52	73	15.79	36.29	70
4B	(~220)	10	-40.70	-10.20	66	13.13		
	298	7	-85.28	-34.41	60	13.06	38.19	301
	(~340)	136	-86.43	-18.18	65			
7	54	159	53.86	6.83	79	14.43	37.15	(62)
	194	159	-19.70	-10.71	64	13.15	38.29	201
8	28	132	35.76	8.08	75	16.08		36
9B	58	138	(57.70)	(7.87)	76	15.04	36.06	64
	160	138	24.80	16.52	75	13.51	37.79	162

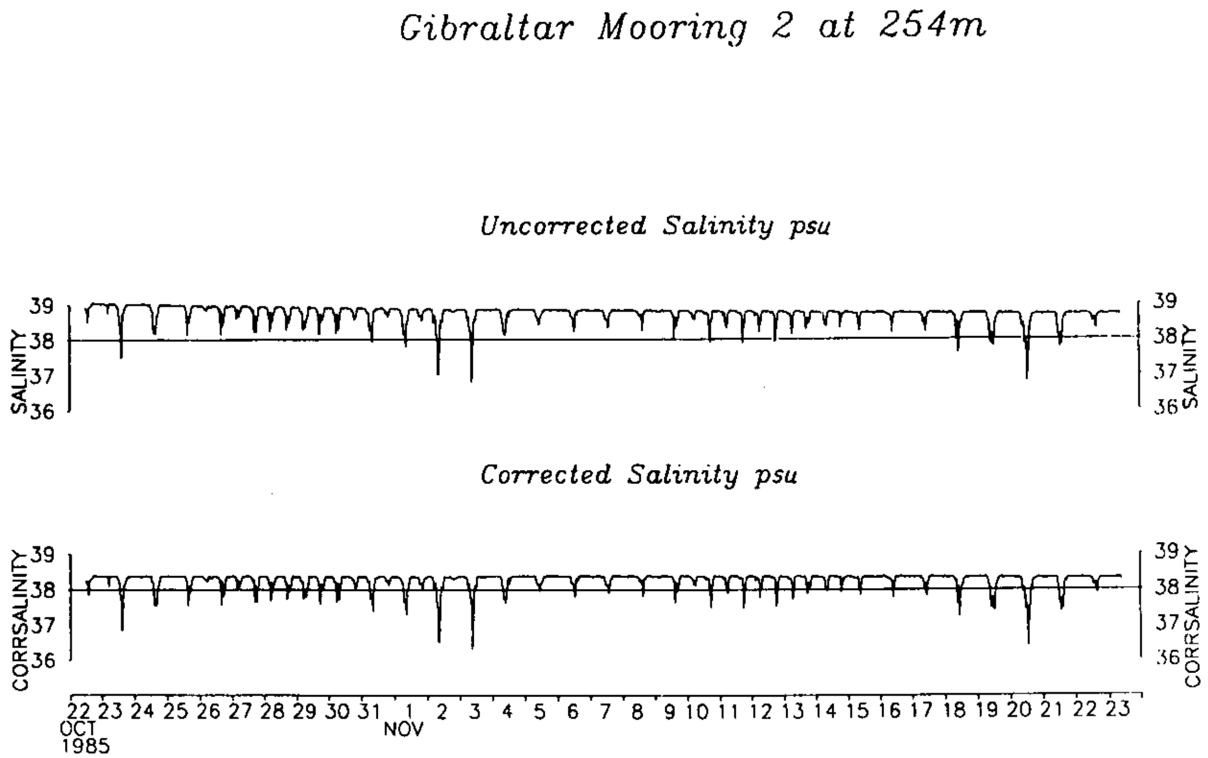


FIG.3. Salinities measured on mooring 2 at 254m depth during October-November 1985. Note the bias toward high (unrealistic) salinities and the slow drift toward fresher values. Such bias and drift are typical for moored conductivity time series. A corrected salinity record was created for each current meter time series by eliminating the bias and drift based on a maximum salinity of 38.4psu.

along-strait current) of order 40cm s^{-1}, but the tidal oscillations are still large enough to reverse the mean outflow during a portion of each day, even at 306m depth, only 15m above the bottom. The cross-strait velocities (Fig.4b) exhibit tidal oscillations of order 10cm s^{-1} and the corrected salinity time series (Fig.4c) also exhibit strong semidiurnal oscillations[1]. In the deeper part of the water column, the variations away from the maximum value of 38.4psu are small, indicating that the current meter is nearly always in the Mediterranean Water. Higher in the water column, there is an increasing number of salinity spikes toward lower salinity, that indicate the instrument is occasionally in Atlantic water. At 123m depth, at the top of the mooring, the spikes appear to be reversed: toward higher salinity from a base at about 36.1psu. This reversal indicates that the uppermost instrument spends the majority of its time in Atlantic water, but often is in Mediterranean water.

All salinity time series on each mooring are used to derive time series for the depths of the 37, 37.5 and 38psu isohalines. The depth interval between these isohalines defines the interfacial region that separates Atlantic Water with salinities less than 37psu in the upper water from Mediterranean Water with salinities greater than 38psu in the deeper water. At each 30-minute sampling interval, the salinities and pressures measured by all instruments on one mooring are interpolated/

[1]The oscillations in salinity are not due to mooring motion. The uppermost current meter on mooring 2 had a maximum downward dip of 28m from its minimum pressure of 123m. Such a small dip in such strong currents is due to the relatively short vertical extent of the mooring. We will show shortly that the interface between Atlantic and Mediterranean water oscillates vertically by 51m over semidiurnal periods at the sill.

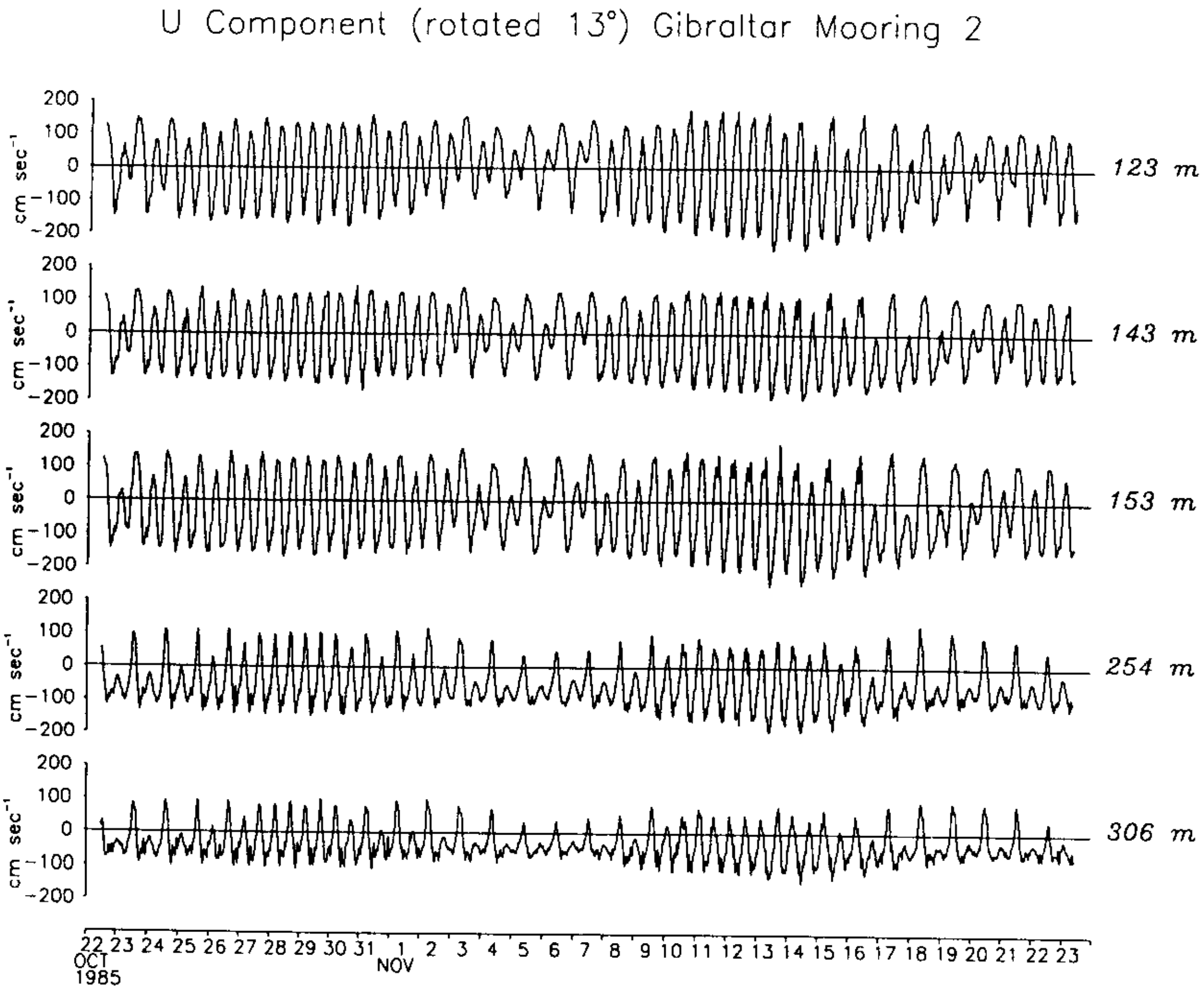
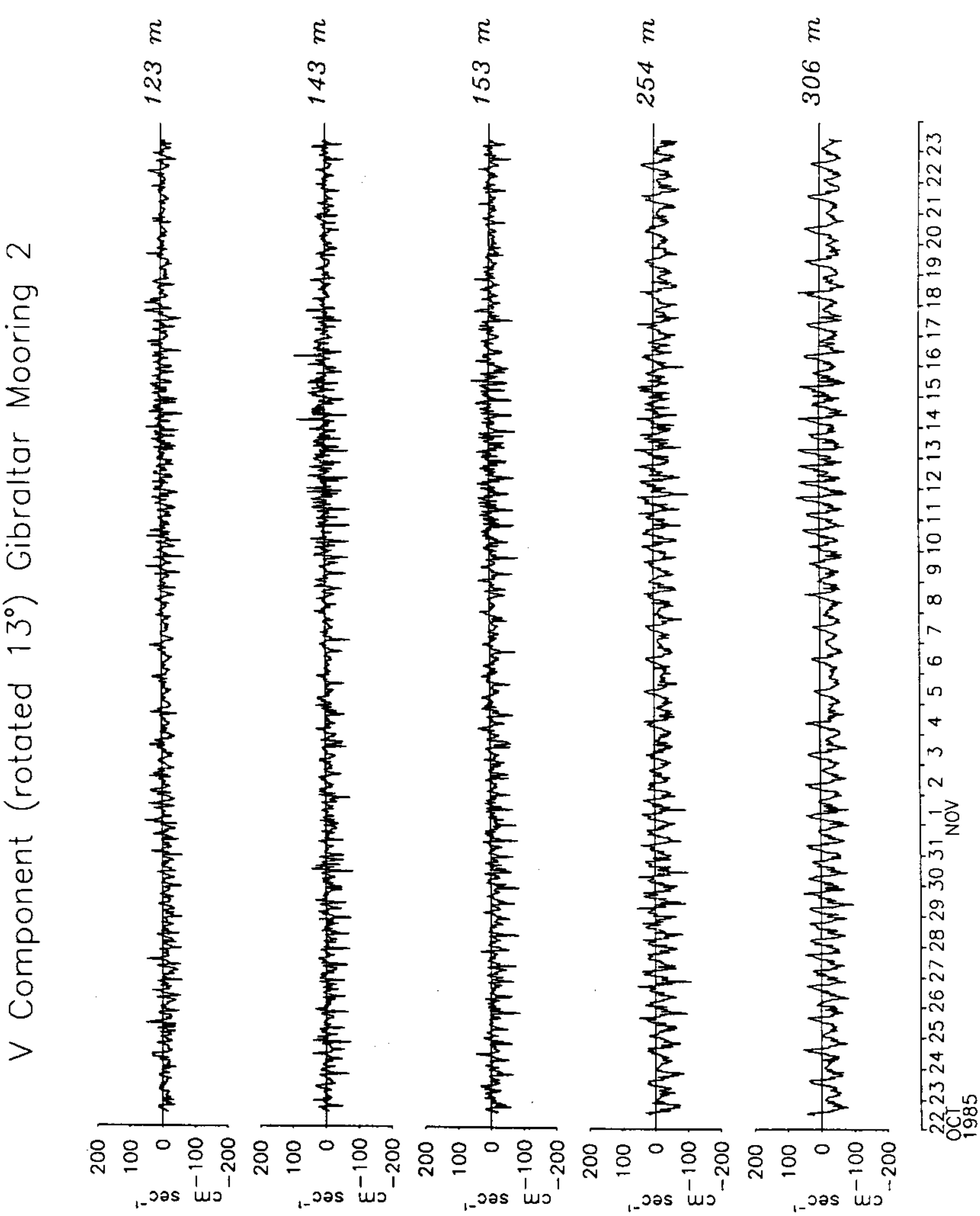


FIG.4. Time series of along-strait (a, above) and cross-strait (b, overleaf) velocities and corrected salinities (c, overleaf) on mooring 2 during October-November 1985. Along-strait direction is defined to be 77°T based on the average principal axis orientation of the current fluctuations and on the physical orientation of the Strait of Gibraltar. Cross-strait direction is then defined to be 347°T.

extrapolated to find the pressures of the 37, 37.5 and 38psu isohalines. If all instruments measure salinities less than 37psu, so that the interfacial region is deeper than the deepest instrument, or greater than 38psu, so that the interfacial region is shallower than the shallowest instrument, there is a gap where no isohaline depths are initially calculated. The time series of the interpolated/ extrapolated depths of the 37, 37.5 and 38psu isohalines are shown at the sill for mooring 2 in Fig.5a. Because gappy time series are difficult to deal with, the gaps in isohaline depths are filled by determining the average vertical salinity gradient at the edges of each gap. This vertical salinity gradient is then used to extrapolate upwards or downwards from the salinity time series on the current meter closest to the interfacial region during the time period of the gap. If the pressure of an isohaline is extrapolated to a value less than 0dbar (the sea surface), the isohaline depth is set to 0. The time series of isohaline depths at the sill on mooring 2 with the gaps filled by this procedure is shown in Fig.5b.

FIG.4b


V Component (rotated 13°) Gibraltar Mooring 2
123 m
143 m
153 m
254 m
306 m
200 100 0 −100 −200
cm sec⁻¹
22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
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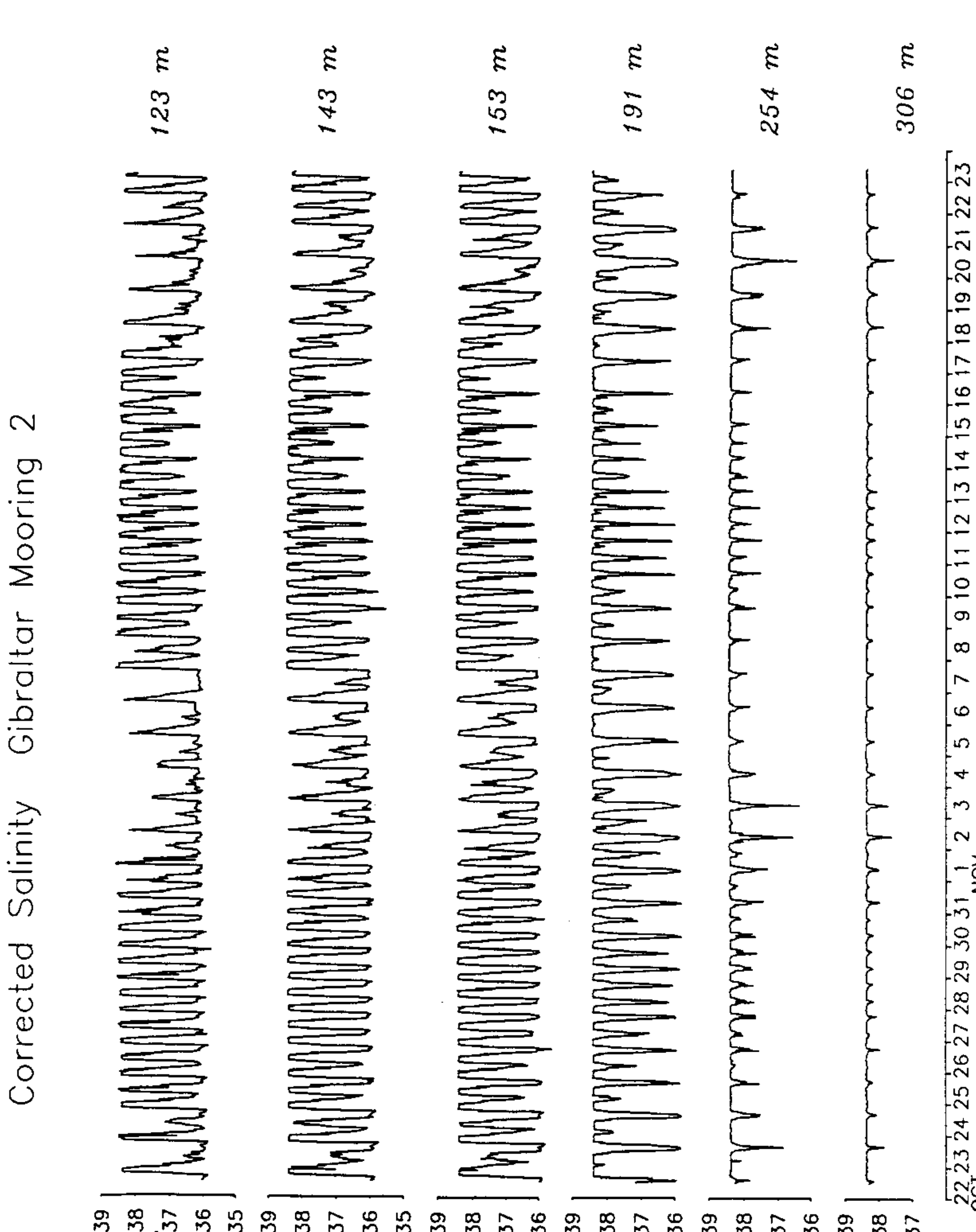
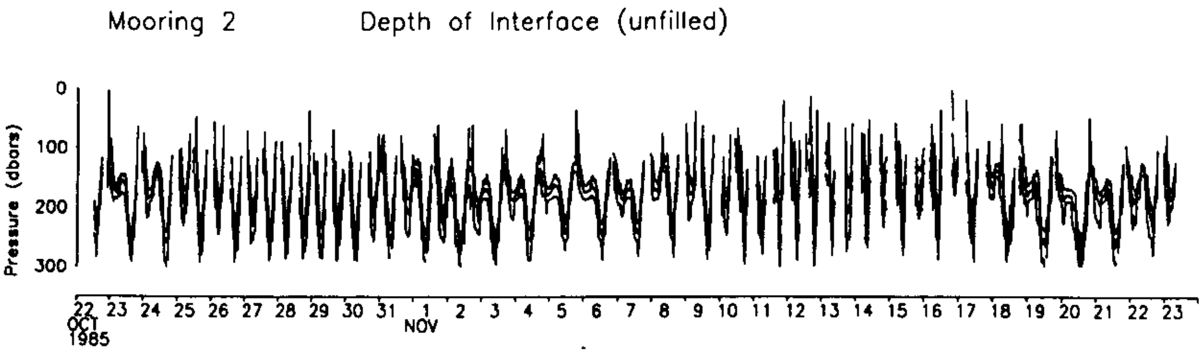
1985

FIG 4c


Corrected Salinity Gibraltar Mooring 2
123 m
143 m
153 m
191 m
254 m
306 m
Salinity
39 38 37 36 35
22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
OCT
1985
NOV



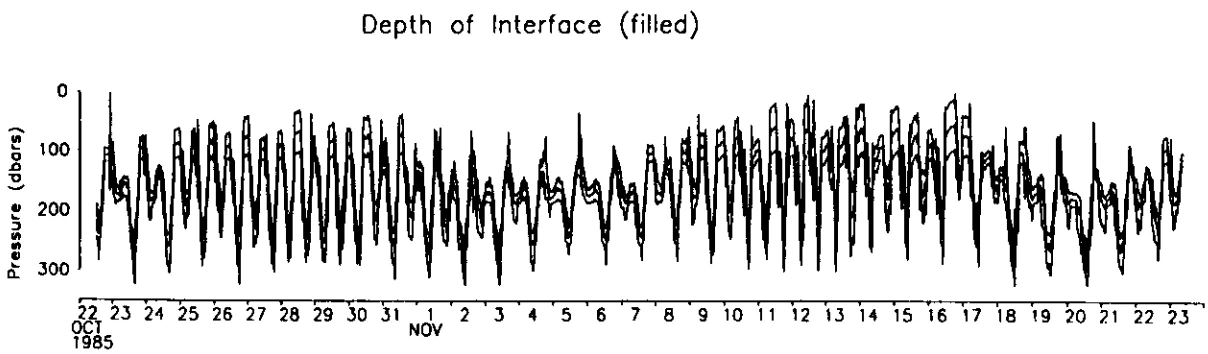


FIG.5. Depths of the 37, 37.5 and 38psu isohalines on mooring 2 during October-November 1985. The upper, unfilled time series are the result of interpolating salinity and pressure time series from the 6 current meters on mooring 2. The lower, filled time series are the result of the combined temporal interpolation-vertical extrapolation technique designed by Esther Brady to create uniform time series.

3. TRANSPORT DEFINITIONS

Traditional estimates of the mean transports through the Strait of Gibraltar have been expressed as average values of the inflow and outflow at nominal salinity values. Generally, a typical salinity difference, $\Delta S = S_M - S_A$ where S_M and S_A are the nominal Mediterranean and Atlantic salinities, of about 2psu between the outflowing and inflowing waters is assumed and is combined with a value for the net evaporation, E, over the Mediterranean basin to yield the outflow and inflow transports, Q_M and Q_A of Mediterranean and Atlantic waters:[1]

[1]The definition of sign of the outflow can be confusing. While we will call Q_M the outflow, Q_M will generally be negative as the Mediterranean water typically flows westward.

$$Q_M = -\frac{S_A}{\Delta S}E \qquad Q_A = \frac{S_M}{\Delta S}E. \qquad (1)$$

Such estimates have typically varied between 1 and 2 x $10^6 m^3 s^{-1}$ principally depending on the estimate of E (Table 1). Of course, the inflow and outflow do not occur at constant salinity, so that with measurements of the flow over the Gibraltar sill it is important to define both the inflow and outflow transports *and* their associated salinities.

In concept, the quantity that remains constant throughout the Strait of Gibraltar is the outflow salinity transport, $Q_M(\Delta S)$. Rearranging the mass and salt conservation equations for the Mediterranean basin:

$$Q_A + Q_M = E$$
$$Q_A S_A + Q_M S_M = 0 \qquad (2)$$

we find that the outflow salinity transport is proportional to the product of the net evaporation and the Atlantic water salinity:

$$Q_M(\Delta S) = -E\,S_A, \qquad (3)$$

which is effectively constant since the Atlantic water salinity varies by only about 1% through the Strait. Thus, while mixing and entrainment in the Strait may change the salinity difference between the inflowing and outflowing waters and the size of the inflow and outflow transports, the outflow salinity transport remains constant. From the observations, one needs to define not only the inflow and outflow transports but also the outflow salinity transport. In return, the observed outflow salinity transport provides a direct estimate of the net evaporation over the Mediterranean basin.

To estimate the inflow and outflow transports and the outflow salinity transport, we will use the measurements on moorings 1, 2, 2B, 3 and 3B deployed across the sill section from Punta Alboassa in Morocco to Punta Paloma in Spain. This section has the minimum cross-sectional area (3.16 x $10^6 m^2$) of any section across the Strait of Gibraltar and its deepest point of 284m is at the sill of the Strait of Gibraltar. Due to the configuration of the sill section, as described by BRYDEN and KINDER (1991b) for their hydraulic model analysis, the direction of along-strait currents for mooring 1 is taken to be 98°T for the transport estimates and the along-strait direction for all other moorings is 77°T. Because 17 of the 21 current records from the moorings on the sill section were deployed below the mean depth of the interface between the Atlantic and Mediterranean waters, these measurements are best suited for determining the transport of the outflowing Mediterranean water. Hence, in the following analyses, the estimates of outflow transport are considered to be generally more reliable than the inflow transport estimates.

There appear to be two reasonable ways to estimate the mean inflow and outflow transports across the Gibraltar sill. The first is to integrate the time-averaged along-strait velocities for all current meters vertically from the bottom up to the depth of zero velocity and then laterally across the sill section to determine the outflow:

$$\overline{Q}_M = \int dy \int_{Bottom}^{z(\bar{u}=0)} \bar{u}(z)\,dz \qquad (4a)$$

and then similarly to integrate vertically from the depth of zero velocity up to the sea surface to determine the inflow:

$$\bar{Q}_A = \int dy \int_{z(\bar{u}=0)}^{0} \bar{u}\,(z)\, dz \qquad (4b)$$

The second method is to find the depth of the interface, h(t) between Mediterranean and Atlantic waters at each instant of time; to integrate the along-strait velocities vertically from the bottom up to the depth of the interface to determine the instantaneous outflow; and to integrate the velocities vertically from the interface depth up to the sea surface to determine the instantaneous inflow:

$$Q_M(t) = \int dy \int_{Bottom}^{h(t)} u\,(z,t)\, dz \qquad (5a)$$

$$Q_A(t) = \int dy \int_{h(t)}^{0} u\,(z,t)\, dz \qquad (5b)$$

Then the mean inflow and outflow transports can be estimated by time-averaging these instantaneous transports.

We will describe the results of each of these methods for determining the exchange between the Atlantic and Mediterranean basins across the Gibraltar sill. While the two approaches appear initially to yield radically different results, careful definition and determination of the outflow salinity transport for each approach and of the contribution to the exchange by the tidal oscillations demonstrate that the two approaches yield consistent results for the exchange. Generally, we conclude that the second approach of determining instantaneous transports provides more insight into the nature of the exchange across the Gibraltar sill.

4. TRANSPORT ESTIMATES FROM MEAN CURRENTS

The first method for estimating the mean inflow and outflow transports starts with the profile of time-averaged currents at each mooring (Fig.6). Because moorings 1, 2B and 3 offer the longest measurement periods at the northern, central and southern mooring sites on the sill cross-section, we will determine the time-averaged transports from these moorings[1]. From interpolation or extrapolation of the mean velocity profiles, we determine that the depth of zero mean inflow-outflow velocity slopes downward from 84m at mooring 1 on the northern side of the sill-section to 120m at mooring 2B on the sill to 134m at mooring 3 on the southern side[2].

To determine an average outflow, we integrate vertically the interpolated time-averaged velocity profile at each mooring, $\bar{u}_i(z)$, and then sum the 3 mooring contributions

$$Q_M = \sum_{i=1}^{3} \int_{Bottom}^{z(\bar{u}=0)} \bar{u}_i(z) L_i(z) dz = -0.385Sv, \qquad (6a)$$

where $L_i(z)$ is the effective cross-sectional width at each depth for each mooring determined from the digitized cross-section bathymetry described by BRYDEN and KINDER (1991b), to estimate the average outflow to be .385Sv. Likewise, to determine an average inflow, we extrapolate the time-averaged velocity profile at each mooring up to the sea surface, vertically integrate, and sum over the 3 moorings as before to estimate the average inflow to be

[1]Measurements on moorings 1 and 3 extended from October 1985 to April 1986, while the measurements on mooring 2B extended from May to October 1986. It will be argued later that there is no significant difference in mean transports for these two periods.

[2]For comparison, the month-long measurements on Mooring 2 and 3B yield depths of zero mean inflow-outflow equal to 115m at mooring 2 and 157m at mooring 3B.

$$Q_A = \sum_{i=1}^{3} \int_{z(\bar{u}=0)}^{0} \bar{u}_i(z) L_i(z) dz = +0.505\text{Sv}. \qquad (6b)$$

Such average values for the inflow and outflow are surprisingly low. For example, the outflow estimate, which should be considered more reliable due to the preponderance of current meters in the deeper waters, is a factor of 3 smaller than the classic value of 1.2Sv determined by LACOMBE and RICHEZ (1982) from shipboard measurements during the 1960s.

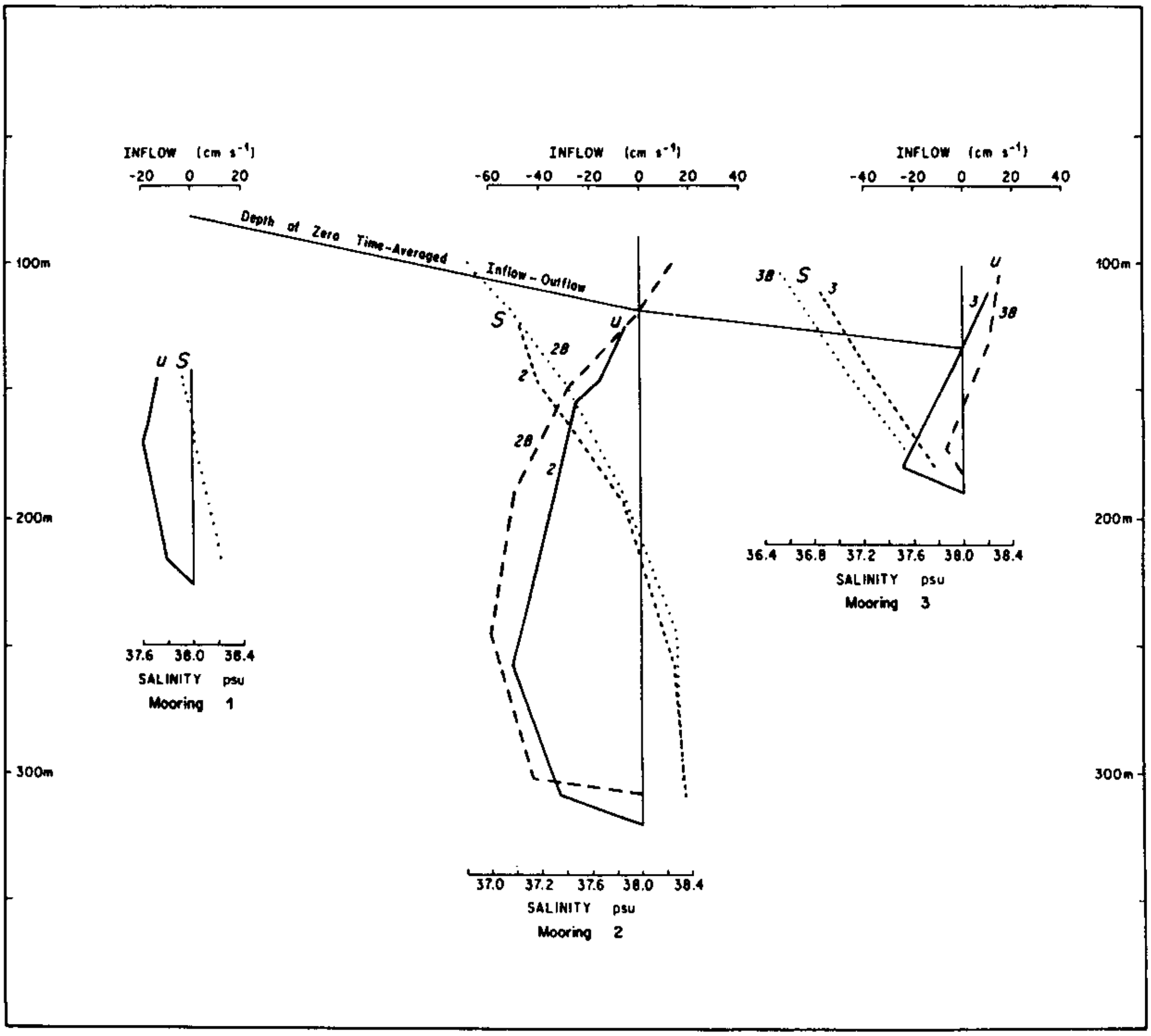


FIG.6. Vertical profiles of record-length averaged along-strait currents ($\bar{u}$) and salinities ($\bar{S}$) for each of the moorings deployed on the sill section. Also indicated is a schematic of the depth of an interface defined to be the location where the average along-strait velocity is zero, i.e. it switches from outflow below to inflow above.

5. CONTRIBUTION OF THE TIDES TO THE MEAN EXCHANGE

The reason that these estimates of the average inflow and outflow are so small is that they do not include all of the exchange between the Atlantic and Mediterranean across the Gibraltar sill. We argued above that the outflow salinity transport must be determined in order to properly quantify the exchange. To determine the outflow salinity transport from the time-averaged statistics at each mooring, we must calculate:

$$\text{Outflow Salinity Transport} = \sum_{i=1}^{3} \int_{\text{Bottom}}^{0} [\bar{u}_i(z)\,(\bar{S}_i(z) - 36.1\text{psu}) + \overline{u'S'}]\, L_i(z)dz = 1.56 \times 10^3 m^3 s^{-1} \qquad (7)$$

where $\overline{u'S'}$ represents an eddy salinity flux due to the correlation between the fluctuations in inflow-outflow velocity and in salinity measured at each current meter. In this estimate, we have subtracted a basic Atlantic water salinity value of 36.1psu in order to minimize the effect of the small imbalance between the mean inflow and outflow transports[1].

Now, the eddy salinity flux dominates the magnitude of the outflow salinity transport. For example at mooring 2B (Fig.7), the outflow salinity transport due to the mean flow is confined to the deep regions of the sill below 175m depth. The eddy salinity flux contribution, on the other hand, is large in the depth range where the interface betwen Atlantic and Mediterranean waters normally resides. The relative contributions to the outflow salinity transport by the mean flow and by the temporal variability are estimated as follows. First, the average salinities of the average outflow and inflow can be determined to be 37.9psu and 36.7psu respectively from

$$S_M = 36.1\text{psu} + \frac{\sum_{i=1}^{3} \int_{\text{Bottom}}^{z_i(\bar{u}=0)} \bar{u}_i(z)(\bar{S}_i(z) - 36.1\text{psu})L_i(z)dz}{\sum_{i=1}^{3} \int_{\text{Bottom}}^{z_i(\bar{u}=0)} \bar{u}_i(z)L_i(z)dz} = 37.9\text{psu}$$

$$S_A = 36.1\text{psu} + \frac{\sum_{i=1}^{3} \int_{z_i(\bar{u}=0)}^{0} \bar{u}_i(z)(\bar{S}_i(z) - 36.1\text{psu})_i(z)dz}{\sum_{i=1}^{3} \int_{z_i(\bar{u}=0)}^{0} \bar{u}_i(z)L_i(z)dz} = 36.7\text{psu}$$

Effectively then, the mean outflow of -0.385Sv occurs at a salinity difference of 1.2psu for an outflow salinity transport of only $-0.46 \times 10^3 m^3 s^{-1}$. The eddy salinity flux,

$$\sum_{i=1}^{3} \int_{\text{Bottom}}^{0} \overline{u'S'}(z)L_i(z)dz = -1.10 \times 10^3 m^3 s^{-1} \qquad (8)$$

on the other hand, contributes more than twice as much outflow salinity transport so that the total outflow salinity transport is $-1.56 \times 10^3 m^3 s^{-1}$. Dividing this outflow salinity transport by the Atlantic water salinity of 36.1psu then yields a net average evaporation over the Mediterranean basin of 54cm y^{-1}.

[1]The imbalance of $0.12 \times 10^6 m^3 s^{-1}$ appears to be too large to represent realistically the net evaporation over the Mediterranean basin since it would equal a net evaporation of 150cm y^{-1} that is a factor of 3 larger than our final estimate of the net evaporation determined from the estimate of outflow salinity transport. The imbalance most likely reflects error in the less reliable estimate of the inflow transport.

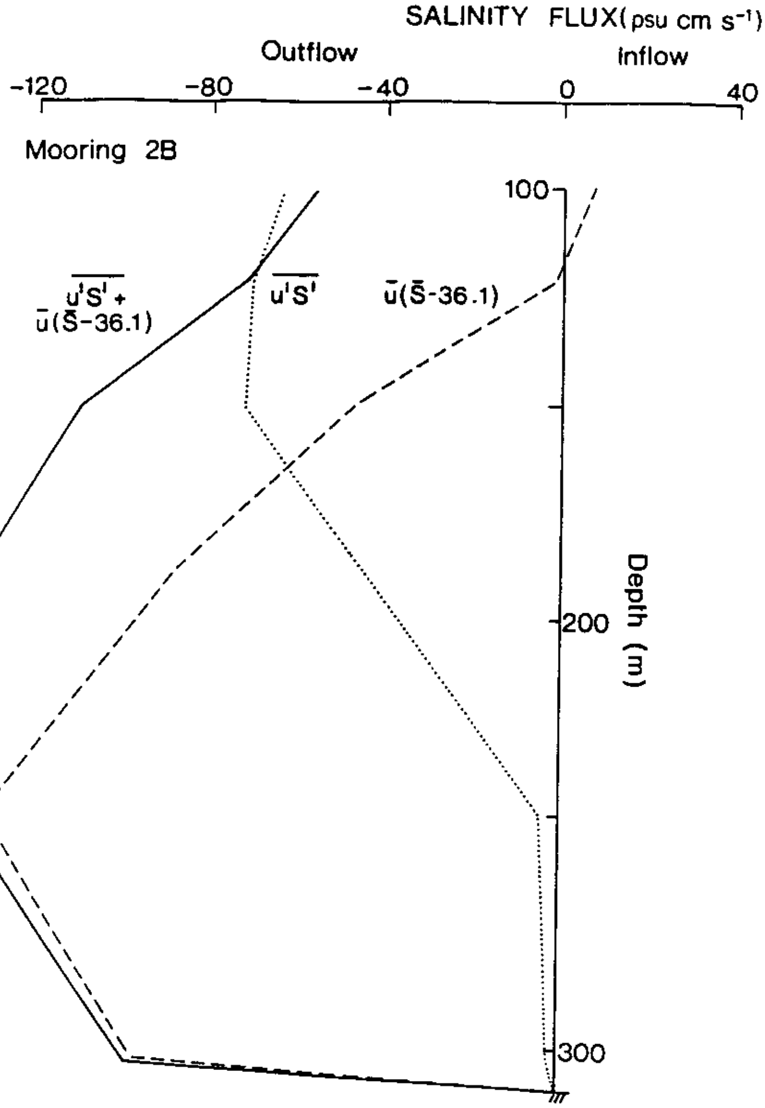


FIG.7. Vertical profile of the time-averaged outflow salinity transport on mooring 2B at the sill. The salinity transport is separated into a contribution due to the mean flow and mean salinity profile, $\bar{u}(\bar{S}-36.1)$, and an average contribution due to temporal (principally tidal) fluctuations in the currents and salinity, $\overline{u'S'}$. The mean flow contribution occurs principally in the deep regions of the sill where there is a strong outflow of salty Mediterranean water, while the contribution from the fluctuations is large in the 100 to 150m depth range where the interface oscillates up and down over the tidal period.

There is a substantial eddy salinity flux at nearly every current meter due to a significant correlation between high salinity and strong outflow velocity, particularly for those current meters in the depth range of the interface between Atlantic and Mediterranean waters. For example, Fig.8a shows the scatter plot between inflow-outflow velocity and salinity measured for 6 months at 110m depth on mooring 3. At every instrument, higher salinity is associated with outflow velocity and lower salinity with inflow velocity and most of this correlation is due to tidal fluctuations. For example, for the 110m record on mooring 3 (Fig.8a), the correlation coefficient between inflow velocity and salinity is -.79 and the resulting eddy salinity flux, $\overline{u'S'}$, is -48.3psu cm s^{-1}. Tidal analysis (Table 3) indicates that the M_2 tidal fluctuations contribute 29.3psu cm s^{-1}, or 61%, of this outflow salinity flux while the S_2, O_1, K_1, N_2, K_2 and M_4 tides contribute an additional 22%. Thus, these tides are responsible for 83% of the eddy salinity flux in this record.

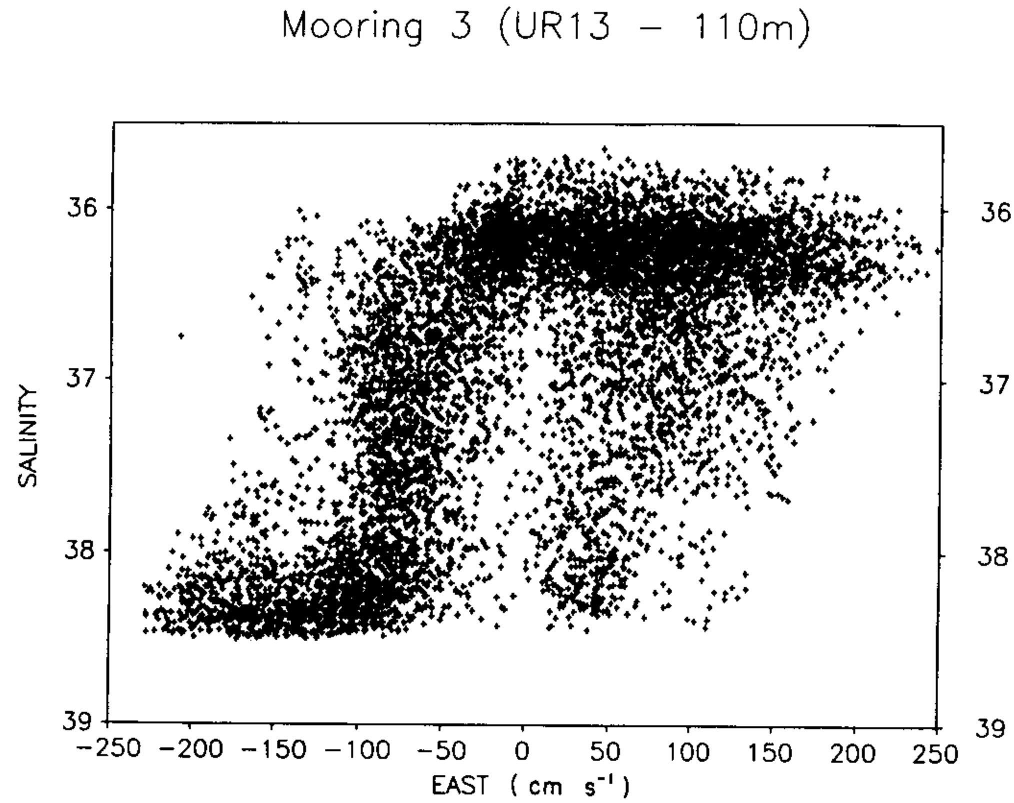


FIG.8a. Scatter plot of along-strait (77°T) velocity versus salinity for the six-month current meter record at 110m depth on mooring 3.

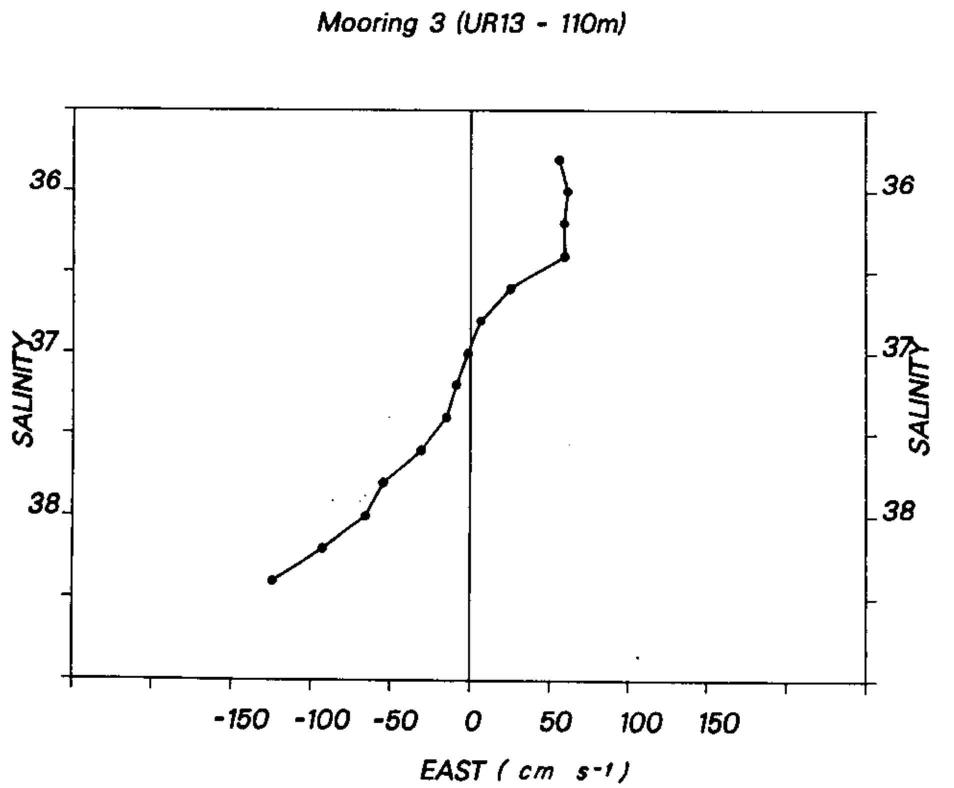


FIG.8b. Average along-strait velocity for salinity bins of 0.2psu. The salinity where the average velocity changes from inflow to outflow is used to define the salinity of the interface between Mediterranean and Atlantic waters. R13 refers to the rotation of currents by 13° counterclockwise from east.

TABLE 3. Tidal amplitudes and phases for six-month record on mooring 3 at 110m depth.

Tidal Constituent		Inflow Velocity - u Amp (cm s^{-1})	Phase (°)	Salinity - S Amp (10^{-2}psu)	Phase (°)	Salinity Flux uS cos(Δϕ)/2 (psu cm s^{-1})
M_2	(12.42 hours)	117	146	76	15	-29.3
S_2	(12.00 hours)	39	174	24	46	-2.9
O_1	(25.82 hours)	29	355	22	185	-3.2
K_1	(23.93 hours)	26	69	20	252	-2.5
N_2	(12.66 hours)	24	129	16	358	-1.2
K_2	(11.97 hours)	12	173	12	46	-0.4
M_4	(6.21 hours)	10	216	13	358	-0.5

In terms of the depth of the interface between Mediterranean and Atlantic waters, the eddy salinity flux can be explained as a correlation between the depth of the interface and the strength of the inflow velocity. When the salinity at a particular instrument is high, the interface is at relatively shallow depth; when the salinity is low, the interface is relatively deep. Thus, there is strong outflow when the salinity is high and the interface is shallow, resulting in a strong outflow of a thick layer of Mediterranean water. And there is strong inflow when the salinity is low and the interface is deep resulting in a strong inflow of a thick layer of Atlantic water. We can make an estimate of this effective exchange of Atlantic and Mediterranean waters across the Gibraltar sill by determining the covariance between the velocity at the interface and the depth of the interface, h_i where h_i is the depth of the 37psu isohaline at each mooring:

$$\text{Exchange due to Temporal Fluctuations} = \sum_{i=1}^{3} \overline{u'h_i'}L_i(z=\overline{h}_i) = 0.41\text{Sv} \qquad (9)$$

where L_i is the effective width of the cross-section for each mooring at the depth of the mean interface (Table 4). This exchange is equally both an inflow and an outflow; that is, it effectively increases the inflow by 0.41Sv for a total Atlantic layer inflow of 0.91Sv and it increases the outflow by -0.41Sv to a total Mediterranean layer outflow of -0.79Sv. With reference to these estimates of the time-averaged exchange due to the combination of the time-averaged currents and the eddy fluxes, we conclude that the total exchange is due approximately half to the temporal fluctuations and half to the time-averaged flow.

From a calculation similar to that for the outflow salinity flux, it is principally the M_2 semidiurnal tide that accomplishes the eddy exchange across the Gibraltar sill. LAVIOLETTE and LACOMBE (1988) had suggested that the M_2 tide could contribute to the outflow, but they were unable to quantify the contribution based on their synoptic measurements. Tidal analyses for the depth of the interface taken to be the 37psu isohaline and for current at or near the interface depth indicate that the inflow velocity and interface depth are close to being in phase for the dominant M_2 tidal variability. The velocity does peak at each mooring before the interface achieves its greatest depth but the phase difference is only 35° at mooring 1, 36° at mooring 2B and 51° at mooring 3. It is straightforward to calculate that these M_2 fluctuations accomplish 0.25Sv, or 62%, of the eddy exchange (Table 5). Thus, we can understand the principal process of eddy exchange across the sill as follows. On each M_2 semidiurnal cycle, when the inflowing tide is a maximum, the interface is deeper than average and a bolus of Atlantic water crosses the sill into the Mediterranean. On the outflowing tide, the interface is shallower than average and a bolus of Mediterranean water crosses the sill into the Atlantic. While there is no average tidal current at each depth, the tides do transport water types effectively across the sill. Although the M_2 fluctuations contribute the bulk of the exchange due to the temporal variations, tidal analyses of the interface depth and currents measured near the interface (Table 5) indicate that the S_2, O_1, and K_1 tides also contribute .029, .022 and .019Sv respectively to the exchange across the sill as well. The total exchange accomplished by these four principal tidal components is 0.32Sv, or nearly half of the total exchange across the sill.

TABLE 4. Eddy exchange across the Gibraltar sill. Moorings 1, 2B and 3 were deployed on the north side, at the sill, and on the south side of the sill section. Variances and covariances for u, the along-strait velocity, and h_{37}, the depth of the 37psu isohaline that marks the interface between Atlantic and Mediterranean waters, indicate strong positive correlation coefficients, C, between strong inflow and deep interface. At mooring 1, u is taken to be the extrapolated velocity at 75m depth; at mooring 2B, u is the measured velocity at 112m depth; at mooring 3, u is the measured velocity at 110m depth. The effective cross-sectional width for mooring 1 is the distance from the 82m isobath at the northern boundary of the sill section to a point halfway between moorings 1 and 2B. The width for mooring 2B is the distance between the points halfway between moorings 1 and 2B and moorings 2B and 3. The width for mooring 3 is the distance from the point halfway between moorings 2B and 3 and the 123m isobath at the southern boundary of the sill section.

Mooring	$\overline{u'h'_{37}}$ (m^2s^{-1})	$\overline{u'^2}$ (m^2s^{-2})	$\overline{h'^2_{37}}$ (m^2)	$C_{\overline{u'h'_{37}}}$	$\overline{h_{37}}$ (m)	Cross-Sectional width (km)
1	28.5	1.297	2402	0.51	82	6.7
2B	37.8	0.968	2607	0.75	131	4.3
3	31.3	0.750	3374	0.62	123	1.8

We label the above values of the exchange (inflow = 0.91Sv, outflow = -0.79Sv, outflow salinity transport = $-1.56 \times 10^3 m^3 s^{-1}$) as statistical estimates because they utilise the longest current meter records at moorings 1, 2B and 3 without regard to possible seasonal variations in the exchange that could affect the combination of October-to-April measurements on moorings 1 and 3 with the May-to-August measurements on mooring 2B. In addition, the above statistical estimates of the inflow and outflow transports do not take into account the slight asymmetry of upward or downward displacements of the interface on the transports as a result of the decrease in width of the sill section with increasing depth. To take into account such hypsometric effects, the interface depth, inflow and outflow need to be defined continuously in time, as carried out in the following sections.

6. TEMPORALLY VARYING ESTIMATES OF THE EXCHANGE

The second method for determining the inflow and outflow through the Strait of Gibraltar based on Eq.5 includes making time series estimates of the upper layer mass transport (ULT), lower layer mass transport (LLT), and outflow salinity transport (OST). It requires a definition of the depth of the interface between inflowing Atlantic water and outflowing Mediterranean water at each instant of time and then vertical integration of the lower layer flow from the bottom up to the interface and of the upper layer flow from the interface up to the sea surface according to Eq.5. Outflow salinity transport (OST following Eq.3) can also be estimated at each instant of time with a method similar to that used for the mean exchange:

TABLE 5. Principal tidal contributions to the sill exchange. As in Table 4, u is the along-strait velocity and h_{37} is the depth of the 37psu isohaline. Tidal analyses for the long records on moorings 1, 2B and 3 yield amplitude and phase for the principal M_2, S_2, O_1 and K_1 tides. The contribution of each tidal constituent to the exchange is determined from the cospectrum $\overline{u'h'_{37}}$ at the particular frequency of the tide. The cospectrum can be compared directly to the covariances, $\overline{u'h'_{37}}$, in Table 4 to determine the fraction of exchange accounted for by each tidal component.

	u		h_{37}		$\overline{u'h'_{37}}$
	AMP ($m\,s^{-1}$)	PH (°)	AMP (m)	PH (°)	$0.5\ Uh_{37}\cos(\Delta PH)$ (m^2s^{-1})
Mooring 1					
M_2	1.09	136	33.4	171	15.0
S_2	.41	156	8.3	210	1.0
O_1	.28	21	14.1	46	1.8
K_1	.27	96	15.3	127	1.8
					19.6 Total
Mooring 2B					
M_2	1.24	152	51.4	188	25.8
S_2	.63	190	15.7	222	4.2
O_1	.25	11	12.0	33	1.4
K_1	.18	88	10.8	100	1.0
					32.4 Total
Mooring 3					
M_2	1.18	146	61.8	197	23.0
S_2	.39	174	16.9	228	2.4
O_1	.29	354	15.8	22	2.0
K_1	.26	69	13.6	91	1.6
					29.0 Total

$$OST = Q_M(S_M - S_A) = \int dy \int_{Bottom}^{0} u(z,t)\,(S(z,t) - 36.1psu)\,dz \qquad (10)$$

Definition of the interface at each instant of time, h(t), is a critical step for making time series estimates of the inflow and outflow.

It is not possible to define the interface based on a depth of zero velocity between inflow and outflow at each instant of time. The tidal currents are strong and barotropic in character, that is the tidal velocities are nearly in phase vertically and they are larger than the mean inflow or outflow at all depths (Fig.3). Thus, for much of each tidal cycle, the flow throughout the water column is directed either eastward into the Mediterranean or westward out toward the Atlantic and there is no depth where the velocity is zero.

Conceptually, the interface is a water mass boundary between fresher (S = 36.1psu) Atlantic water and saltier (S = 38.4psu) Mediterranean water. For this reason, we prefer to define the interface in terms of a particular isohaline marking the water mass boundary. Initially, we found the depths of the 37, 37.5 and 38 psu isohalines (e.g. Fig.5) at each mooring since these isohalines determine a transition region between pure Atlantic water and pure Mediterranean water. In order to pick a single isohaline to define the interface, scatter plots of velocity versus salinity are made for each current meter record on the sill section within the interfacial region above 140m depth (e.g.

Fig.8a); average along-strait velocity is then calculated in salinity bins of 0.2psu (e.g. Fig.8b); and the salinity where the average along-strait velocity switches from inflow to outflow is identified. For all current meter records, the salinity of this zero-crossing varies only from 36.6 to 37.4psu. Thus, the 37psu isohaline is taken to define the interface. Such definition is consistent with the traditional choice by LACOMBE and RICHEZ (1982).

The depth of the interface, that is the depth of the 37psu isohaline, oscillates vertically at the sill with a standard deviation value of 47m for mooring 2B. The M_2-tide is the dominant contributor to the variability in the Strait (CANDELA, WINANT and RUIZ, 1990) and M_2-tidal fluctuations in the interface depth have an amplitude of 51m at mooring 2B. On the sill, the interface achieves its shallowest depth at a phase of 8° with respect to Greenwich, or about 100 minutes before high water at the sill which has a phase of about 57° (CANDELA, WINANT and RUIZ, 1990). Rather than compensate for the surface tidal pressure then, these tidal fluctuations in interface depth enhance the deep pressure signals, though the added baroclinic pressure signal due to the depth variations of the interface is only about 9 millibars or 16% of the sea level pressure amplitude of 55 millibars for the M_2 tide (CANDELA, WINANT and RUIZ, 1990).

With this definition of the depth of the interface, the estimates of upper layer transport, lower layer transport and outflow salinity transport are made at 30 minute intervals according to Eqs 5 and 10. The upper layer transport is of Atlantic water and the lower layer transport is of Mediterranean water since we have defined the interface as a water mass boundary. It is important to note that the Atlantic water transport does not have to be positive, i.e. an inflow, at all times, nor does the Mediterranean water transport have to be an outflow at all times. In fact, there are times in the tidal cycle when the Atlantic water flows out of the Mediterranean and times when Mediterranean water flows back into the Mediterranean.

To estimate transports at each 30 minute interval, along-strait velocity is linearly interpolated or extrapolated vertically at each mooring to values at 5m depth intervals from the bottom to the sea surface. A filter is put on the extrapolated velocities such that velocities in excess of ±400cm s^{-1} are set to ±400cm s^{-1}. Salinity is also interpolated or extrapolated vertically at each mooring to values at 5m depths. For the situation when the interface is above the shallowest instrument on the mooring, a salinity of 37psu at the depth of the interface is used along with the salinity measurements on the mooring to extrapolate salinity up to the sea surface. A filter is put on extrapolated salinities such that salinities less than 35.8psu are set equal to 35.8psu and salinities greater than 38.5psu are set equal to 38.5psu. Examination of CTD data sets during the Gibraltar Experiment (BRAY, 1986; KINDER, BURNS and BROOME, 1986; KINDER, BURNS and WILCOX, 1987; SHULL and BRAY, 1989) suggests that 35.8psu and 38.5psu are reasonable extreme values for the Atlantic water and Mediterranean water salinities on the sill section. We examined the individual profiles on moorings 1, 2, 2B and 3 for situations when the velocities were ±400cm s^{-1} or when the salinities were 35.8psu and found that nearly all extreme values are in the upper waters above 50m depth where there are no direct measurements. For this reason, the estimates of upper layer transport must be considered to be the most uncertain of the transport estimates and it is essential to subtract a reference Atlantic water salinity in estimating the outflow salinity transport.

The optimal period for estimating the exchange through the Strait of Gibraltar with these measurements is the 32-day period during October-November 1985 when 16 current meter records on three moorings 1, 2 and 3, across the sill section are available. After mooring 2 parted prematurely in November 1985, there is a further five-month period through April 1986 when the 7 current meters on moorings 1 and 3 provide reasonable estimates on the temporal variability in the exchange across the sill. To obtain a longer record of the exchange, the 6 current meters on mooring 2B are used to estimate the exchange for an additional 3 months from May to August 1986.

We estimate upper layer transport, lower layer transport and outflow salinity transport for each of these time periods, taking some care to ensure that the estimates of the exchange are consistent for the three periods so that the low frequency variability over a 9 month period can be assessed.

7. EXCHANGE DURING OCTOBER-NOVEMBER PERIOD OF BEST SPATIAL COVERAGE

First, estimates of the exchange are made for the optimal 32-day period when moorings 1, 2 and 3 provide measurements of the flow across the sill. We estimate upper layer transport, lower layer transport and outflow salinity transport at 30-minute intervals (Fig.9) by vertically integrating the profiles of along-strait velocity, u, and salinity, S, at each mooring using the effective cross-sectional width at each depth for each mooring, $L_i(z)$, defined above:

$$ULT(t) = \sum_{i=1}^{3} \int_{h(t)}^{0} u_i(z,t)L_i(z)dz$$

$$LLT(t) = \sum_{i=1}^{3} \int_{Bottom}^{h(t)} u_i(z,t)L_i(z)dz \qquad (11)$$

$$OST(t) = \sum_{i=1}^{3} \int_{Bottom}^{0} u_i(z,t)(S_i(z,t) - 36.1psu)L_i(z)dz$$

From these 32-day time series of transports, the time-averaged upper layer transport of Atlantic water is 0.93Sv directed into the Mediterranean; the time-averaged lower layer transport of Mediterranean water is -0.68Sv directed out over the sill into the Atlantic; and the time-averaged outflow salinity transport is $-1.50 \times 10^3 m^3 s^{-1}$. Such time averages agree reasonably well with the estimates of the mean exchange based purely on the statistics of the current meter records as described above[1]. Such agreement provides some confirmation that the procedures of interface determination and vertical extrapolation and filtering have not altered the basic character of the exchange through the Strait.

These time series estimates of transports through the Strait of Gibraltar exhibit strong semidiurnal tidal fluctuations: the M_2-tidal fluctuations in upper layer transport have an amplitude of 2.3Sv with a phase of 151° and in lower layer transport have an amplitude of 1.3Sv with a phase of 144°. Thus, the tidal fluctuations are indeed large enough to reverse the inflow of Atlantic water in the upper layer and the outflow of Mediterranean water in the lower layer. To estimate the uncertainty in the time-averaged inflow of Atlantic water and outflow of Mediterranean water, we determine the standard error of the upper layer and lower layer transports based on an assumption of independent estimates of these transports every semidiurnal tidal period. With 61 semidiurnal

[1]The data are somewhat different between these estimates and the earlier statistical estimates. Here moorings 1, 2 and 3 are used for the October-November 1985 time period while in the statistical estimates moorings 1 and 3 were used for their full record length October 1985 to April 1986 and mooring 2B for its full record length May to October 1986.

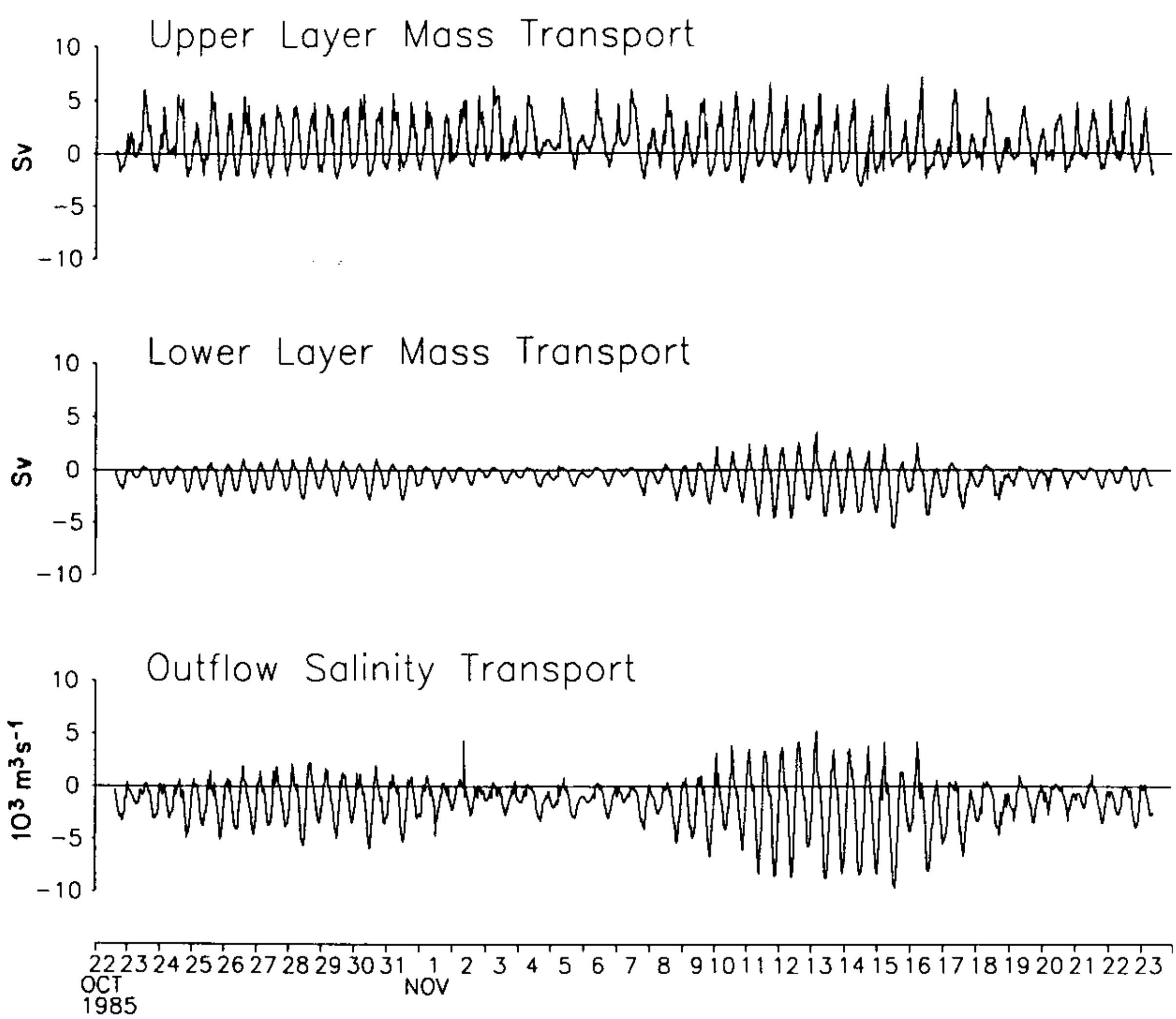


FIG.9. Time series of 30-minute values of upper layer mass transport, lower layer mass transport and outflow salinity transport during October-November 1985 when moorings 1, 2 and 3 were all measuring the sill exchange. At each instant of time the upper layer mass transport is the integral of the along-strait velocity from the depth of the 37psu isohaline up to the sea surface and across the strait. The lower layer transport is similarly the integral of along-strait velocity from the bottom up to the depth of the 37psu isohaline and across the strait. The outflow salinity transport is the integral of along-strait velocity times the salinity anomaly above the basic Atlantic water salinity of 36.1psu from the bottom to the sea surface and across the sill section.

tidal periods in the 32 day measurement period, the standard error in the mean Atlantic water inflow is ±0.27Sv, the standard error in Mediterranean outflow is ±0.15Sv, and the standard error in outflow salinity transport is ±0.27 x $10^3m^3s^{-1}$.

There may also be bias errors in these estimates of the exchange, particularly for the upper layer transports since they are based primarily on extrapolations of measurements made below the interface. In making these estimates, we particularly worried about the reliability of the upper layer transport of Atlantic wter, and we admit to a certain satisfaction that the time-averaged inflow does balance the time-averaged outflow within its standard error. On the basis of mass and salt conservation requirements for the Mediterranean basin, the inflow and outflow should balance within about 0.05Sv. Because of the uncertainty in upper layer transport estimates, we do not attribute the sum of the time-averaged inflow and outflow to be a reliable estimate of the net evaporation over the Mediterranean basin. Instead, we would argue that this sum is due to the uncertainty in determination of the upper layer Atlantic water inflow.

Using these Gibraltar measurements, we can estimate of the net evaporation over the Mediterranean basin from the outflow salinity transport according to Eq.3. By dividing the time-averaged outflow salinity transport of 1.50 x $10^3 m^3 s^{-1}$ by the Atlantic water salinity of 36.1psu, a direct estimate of 52cm y^{-1} is made for the net evaporation over the Mediterranean basin (surface area = 2.52 x $10^{12} m^2$). Again, the lack of direct measurements in the upper layer casts some uncertainty on this estimate of outflow salinity transport. To decrease the uncertainty, we had first subtracted the basic Atlantic water salinity of 36.1psu before carrying out the salinity transport calculations so that, even if there were an error in upper layer mass transport of 1Sv, it would only be multiplied by a salinity anomaly of order 0.1psu and the resulting error in outflow salinity transport would be only of order 0.1 x $10^3 m^3 s^{-1}$. The second check on the salinity transport involves estimating the outflow salinity transport separately for the lower layer and for the upper layer. We expect the lower layer outflow of high salinity Mediterranean water to contribute most of the salinity flux and it does contribute -1.33 x $10^3 m^3 s^{-1}$ to the total outflow salinity transport of -1.5 x $10^3 m^3 s^{-1}$. The upper layer contributes only -0.17 x $10^3 m^3 s^{-1}$ to the salt transport and we argue that this is a reasonable contribution given that correlations between strong outflow velocity and high salinity above the 37psu isohaline surely do add to the outflow salinity transport. We would estimate, however, that the upper layer contribution to the outflow salinity transport might have a bias error as large as a factor of 2, so that the total outflow salinity transport could be as large as -1.67 x $10^3 m^3 s^{-1}$, equivalent to a net evaporation of 58cm y^{-1}.

Overall for the 32-day period of measurements on moorings 1, 2 and 3, we estimate the time-averaged outflow of Mediterranean water over the Gibraltar sill to be -0.682Sv ±0.15Sv. We estimate that the time averaged outflow salinity transport is -1.50 x $10^3 m^3 s^{-1}$, but it may be as large as -1.67 x $10^3 m^3 s^{-1}$ due to uncertainty in the upper layer contribution, and the mean value has a standard error of ±0.27 x $10^3 m^3 s^{-1}$. Thus, our estimate for the net evaporation over the Mediterranean basin based on measurements of the exchange through the Strait of Gibraltar lies between 52 and 58cm y^{-1}, with a standard error uncertainty of ±9cm y^{-1}. Based on this estimate of the net evaporation, we would calculate that the mean inflow of Atlantic water should be 0.042 ± 0.01Sv larger than the absolute value of the mean outflow of Mediterranean water, and hence our best estimate for the mean inflow is +0.724Sv ±0.16Sv. This 'best' estimate of the mean inflow is indirect, but it does lie within the uncertainty of the direct estimate of the time-averaged Atlantic water inflow transport of 0.93 ±0.27Sv described above.

These are the first estimates of the Gibraltar exchange that utilize more than one mooring or one site to measure the inflow and the outflow across the sill. In an attempt to assess the usefulness of multiple moorings, calculations of the exchange across the Gibraltar sill are made on the basis of each mooring by itself, assigning the entire cross-sectional width of the sill section to the current and salinity profiles obtained from the individual moorings 1, 2, 2B and 3 (Table 6). Current and salinity profiles on moorings 1 and 3 are extrapolated downward to depths as great as 285m, the sill depth of the Strait, as well as upward to the sea surface for these calculations. The estimates of lower layer outflow of Mediterranean water for moorings 1 and 3 are substantially smaller than the estimate based on mooring 2 which is quite close to the mean value of -0.68Sv derived from all three moorings above. Such a result indicates that it is essential to make direct current measurements in the deep parts of the sill section below 200m depth for an accurate estimate of the outflow of Mediterranean water. Because the deep regions of the sill section are quite confined (the width between the 200m isobaths on the sill section is only 6.9km), a single mooring at or near the sill can provide reasonable measurements of the Mediterranean outflow. Similar results and implications are found for estimating the outflow salinity transport by comparing the values obtained for the three moorings: it is essential to make direct current and salinity measurements in the deep part of the sill section in order to estimate accurately the outflow salinity flux. For the upper layer transport, the estimates of the inflow of Atlantic water using only mooring 2 or mooring 2B at the sill are much larger than the mean inflow of 0.92Sv derived from all three moorings above. This result appears to be due to the facts that the interface depth at mooring 1 and over the relatively broad region north of mooring 1 is substantially shallower than the interface depth at the sill, so that there is less area of the upper layer inflow than would be estimated from mooring 2 alone, and that the currents in the northern part of the Strait are somewhat smaller than those at the sill. The upper layer transport derived from mooring 3 alone is quite a good estimate of the inflow of Atlantic water, but this appears to be fortuitous due to a combination of smaller currents and deeper interface than are typical of the sill cross-section. In summary, we conclude that a single mooring at or near the sill measuring the currents particularly below 150m depth down to the sill depth of 285m can provide an accurate estimate of the lower layer outflow of Mediterranean water across the sill but that several moorings across the sill section are needed to measure the upper layer inflow of Atlantic water because of cross-strait variations in the interface depth and in the size of the currents.

TABLE 6. Estimates of Gibraltar exchange from single moorings. Upper and lower layer transports are defined to be the vertically and horizontally (cross-strait) integrated flows above and below the 37psu isohaline defined by the instantaneous salinity and pressure measurements on the particular mooring. Velocity measurements on each mooring are linearly interpolated and extrapolated vertically to the bottom (285m depth) and to the sea surface at each instant of time. The cross-strait distance at each depth is the distance between the isobaths on the sill cross-section.

	Upper Layer Mass Transport (Sv)	Lower Layer Mass Transport (Sv)	Outflow Salinity Transport ($10^3 m^3 s^{-1}$)	Period
Mooring 1	.69	-.40	-.95	Oct-Nov 85
Mooring 2	1.35	-.78	-1.68	Oct-Nov 85
Mooring 3	.94	-.61	-1.21	Oct-Nov 85
Mooring 1	.52	-.45	-.96	Oct 85 - May 86
Mooring 3	1.22	-.65	-1.34	Oct 85 - Apr 86
Mooring 2B	1.44	-.80	-1.68	May-Aug 86

8. NINE-MONTH TIME SERIES OF THE EXCHANGE

To extend the estimates of exchange through the Strait of Gibraltar to as long a time period as possible, we utilise the measurements on moorings 1 and 3 to estimate the exchange for the period October 1985 to April 1986 and the measurements on mooring 2B for the period May to August 19086. All 7 current meters on moorings 1 and 3 made continuous measurements during the entire 6-month deployment period from October 22 1985 to April 21 1986. The temporal gap in moorings from late April to late May 1986 was planned as part of the Gibraltar Experiment in order to allow WESSON and GREGG (1994) to carry out an extensive series of tethered microstructure profiles without fears of snagging a mooring with the tether (BRYDEN and KINDER, 1986). The current meters on mooring 2B, deployed on May 29, gradually failed over the 5-month lifetime of the mooring due to vibration so that the current meter at 112m depth ceased measuring currents after 31 days, the 181m instrument ceased after 41 days, the 90m and 135m instruments ceased after 82 days, and the 233m instrument ceased after 92 days. We judged that reliable transport estimates could be made only for the first 82 day period from 29 May to 19 August 1986 when at least 4 instruments provided current measurements. The interface time series, however, is continuous for the entire 137-day deployment period as vibration did not adversely affect the temperature, conductivity and pressure measurements.

To ensure that upper layer, lower layer and outflow salinity transports are consistently determined for the three time periods (October-November using moorings 1, 2 and 3; November-April using moorings 1 and 3; and May-August using mooring 2B), regression for daily-averaged transport estimates ULT, LLT and OST during the October-November time period are carried out to derive linear fits of the transports using mooring 1 and 3 (denoted with a subscript 13) and using mooring 2 (denoted with a subscript 2) to the optimal transports derived from moorings 1, 2 and 3 (denoted with a subscript 123):

$$\begin{aligned} \mathrm{Trans}_{123} &= A^{*}\mathrm{Trans}_{13} + B \\ &\text{and} \\ \mathrm{Trans}_{123} &= C^{*}\,\mathrm{Trans}_{2} + D \end{aligned} \tag{12}$$

where each set of regressions (12) is carried out 3 times, for Trans = ULT, for Trans = LLT and for Trans = OST, to determine the coefficients A, B, C and D (Table 7). Then the resulting regression coefficients are applied to derive scaled transport estimates using moorings 1 and 3 for the period October to April and using mooring 2B for the period May to August:

$$\begin{aligned} \mathrm{Trans}_{13}\mathrm{Scaled} &= A^{*}\mathrm{Trans}_{13} + B \\ &\text{and} \\ \mathrm{Trans}_{2B}\mathrm{Scaled} &= C^{*}\mathrm{Trans}_{2B} + D. \end{aligned} \tag{13}$$

The basis for such scaled transport estimates is CANDELA, WINANT and BRYDEN's (1989) result that the low-frequency currents vary consistently together primarily as a nearly uniform fluctuation in along-strait current at all depths and locations on the sill section. In their analysis, a single empirical orthogonal function (EOF) accounted for more than 80% of the low-frequency variance in along-strait currents in the Strait and the form of this primary EOF was nearly barotropic on the sill section. Here, we present the low-frequency along-strait currents on mooring 3 (Fig.10a) to illustrate the pronounced vertical correlation throughout the water column; the along-strait currents at about 140m depth on moorings 1 and 3 (Fig.10b) to illustrate the pronounced lateral correlation across the sill section; and along-strait currents on moorings 8, 3 and 7 (Fig.10c) to illustrate the pronounced lateral correlation along the axis of the Strait. Correlation coefficients are typically 0.8 and higher. Thus, the low-frequency variations observed in any current meter record on the sill are indicative of the variations in flow throughout the Strait. The resulting 9-month time series of scaled transports through the Strait (Fig.11) then should represent consistent estimates of the Atlantic water inflow, Mediterranean outflow and outflow salinity transport for describing the low frequency variability in the exchange between the Atlantic and Mediterranean basins.

TABLE 7. Consistent transport estimates. Variables ULT, LLT and OST refer to upper layer transport, lower layer transport, and outflow salinity transport respectively. Regressions for each variable are carried out on daily-averaged values for the October-November time period. The transports determined using Moorings 1, 2, 3 are considered to be the standard and the linear regressions are used to determine how to scale transports using only moorings 1 and 3 or only mooring 2 to make them consistent with the transports using all 3 moorings.

Regression:	$Trans_{123}$	=	A x $Trans_{13}$ + B	for October-November time period using daily averaged values
	Trans		A	B
	ULT		1.180	.005
	LLT		1.033	-.124
	OST		1.035	-.278
Regression:	$Trans_{123}$	=	C x $Trans_2$ + D	for October-November time period using daily averaged values
	Trans		C	D
	ULT		0.490	.282
	LLT		0.696	-.136
	OST		0.709	-.306
Then	$Trans_{13}$ Scaled	=	A x $Trans_{13}$ + B	for October-April time period
	$Trans_{2B}$ Scaled	=	C x $Trans_{2B}$ + D	for May-August time period

From these long time series of consistent transports, the 9-month average Atlantic water inflow is 0.935Sv; the average Mediterranean water outflow is -0.718Sv; and the average outflow salinity transport is -1.54 x $10^3 m^3 s^{-1}$. Thus, these 9-month averages are similar to the 32-day averages for the October-November period of best instrument coverage. It is worth noting that the similarity of the averages cannot be attributed purely to the regression techniques, since the regression coefficients are based only on October-November measurements. Currents could have been stronger or weaker in the later periods, so that the transports could have been higher or lower.

While there is little difference in the 32-day and 9-month averaged transports, there is substantial low frequency variability in the daily averaged transports (Fig.11). The daily values of lower layer transport always represent an outflow of Mediterranean water, but the outflow varies from a minimum of -0.33Sv to a maximum of -1.62Sv, with a standard deviation of 0.22Sv. On the other hand, the daily values of upper layer transport actually change sign so that for a short period in late February the Atlantic water appears to flow back out toward the Atlantic. For the most part, upper layer transports represent Atlantic water flowing into the Mediterranean with a maximum daily averaged inflow estimated to be 2.09Sv, a minimum (reverse) flow of -0.60Sv, and a standard deviation of 0.37Sv. The outflow salinity transport is always of one sign, but it does vary from a maximum of -2.90 x $10^3 m^3 s^{-1}$ to a minimum of -0.61 x $10^3 m^3 s^{-1}$ with a standard deviation of 0.40 x $10^3 m^3 s^{-1}$.

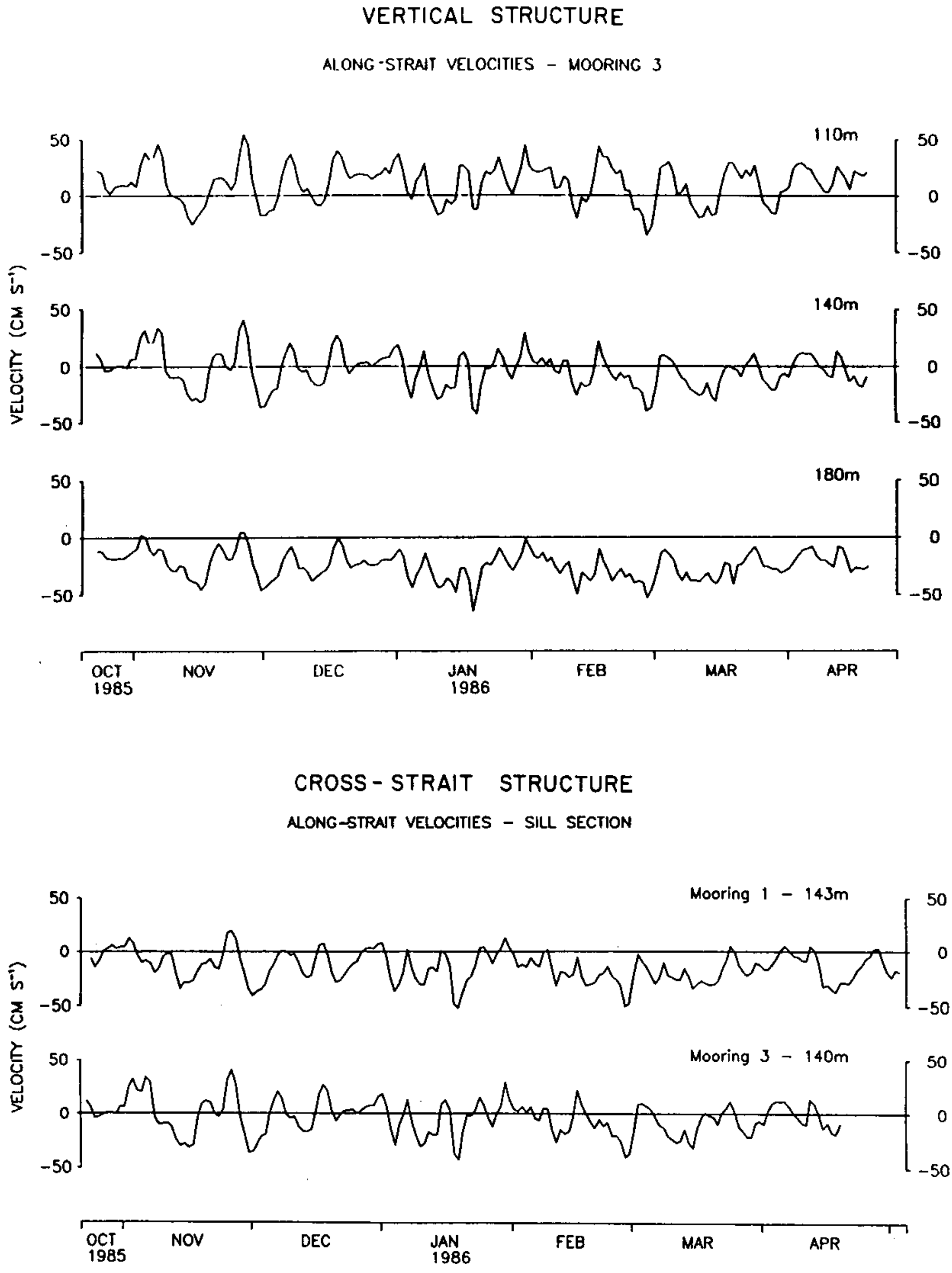


FIG. 10. Spatial structure in along-strait currents. (a) Daily averaged along-strait velocities at 110, 140 and 180m depths on moorings 3 exhibit strong vertical correlations. (b) Daily averaged along-strait velocities at about 140m depth on moorings 1 and 3 on the northern and southern sides of the Strait exhibit strong cross-strait correlation. (c, overleaf) Daily averaged along-strait velocities in the upper waters on moorings 8, 3 and 7 along the axis of the Strait exhibit strong along-strait correlations.

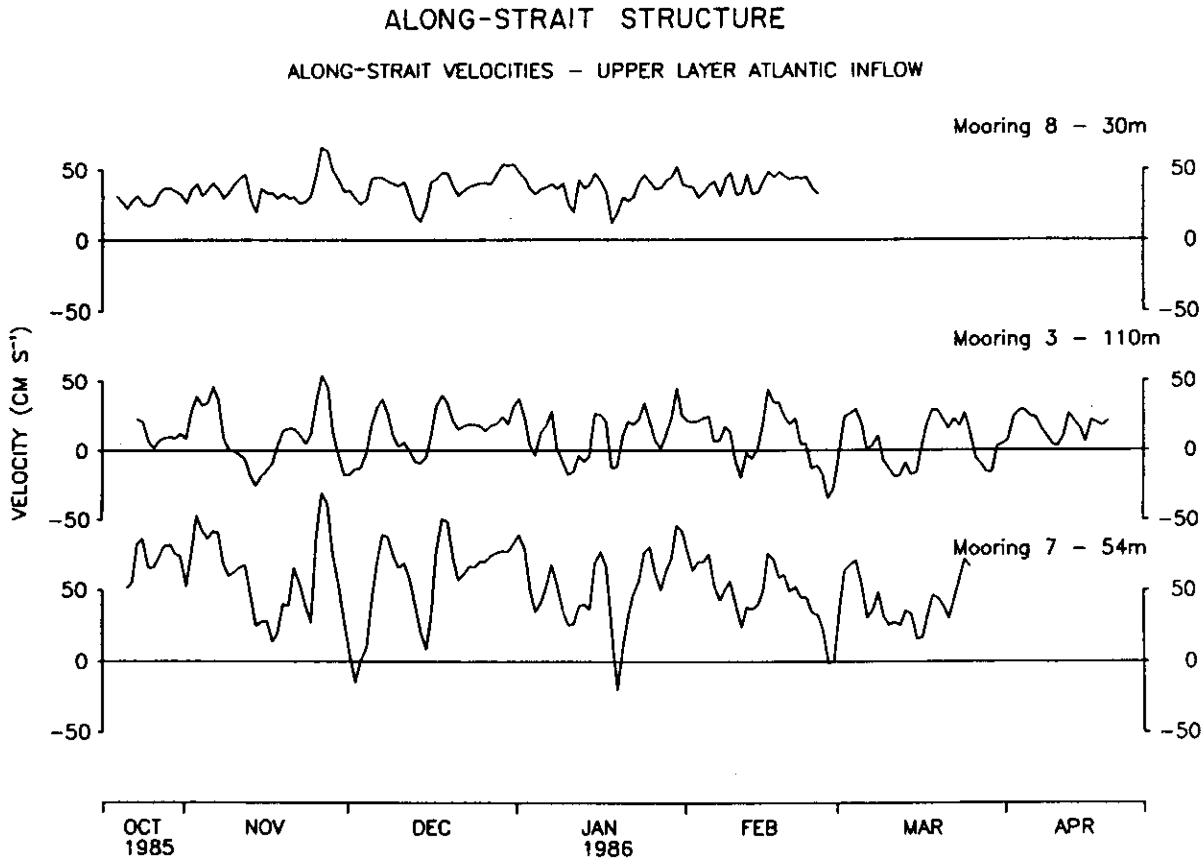


FIG.10C

The temporal variability in transports appears to have a dominant period of about 15 days. In particular, there are peaks in the autocorrelation function for the outflow transport at lags of 15, 36 and 49 days. Also, autospectra of inflow transport and outflow transport estimates using mooring 1 and 3 for the period October to April and using mooring 2B for the period May to August exhibit a band of high energy at periods of 15 to 22 days. Square-integral time scales (integral of the square of the autocorrelation function) are estimated to be 2.9 days for ULT and 4.8 days for LLT. With these integral time scales and with the estimated standard deviations in ULT and LLT over the 259-day period of measurements, the standard error due to the low-frequency temporal variability in the mean inflow is 0.04Sv and the standard error in the mean outflow is 0.03Sv. While these standard errors are small, it is important to remember that there is larger real uncertainty in the mean transport estimates due to spatial sampling problems, particularly due to the lack of adequate instrumentation in the upper layer above 90m depth.

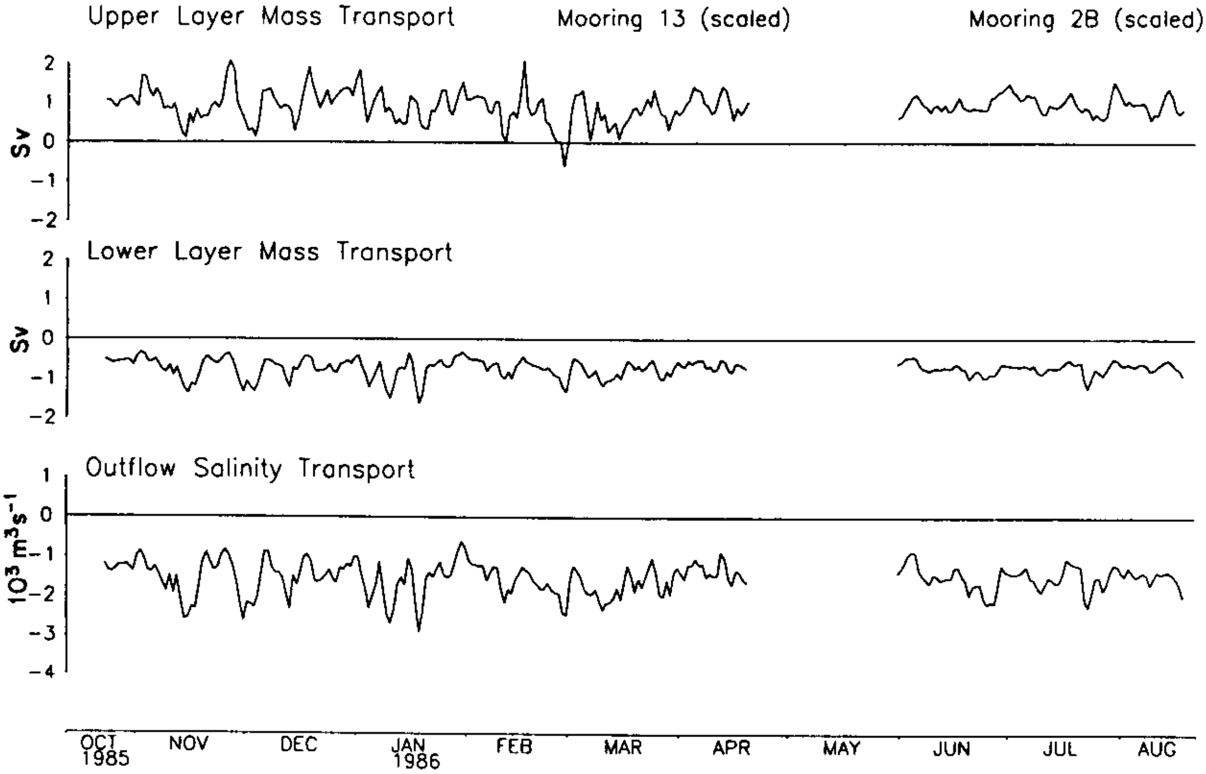


FIG.11. Time series of daily averaged upper layer mass transport, lower layer mass transport and outflow salinity transport from October 1985 to August 1986. Transports are defined as for Fig.9. Transport estimates from mooring 1 and 3 (October 1985 - April 1986) and from mooring 2B (May-August 1986) are scaled so that they are consonant with the optimal values derived from moorings 1, 2 and 3 during October-November 1985 according to the regressions in Table 7.

9. CROSS-STRAIT SLOPE OF THE INTERFACE

In the Strait of Gibraltar, there is a well known cross-strait slope to the interface between the upper inflowing Atlantic water and the lower outflowing Mediterranean water with the interface banked up against the European continental slope. These current meter measurements with accompanying salinity time series provide unprecedented information on the character of the interface and its fluctuations. Previous measurements of the interface have relied on time series hydrographic stations over one to two days to resolve the amplitude of the tidal fluctuations (e.g. LACOMBE and RICHEZ, 1982). The tidal fluctuations in the depth of the interface have already been described as part of the demonstration on how the correlation between interface depth and inflow velocity at tidal periods contributes to the exchange across the sill. Here, the time-averaged cross-strait slope of the interface and its relation to the vertical shear in along-strait currents are described.

The time-averaged depths of the 37psu isohaline during October-November 1985 are 98.7 at mooring 1 on the northern side of the sill section, 135m at mooring 2 on the sill and 134.0 at mooring 3 on the southern side. From these averages and from the bathymetry of the sill cross-section as described by BRYDEN and KINDER (1991b), we calculate that the upper layer flow above the 37psu isohaline occupies on average 2.01 x 10^6m^2, or 64% of the total sill cross-sectional area of 3.16 x 10^6m^2, while the lower layer flow occupies 1.15 x 10^6m^2 or 36% of the sill area. Dividing the mean upper and lower layer transports by these areas yields area-averaged, or 'typical', velocities of 36cm s^{-1} for the inflowing Atlantic water and -59cm s^{-1} for the outflowing Mediterranean water.

For the longer 6-month period from October to April when moorings 1 and 3 recorded data, the time-averaged depths of the 37psu isohaline are slightly shallower: 82.3m at mooring 1 and 123.9m at mooring 3. For this longer period, the average cross-strait slope of the interface is 4.6 x 10^{-3}, or a 42m change in depth across the 9km distance between moorings 1 and 3. Geostrophically, this cross-strait slope of the interface should be balanced by the vertical shear in the along-strait currents between inflow above and outflow below. In modelling the flow through the Strait of Gibraltar as a two-layer exchange (e.g. BORMANS and GARRETT, 1989a), a reduced gravity model is generally used with the geostrophic balance in the form:

$$g'h_y = f(u_1 - u_2) \tag{14}$$

where $g' = g(\rho_2-\rho_1)/\rho_2$, ρ is the density, h_y is the cross-strait slope of the interface, f is the Coriolis parameter, u is the along-strait velocity, 1 denotes the upper layer and 2 denotes the lower layer. For the observed interface slope and the difference between the 'typical' upper and lower layer velocities, we calculate a g' equal to 1.77cm s^{-2} and a density difference of 1.86 x 10^{-3}gm cm^{-3} between the upper Atlantic water and lower Mediterranean water. Such a density difference is similar to the observed density difference between Mediterranean water and Atlantic water as used in two-layer models (e.g. FARMER and ARMI, 1986).

More direct geostrophic comparisons can be carried out by comparing the time-averaged cross-strait density difference between moorings 1 and 3 on the northern and southern sides of the sill section with the vertical differences in along-strait velocity at moorings 2 and 2B in the central sill region (Table 8). Density differences are best estimated for the depth interval between 140 and 180m where each of moorings 1 and 3 had three current meters (Table 2). The observed cross-strait density gradients of 0.4 to 0.8 x 10^{-9}g cm^{-4} imply geostrophically vertical shears in along-strait velocity of 0.4 to 0.9 x 10^{-2}s^{-1} (Table 8a). These vertical shears are then integrated using the trapezoidal rule for the depth intervals between the current meters on moorings 2 and 2B, where the observed vertical differences in velocity of order 20cm s^{-1} over approximately 30m depth seem well matched to the geostrophically predicted velocity differences (Table 8b). While these comparisons are favourable, there are several cautionary aspects that prevent precise conclusions. First, the observed vertical shears in velocity at mooring 1 are much smaller than those at moorings 2, 2B and 3, indicating cross-strait variability in the vertical shears. Also, the comparisons in Table 8 represent point estimates of the vertical shear, but cross-strait averages of the geostrophic shear. Furthermore, the geostrophic estimates are based on time-averaged density differences over the period from October to April, while the observed velocity difference at mooring 2 is an average over the October-November time period and the differences at mooring 2B are averages over the May-August time period. Hence the observed and predicted velocity differences are for different time periods. Despite these cautionary notes, there is reasonable agreement between the observed and geostrophically predicted velocity differences which are each of order 20cm s^{-1} over a 30m depth interval in the interface region at the Gibraltar sill.

A second type of geostrophic comparison is to correlate the temporal fluctuations in the daily averaged vertical shear of along-strait current at moorings 1 and 3 and the daily-averaged cross-strait difference in interface depth between moorings 1 and 3 for the six-month time period from October to April. The time series of the vertical shear at mooring 3 and of the difference in depth of the 37.5psu isohaline (Fig.12) are significantly correlated with a correlation coefficient of 0.55. (The 37.5psu isohaline is chosen here to represent the interface because it is better resolved by the distribution of instruments on mooring 1.) The vertical shear at mooring 1, however, is smaller than, and negatively correlated (although not significantly) with, either the shear at mooring 3 or the interface depth difference time series. It may be that during periods of large interface slope the Atlantic water inflow becomes effectively separated from the northern boundary so that the shear at mooring 1 reflects the smaller shear within the Mediterranean water rather than the stronger shear between Atlantic and Mediterranean waters. For the central and southern parts of the sill, the correlation between the observed shear and the slope of the interface on low-frequency time scales has the sign expected from geostrophic arguments such that larger interface slopes are correlated with stronger vertical shears in the along-strait currents. The standard deviation of the interface slope is 55% as large as the mean slope, and the standard deviation of the vertical shear on mooring 3 is 48% as large as the mean shear. Thus the interface slope and vertical shear exhibit low-frequency fluctuations that are about half as large as the mean slope and mean shear. This low-frequency variability appears to be dominated by fortnightly fluctuations, as will be shown next.

TABLE 8. Thermal wind shear and geostrophic comparison. (a) The cross-strait density gradient, $\partial\rho/\partial y$, determined from temperature, salinity and pressure time series on moorings 1 and 3 is evaluated at 140, 160 and 180dbar and the implied thermal wind shear in along-strait velocity, $\partial u/\partial z$ is estimated. (b) Geostrophic comparisons are carried out between the observed current differences on moorings 2 and 2B and the geostrophically predicted current differences from the thermal wind shears in (a) for the specific depth intervals of the instruments.

(a) Cross-strait density gradient and thermal wind shear in inflow-outflow velocity

	Mooring 1		Mooring 3		$\frac{\partial\bar{\rho}}{\partial y}=\frac{\Delta\sigma_\theta(1\text{-}3)}{8.99\text{km}}$	$\times g/\rho_o f(=1.11$	$\frac{\partial\bar{u}}{\partial z}$
Pressure	$\bar{S}$(psu)	$\bar{\sigma}_\theta(10^{-3}\text{g cm}^{-3})$	S(psu)	$\sigma_\theta(10^{-3}\text{g cm}^{-3})$	$(\times10^{-9}\text{g cm}^{-4})$	$\times10^7\text{cm}^4\text{g}^{-1}\text{s}^{-1})$	$(\times10^{-2}\text{s}^{-1})$
140dbar	37.906	28.563	37.178	27.802	.847		.943
160dbar	37.986	28.634	37.457	28.098	.596		.664
180dbar	38.046	28.747	37.743	28.400	.387		.431
					Cross-Strait Density Gradient		Vertical Shear

(b) Geostrophic comparison

	Time-Averaged along-strait velocity difference $\Delta u(\text{cm s}^{-1})$	
	Observed	Geostrophically predicted
Mooring 2		
127-158 dbar	19.5	26.5
Mooring 2B		
123-153 dbar	22.8	27.5
153-191 dbar	24.5	20.6
123-191 dbar	47.3	48.1

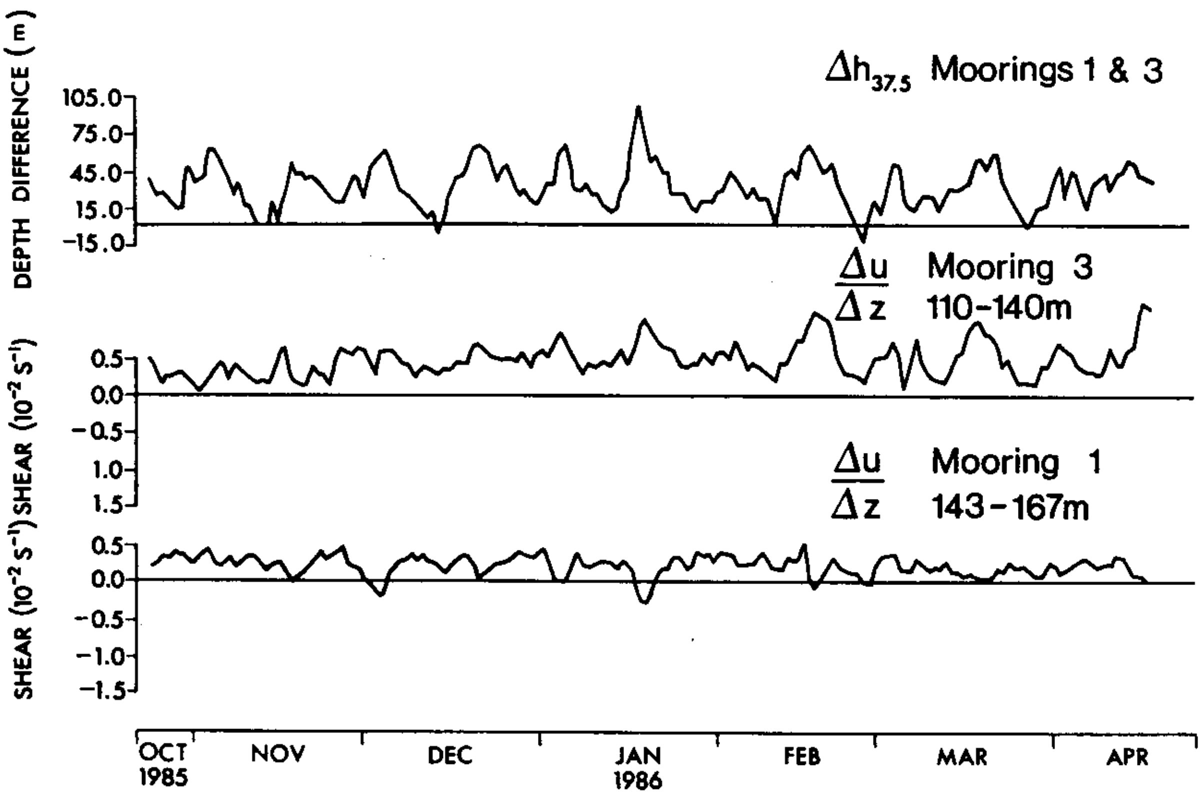


FIG.12. Comparison of the daily-averaged cross-strait difference in depth of the 37.5psu isohaline between moorings 1 and 3, $\Delta h_{37.5}$, and the observed vertical shears in along-strait currents on moorings 3 and 1. The thermal wind relation implies that the series should be correlated for geostrophic fluctuations. There is good correlation of the interface depth difference with vertical shear on mooring 3 but poor correlation with shear on mooring 1.

10. FORTNIGHTLY VARIATIONS

A common question is whether there are fluctuations in the exchange across a sill at fortnightly period. Any observed fortnightly signal in the exchange might then be related to the spring-neap cycle in semidiurnal tidal forcing. For example, GEYER and CANNON (1982) observed a maximum exchange across the sill in Puget Sound near neap tides and argued that it was due to less tidal mixing during the neap period of smaller amplitude tidal currents. Here in the Strait of Gibraltar, the regular oscillations in outflow transport at about 15-day period (Fig.11) are suggestive of a fortnightly cycle. Indeed, tidal analyses of the 180-day time series of ULT and LLT derived from moorings 1 and 3 yield fortnightly amplitudes of 0.103Sv in the inflow transport and of 0.083Sv in the outflow transport with phases relative to Greenwich of 257° and 227° respectively. These phases imply that positive transports (directed eastward toward the Mediterranean) occur in both the upper layer and lower layer 2 to 3 days after the time when the sun and moon are 90° out of phase. Thus, there is maximum inflow of Atlantic water but minimum outflow of Mediterranean water just after neap tides, while there is minimum inflow and maximum outflow just after spring tides.

These fortnightly variations in transport are associated primarily with fluctuations in along-strait currents in the central and southern parts of the sill. From the long records above 200m depth on the sill at mooring 2B and on the southern side of the sill section at mooring 3, the amplitudes of the fortnightly current signals increase vertically from 5 to 20cm s^{-1} with phases of 220° to 310° and with larger amplitudes at shallower depths (Table 9). In contrast, at mooring 1 on the northern side of the sill section the fortnightly current variations are less than 5cm s^{-1}. The depth of the interface between upper layer Atlantic water inflow and lower layer Mediterranean water outflow similarly exhibits a fortnightly cycle in the central and southern regions but effectively no fortnightly cycle in the northern part of the sill at mooring 1 (Fig.13). The amplitude of the fortnightly signal in interface depth is 19.5m at mooring 3, 15.3m at mooring 2B, and 1.5m at mooring 1, with phases of 220°, 228° and 233° respectively; that is, the interface is deeper just after neap tides when the inflowing along-strait currents achieve maximum amplitude. Similar to the analysis of semidiurnal tidal fluxes presented above, this coherence between maximum inflow and deepest interface over the fortnightly cycle in the central and southern regions effectively contributes both a mean inflow and a mean outflow to the total exchange across the sill. In contrast to the semidiurnal tidal fluxes, however, this fortnightly cycle in exchange is small, of order 0.003Sv, due to the combination of relatively small interface and current signals and the confinement of the fortnightly signals to the central and southern portions of the sill. The major fortnightly cycle in the Strait is a nearly unidirectional current fluctuation of order 10cm s^{-1} at all depths that is directed into the Mediterranean just after neap tides.

TABLE 9. Amplitude and phase of the fortnightly (M_{sf}) cycles in upper layer transport (ULT), lower layer transport (LLT), interface depths from the long records on moorings 1, 2B and 3, cross-strait difference in interface depth between moorings 1 and 3 (h_1-h_3), and currents for the long records on moorings 1, 2B and 3.

			Amplitude		Phase	
Transport			(Sv)			
	ULT		.103	±.065	256°	±37°
	LLT		.083	±.049	227°	±34°
Interface Depth			(m)			
	h_1		1.5	±4.4	233°	±175°
	h_{2B}		15.3	±3.1	228°	±12°
	h_3		19.5	±3.5	220°	±10°
	h_1-h_3		18.3	±3.1	217°	±10°
Current			(cm s^{-1})			
	Mooring 1	U_{140}	4.3	±2.9	7°	±39°
		U_{156}	4.3	±2.4	13°	±33°
		U_{167}	3.9	±1.4	13°	±30°
		U_{215}	2.1	±1.2	20°	±33°
	Mooring 2B	U_{90}	15.0	±5.3	234°	±20°
		U_{112}	18.0	±3.9	245°	±12°
		U_{135}	14.3	±3.3	270°	±13°
		U_{181}	9.7	±2.3	306°	±18°
		U_{233}	7.2	±2.5	353°	±18°
		U_{299}	5.0	±2.7	87°	±34°
	Mooring 3	U_{110}	16.8	±2.9	222°	±10°
		U_{140}	11.4	±2.8	223°	±14°
		U_{180}	5.0	±2.1	230°	±25°

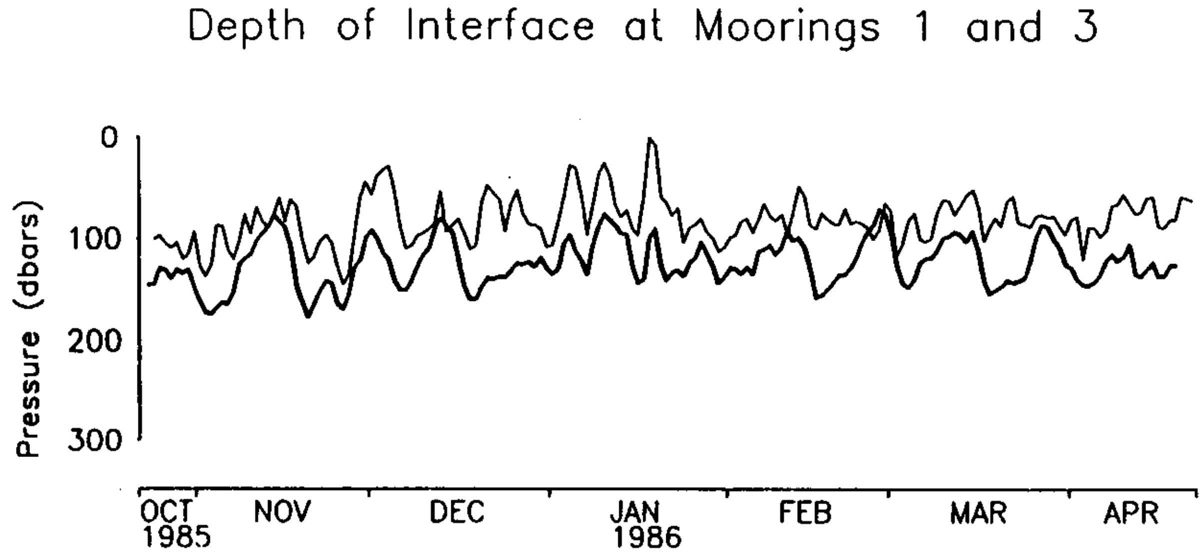


Fig. 13. Daily averaged depths of the interface defined by the 37psu isohaline on mooring 1 and on mooring 3. Note the greater depth of the interface on mooring 3 on the southern side of the sill section and the strong oscillations in mooring 3 interface depth with a period of about 14 days.

Because the fortnightly cycle in interface depth in the central and southern regions of the sill is not matched by a fortnightly cycle in interface depth in the northern region of the sill, there is a distinct fortnightly variation in the slope of the interface across the sill section. Since the interface slopes downward toward the south in the mean, the slope is largest just after neap tides. Tidal analysis of the difference between the depths of the 37psu isohaline at mooring 3 and at mooring 1 indicates that the fortnightly amplitude of the interface depth difference is 18.3m, nearly all of it due to the fortnightly cycle of amplitude 19.5m at mooring 3. Since the mean depths of the 37psu isohaline are 82.3m at mooring 1 and 123.9m at mooring 3, the fortnightly cycle in interface slope has an amplitude that is 44% of the time-averaged slope. These fortnightly variations in interface slope across the sill seciton, which are correlated with the variations in vertical shear in along-strait currents (Fig.12), account for about 70% of the total low-frequency variability in interface slope.

It is common to try to relate this fortnightly cycle in interface slope to a fortnightly signal in exchange, defined to be the difference ULT-LLT or the sum of the inflow and the outflow. In this vein, stronger interface slopes are often taken to indicate both stronger eastward inflow and stronger westward outflow leading to larger values of the exchange. At the Gibraltar sill, however, the available current meter records indicate that the increased shear at neap tides is the result of added eastward or inflow velocity at all depths at neap tides, with the added inflow being larger at shallower depths. Thus, the observed fortnightly cycle in shear does not appear to relate to stronger exchange, i.e. stronger inflow and stronger outflow. In fact, the fortnightly signal in the exchange, ULT-LLT, is only 0.003Sv, much smaller than the fortnightly cycle in either inflow or outflow. Rather, the observed fortnightly cycle in shear represents stronger inflow in the surface layer and weaker outflow in the lower layer near neap tides.

In conclusion, there is a fortnightly cycle in observed along-strait currents with stronger eastward flow at all depths near neap tides so that the upper layer transport achieves a maximum eastward inflow and the lower layer transport achieves a minimum westward outflow just after neap tides. The amplitudes of the fortnightly cycles in upper layer transport and lower layer transport are about 12% as large as the mean inflow and outflow. There is also a fortnightly cycle in the slope of the interface across the Strait of Gibraltar with stronger slopes occurring near neap tides. The stronger interface slopes do accompany stronger vertical shears in along-strait currents, but the current shears are due to larger fortnightly amplitudes in observed currents at shallower depths. Thus, there appears to be little fortnightly cycle in the size of the exchange across the sill despite the substantial fortnightly cycle in interface slope.

11. ANNUAL SIGNALS

With data sets that are a little less than a year in duration, it is risky to estimate the size of the annual cycle for any variable. There is, however, much interest in whether or not the exchange through the Strait of Gibraltar exhibits changes through the year. The interest principally derives from work by GARRETT and collaborators who first showed that the sea level difference across the Strait, and hence by dynamical implication the geostrophic surface inflow, exhibits a seasonal cycle such that inflow currents are strongest in the spring (BORMANS, GARRETT and THOMPSON, 1986). Further stimulation for determining annual cycles is provided by GARRETT, BORMANS and THOMPSON's (1990) argument that the nature of the exchange across the sill switches from maximal to submaximal during the course of a year. They suggest that the flow is maximal for the period after February-March when the Mediterranean reservoir of intermediate and deep water has just refilled due to wintertime water formation, but that the flow switches to a submaximal state later in the year after the supply of newly formed water has drained out over the sill. To provide more grist for Garrett's mill, we make the following estimates of the annual cycles in inflow, outflow and interface depth from the time series measurements on the sill during the period from October 1985 to October 1986.

The scaled upper and lower layer transports for the period October 1985 to August 1986 (Fig.11) and the depth of the interface at mooring 3 for the period October 1985 to April 1986 (Fig.14) are least square fitted to sine and cosine functions, $A \sin \omega t + B \cos \omega t$ where ω is the annual frequency and t is year-day, to determine the coefficients A and B. While the time series for the depth of the interface could have been extended using the interface depth from mooring 2B, we decided that, because moorings 3 and 2B were deployed at different locations on the sill section, there could be a discrete jump in the mean depth of the interface between the two series. The alternative of removing the means separately for each of the two pieces would also compromise any estimate of the annual signal since there would then be zero difference between the 6 month period when mooring 3 was deployed and for the following 5 month period when mooring 2B was deployed, thereby suppressing any real annual signal. Hence, we use only the 6-month time series of interface depth at mooring 3 in fitting the annual cycle. Because of the scaling described above to make the upper and lower layer transports consistent for the measurement periods of moorings 1 and 3 and of mooring 2B, the complete transport time series are used. The least squares estimates of A and B are then transformed into estimates of amplitude and phase for each annual signal.

The upper layer transport exhibits an annual cycle with an amplitude of 0.12Sv and a phase such that maximum inflow occurs on year-day 261 (18 September). The lower layer transport has an annual cycle amplitude of 0.03Sv and maximum outflow occurs on year-day 23 (23 January). The depth of the interface has an annual cycle amplitude of 18m and minimum depth is achieved on year-day 40 (9 February). With less than a year of data, estimates of error bars on these amplitudes and phases would be meaningless. Thus, the yearly cycle in outflow appears to be small. The inflow, which is poorly resolved due to the lack of instruments in the upper layer, has a larger signal but its maximum is in September, nearly 180° out of phase with the maximum surface currents inferred by BORMANS, GARRETT and THOMPSON (1986) from long-term sea level measurements. The annual cycle in interface depth appears to be the most robust of these estimates: one can almost 'see' the February minimum above the low-frequency variability in the year-long time series that includes mooring 2B (Fig.14); and minimum depth in mid winter corresponds with GARRETT, BORMANS and THOMPSON's (1990) arguments for a wintertime shallowing of the interface due to wintertime renewal of the Mediterranean reservoir. In summary, these estimates of annual cycles in inflow, outflow and interface depth indicate that maximum outflow, minimum inflow and shallowest interface depth occur in mid to late winter, between 23 January and 18 March. But it is important to remember that these estimates are based on only one year of measurements and hence have great uncertainty.

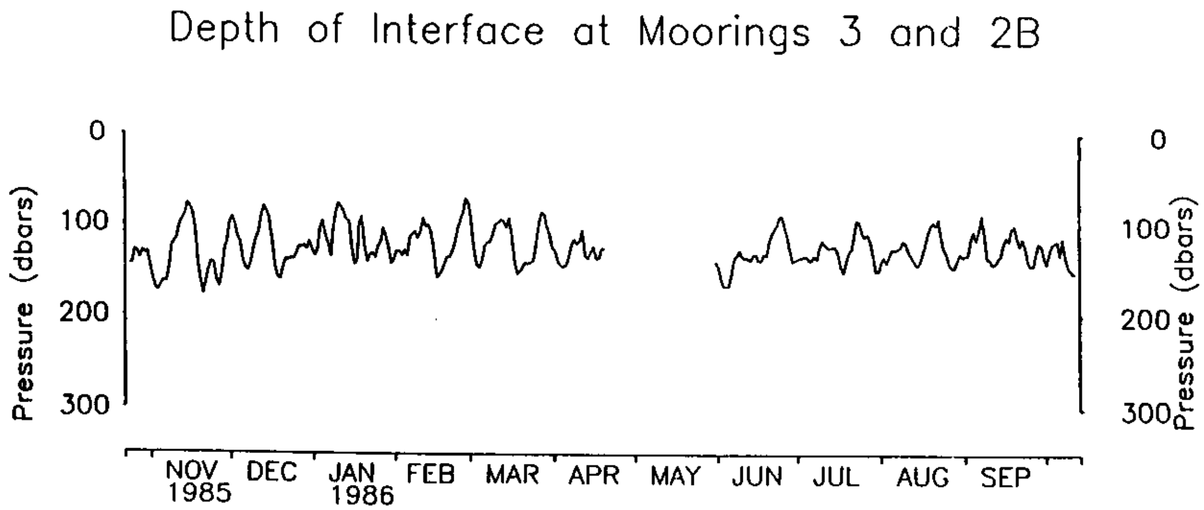


FIG.14. Daily averaged depth of the interface defined by the 37psu isohaline on mooring 3 from October 1985 to April 1986 and on mooring 2B from May to October 1986.

12. DISCUSSION

It is difficult to overemphasize the importance of time series salinity measurements for defining the exchange across the Gibraltar sill. At the outset of this analysis, we were naive enough to think that the mean exchange could be determined simply by time-averaging the current meter measurements and integrating the average currents vertically and horizontally across the strait. Such a procedure produced our first estimate of the outflow over the sill of only 0.38Sv, a factor of 3 smaller than LACOMBE and RICHEZ's (1982) standard value of 1.2Sv and a factor of 2 smaller than the time-averaged outflow of Mediterranean water found here. Without salinity time series, we would be forced to accept this low value for the outflow. The shock of such a low outflow transport, however, forced a reconsideration of what is meant by outflow and by exchange; and the importance of the salinity measurements for defining the water mass characteristics of the flow at every instant of time became clear.

The salinity measurements allow us to estimate the relative contributions of the mean currents and of the time-varying (principally tidal) fluctuations in effecting the exchange across the sill in a statistical sense. In fact, the fluctuations account for half of the total exchange due to the correlation between strong outflow and high salinity at every instrument. Secondly, the salinity measurements enable us to determine continuously the depth of various isohalines, to define a particular isohaline, the 37psu isohaline, as the interface between Atlantic and Mediterranean waters, and then to understand the mechanism of the time dependent exchange process in which strong outflow is associated with shallow interface over the tidal cycle so that a large bolus of Mediterranean water crosses the sill on the outflowing tide while a large bolus of Atlantic water crosses the sill on the inflowing tide. Thirdly, the definition of the interface as a water mass boundary allows the development of time series for the upper layer transport of Atlantic water and for the lower layer transport of Mediterranean water so that the tidal and low-frequency fluctuations in the inflow and outflow can be assessed. Finally, the salinity measurements allow a determination of the outflow salinity transport which is essentially a direct estimate of the net evaporation over the Mediterranean basin.

The estimate of net evaporation over the Mediterranean basin of 52cm y^{-1} derived from these measurements at the Gibraltar sill appears to be inherently more accurate than previous estimates of net evaporation, that have ranged from 47 to 131cm y^{-1} (Table 1), derived from bulk formula, rainfall determined from coastal stations, and river runoff. Bulk formula methods are notorious for the arguments over their uncertainties and biases. Rainfall is hopeless to measure at sea with all the spray, and coastal station rainfall measurement is subject to local topographic effects. In contrast, the measurements of current and salinity at the Gibraltar sill effectively provide a spatial integration of the air-sea fluxes over the entire Mediterranean basin. BUNKER, CHARNOCK and GOLDSMITH (1982) were the first to utilise the Gibraltar exchange to constrain traditional bulk formula parameterizations of air-sea exchange over the Mediterranean basin. GARRETT, OUTERBRIDGE and THOMPSON (1993) have recently re-examined the bulk formula estimates of air-sea heat and freshwater exchange in the light of the new direct estimates of net evaporation of 52cm y^{-1} reported here and of net heat gain of about $5Wm^{-2}$ carried out with these same measurements by MACDONALD, CANDELA and BRYDEN (1994) to identify where traditional parameterizations are in error. They conclude that the measured exchanges across the Gibraltar sill indicate that bulk formula estimates of evaporation are accurate so that the problem in net heat flux from bulk formula must lie with incoming radiation values that are too high. HARZALLAH, CADET and CREPON (1993) have recently used a global atmospheric model to determine the divergence in water vapour flux over the Mediterranean basin. Their resulting estimate for the freshwater flow through the Strait of Gibraltar of $30 \times 10^6 m^3 s^{-1}$ is equivalent to a net evaporation of only 37cm y^{-1} or to an outflow salinity transport of only $1.1 \times 10^3 m^3 s^{-1}$, but there may be substantial uncertainties in the atmospheric freshwater balance due to the coarse resolution of the Mediterranean basin in the global model. Thus, the measurements of exchange across the Gibraltar sill provide values for the net air-sea heat exchange and for net evaporation over the Mediterranean basin that are more accurate than traditional bulk formula estimates or those based on atmospheric flux divergence; and the heat and freshwater transports across the Gibraltar sill may in fact be useful for diagnosing problems in the alternative methods.

The observed outflow and inflow transports across the Gibraltar sill reported here of 0.7Sv are smaller than the values of about 1.2Sv reported by LACOMBE and RICHEZ (1982). We would not attribute the difference to long-term variability without carefully considering other differences. LACOMBE and RICHEZ's estimates were based on daily averaged currents measured by lowering current meters from a ship anchored at station A4, west of the sill, and there were no salinity values attached to the currents. West of the sill, the outflowing Mediterranean water quickly loses its high salinity signature (PRICE, O'NEIL-BARINGER, LUECK, JOHNSON, AMBAR, PARRILLA, CANTOS, KENNELLY and SANFORD (1993) and its transport must increase accordingly so that the outflow salinity transport remains constant. If the effective salinity contrast between Mediterranean and Atlantic waters at A4 were only 1.3psu rather than the 2.2psu found here at the sill, the two sets of transport would be essentially equivalent. In fact, RICHEZ and GASCARD (personal communication) did estimate the average salinities for the inflow and outflow over 12 tidal cycles during May and June 1961 to determine that the salinity difference at A4 between the inflow and outflow was 1.56psu (S_M = 37.81, S_A = 36.25) but this was during a period of strong outflow (Q_M = 1.33Sv) so that their outflow salinity transport still matched the 2.0 x $10^3m^3s^{-1}$ value in LACOMBE and RICHEZ (1982). Thus, we would ascribe much of the difference between the new transports of 0.7Sv and LACOMBE and RICHEZ's transports of 1.2Sv as being due to different salinities in the measured outflows as a result of mixing west of the sill. For future Gibraltar measurement or monitoring programmes, it is essential to determine not only the outflow but also the effective salinity of the outflow in order to assess long-term changes in the exchange.

It is useful to compare the observed exchange with the theoretically predicted maximum exchange from hydraulic control modelling (Table 10). In summarizing the developments of hydraulic control models applied to the Strait of Gibraltar, BRYDEN and KINDER (1991b) tabulated the theoretically predicted inflow, outflow and salinity difference as a function of ent evaporation over the Mediterranean basin. From the above analysis of the Gibraltar measurements, there are two primary estimates of the observed exchange: the outflow of Mediterranean water of -0.68Sv and the outflow salinity transport of -1.50 x $10^3m^3s^{-1}$, that is equivalent to a net evaporation of 52cm y^{-1}. The analysis also provides secondary estimates of the inflow, equal to the outflow plus the evaporation, of 0.72Sv, and of the salinity difference of 2.20psu determined by dividing the outflow salinity transport by the outflow transport. Interpolation of BRYDEN and KINDER's (1991b) tabulated predictions to a net evaporation of 52cm y^{-1} yields a predicted outflow of -0.84Sv, a predicted inflow of 0.88Sv and a predicted salinity difference of 1.80psu. Thus, the observed flows are about 20% smaller than the theoretically predicted maximum exchange through the Strait of Gibraltar.

At first, agreement between the observed exchange and the theoretically predicted exchange within 20% may seem reasonably successful. Furthermore, the observed exchange is satisfyingly less than the predicted maximum exchange, perhaps lending support to GARRETT, BORMANS and THOMPSON's (1990) argument that the Gibraltar exchange is sometimes submaximal. There is, however, a marked difference beween the modes of exchange in the models and in the observations. In the models, the two-layer flow is steady and it achieves critical composite Froude number of 1 at the sill and at the narrowest section. As noted by FARMER and ARMI (1986), the lower layer outflow essentially achieves critical Froude number at the sill in the hydraulic control models. In the observations, only half of the total exchange is carried by the time-averaged flows and the remaining half is effected by the tidal fluctuations. Froude number calculations reveal that the Froude number for the 'typical' time-averaged flows at the sill is about 0.25, substantially subcritical. For the instantaneous tidal currents, the Froude number at the sill is generally subcritical but achieves supercritical values about 10% of the time, mostly on the outflowing tide (Fig.15). Surprisingly, despite strong outflow velocities on the outflowing tide, the lower layer Froude number is nearly always less than 1 because the interface rises on the outflowing tide making the lower layer very thick so that $U_2^2/g'h_2$ remains less than 1. Surprisingly then, the supercritical Froude numbers on the outflowing tide are principally due to the thinness of the upper layer flow, so that $U_1^2/g'h_1$ is greater than 1.

TABLE 10. Comparison between observed and predicted exchanges. The observed outflow salinity transport of $-1.50 \times 10^3 m^3 s^{-1}$ divided by the Atlantic water salinity of 36.1psu and by the surface area of the Mediterranean basin of $2.52 \times 10^{12} m^2$ provides the value for the observed net evaporation of 52cm y^{-1}. The predicted outflow, inflow and salinity difference are derived by interpolation of BRYDEN and KINDER's (1991b) Table 1 for the maximal exchange as a function of net evaporation to a value for the net evaporation of 52cm y^{-1}.

	Net Evaporation $e(cm\ y^{-1})$	Outflow $Q_M(x10^6 m^3 s^{-1})$	Inflow $Q_A(x10^6 m^3 s^{-1})$	Salinity Difference $\Delta S(psu)$
Observed	52	-.68	.72	2.20
Predicted for e =	52	-.84	.88	1.80

Such difference in the modes of exchange between the models and observations suggests that the models must incorporate time-dependent processes in order to properly predict the exchange across the Gibraltar sill. FARMER and ARMI (1986) modelled the time-dependent problem as a succession of steady states with varying barotropic net flow to represent the tidal currents. They argued that steady-state conditions would be valid if the time it takes for an interfacial wave to travel between the control points at the sill and the narrowest section were less than a quarter tidal period, a condition not really valid for the Gibraltar situation where interfacial wave typically take 6 hours to travel from the sill to the narrowest section (WATSON and ROBINSON, 1990). Averaging over the series of steady states, FARMER and ARMI (1986) noted that the exchange always increases due to the fluctuations and the exchange more than doubles for tidal current amplitudes as large as the steady maximal exchange flows.

Recently, HELFRICH (1994) has combined theoretical and laboratory models to solve the time dependent exchange through a strait as a function of the tidal forcing and of the length of the strait. There are only two nondimensional parameters: the ratio of the tidal flow to the steady maximal exchange; and the ratio of the period of the tidal forcing to the time it takes an interfacial wave to propagate between the two control points at the sill and manowest section. He shows that the time dependent exchange for parameters applicable to the Strait of Gibraltar is substantially less than the doubling determined by FARMER and ARMI (1986), who effectively assumed the second parameter to be infinite. For Gibraltar parameters, HELFRICH (1994) suggests that the exchange predicted by the time-dependent model should be approximately 20% more than the steady, maximal exchange; but he also notes that mixing in the interfacial region between the inflow and outflow reduces the time-dependent exchange of pure Atlantic and Mediterranean waters by about 20%. Thus, the theoretically predicted exchange for a hydraulic control model including realistic tidal forcing and interfacial mixing is within 5% of the steady maximal exchange, yielding an outflow of Mediterranean water of 0.80Sv which is still about 15% larger than the measured outflow of 0.68Sv. Friction and rotation which are still not included in the model may yet account for the difference between the measured and predicted exchanges.

In terms of designing an observational strategy for long-term measurements of the exchange through the Strait of Gibraltar, the above analysis indicates that a single mooring at the sill with 4 to 8 current meters combining current, temperature, conductivity and pressure measurements can monitor the outflow of Mediterranean water and the outflow salinity transport, two basic measures of the exchange. On the other hand, monitoring the upper layer inflow is more difficult. With present current measuring technology, it is not clear how to measure directly the inflow, as surface moorings are unlikely to survive the high currents and high density shipping and fishing activities in the Strait and bottom-mounted, upward-looking Doppler current profilers cannot yet measure remotely the salinity of the flows.

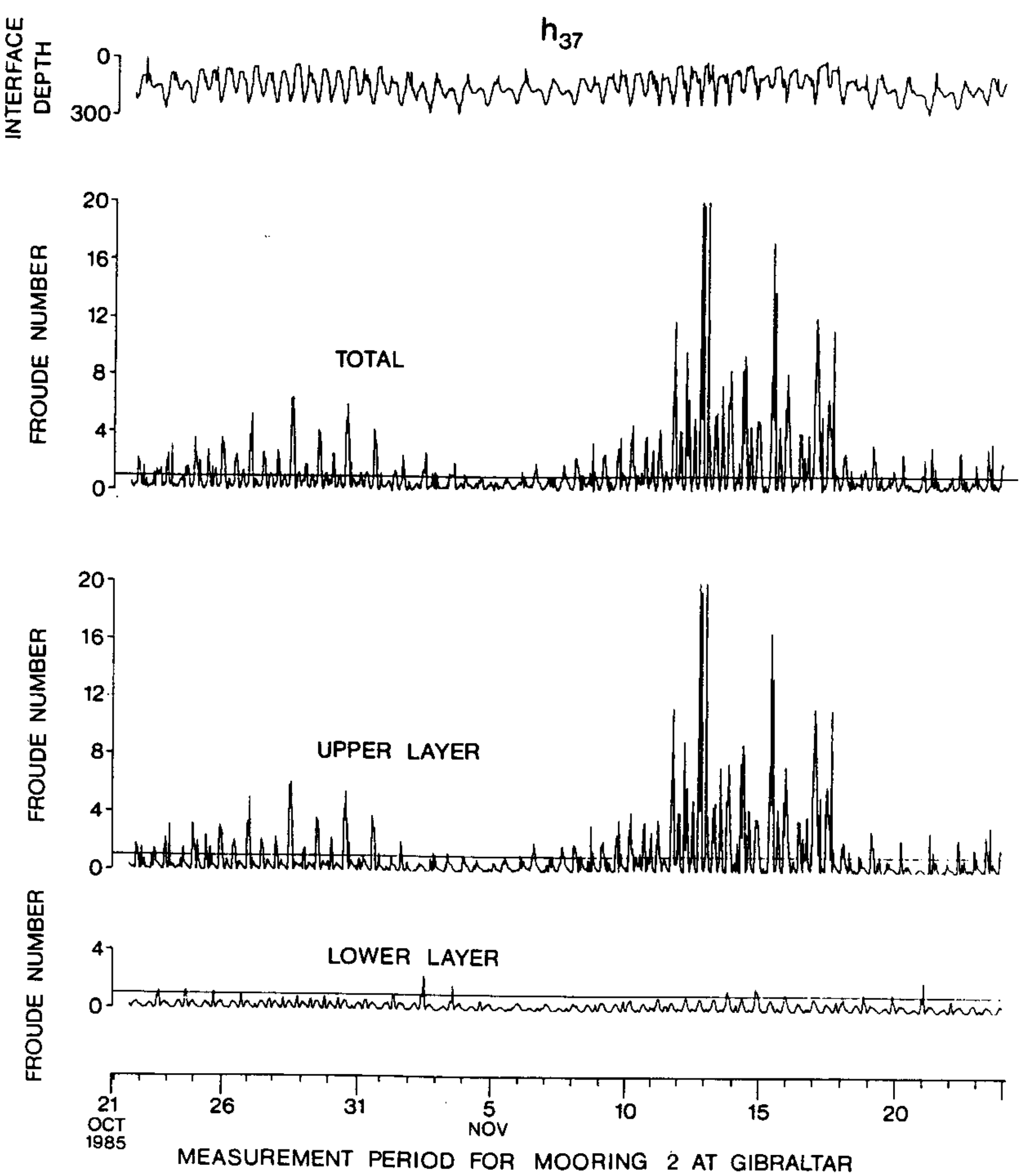


FIG.15. Froude numbers for the flow on mooring 2 at the Gibraltar sill during October-November 1985. The upper and lower layer Froude numbers are defined to be $U_1^2/g'H_1$ and $U_2^2/g'H_2$ where H_1 is the depth for the 37psu isohaline, H_2=284-H_1, U_1 is the along-strait velocity at depth = H_1+284/2, and g' is taken to be 2cm s^{-2}. Note that the lower layer Froude number is nearly always less than the critical value of 1 and that the upper layer Froude number reaches supercritical values above 1 for a short period on nearly every tidal cycle except during neap tides around 5 November. The total Froude number is the sum of the upper and lower layer Froude numbers. The depth of the 37psu isohaline is shown at the top in order to illustrate that supercritical Froude numbers are achieved principally when the interface is shallow.

An added complication is the horizontal variation in the strength of the inflow currents implied by these measurements across the 30km width of the sill section at the surface. Hence, direct measurement of the upper layer inflow remains a research question that needs to be addressed with a field experiment consisting of several conventional subsurface moorings and several bottom-mounted Doppler moorings deployed across the sill section in order to use the conventional moorings to define the interface depth and salinity of the flows and the Doppler instruments to measure the currents up to the surface. Simultaneous pressure gauge or sea level measurements on the northern and southern sides of the sill section would provide time series of pressure difference across the strait that should be related geostrophically to low-frequency variations in the surface currents. Determining how such pressure difference variations combined with measured interface depth variations are related to variations in upper layer inflow transport would be an important result from such an experiment that should allow previous and future pressure difference measurements to be used to define the long-term variations in the inflow.

Thus, our choice at present for an efficient monitoring strategy for the Strait of Gibraltar would be to combine the single conventional current meter mooring at the sill measuring outflow, outflow salinity transport, and depth of the interface with shallow pressure gauges on the northern and southern sides of the sill section to provide an index on the strength of the inflow. At some time, a larger experiment should be carried out to define how this index of the inflow is related quantitatively to the inflow transport.

Eight years after the field work ended, it is worthwhile to state a summary of the progress made in achieving the three goals of the Gibraltar Experiment (BRYDEN and KINDER, 1986):

(1) to understand how the dynamical constraints for flow through a narrow and shallow strait act to control the amount of exchange between the Atlantic and Mediterranean;

(2) to measure the exchange through the Strait and its temporal variations over tidal to seasonal time scales; and

(3) to define a measurement strategy for long-term monitoring of the exchange.

First, the exciting developments in hydraulic control models of the two-layer flow through the Strait of Gibraltar by Armi and Farmer, Bormans and Garrett, Dalziel, and Helfrich have clearly increased understanding on how the physical configuration of the strait and the nonlinear dynamics of the flows do constrain the maximal exchange possible through a strait and sill region. Progress is still needed in extending hydraulic control theory to accommodate mixing, friction and rotation in a fully time dependent model of the exchange through the Strait of Gibraltar. Secondly, while the year-long measurements of the exchange had multiple technical difficulties, high quality measurements of the exchange across the sill were made for 31 days and consistent analysis allows a nine-month time series of the exchange to be developed. While these measurements do serve to quantify how important the tidal fluctuations are to effecting the exchange across the sill, longer term measurements are still needed to define the seasonal and interannual variability in the exchange. Finally, a long-term strategy is put forward to monitor cost-effectively the outflow of Mediterranean water into the Atlantic and the net evaporation over the Mediterranean basin and to provide an index for the inflow of Atlantic water into the Mediterranean. Such monitoring is essential for determining whether the exchange switches between maximal and submaximal on seasonal or interannual time scales. True monitoring of the inflow must await more extensive field measurements of the upper layer inflow to define how the variations in the inflow transport are related to measurements of pressure difference and interface depth. Thus, while there is need for future work in all three areas, substantial progress has been made on each of the broad goals set out for the Gibraltar experiment a decade ago.

13. ACKNOWLEDGEMENTS

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14. REFERENCES

Armi, L. (1986) The hydraulics of two flowing layers with different densities. *Journal of Fluid Mechanics*, **163**, 27-58.

Armi, L. and D.M. Farmer (1985) The internal hydraulics of the Strait of Gibraltar and associated sills and narrows. *Oceanologica Acta*, **8**, 37-46.

Armi, L. and D.M. Farmer (1986) Maximal two-layer exchange through a contraction with barotropic net flow. *Journal of Fluid Mechanics*, **164**, 27-51.

Armi, L. and D.M. Farmer (1988) The flow of Mediterranean Water through the Strait of Gibraltar (also: Farmer, D.M. and L. Armi. The flow of Atlantic Water through the Strait of Gibraltar). *Progress in Oceanography*, **21**, 1-105.

Bethoux, J.P. (1979) Budgets of the Mediterranean Sea. Their dependence on the local climate and on the characteristics of the Atlantic waters. *Oceanologica Acta*, **2**, 157-163.

Bormans, M. and C. Garrett (1989a) The effect of rotation on the surface inflow through the Strait of Gibraltar. *Journal of Physical Oceanography*, **19**, 1535-1542.

Bormans, M. and C. Garrett (1989b) The effects of nonrectangular cross section, friction, and barotropic fluctuations on the exchange through the Strait of Gibraltar. *Journal of Physical Oceanography*, **19**, 1543-1557.

Bormans, M., C. Garrett and K.R. Thompson (1986) Seasonal variability of the surface inflow through the Strait of Gibraltar. *Oceanologica Acta*, **9**, 403-414.

Bray, N.A. (1986) Gibraltar Experiment CTD Data Report: March-April 1986, USNS *Lynch*. Scripps Institution of Oceanography References Series 86-21, 212pp.

BRYDEN, H.L. (1993) Sill exchange to and from enclosed seas. *Symposium, "Mediterranean Sea 2000", September 1991*. N.F.R. DELLA CROCE, editor, Istituto Scienze Ambientali Marine, Santa Margherita Ligure, 17-36.

BRYDEN, H.L. and T.H. KINDER (1986) Gibraltar Experiment. A plan for dynamic and kinematic investigations of Strait mixing, exchange and turbulence. *Woods Hole Oceanographic Institution Technical Report* **WHOI-86-29**, 83pp.

BRYDEN, H.L. and T.H. KINDER (1991a) Recent progress in strait dynamics. *Reviews of Geophysics*, Supplement, 617-631.

BRYDEN, H.L. and T.H. KINDER (1991b) Steady two-layer exchange through the Strait of Gibraltar. *Deep-Sea Research*, **38** (Supplement 1), S445-S463.

BRYDEN, H.L. and R.D. PILLSBURY (1990) Measurement of flow through the Strait of Gibraltar. *Advances in Water Resources*, **12**(2), 64-69.

BRYDEN, H.L. and H.M. STOMMEL (1984) Limiting processes that determine basic features of the circulation in the Mediterranean Sea. *Oceanologica Acta*, 7(3), 289-296.

BRYDEN, H.L., E.C. BRADY and R.D. PILLSBURY (1989) Flow through the Strait of Gibraltar. In: *Seminario Sobre la Oceanografia Fisca del Estrecho de Gibraltar, Madrid, 24-28 Octubre 1988*, J.P. ALMAZAN, H. BRYDEN, T. KINDER and G. PARRILLA, editors, SECEG, Madrid, 166-194.

BUCHANAN, J.Y. (1877) On the distribution of salt in the ocean. *Journal of the Royal Geographical Society*,**47**, 72-86.

BUNKER, A.F., H. CHARNOCK and R.A. GOLDSMITH (1982) A note on the heat balance of the Mediterranean and Red Seas. *Journal of Marine Research*, **40** (Supplement), 73-84.

CANDELA, J., C.D. WINANT and H.L. BRYDEN (1989) Meteorologically forced subinertial flows through the Strait of Gibraltar. *Journal of Geophysical Research*, **94**, 12667-12674.

CANDELA, J., C. WINANT and A. RUIZ (1990) Tides in the Strait of Gibraltar. *Journal of Geophysical Research*, **95**, 7313-7335.

CARPENTER, W.B. and J.G. JEFFREYS (1870) Report on deep-sea researches carried on during the months of July, August, and September 1870 in HM surveying-ship *Porcupine*. *Proceedings of the Royal Society, London*, **19**, 146-221.

CARTER, D.B. (1956) The water balance of the Mediterranean and Black Seas. *Climatology*, Drexel Institute of Technology, Laboratory of Climatology, **9**, 123-175.

DALZIEL, S.B. (1990) Rotating two-layer sill flows. In: *The Physical Oceanography of Sea Straits*, L.J. PRATT, editor, Kluwer, Boston, 343-371.

DALZIEL, S.B. (1991) Two-layer hydraulics: A functional approach. *Journal of Fluid Mechanics*, **223**, 135-163.

DALZIEL, S.B. (1992) Maximal exchange in channels with nonrectangular cross sections. *Journal of Phyusical Oceanography*, **22**, 1188-1206.

DEACON, M. (1971) *Scientists and the Sea, 1650-1900: A Study of Marine Science*. Academic Press, New York, 445pp.

FARMER, D.M. and L. ARMI (1986) Maximal two-layer exchange over a sill and through the combination of a sill and contraction with barotropic flow. *Journal of Fluid Mechanics*, **164**, 53-76.

FOFONOFF, N.P. and R.C. MILLARD JR (1983) Algorithms for computation of fundamental properties of sea water. *UNESCO Technical Papers in Marine Science*, **44**, 53pp.

GARRETT, C., M. BORMANS and K. THOMPSON (1990) Is the exchange through the Strait of Gibraltar maximal or submaximal? In: *The Physical Oceanography of Sea Straits*, L.J. PRATT, editor, Kluwer Boston, 271-294.

GARRETT, C., R. OUTERBRIDGE and K. THOMPSON (1993) Interannual variability in Mediterranean heat and buoyancy fluxes. *Journal of Climate*, **6**, 900-910.

GEYER, W.R. and G.A. CANNON (1982) Sill processes related to deep-water renewal in a fjord. *Journal of Geophysical Research*, **87**, 7985-7996.

HARZALLAH, A., D.L. CADET and M. CREPON (1993) Possible forcing effects of net evaporation, atmospheric pressure, and transients on water transports in the Mediterranean Sea. *Journal of Geophysical Research*, **98**, 12341-12350.

HELFRICH, K.R. (1994) Time-dependent two-layer hydraulic exchange flows. *Journal of Physical Oceanography*, **24**, (in press).

HOPKINS, T.S. (1978) Physical processes in the Mediterranean basins. In: *Estuarine Transport Processes*, B. KJERVE, editor, University of South Carolina Press, Columbia, 269-310.

KINDER, T.H. and H.L. BRYDEN (1987) The 1985-1986 Gibraltar Experiment. *EOS*, **68**, 786-787 and 793-795.

KINDER, T.H. and H.L. BRYDEN (1988) Gibraltar Experiment: Summary of the field program and initial results of the Gibraltar Experiment. *Woods Hole Oceanographic Institution Technical Report*, **WHOI-88-30**, 118pp.

KINDER, T.H. and H.L. BRYDEN (1990) The aspiration of deep waters through Straits. In: *The Physical Oceanography of Sea Straits*, L.J. PRATT, editor, Kluwer, Boston, 295-319.

KINDER, T.H., D.A. BURNS and R.D. BROOME (1986) Hydrographic measurements in the Strait of Gibraltar, November 1985. *Naval Ocean Research Development Activity (NORDA) Report*, **141**, 332pp.

KINDER, T.H., D.A. BURNS and M.R. WILCOX (1987)Hydrographic measurements in the Strait of Gibraltar, June 1986. *Naval Ocean Research Development Activity (NORDA) Technical Note*, **378**-1, 355pp.

LACOMBE, H. (1961) Année Géophysique Internationale 1957-1958, Participation francaise: Contribution à l'étude du régime du Détroit de Gibraltar, Etude dynamique. *Cahiers Océanographiques*, **13**, 73-107.

LACOMBE, H. (1971) Le Détroit de Gibraltar, océanographie physique. *Notes et Mémoires du Service Géologique du Maroc*, **222**, 111-146.

LACOMBE, H. and C. RICHEZ (1982) The regime of the Strait of Gibraltar. In: *Hydrodynamics of Semi-Enclosed Seas*, J.C.J. NIHOUL, editor, Elsevier, Amsterdam, 13-73.

LACOMBE, H. and P. TCHERNIA (1972) Caractères hydrologiques et circulation des eaux en Méditerrannée. In: *The Mediterranean Sea: A Natural Sedimentation Laboratory*. D.J. STANLEY, editor, Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania. 765pp.

LA VIOLETTE, P.E. and H. LACOMBE (1988) Tidal-induced pulses in the flow through the Strait of Gibraltar. *Oceanologica Acta*, **SP**, 13-27.

MACDONALD, A.M., J. CANDELA and H.L. BRYDEN (1994) Net heat transport through the Strait of Gibraltar. In: *Seasonal and Interannual Variability of the Western Mediterranean*, P. LA VIOLETTE, editor, American Geophysical Union, (in press).

MARSIGLI, L.F. (1681) Internal observations on the Thracian Bosphorus, or true channel of Constantinople, represented in letters to her majesty, Queen Christina of Sweden. Translated by E. HUDSON, in *Oceanography: Concepts and History*, M.B. DEACON, editor, Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania, 33-44.

NIELSEN, J.N. (1912) Hydrography of the Mediterranean and adjacent waters. *Report of the Danish Oceanographical Expedition 1908-1910, Copenhagen*, **1**, 77-191.

PILLSBURY, R.D., D. BARSTOW, J.S. BOTTERO, C. MILLEIRO, B. MOORE, G. PITTOCK, D.C. ROOT, J. SIMPKINS III, R.E. STILL and H.L. BRYDEN (1987) Gibraltar Experiment: Current measurements in the Strait of Gibraltar. *Oregon State University Technical Report*. **87-29**, 284pp.

PRICE, J.F. and M. O'NEIL-BARINGER (1994) Outflows and deep water production by marginal seas. *Progress in Oceanography*, **33**, 157-196.

PRICE, J.F., M. O'NEIL-BARINGER, R.G. LUECK, G.C. JOHNSON, I. AMBAR, G. PARRILLA, A. CANTOS, M.A. KENNELLY and T.B. SANFORD (1993) Mediterranean outflow mixing and dynamics. *Science*, **259**, 1277-1282.

REID, J.L. (1979) On the contribution of the Mediterranean Sea outflow to the Norwegian-Greenland Sea. *Deep-Sea Research*, **26**, 1199-1223.

SCHOTT, G. (1915) Die Gewasser des Mittelmeeres. *Annalen der Hydrographie und Maritimen Meteorologie*, **43**, 63-79.

SHULL, S. and N.A. BRAY (1989) Gibraltar Experiment CTD Data Report II: September-October 1986, USNS *Lynch*. *Scripps Institution of Oceanography Reference Series*, **89-23**, 258pp.

STOMMEL, H., H. BRYDEN and P. MANGELSDORF (1973) Does some of the Mediterranean outflow come from great depth? *Pure and Applied Geophysics*, **105**, 879-889.

SVERDRUP, H.U., M.W. JOHNSON and R.H. FLEMMING (1942) *The Oceans: Their Physics, Chemistry and General Biology*, Prentice-Hall, New York, 1087pp.

TIXERONT, F. (1970) Le bilan hydrologique de la Mer Noire et de la Méditerranée. *Cahiers Océanographiques*, **22**, 227-237.

WATSON, G. and I.S. ROBINSON 91990) A study of internal wave propagation in the Strait of Gibraltar using shore-based marine radar images. *Journal of Physical Oceanography*, **20**, 374-395.

WESSON, J.C. and M.C. GREGG (1994) Mixing at Camarinal Sill in the Strait of Gibraltar. *Journal of Geophysical Research*, **99**, (in press).

WÜST, G. (1952) Der Wasserhaushalt des Mittellandischen Meeres und der Ostsee in vergleichender Betrachtung, *Revista Geofisica Pura e Applicata*, **21**, 1-14.