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The seasonal cycles of stratification and circulation in the Thermaikos Gulf Region Of Freshwater Influence (ROFI), north-west Aegean

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Abstract

The Thermaikos Gulf is a shallow basin in the north-west Aegean. Communication with the open Aegean is restricted by the long (170 km), narrow ($\sim$50 km) nature of the Gulf and the weak tidal flows. In consequence, the northern section of the Gulf experiences severe water quality problems arising from the untreated sewage from the city of Thessaloniki (population 1.1 million), pollutant discharges from industry around the Gulf, and nutrient input from three rivers, which flow in near the head of the Gulf. New observations over a 16-month period during 1994–95 indicate distinct winter and summer circulation regimes.

In winter (December–April), strong freshwater input ($\sim$350 m^3/s) generates a thin (5 m), low salinity, surface layer which flows southward over much of the Gulf, above relatively homogeneous high-salinity waters that flow to the north. In the low-salinity layer, close to the river deltas, short pulses of extremely low-salinity water occur daily, principally as the result of releases from the Aliakmon hydro-electric power dam. Between October and February, a cold, dense water mass is observed in the deeper water of the eastern Gulf, which appears to originate in the shallow waters of central Saloniki Bay as the result of cooling during northerly gales. During winter it appears that buoyancy forcing from high run-off, in combination with persistent southward wind stress results in wind-enhanced estuarine exchange.

In summer (July–September), the surface low-salinity layer is not well defined and is confined to the western Gulf in the vicinity of the river sources. Throughout the Gulf, a thicker (10–20 m) mixed layer with low salinity, warm waters overlies a strong pycnocline. A weak barotropic gyre is observed in the Gulf at this time.

Monthly estimates of the total freshwater content of the northern Gulf indicate that this layer results in an accumulation of freshwater in the Gulf over the summer, when the local river input is at a minimum. It appears that this freshwater accumulation results from an influx of freshwater from low-salinity surface waters extending across the Northern Aegean at this time as a result of freshwater input from the Dardanelles Strait. A dramatic feature of the summer regime is the occurrence of abrupt changes of the depth of the warm, low-salinity layer or level of the Gulf's pycnocline. During these events, which result in relatively strong currents, the pycnocline rises sharply (by up to 10 m), and remains elevated for 3–14 days before dropping more gradually to its previous level. These displacements appear to represent the Gulf's adjustment to wind-forced pycnocline slopes across the Northern Aegean.

Keywords: ROFI; Seasonal thermohaline circulation; Kelvin wave; Wind forcing; Thermaikos; Aegean; Mediterranean

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1. Introduction

The Thermaikos Gulf is a small Gulf in the Northern Aegean, in the Eastern Mediterranean (Fig. 1a). It constitutes the far north-western section of the Aegean Sea, and is a shallow elongated embayment on the continental shelf which extends approximately 200 km north from the Sporades Basin (Fig. 1b). The city of Thessaloniki (population 1.2 million) is located on its northern coast, and three rivers flow into the northern Gulf along its western coast. Bathymetry in the region is generally flat and gradually deepening from 30 m in the north to approximately 130 m in the south at the Shelf break, where the Gulf ends through a sharp submarine escarpment to the deep waters of the Sporades Basin (Lykonis and Chronis, 1989).

The practical justification for studying the Gulf arises from the fact that the Saloniki Bay (Fig. 1a) receives waste in the form of, largely untreated, sewage from the city of Thessaloniki (population 1,200,000), and industrial effluent from some 250 factories located around its coast. The Gulf also receives both agricultural and industrial pollutants indirectly from its tributary rivers. The nutrient enrichment (Balopoulos and Friligos, 1993) from sewage and fertilisers results in toxic blooms whilst the input of industrial effluent (from oil refineries, paper mills and chemical plants) results in abnormally high levels of heavy metals and chemical pollutants (Chester and Voutsinou, 1981; Voutsinou-Taliadouri and Satsmajis, 1983). The distribution and levels of bio-geochemical parameters and pollutants, in the Gulf, are presented in Voutsinou-Taliadouri and Varnavas (1995).

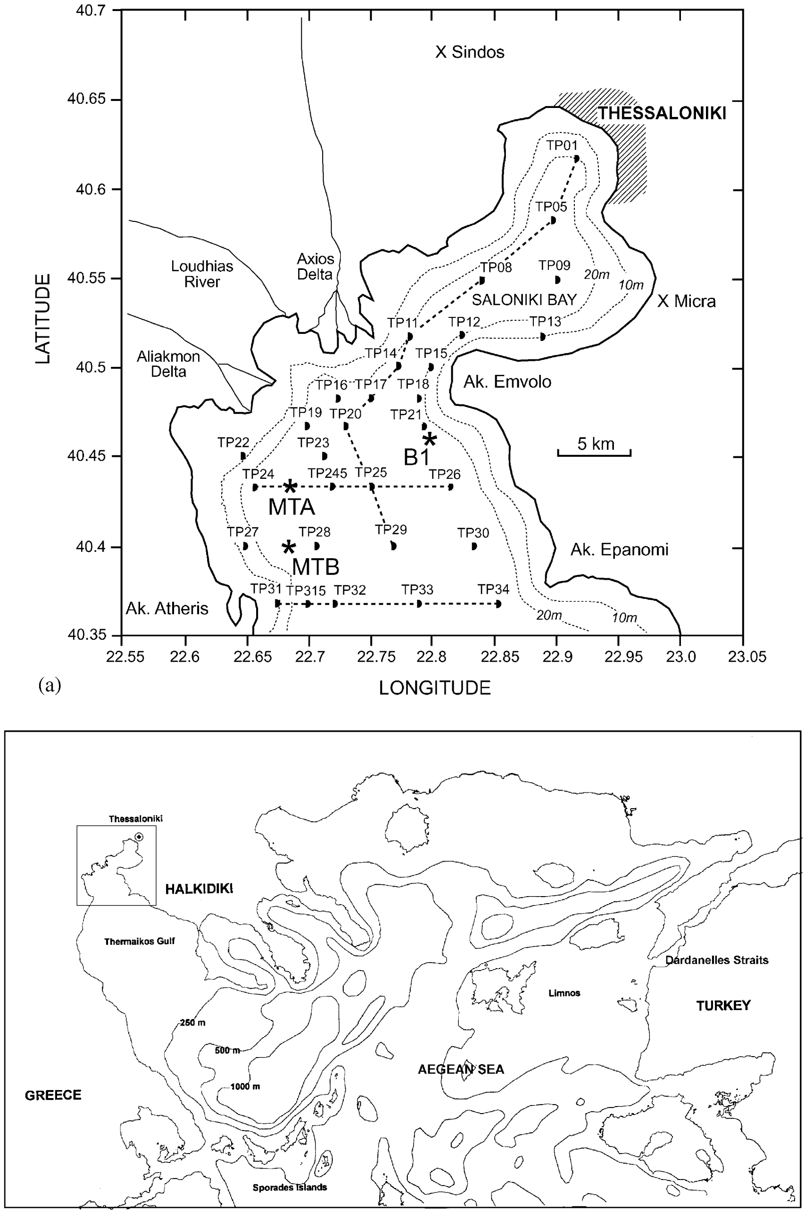
Prior to this study no systematic survey of the seasonal cycle of the dynamics and stratification of the Gulf had been undertaken, although several observational studies were completed between 1975 and 1980 (Balopoulos, 1982; Balopoulos, 1985a, b, 1986; Balopoulos et al., 1986a, b; Balopoulos and Friligos, 1993; Balopoulos and James, 1984a, b; Balopoulos and Voutsinou-Talidouri, 1988). Previous studies were based on seasonal three-monthly CTD surveys of the Gulf (Robles et al., 1983; Sultan, 1981; Sultan et al., 1987; Durrieu de Madron et al., 1992), driftcard and drogue releases (Balopoulos and James, 1984a, b), a summer moored instrument program (Balopoulos et al., 1986a) and a satellite image study (Balopoulos et al., 1986b). A 1-month survey of sea level variations in the northern Gulf was undertaken by Wildings et al. (1980), which highlighted the occurrence of short period seiching across Saloniki Bay. An overview of seasonal variations in the stratification and circulation in the Aegean Sea is presented in Poulos et al. (1997).

The region is characterised by weak tides (Tsimplis, 1994) and strong seasonal cycles in heating, wind forcing and freshwater input.

The main freshwater input is supplied by three rivers flowing into the Gulf on its western coast (Fig. 1a). The two largest, the Axios and Aliakmon, have multi-channel delta systems aligned to the south and east, respectively. Flow in the Aliakmon is controlled by daily releases from a hydro-electric power (HEP) dam. The other river the Loudhias is a minor input which is only significant during summer when, as the result of collected irrigation water, it has its maximum flow. The total river input observed over the survey period (January 1994 and July 1995) is presented in Fig. 2. Data for these estimates came from several sources, which will be presented in Section 2.

There are strong seasonal and short-term variations in the total freshwater input rate to the Gulf, between maximum and minimum daily mean values of about 350 and 50 $m^3 s^{-1}$, respectively. During recent decades there has been a 50% reduction in the total freshwater input to the Gulf, largely as the result of the extraction of river water for irrigation, and the construction of a series of HEP dams on the Aliakmon.

Winds at the Micra weather station (collected by the Hellenic Meteorological Society) at the airport on the eastern coast of Saloniki Bay (Fig. 1a) are presented in Fig. 2. Winds over the Gulf are generally relatively weak (Livadas and Sahsamanoglou, 1973), being greater than force 7 (15 $m s^{-1}$), $<1\%$ of the time. During winter, persistent southward winds are observed, which dominate the annual mean, whilst during summer, the winds are more variable but on average blew weakly to the east. Strong southward gales known



(a)

(b)

Fig. 1. (a) The region of the Thermaikos Gulf selected for the survey, indicating the location of instrument mooring and CTD stations together with the bathymetry. The positions of the mooring stations MTA and MTB (together with mooring station B1 from the 1976 Balopoulos survey) are indicated with *s and the CTD stations are indicated with half circles. (b) Map showing the location and bathymetry (in meters) of the Thermaikos Gulf in relation to the Northern Aegean Sea region.

locally as the 'Vardharis', lasting 4–6 days, with associated wind speeds up to $20\,\mathrm{m\,s^{-1}}$ and sharp drops in air temperature, are observed throughout the year but they tend to be weaker and less frequent in summer. Diurnal 'sea-breeze' winds are observed over the Gulf, which are principally directed north–south and are particularly energetic during summer.

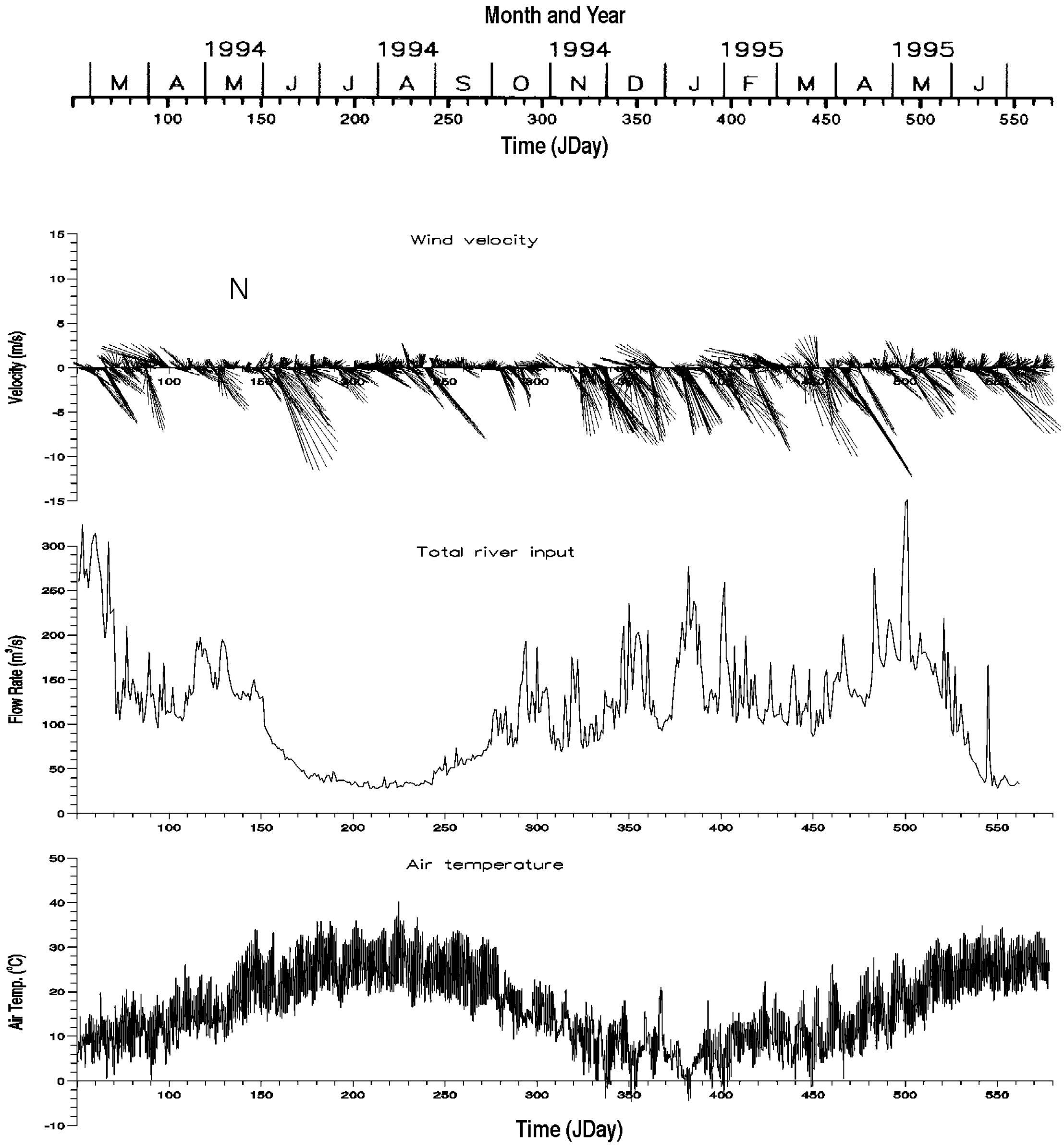


Fig. 2. The seasonal cycles of (a) low-pass wind velocity, (b) total river input and (c) air temperature over the survey duration. Data for wind and air temperature are from the Micra station. River inputs are derived from estimates for each of the separate sources (see Section 2).

In the Aegean to the south of the Gulf, persistent southward 'Etesian winds', termed 'the Meltemi', are observed between May and September (Carapiperis, 1970; Livadis and Sahsamanoglou, 1973). During May and June they blow intermittently, but from mid-July to mid-September they are more persistent and have greater intensity (Balopoulos, 1982). Over the Thermaikos Gulf, however, southward winds during summer are much less persistent and generally weaker than those to the south.

Air temperature data collected at the Micra weather station on the eastern coast of Saloniki Bay (Fig. 1a) by the Hellenic Meteorological Society over the survey period are presented in Fig. 2. The large variations in air temperature during the survey of -4.6°C to 40.2°C are characteristic of the extreme temperature ranges observed in Greece. These include both diurnal temperature fluctuations, of up to 10°C, and strong seasonal variations in the daily mean temperature. Observations of the daily total rainfall at Sindos (collected by the Land Reclamation Institute) over the survey period indicate that the majority of the rainfall occurs during short isolated storm events, which are scattered through the year, although less frequent during summer.

In this paper we present the findings of a year-long survey of the northern section of the Thermaikos Gulf (Fig. 1a) which aimed to observe the seasonal cycle of stratification and circulation in a low-tidal energy region of freshwater influence or ROFI. The study formed a component of the 'Processes in Regions of Freshwater Influence (PROFILE)' project, which studied the dynamics of several European ROFIs, including the Clyde Sea, the Rhine outflow, the German Bight and the Po (Huthnance, 1996; Simpson, 1997).

2. Observations

An observational program of the northern Gulf, to the north of the Epanomi Headland (Fig. 1a), was undertaken between March 1994 and July 1995. The observational effort involved the deployment of long-term moored instrumentation at two locations (MTA and MTB), both in 29 m water depth, on the western side of the Gulf. Since we were concerned about the possible data losses due to fishing and extreme levels of bio-fouling in the region, mooring sites were selected both in the western Gulf with the aim of achieving a full seasonal cycle through combination of data from the two locations. These time series data were put into a spatial context by data collected during CTD surveys at stations (Fig. 1a) undertaken at approximately monthly intervals.

In April 1994, a mooring with limited instrumentation, comprising a mid-depth Aanderaa RCM4 with temperature and conductivity sensors and a surface Aanderaa RCM4 (with its rotor and vane assembly removed) temperature-conductivity logger, was deployed at the MTA site. From June 1994, fully instrumented moorings, with Aanderaa RCM4 surface temperature–conductivity loggers and three Aanderaa RCM4 recording current meters with temperature and conductivity sensors at 5, 14, and 24 m depths, were deployed at both locations. At this time a Seabird SBE26 wave-tide gauge was deployed at the MTA site. All instruments were set to record data at 10 min intervals and were serviced on a monthly basis until November 1994 when additional instrumentation, including an Aanderaa T7 thermistor chain, were deployed. At this time, the deployment duration was increased to 2 months and the instrument sampling interval was switched to 20 min. Surface currents were measured from January 1995 at MTA, using an Aanderaa RCM 4, moored on a rig designed to minimise wave oscillation, loosely tethered to the sub-surface float.

For temperature and salinity, moored instruments were calibrated against CTD data from the Seabird SBE 19 profiler. Temperature data are accurate to within 0.02°C. Salinity data accuracy were reduced considerably due to the necessity to post-correct conductivity for the effect of bio-fouling in the region, as detailed in Hyder (1997). The salinity data quoted in this paper are therefore only accurate to within ~ 0.4, although relative changes of less than this remain significant. The fouling also resulted in the irrecoverable loss of current speed data when rotors became fouled. Otherwise, current speeds are accurate to $0.01\,\mathrm{m\,s^{-1}}$.

Although problems were encountered with severe levels of bio-fouling in the region, a good data return was achieved from all of the instruments, and the new observations provide good seasonal coverage of the circulation and stratification of the northern Gulf.

Meteorological data of air temperature, air pressure, humidity, cloud cover, wind speed and direction were collected by the Hellenic Meteorological Society at the Micra station on the eastern coast of Saloniki Bay (Fig. 1a). Data of rainfall and irradience were collected at Sindos (Fig. 1a) by the Land Reclamation Institute.

The river systems flowing into the Gulf are complex with quantities of water extracted downstream of the flow measurements so total freshwater input values are estimates derived from a number of sources. Daily observations of the Axios level were provided by the Ministry of the Environment and Public Works and were calibrated against weekly flow rate measurements undertaken by the Land Reclamation Institute to provide daily flow rate estimates. Daily volume releases from the Aliakmon river were provided by the Public Electricity Enterprise and have been converted to daily flow rates.

Both the Aliakmon and Axios rivers are diverted downstream of the measurements and used for irrigation purposes. Estimates of the volume losses for irrigation purposes were provided by the Land Reclamation Institute. A level recorder was deployed by scientists at the Aristotle University of Thessaloniki downstream of where the irrigation return channel rejoins the main channel. This data was not calibrated to give flow estimates but does provide estimates of extreme, daily variations in the Aliakmon discharge due to releases from its HEP dam.

Flow in the Loudhias river is much less than the other sources and is largely irrigation return flow which has a consistent annual cycle (with an anomalous maximum during summer). Observations were undertaken by the Land Reclamation Institute until July 1994 when they were terminated. The mean daily flow rates between 1992 and 1994 were therefore used to estimate flow in this river over the survey period. Details of the individual flow rates, and necessary corrections are presented in Hyder (1997). Due to the uncertainties in each of the sources the overall accuracy of the total input is estimated to be only $\pm 35\,\mathrm{m^3\,s^{-1}}$.

3. Results

In this section, we consider the observations and some of their direct implications concerning the seasonal thermo-haline and circulation cycles. We then present details of observations of the characteristics of perturbations to the level of the pycnocline which are evident in the T/S time series during summer. All of the CTD sections for each of the monthly CTD surveys are presented in full in Hyder (1997).

3.1. The thermo-haline seasonal cycle

The surface and bottom temperature, salinity and density throughout the study are presented as time series in Fig. 3. The corresponding cycles of wind, freshwater and air temperature are presented in Fig. 2. To summarise the seasonal cycle of stratification, time-series data from the moored instruments (which have high resolution in time) and profile data from the CTD surveys (providing good vertical resolution) have been combined and interpolated on to a regular grid. For the northern MTA mooring this data is presented as depth–time contours of temperature, salinity and density in Fig. 4.

During the winter periods (December–April, day 60–120, 340–480) when run-off was high (Fig. 2), a low-salinity surface layer occupied the upper 5–8 m across the northern Gulf (Figs. 3 and 4) and overlay relatively homogenous, high salinity (≈ 38) deeper waters. The temperature profile was frequently thermally inverted between November and March, with surface waters cooler by up to 2°C (Fig. 3). Haline stratification was apparent in the upper layer, which extended across much of the Gulf, although the lowest salinity waters were usually concentrated towards the western coast (Hyder, 1997). However, both the extent of the low salinity layer and stratification within the layer varied considerably between surveys with changes in the level of the river input. Surface salinity variations between 22 and 36 were observed at the MTA site (Fig. 3), including daily pulses of extremely low-salinity water. These pulses appear to result from daily flow surges in the Aliakmon river, due to releases from its HEP dam (Hyder, 1997), as can be seen in Fig. 5.

A cold, dense water mass of temperature 8.55°C, salinity 37.80 and density $29.4\,\mathrm{kg\,m^{-3}}$ was observed extending southward from Saloniki Bay

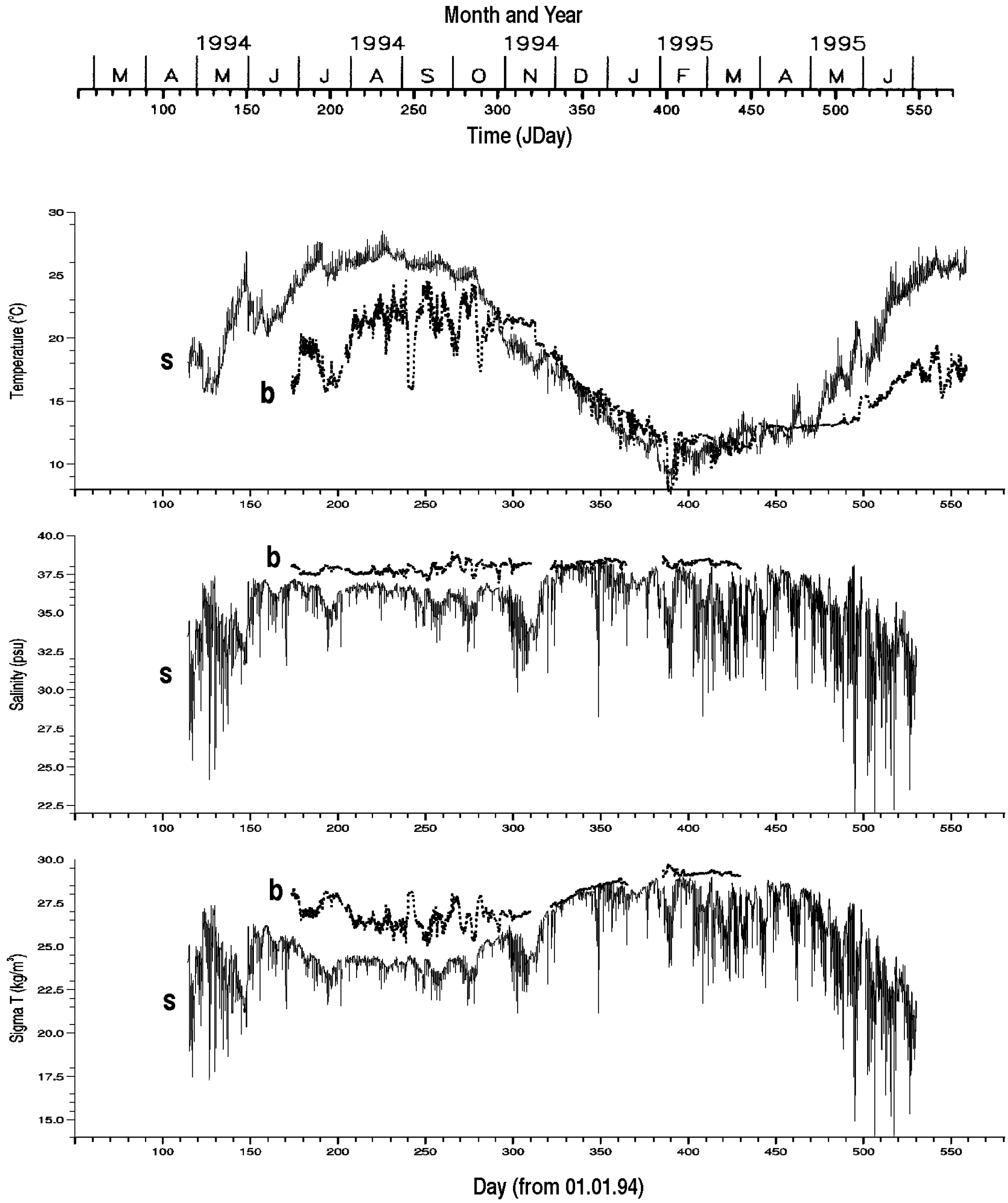


Fig. 3. The seasonal cycles of surface s (1 m) and bottom b (24 m) temperature, salinity and density at the MTA mooring (for location see Fig. 1a) over the survey duration. Spiking in salinity and density traces are real variations apparently due to daily releases from the Aliakmon hydro-electric power dam.

between October and February (Fig. 6). At its northern extent at station TP08, the waters were completely mixed after strong, northerly wind events, suggesting that bottom water may have flowed south along the seabed after being formed by preferential cooling in these shallow waters. Around day 400, this cold dense water was briefly observed at 24 m at the MTA location.

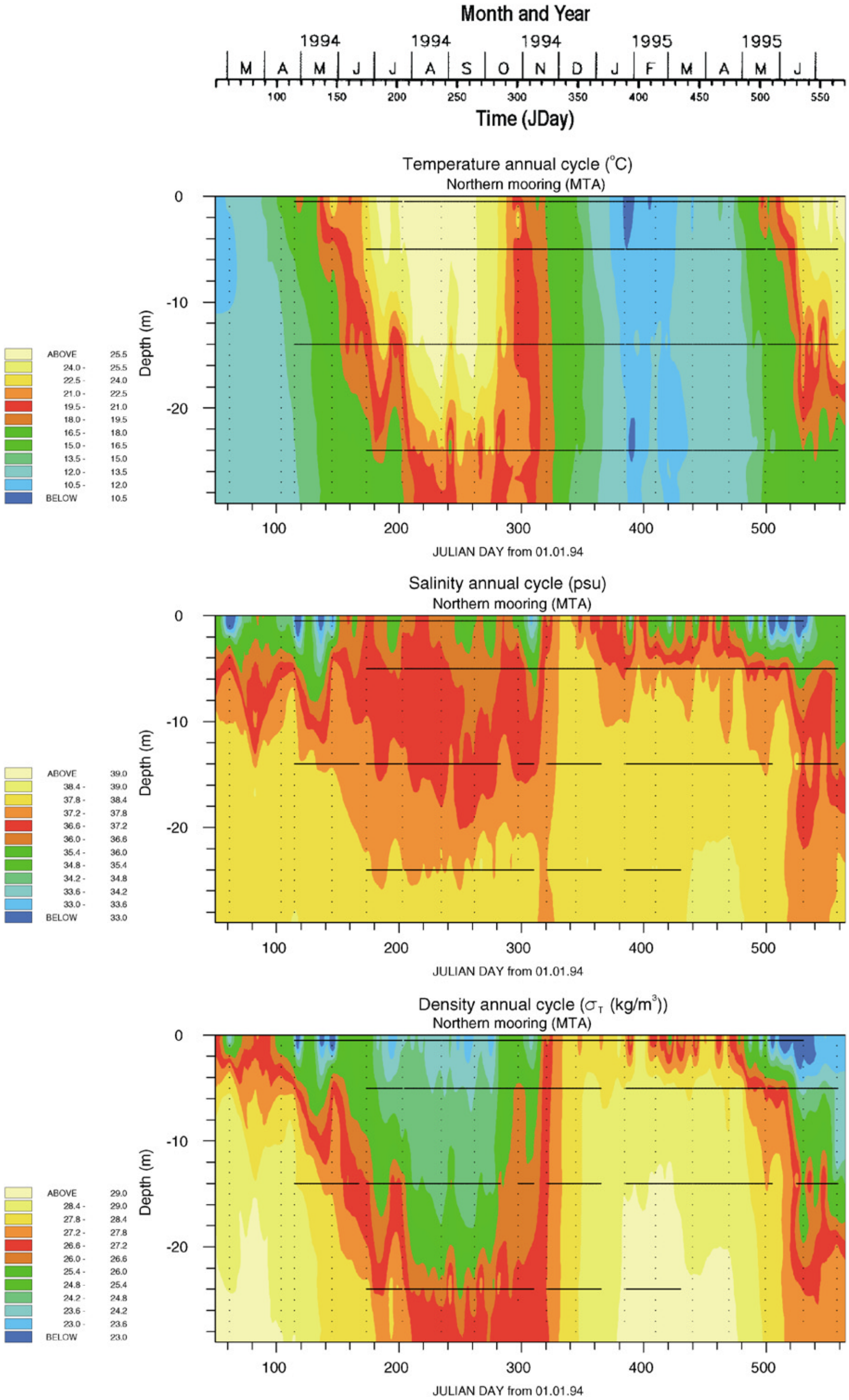


Fig. 4. Depth–time salinity contour plots presenting the seasonal cycles of temperature, salinity and density at the MTA mooring station (for location see Fig. 1a). Individual data points are marked with black dots. It should be noted that prior to day 105, moored instruments had not been deployed so data is interpolated from only monthly CTD profiles. However, this period has been included since it improves the coverage of the annual cycles.

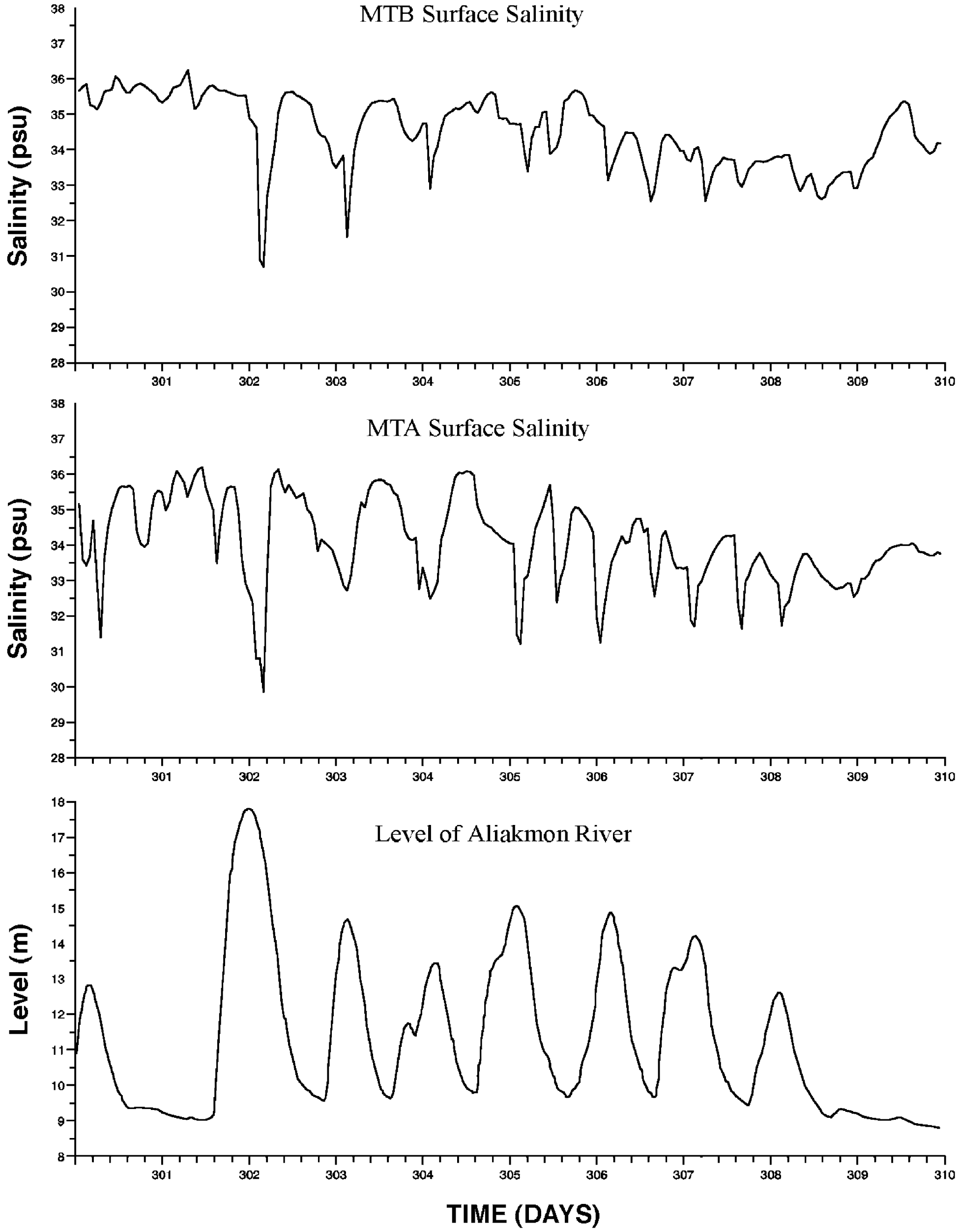


Fig. 5. Time series of the variation in salinity at the MTA and MTB mooring stations together with the level of the Aliakmon river for a typical 10-day period in November 1994 (days 300–310). The level of the Aliakmon river were observed with a water level recorder downstream of the hydro-electric power dam. Since the principle flow estimates were daily averages, these observations provide the only available estimates of relative changes in the Aliakmon flow rate over the daily cycle.

In spring (May–June, day 120–180, 480–540), intense heating resulted in a rapid increase in surface temperature to its maximum of approximately 26°C (at around day 200). The near-bed temperature also started to increase about 20 days later, although less rapidly than at the surface

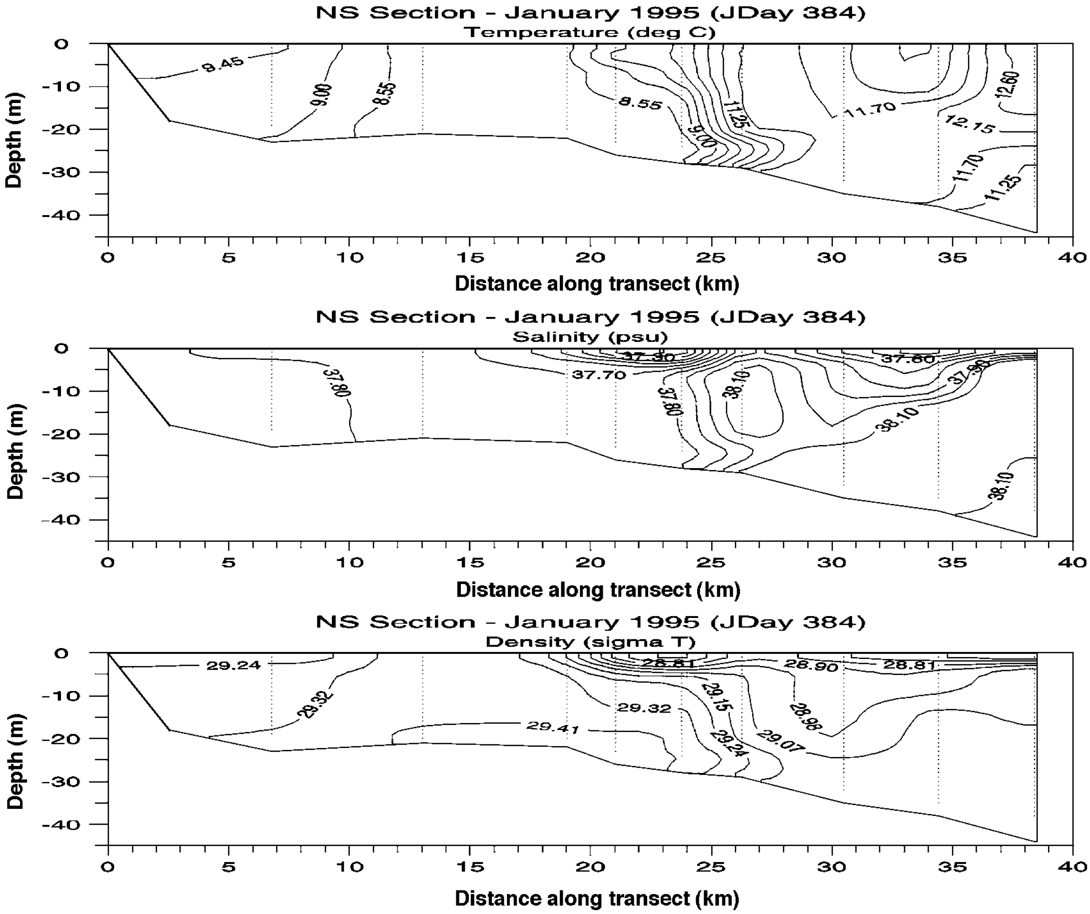


Fig. 6. North–south temperature, salinity and density sections during the January 1995 survey. The locations of the CTD stations are marked with arrows on the x-axis.

(Fig. 3). The surface to bottom temperature difference increased to a maximum of about 9°C in early summer. During this period the formation and gradual deepening (to 12 m) of a surface warm, low salinity, mixed layer was observed. There was also a reduction in the salinity of both the mixed layer and in the underlying pycnocline until, by day 180, most of the water in the upper 20 m of the water column had salinity <36.5 (Fig. 4).

During summer (July–September, day 180–280, 540–560), when the run-off was low, a warm, deep mixed layer extended to between 10 and 20 m, and overlay a strong pycnocline with both thermal and haline gradients (Fig. 4). The surface low-salinity layer was poorly defined, confined to a small region close to the river mouths, and only observed intermittently at the mooring location. At irregular intervals, strong perturbations to the depth of the mixed layer or level of the pycnocline were observed, which we consider in more detail later in this section.

In autumn (September–December, day 280–340), surface temperatures were up to 3°C cooler than those of the underlying waters due to the sharp drop in air temperature. However, the water column remained stable because of increased surface haline stratification probably due to run-off associated with a storm event. Cooling continued and eventually resulted in the break-down of the surface mixed layer at the mooring sites and complete mixing of the water column, which persisted for about 20 days. The surface freshwater layer was intermittent over this period.

3.2. The seasonal circulation cycle

Tides in the Gulf were very weak ($<1.5\,\mathrm{cm\,s^{-1}}$). However, relatively strong rotary surface diurnal currents of up to $40\,\mathrm{cm\,s^{-1}}$ were observed throughout the annual cycle. These were particularly energetic in the upper 3 m of the water column (Hyder, 1997) where they dominated the observed currents. These diurnal currents are discussed in Hyder et al. (2002). We concentrate on the residual (or low pass) currents (of period >1 day) which were generally relatively weak ($<10\,\mathrm{cm\,s^{-1}}$), except during perturbations to the level of the pycnocline when current speeds of up to $30\,\mathrm{cm\,s^{-1}}$ were observed.

Progressive vector plots (PVPs) over the seasonal cycle, labelled at the start of the summer and winter periods, have been presented for the surface (1 m) and mid-depth (14 m) current at MTA, together with the wind in Fig. 7. The wind and mid-depth MTA site PVPs present the full survey period since both data returns were almost complete. The surface current observations only commenced in January 1995 but, since the deployment covered a winter, spring and early summer period, these data are sufficient to highlight the distinct seasonal regimes presented below. It is possible that surface currents may be subject to wind drift, however, currents at 5 m are not representative of the upper layer since the layer is at times only 3–4 m in depth. PVPs at all depths are presented in Hyder (1997).

During winter (October–May), there was a relatively strong ($4\,\mathrm{cm\,s^{-1}}$) persistent northward drift at mid-depth whilst at the surface, flow was towards the south-west ($4\,\mathrm{cm\,s^{-1}}$). The current reversal between the northward lower layer flow and the flow to the south in the low-salinity surface layer suggests a classical two-layer

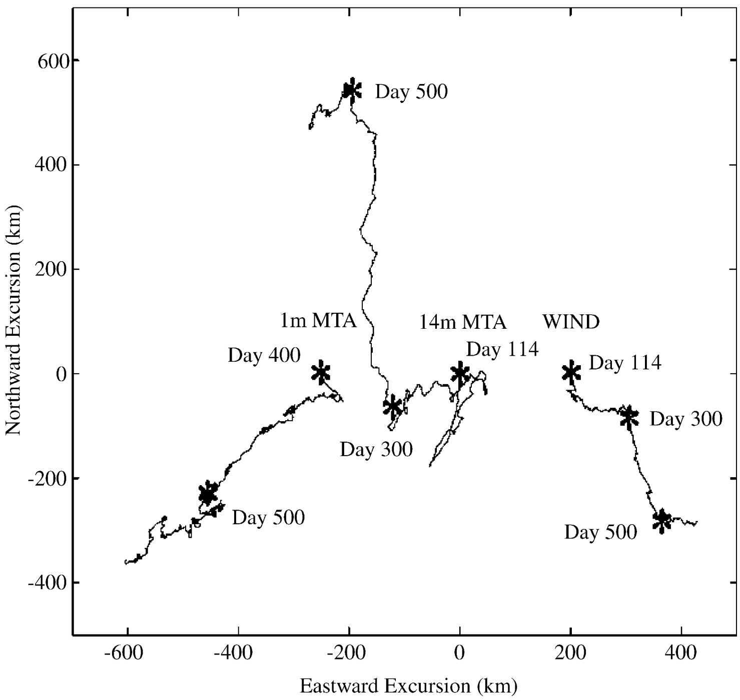


Fig. 7. Progressive vector plots of the surface current, mid-depth current and wind. The plots are labelled at the start of the data period (days 110 and 400) and at days 300 and 500 to highlight seasonal variations. Summer periods are before day 300 and after day 500. Winter periods are between days 300 and 500.

north–south estuarine exchange. The general surface flow to the south is also evidenced by the driftcard releases during the winter of 1976–77 (Fig. 2.10, Balopoulos and James, 1984a). A concentration of lower-salinity waters towards the western coast is evident in some of the winter CTD sections (Hyder, 1997). This is consistent with the effect of rotation, which in the northern hemisphere will tend to force a buoyant plume to turn to the right, and flow coast-parallel with the coast to the right of the direction of flow (Simpson, 1997). Since the cross-sectional area of the lower layer inflow is considerably greater than that of the surface outflow, their equal current speeds, through continuity, suggest there may be a clockwise gyre component to the lower layer circulation with reduced northward or even southward lower layer flow in the eastern Gulf (although without observations in the eastern Gulf it is not possible to confirm this).

During summer (May–October), the flow at the surface and at mid-depth is to the south-west with mean speeds of 4.0 and $2.5\,\mathrm{cm\,s^{-1}}$, respectively. The southward flow at all depths in the western Gulf, through continuity, implies northward flow in the eastern Gulf. This suggests there is a residual anticlockwise barotropic gyre in the Gulf during summer. This is evidenced by the driftcard releases during 1977 (Fig. 2.10, Balopoulos and James, 1984a) which indicate surface currents to the north in the eastern Gulf and to the south in the western Gulf during summer. In addition, this anticlockwise gyre was observed in the residual current survey of 1976 (Balopoulos et al., 1986a) which would have sampled principally the summer circulation regime being undertaken between April and October. It should be noted, however, that the deepest instruments (24 m) in our observations were at the lower bound of the pycnocline during summer so the circulation beneath the pycnocline was not properly resolved.

There is a marked correlation (Fig. 7) between the timing of the winter regime and the period of persistent southward winds. When the residual wind was consistently to the south during winter (day 300–500), the mid-depth flow was northward, i.e. a predominantly two-layer estuarine circulation was apparent (Fig. 7). Conversely, when the residual wind was weakly to the east during summer (days <300 and days >500), the mid-depth flow was principally to the south-west. In particular, the transition from the winter to summer circulation regime at day 500 occurred immediately after the southward winds cease but before the reduction in the freshwater input (Fig. 2). This suggests that it is wind forcing rather than the freshwater input which is the principal forcing of the winter regime. During winter, it appears that the estuarine circulation in the Gulf is reinforced by persistent southward wind stress resulting in the observed predominantly two-layer estuarine exchange.

3.3. Perturbations to the depth of the mixed layer during summer

During summer the pycnocline is generally at its lower level so the perturbations were generally paired with a rapid upward perturbation followed by a period when the pycnocline was elevated, and then a slightly more gradual downward perturbation. We have termed each pair of perturbations an ‘event’.

A typical event was observed in July 1994 between days 190 and 210 (Fig. 8). On day 191, the pycnocline dropped briefly, then rose rapidly by almost 10 m in less than 1 day. It remained elevated for around 14 days, then dropped gradually over a period of about 4 days to its previous level. Water above the pycnocline was warmer and less saline, whilst water below the pycnocline was cooler and more saline. Hence, at mid-depth (Fig. 9), the event was evident as a sharp drop in temperature and increase in salinity as the pycnocline rose, a period of reduced temperature and increased salinity whilst the pycnocline remained elevated, and a period when the salinity and temperature returned gradually to their previous values as the pycnocline lowered. An upward perturbation to the pycnocline represents a shallowing of the surface layer or an outflow of warm, low-salinity waters (and inflow of deeper cool high-salinity waters); whilst a downward perturbation to the pycnocline represents a deepening of the surface layer or an influx of warm low-salinity waters (and outflow of deeper

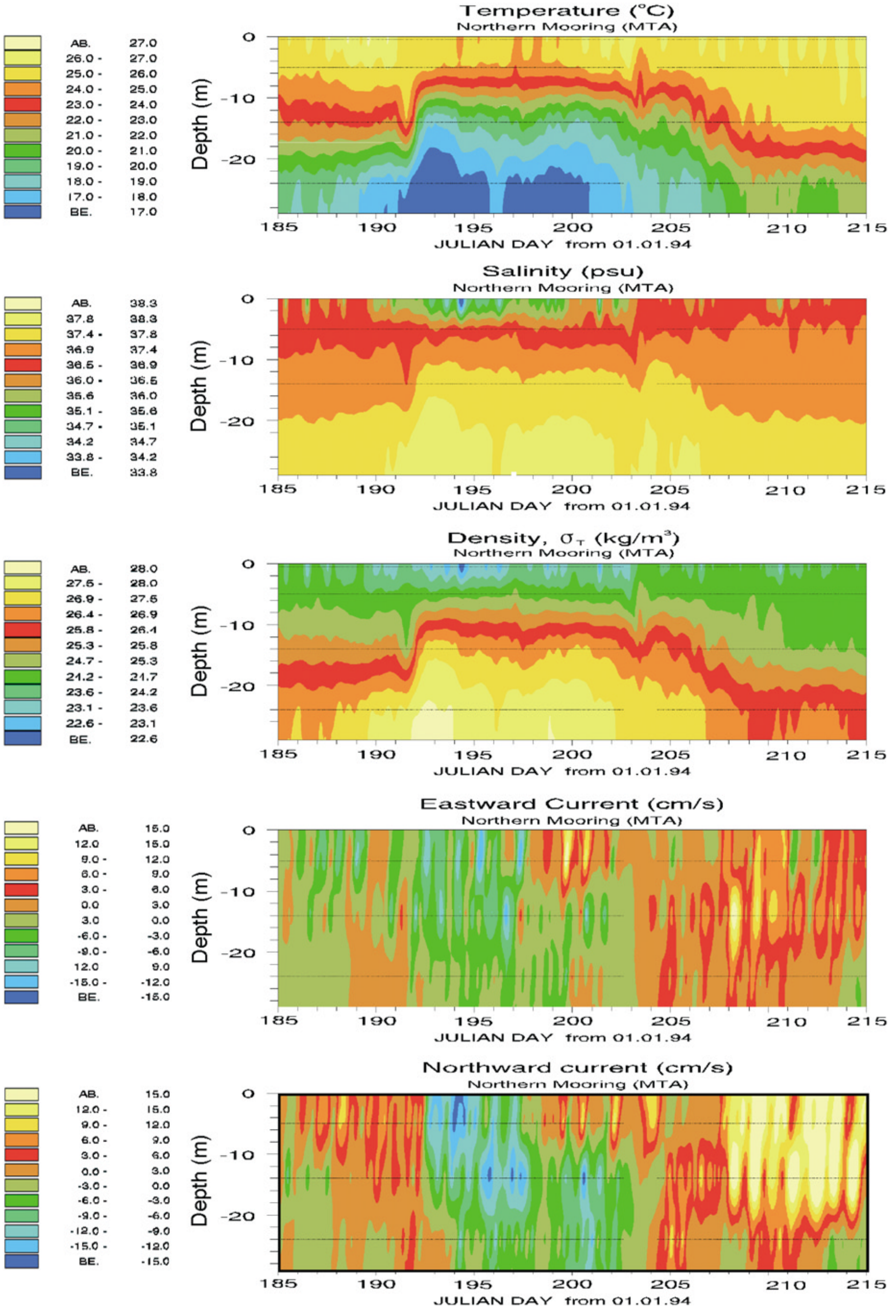


Fig. 8. Depth–time contour plots of temperature, salinity, density, northward current and eastward current at MTA during a typical inflow event observed during July 1994 (days 185–215). For location of MTA see Fig. 1a.

cool high-salinity waters). At the two mooring locations, these temperature and salinity fluctuations occurred almost simultaneously and were similar but not identical in form (Fig. 9).

At MTA and MTB, the mid-depth northward current varied approximately in phase with the mid-depth temperature (Fig. 9), i.e. the current flowed north initially for about 1 day, then flowed

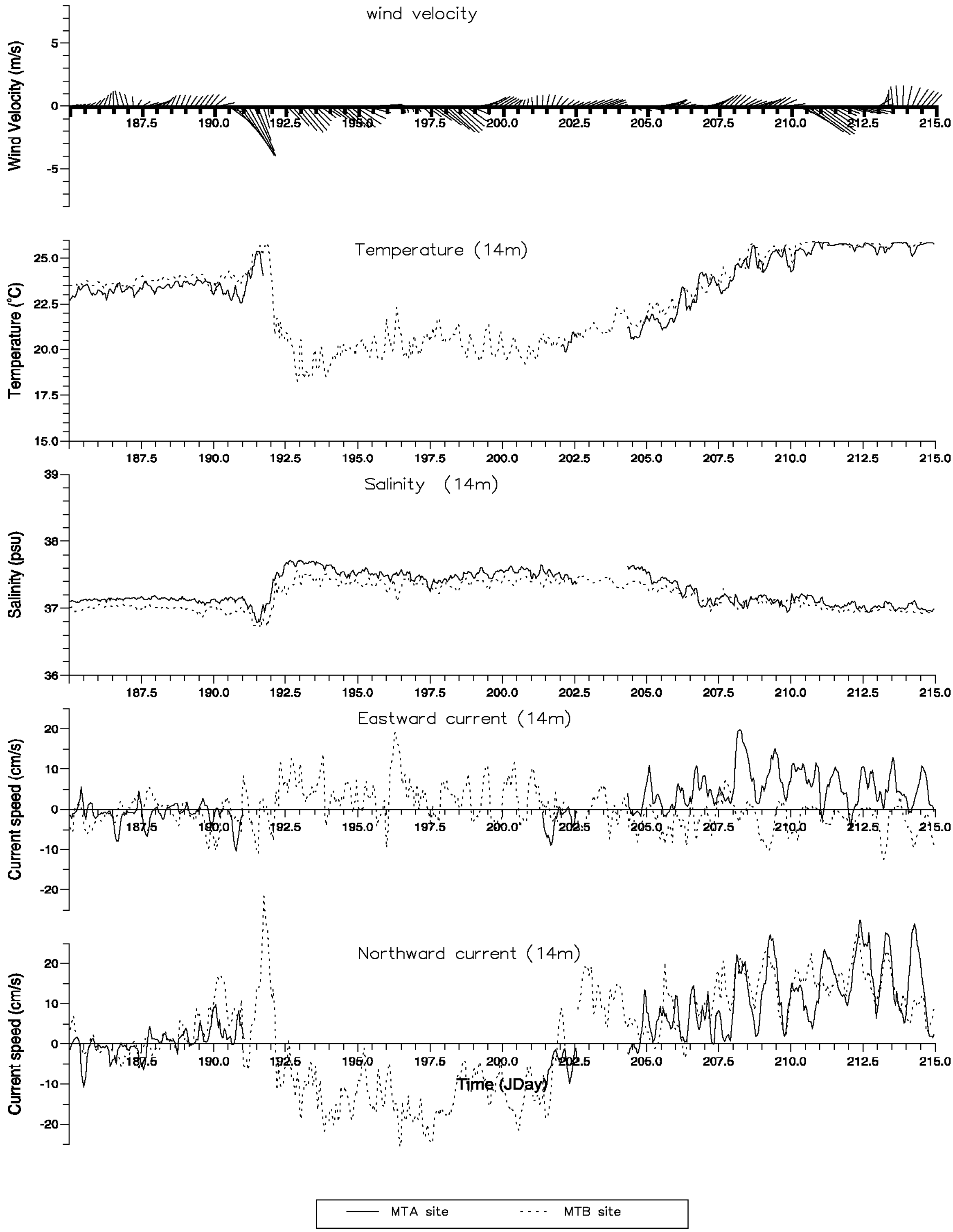


Fig. 9. The variation in the low-pass wind at Micra, the mid-depth temperature, the mid-depth salinity, the northward current and the eastward current at MTA and MTB during a typical inflow event during July 1994 (days 185–215).

south after the pycnocline rose (i.e. mid-depth temperature was reduced) and north after the level fell (i.e. the mid-depth temperature increased). At both moorings flow was parallel to isobaths, which are aligned at 20° and 350° at MTA and MTB, respectively. The barotropic current was estimated from the mean flow at the three instrument depths (5, 14, and 24 m) at the mooring locations. This suggested there was a significant barotropic component to the flow, which flowed south while the pycnocline was elevated, and vice versa. The baroclinic currents appeared to be weaker than the barotropic current. However with such poor resolution both the barotropic and baroclinic current estimates have large associated uncertainties.

Time-series observations from 1976 (Balopoulos, 1982) also indicate the occurrence of pycnocline events. At 7 m above the bed, i.e. 23 m depth, in the eastern Gulf at station B1 (Fig. 1a), the current flowed north-west after the rise in the level of the pycnocline (i.e. when the temperature was reduced) and south-west after the fall in the level of the pycnocline (i.e. when the temperature was increased). In combination with our observations in the western Gulf, these observations suggest that the north–south flow is in the opposite sense in the eastern and western Gulf, with flow parallel to isobaths anticlockwise after the rise in the pycnocline level, and clockwise after the fall in the pycnocline level. It should be noted, however, that since we are comparing different events at the two mooring locations we cannot compare details of the flow structure.

Fig. 10 presents time series of the mid-depth temperature at MTA, the wind over the Gulf at Micra and the wind over the northern Aegean (Fig. 1b) at Limnos between days 120 and 320 (May–December 1994). The mid-depth temperature gradually increased between days 130 and 190, remained stable until day 280, then dropped off until day 300. Imposed on this cycle, were several oscillations (days 150–170) and sharp drops in temperature (days 190, 240 and 280), which indicate the occurrence of perturbations to the level of the pycnocline. Generally (except in spring when the pycnocline depth was shallower and perturbations were more symmetrical), during each event the temperature dropped off sharply (i.e. the pycnocline rose rapidly), then rose more gradually to its previous value (i.e. the pycnocline gradually lowered to its original level). These changes occurred irregularly during both summers, i.e. whenever the warm low-salinity mixed layer was present.

During summer, the wind over the Northern Aegean becomes predominantly southward as a result of the Meltemi wind. Its southward strength generally increased from day 140 to 200, then remained stable until day 290 when it dropped sharply. However, during certain relatively short periods the southward wind ceased and switched abruptly to northward (for example, days 145,155, 165, 185, 195, 225, 237, 265 and 275).

There is an apparent correlation between the timing of the northward wind events over the Aegean and the elevations to the pycnocline in the Gulf. Each upward perturbation is preceded by a period when the Meltemi wind switches to northward (although each period when the Meltemi switches to northward is not always followed by a pronounced upward perturbation to the level of the pycnocline). Furthermore, there is an apparent correlation between the ambient level of pycnocline (i.e. depth of the warm low-salinity layer) and the strength of the Meltemi wind, (i.e. period of maximum strength of southward wind over the Aegean during late June to mid-September 1994 corresponds to period of maximum mixed layer depth).

It should also, however, be noted that the consistent southward wind is not observed over the Gulf at Micra, where the winds were weaker and frequently blew in the opposite sense to the winds further south. Southward wind events over the Gulf appeared to be correlated both with the northward wind events over the Aegean to the south (i.e. gaps in the Meltemi), and with the upward pycnocline displacements over the Gulf. It therefore appears that the northward wind pulses over the Northern Aegean (i.e. gaps in the southward Meltemi wind) and southward pulses wind over the Gulf (which precede the pycnocline perturbations) could both result from an adjustment of the same meteorological system.

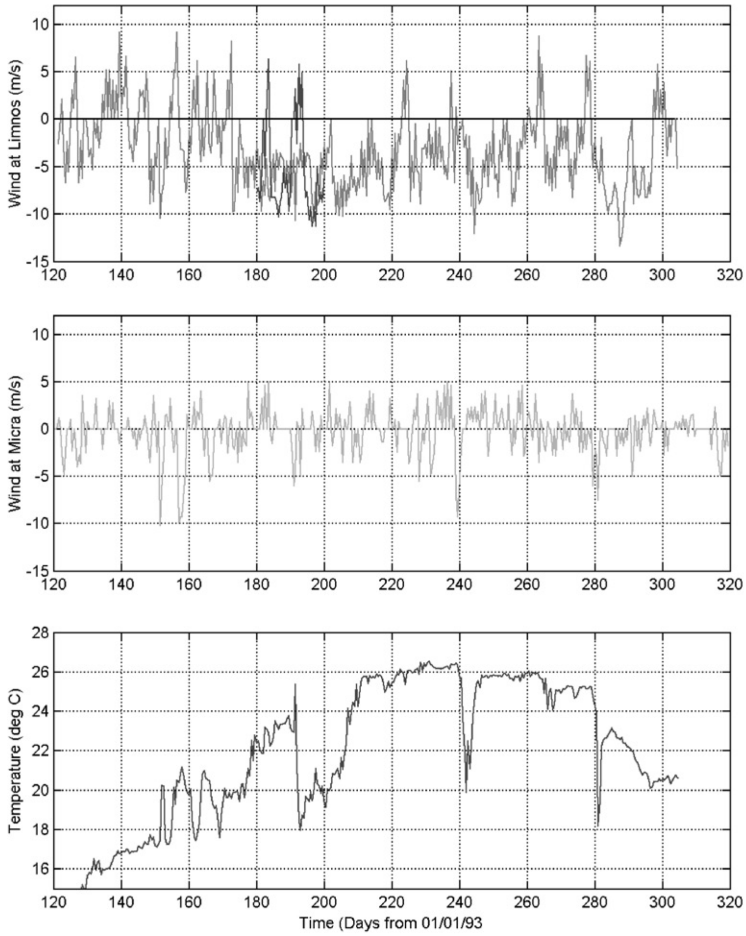


Fig. 10. Time series of the northward wind over the Northern Aegean (at Limnos), the wind over the Gulf (at Micra) and the temperature at 14 m depth at MTA between days 120 and 320 (May–November 1994). For a short period (between days 180 and 200) data from Samos (to the south of Limnos) had been included on the Limnos wind trace to provide evidence of northward wind pulses not observed at Limnos. No attempt has been made to distinguish between the traces since both are representative of wind over the Northern Aegean.

4. Inferences and discussion

From the observations, it has been possible to make a number of inferences concerning the freshwater balance in the Gulf. First, the seasonal cycle of the total freshwater in the Gulf is considered and then we discuss the perturbations to the level of the summer pycnocline. Finally, we present a synthesis of the Gulf's inferred thermohaline and circulation regimes, and discuss the remaining areas of uncertainty in the system and highlight ideas on which to focus future studies.

4.1. The seasonal cycle of total freshwater

To investigate whether the low-salinity layer observed in the Gulf during summer could be supported by the local freshwater input, an analysis was undertaken using data from the monthly spatial surveys to estimate the total volume of freshwater held in the waters of the Gulf to the north of the southern field section. A good approximation to the topography was achieved using a 926 m spaced, horizontal grid. Each grid cell was divided into 1 m thick cells,

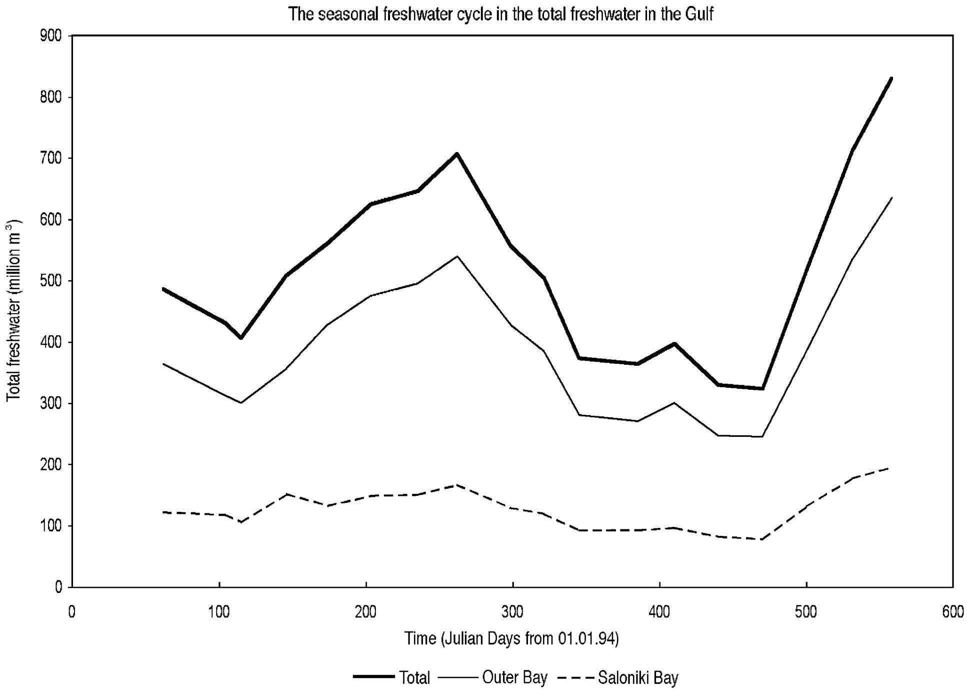


Fig. 11. The seasonal variation in the total freshwater in the Gulf to the north of the southern CTD section (Fig. 1a). The total volumes and surface areas of Saloniki Bay and the region to the south of AK. Emvolo are $0.296 \times 1010\,m^3$ and $1.09 \times 1010\,m^3$, and $1.84 \times 108\,m^2$ and $3.\ 86 \times 108\,m^2$, respectively.

whose salinity S was assumed equal to the salinity at the same depth, at the closest CTD profile. Where the depth of the grid cell was greater than the CTD profile, vertical uniformity between the deepest CTD depth and the seabed was assumed. In the calculation of the freshwater fraction f an ambient Aegean salinity S_0 of 39 (slightly larger than the 38.8 observed) was used to ensure no negative fractions occurred. The freshwater volume in each depth cell was calculated and summed over depth, and then horizontally over the grid to the southern survey section to give the total freshwater volume V_f as follows:

$$V_f = \sum_{x=1}^{m} \sum_{z=1}^{n} \frac{(S_0 - S)}{S_0} A\, \Delta z, \tag{1}$$

where A is the surface area of each cell ($=926^2\,m^2$), Δz is the thickness of each depth cell ($=1\,m$), n is the maximum depth of each of each grid cell and m is the total number of cells in the spatial grid covering the survey area.

The annual variation in the total freshwater volume presented in Fig. 11 shows the build up of freshwater in the Gulf during late spring to a maximum in late summer (days 262, 570). Even in March 1994, after a period of extreme run-off when a very low-salinity layer extended across the whole Gulf, the total freshwater in the Gulf was only about 60% of its late summer level.

The freshwater accumulation rate was calculated as follows:

$$R_a = \frac{\partial V_f}{\partial t} = \frac{(V_{f2} - V_{f1})}{(t_2 - t_1)}, \tag{2}$$

where V_{f1} and V_{f2} are the total freshwater volumes from consecutive surveys undertaken at times t_1 and t_2, respectively. The freshwater balance for the northern Gulf is given by

$$R_a = R - E + P - F, \tag{3}$$

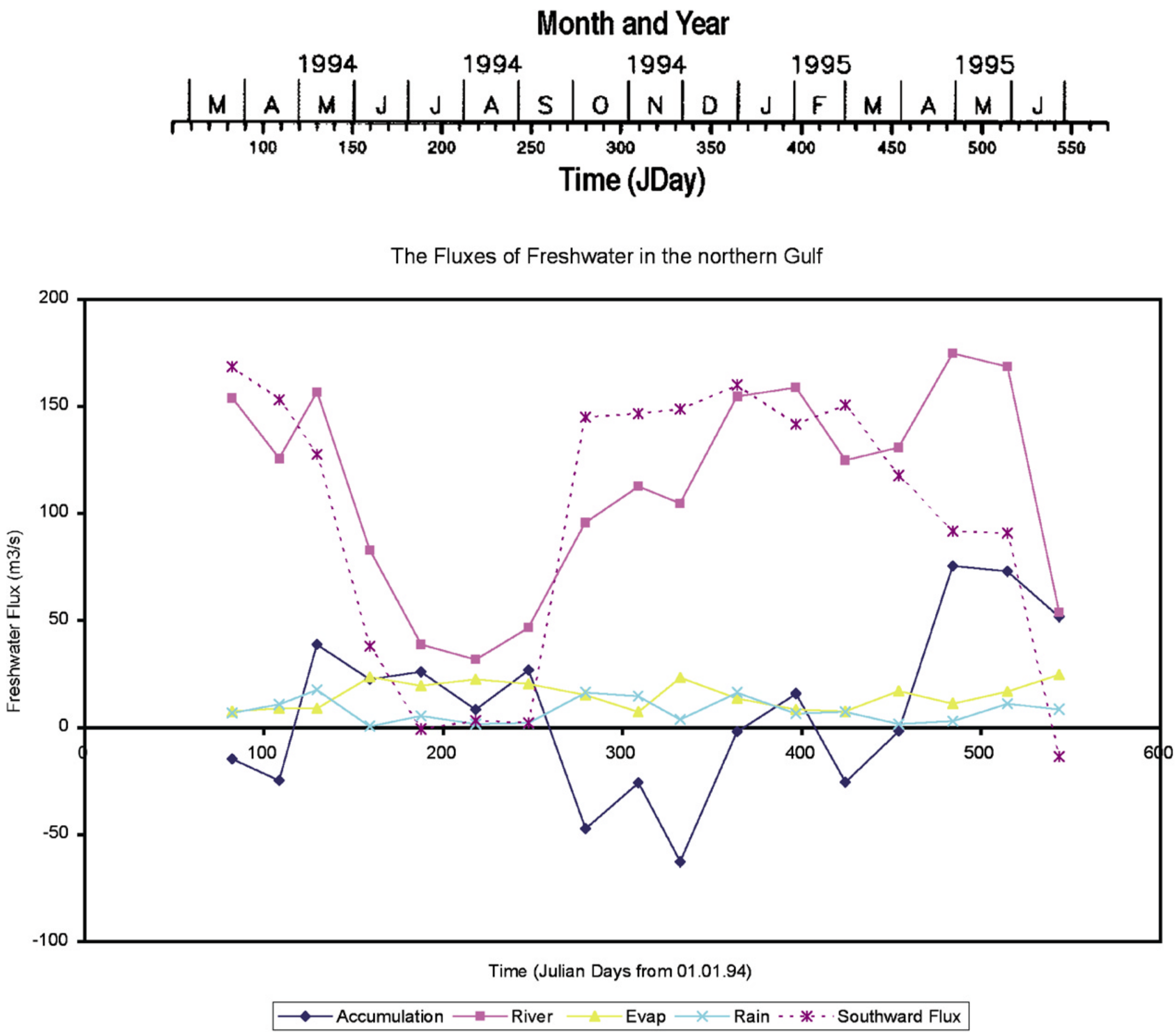


Fig. 12. The seasonal variation in the freshwater accumulation, river input, evaporation, precipitation and inferred freshwater flux through the southern CTD section (see Fig. 1a for the location of the CTD section).

where R is the river input rate, E is the evaporation losses, P in the precipitation input and F is the flux of freshwater leaving the Gulf at the southern boundary. Knowing the accumulation rate, R_a, taking the river input rate, R, and precipitation rate, P, from observations, and estimating the evaporation rate, E, from the relative humidity and sea surface temperature using the formula given by Gill (1982), we can calculate the flux across the southern boundary, F. The resulting cycles of F, R, E, P and R_a are presented in Fig. 12.

From spring to summer (days 110–220, 460–510) freshwater accumulated in the northern Gulf at rates of around ~ 30 and $\sim 60\,\mathrm{m^3\,s^{-1}}$, in 1994 and 1995, respectively (Fig. 12). During the early summer periods (when the freshwater input rate is low) this accumulation rate represented virtually all of the input freshwater when evaporative losses were taken into account. Thus, the flux across the southern field section was zero or on occasions (days 190, 550) slightly negative (Fig. 12).

There are two possible explanations for this freshwater accumulation. The first possibility is that there is an input of freshwater from the Aegean to the south, through a reduction in the Aegean salinity. The second possibility is that the local estuarine exchange at the southern section is reduced to almost zero over summer possibly resulting in a local accumulation. The second mechanism could result indirectly from the first mechanism through an associated reduction in salinity gradients associated with a seasonal reduction in salinity to the south of the survey region.

A local accumulation of input freshwater in the northern Gulf would alone be unlikely to result in the observed low-salinity layer, since the limited freshwater input would require a sharp front immediately to the south of the survey area. This was not observed or evident in summer CTD profiles to the south of the survey area (Christenidis, pers. comm.), which indicated the presence of reduced salinity, warm waters extending to a depth of ~20 m. Furthermore, if such a front existed, it would have been advected across the mooring locations during the pycnocline events, whose current excursions were over 100 km.

Surface salinity contours (Fig. 13) presented recently by Poulos et al. (1997) show a reduction in Aegean salinity during the summer, as the result of freshwater input from the Dardenelles Straits. This figure suggests that the low-salinity waters extend throughout the Gulf. It therefore appears that the accumulation of freshwater in the Gulf during summer results from a reduction in the upper layer Aegean salinity.

In order to investigate the exchange mechanism by which the freshwater exchange with the Aegean occurs we need to look more closely at the observed perturbations to the depth of the low-salinity surface layer.

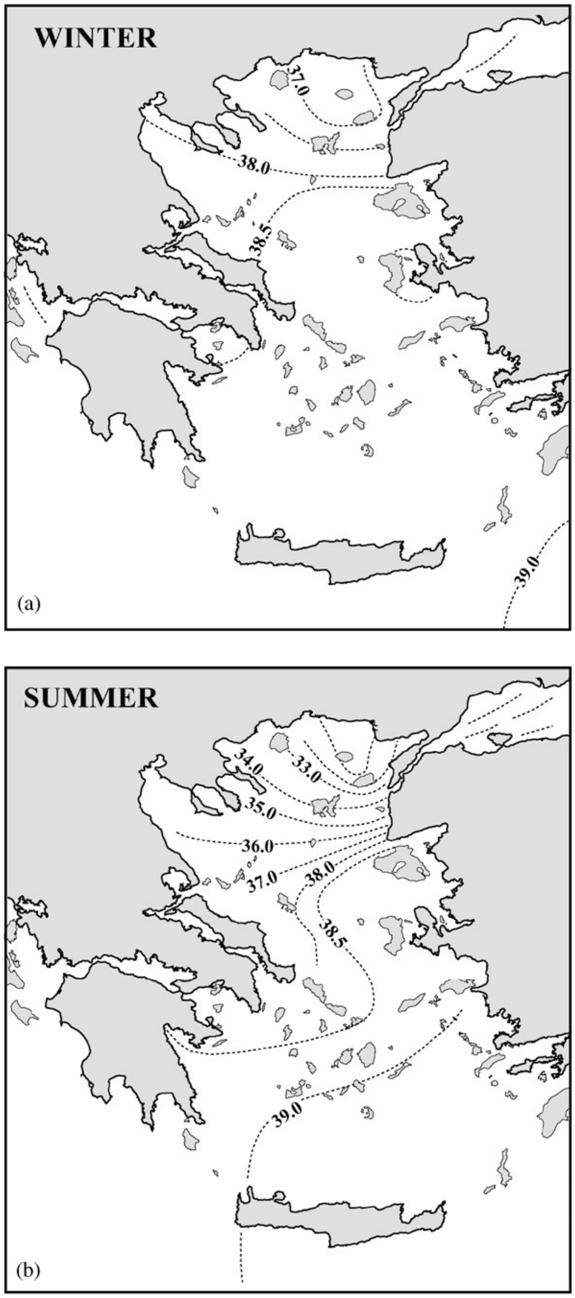


Fig. 13. The spatial distribution in sea-surface salinity over the Aegean Sea during (a) winter and (b) summer (after Poulos et al., 1997).

4.2. Perturbations to the level of summer pycnocline

The variable duration and irregular occurrence of the changes in the pycnocline level suggest they could be wind forced.

The Gulf is connected at its southern extent to the north-western Aegean (Fig. 1b). During summer, persistent Etesian winds, termed the

'Meltemi', blow southwards over the Aegean Sea inducing upwelling along its eastern coast (Georgopoulos, 1984). This upwelling is an indication of a wind-forced, east–west, pycnocline slope across the Aegean, which would be accompanied by a deepening of the pycnocline (i.e. downwelling) along its west coast. This downwelling could propagate into the Gulf resulting in the observed gradual lowering of the level of the Gulf's pycnocline. Conversely, after these winds cease and switch abruptly to northward, the relaxation of the Aegean pycnocline slope would result in a rapid rise of the pycnocline in the western Aegean, which could propagate into the Gulf resulting in the observed abrupt rises in the level of the Gulf's pycnocline.

The periods when the pycnocline was elevated should therefore correspond approximately to times when the Meltemi was not blowing and there was no upwelling in the eastern Aegean. This is confirmed by Fig. 10 which indicates that during summer the wind over the Aegean is generally consistently southward but switches to northward about 5 days prior to the mid-depth temperature increase associated with the pycnocline events, and then remains northerly for approximately the duration of each event. For example the pycncoline event from day 240 to 250 (Fig. 10) is preceded by northward wind at Limnos between days 235 and 240, the pycnocline event from day 280 to 290 is preceded by northward wind at day 275 to 280 and the pycnocline fluctuations between days 150 and 170 and preceded by Limnos wind fluctuations between days 140 and 165.

It appears that the event observed between days 190 and 210, was forced by two separate closely spaced northward wind pulses (at days 185 and 195), which were not observed at Limnos but were observed at Samos, further to the south. During this event it appears that the Aegean pycnocline slope had insufficient time to re-develop in between the two wind events resulting in a long period where the pycnocline in the Gulf was elevated.

It should be noted that whilst the local southward winds over the Gulf would be expected to depress the pycnocline on the western side of the Gulf, the associated southward transport of surface waters by local winds could result in elevations in the pycnocline in the northern Gulf such as those observed. Because of the correlation between the northward winds over the Aegean and local southward winds it is difficult to separate the two processes. However, the ambient mixed layer depth of approximately 15 m during summer is considerably deeper than the value of around 7 m predicted from local mixing using a 1-dimensional numerical model (Hyder, 1997). This suggests that the deep mixed layer results from adjustment to downwelling in the north-western Aegean forced by the Meltemi winds. Hence, the direction and strength of the wind over the northern Aegean appear to control the level of the pycnocline in the Gulf. The adjustment of pycnocline level between the north-west Aegean and the Gulf would also be consistent with the requirement for an external source of freshwater to support the observed reduction in mean salinity, (which implies exchange with the northern Aegean).

Next we consider the dynamics of how the depth of the low-salinity surface layer in the Gulf could adjust to that in the Aegean to the south of the Gulf. The variable duration of the pycnocline events suggests that the perturbations are separate 'step-up' and 'step-down' internal bores. The opposite direction of the currents in the eastern and western Gulf, i.e. anticlockwise and clockwise circulation after the rise and fall in the pycnocline, respectively, suggest these bores propagate around the Gulf coast as internal Kelvin waves. This would be consistent with theory, since the internal Rossby radius of 7 km is small compared with the 20–50 km width of the Gulf. In the Northern Hemisphere, coastally trapped-internal bores propagate anticlockwise, i.e. with the coast on their right.

The speed c of an internal wave at the interface between two layers of density ρ_1 and ρ_2, and of thickness h_1 and h_2, respectively, is given approximately (Simpson and Britter, 1979) by

$$c = \sqrt{g\left(\frac{(\rho_1 - \rho_2)}{(\rho_2)}\right)\left(\frac{h_1 h_2}{h_1 + h_2}\right)} \approx \sqrt{g' h_1}. \quad (4)$$

In the Gulf during summer, the upper layer depth h_1 is 15 m and its density ρ_1 is 1021 kg m^{-3}

whilst the lower layer has depth h_2 and density ρ_2 of 15 m and 1025 kg m^{-3}, respectively. The predicted internal wave speeds are therefore 0.50 m s^{-1} in the northern Gulf, and 0.73 m s^{-1} in the deeper waters of the southern Gulf. The predicted time for the disturbance to propagate the 150 km from the entrance of the Gulf (i.e. the Shelf break) around the Gulf to the mooring location is therefore $\sim$58 h. This is less than the observed lag of around 5 days (although this varied considerably) between the cessation of the wind and the lowering of the pycnocline at the mooring location. However, this difference could represent the time required for the development or relaxation of the Aegean pycnocline slope, when the Aegean wind switches direction.

The coastally trapped internal bores or internal Kelvin waves are particularly interesting since wind-forced pycnocline adjustments are known to occur frequently in the ocean. It is therefore likely that in any system of interconnected stratified gulfs or estuaries, events similar to these could be observed. In particular, similar perturbations would be expected to occur in other Gulfs connected to the Aegean. For example the adjacent Kassandras and Agiou Orous Gulfs; and the narrow Gulfs of Evvoikos and Pagasitikos near Volos (where the associated sharp temperature changes could have implications for their fish farming industries); as well as numerous other Gulfs in the south of Greece.

The possible prevalence of such events is highlighted by the similarity of the observed internal bores to wind-forced salt intrusion events observed in the Choptank river, a tributary estuary on the east coast of Chesapeake Bay, which was been shown to result from a similar mechanism (Sanford and Boicourt, 1990). It was inferred that the Choptank river intrusions are a baroclinic response to a remotely imposed change in density structure which takes the form of an advancing internal wave or bore. Whilst, the observed characteristics of the Thermaikos Gulf inflow events and the Choptank river salt intrusions are similar, there is an important difference between the regions. The Thermaikos gulf is almost 200 km long and over 50 km wide for much its length, whilst the Choptank river is only 25 km long and about 6 km wide. Thus, whilst in the Thermaikos Gulf rotation forces the internal bores around the coast as internal Kelvin waves, in the Choptank river, rotation is not important and the intrusions propagate directly up the estuary. It is also interesting to note that a similar process occurs when Kelvin waves of much larger lengthscales and timescales (>1 month) result from changes in pycnocline depth forced by seasonal climatic oscillations in the India Ocean. A specific example of this process and the resulting semi-annual Kelvin wave is discussed by Sprintall et al. (2000).

The limited vertical resolution provided by four current meters (with the lower instrument close to the lower pycnocline level) makes it difficult to accurately asses vertical current structure during the inflow events. However, the relatively large barotropic current component, whose magnitude was approximately twice that of the baroclinic component, is surprising for a principally baroclinic event. It is also difficult to explain the persistence of these currents for up to 10 days after the changes in the pycnocline level. From the above hypothesis, one would expect the currents to cease after 4 days when the bores have propagated from the mooring sites around the remainder of the Gulf, equating the pycnocline levels inside and outside the Gulf. One possibility is that a secondary circulation exists, such as a gyre circulation around pycnocline domes or bowls, which could be formed by the passage of the internal 'step-down' or 'step-up' bores around the Gulf. Additional observations are required to resolve these issues.

4.3. Synthesis of thermo-haline and circulation regimes

During winter (Fig. 14a) when run-off is high, a shallow, low-salinity layer extends across much of the Gulf, overlying relatively homogenous high-salinity deeper waters. The extent, salinity and stratification within the surface layer vary considerably although the lowest-salinity waters are usually concentrated in the western Gulf. Near the river sources, the surface salinity varies over short-time scales. Daily pulses of very low-salinity water are observed at both mooring locations which

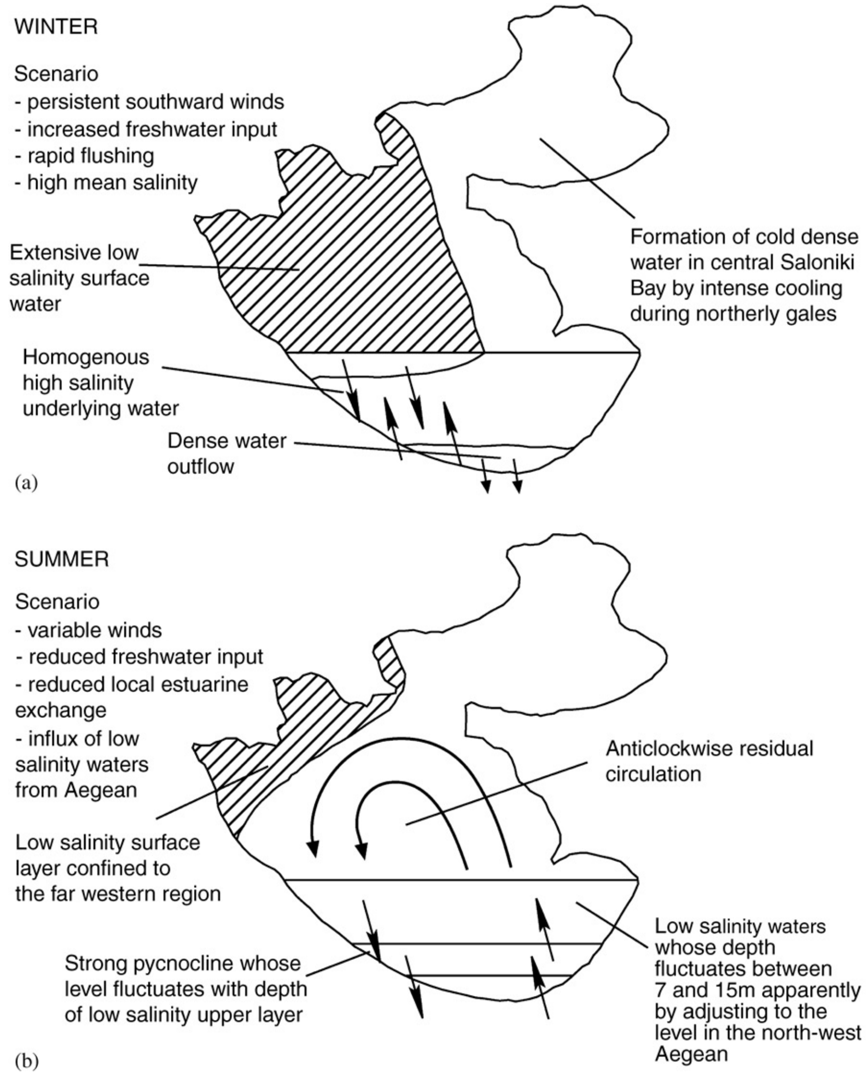


Fig. 14. Schematic diagrams presenting (a) the winter and (b) the summer observed circulation and thermo-haline regimes.

appear to result from daily flow surges in the Aliakmon river due to releases from its HEP dam.

Between October and February, dense water is formed at the head of the Gulf and flows southward along the seabed. The dense water appears to be formed by cooling during northerly gales in the shallow waters of Saloniki Bay. These observations suggest this dense water does not have sufficiently high salinity to represent a source of Sporades deep water. However, it is possible that in the adjacent Gulfs where the freshwater inputs are much smaller, this process could result in the formation of deep waters, as has been observed to occur in the northern Adriatic (Bignami et al, 1990; Zoccolotti and Salusti, 1987). Additional time-series observations in the deep waters of the eastern Gulf are required to determine the properties and magnitude of the dense water outflow in the Gulf.

During summer (Fig. 14b), when run-off from the rivers is low the shallow low-salinity surface layer from the local river input is observed only in the vicinity of the river mouths. A deep mixed layer of warm reduced salinity water extends to the surface through the remainder of the Gulf overlying a strong pycnocline. The depth of this layer increases over spring to an ambient depth during summer of around 15 m. However, its depth frequently fluctuates between its ambient depth of around 15 m and a shallower depth of approximately 7 m. Evidence suggests these fluctuations in the low-salinity layer depth in the Gulf result from an adjustment to wind-forced changes in the depth of the low-salinity layer in the north-western Aegean. These adjustments appear to take the form of coastally trapped internal bores which propagate anticlockwise around the Gulf, and are accompanied by strong currents of up to $30\,\mathrm{cm\,s^{-1}}$, which persist for up to 10 days after the change in pycnocline level. The freshwater balance in the northern Gulf suggests that these adjustments transport freshwater (which originates in the Dardanelles Strait) into the Gulf, from the north-western Aegean.

During winter flow in the Gulf appears to be principally two layers with southward outflow in the shallow low-salinity layer and northward flow in the underlying waters. However, a consideration of continuity suggests there may be a clockwise gyre component to the lower layer flow with reduced northward or even southward flow of water in the eastern Gulf. By contrast, over the summer period, the residual circulation is anticlockwise around the Gulf, through depth, with speeds of 4 and $2.5\,\mathrm{cm\,s^{-1}}$ at the surface and 14 m, respectively. Further work is required to determine whether the summer anticlockwise residual gyre results from a circulation associated with the observed pycnocline fluctuations or from a separate mechanism.

The close timing of the winter regime with the local southward wind, and summer regime with the southward Aegean wind suggest the wind plays a key role in forcing the regimes. However, it appears that the spring and autumn transitions involve a degree of overlap between the summer and winter regimes.

Considering first the summer to winter transition between days 260 and 360 (August–December 1994). A sharp drop in the total freshwater in the Gulf is observed between days 260 and 340. There is an intermittent resumption of the local exchange at around day 280 (associated with an increase in the local freshwater input), followed by an abrupt breakdown in stratification and removal of the deeper mixed warm low-salinity layer at around day 320. A strong surface thermal inversion is observed between days 290 and 320. The water column is then completely mixed until day 340, when the shallow estuarine exchange resumes. The transition appears to result principally from local forcing since it coincides with a strong southward wind event over the Gulf, a sharp drop in air temperature and an increase in the local freshwater input between days 280 and 300. However, at day 290, there is also a cessation of the southward Meltemi wind, which would also be expected to result in a rise in the pycnocline level and an outflux of warm, low-salinity surface waters. It is therefore difficult to isolate which of the two processes dominates the transition.

During the spring to summer transition between days 120 and 180 (late April to June 1994). An increase in the total freshwater volume in the Gulf was observed apparently due to the formation and gradual deepening of the low salinity warm mixed layer. This occurs simultaneously with the increase in the southward wind over the Aegean, which would be expected to result in downwelling of the low-salinity surface waters in the north-west Aegean. Hence, it appears that the build up of freshwater in the Gulf over this period is principally due to an adjustment to wind forced downwelling over the Aegean. Local forcing is unlikely to be dominant since from Fig. 2 it is apparent that during this period there is a marked decrease in the local freshwater input to the Gulf and the local wind forcing is relatively weak.

In conclusion, the new observations have indicated distinct winter and summer regimes as well as highlighting several interesting dynamical processes, which emphasise the importance of wind forcing in a low tidal energy ROFI. The persistent southward local winds together with increased local river input observed during winter appear to result in a wind-enhanced estuarine exchange. By contrast, during summer, it appears that the mixed layer depth and circulation in the

Gulf may be governed by fluctuations in the southward Meltemi wind over the Northern Aegean together with freshwater input from the Dardanelles Strait, i.e. the Gulf becomes part of the larger Dardanelles ROFI system.

Further observations, including well-separated moorings in the Eastern Gulf are required to determine the propagation and current structure of the internal bores associated with the fluctuations in the Gulf's pycnocline level. These would allow us to quantify their effect on the flushing of the Gulf (although the weak residual circulation over this period suggest the reversing currents due to the paired perturbations may result in relatively weak flushing).

The inferred exchange between the Gulf and Northern Aegean suggests that to successfully model the Gulf system, further observations and well calibrated 3-dimensional models of the whole Northern Aegean system will be required. Only once this has been achieved will we be able to accurately estimate exchange with the Aegean to allow informed management of pollutant input to the Gulf.

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