ASSESSMENT AND MONITORING OF THE FISHERY RESOURCES AND ECOSYSTEMS IN THE STRAITS OF SICILY

MiPAAF

MedSudMed

GCP/RER/010/ITA

Sea temperature, salinity and total velocity climatological fields for the south–central Mediterranean Sea

MedSudMed Technical Documents No. 14
GCP/RER/010/ITA/MSM-TD-14

Rome (Italy), June 2010

Preface

The Regional Project "Assessment and Monitoring of the Fishery Resources and the Ecosystems in the Straits of Sicily" (MedSudMed) is executed by the Food and Agriculture Organization of the United Nations (FAO) and funded by the Italian Ministry of Agriculture, Food and Forestry Policies (MiPAAF).

MedSudMed promotes scientific cooperation between research institutions of the four participating countries (Italy, Libyan Arab Jamahiriya, Malta and Tunisia), for the continuous and dynamic assessment and monitoring of the status of the fisheries resources and the ecosystems in the Straits of Sicily.

Research activities and training are supported to increase and use knowledge on fisheries ecology and ecosystems, and to create a regional network of expertise. Particular attention is given to the technical coordination of the research activities between the countries, which should contribute to the implementation of the Ecosystem Approach to Fisheries (EAF). Consideration is also given to the development of an appropriate tool for the management and processing of data related to fisheries and their ecosystems.

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GCP/RER/010/ITA Publications

The MedSudMed Project publications are issued as a series of Technical Documents (GCP/RER/010/ITA/MSM-TD-00) related to meetings, missions and research organized by or conducted within the framework of the Project.

Comments on this document would be welcomed and should be sent to the Project headquarters:

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Preparation of this document

This document is one of the results of a study conducted in the framework of the FAO Project "Assessment and Monitoring of the Fishery Resources and the Ecosystems in the Straits of Sicily" (MedSudMed). The oceanographic work initiated during the execution of the MedSudMed Pilot Study: spatial distribution of demersal fishery resources, environmental factors and fishing activities in GSA 15 (Malta Island), now covers the entire Project area.

The document provides preliminary information on some oceanographic features (temperature, salinity, circulation and climatology) of the water masses in the Project area based on a numerical model approach. The results achieved cannot be considered complete and exhaustive, however they represent part of the necessary background for an improved understanding of the oceanographic features in the south–central Mediterranean.

Acknowledgements

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ABSTRACT

Climatological characteristics of water masses and circulation in the south–central Mediterranean Sea (Straits of Sicily and surrounding areas) have been estimated and compared with previous knowledge by using a model-based approach. The climatological fields have been calculated in the form of monthly and seasonal averages from the output of a numerical model run over a period of five years (4th January 2000 – 27th December 2004). The numerical model is a 3D primitive equation, mesoscale resolving regional ocean model based on POM (Princeton Ocean Model). The support of literature and satellite data proved to be fundamental to correctly interpret model results and vice-versa. Results show distribution of the main water masses comparable to the literature and confirm the hypothesis of a counter phase behaviour for the two main branches of the Algerian Current entering in the Straits of Sicily, the ATC (Atlantic Tunisian Current) stronger in winter and the AIS (Atlantic Ionian Stream) stronger during summer. The model results offer a detailed description in time and space of the hydrological characteristics of this very dynamic part of the Mediterranean and offer a basis for linkages to ecological and biological implications.

Table of contents

1. Background rationale

The FAO Regional Project “Assessment and monitoring of fisheries resources and the ecosystem – MedSudMed” has promoted research activities to improve knowledge on fishery ecosystems, with a view to the sustainable exploitation of living marine resources in the Straits of Sicily (south–central Mediterranean). A Pilot Study in the waters around the Maltese Islands was carried out to provide an overview of the spatial distribution of different life stages of fisheries resources in relation, among others, to the oceanographic factors characterising the area (Camilleri *et al*., 2008). In the Pilot Study the system of current and water mass circulation in GSA 15 was preliminarily described.

The results of the Pilot Study revealed that the spatial distribution of the main fishery resources overlaps the limits of the current GSAs and is strictly related to environmental factors such as water currents, up- down-welling and passive transportation of planktonic larvae. The analysis of oceanographic factors showed that some fishery resources are sustained by young individuals transported from adjacent GSAs during early life stages. However, in the Pilot Study the analysis of the water mass circulation and environmental factors was limited to GSA 15, resulting in a partial description of the general features characterising the entire MedSudMed area.

To improve knowledge on the complex system of environmental factors in the south-central Mediterranean, the MedSudMed Project supported the expansion of the oceanographic analysis initiated in the framework of the Pilot Study to cover the entire Project area. A model-based approach was used to produce thematic maps of the main environmental and climatological features in this area of the Mediterranean. The outputs of this study and the resulting maps were presented during the 6th Coordination Committee meeting (Salammbô, Tunisia 4-5 February 2008) and made available on the Project web site (http://www.faomedsudmed.org/html/oceanographic/ocean_search.asp). Based on the results of the study, this document provides a preliminary description of the general circulation and the climatological characteristics of water masses in the south-central Mediterranean (Straits of Sicily and surrounding areas).

2. General morphology of the Straits of Sicily

The Straits of Sicily comprise a large and dynamically active area, bordered by Sicily, Tunisia and Libya, and characterized by a complex bathymetry with wide continental shelves, deep and shallow channels and wide abyssal plains (refer to Fig. 1). The region of the Straits of Sicily also includes the national waters of Malta.

Its central position in the Mediterranean basin plays a crucial role in the passage of the superficial and intermediate water masses in transit between the eastern and the western Mediterranean sub-basins. It also prevents the direct mixing of the water masses from the deep and bottom layers of the two sub-basins. The influence of the area’s geometry on the water mass dynamics is very important; the fan-shaped configuration of the land boundaries has its narrowest constriction on the western extremity where the channel between Cape Bon (Tunisia) and Cape Lilibeo (Sicily) is only 143 Km wide. The highly irregular bottom topography in the form of a submarine ridge further limits the flow. This ridge is characterised by shallow banks along the Tunisian and Sicilian coasts, a narrow central passageway cuts along the NW-SE axis of the strait and forms an intermediate basin with an average depth of 500 m.

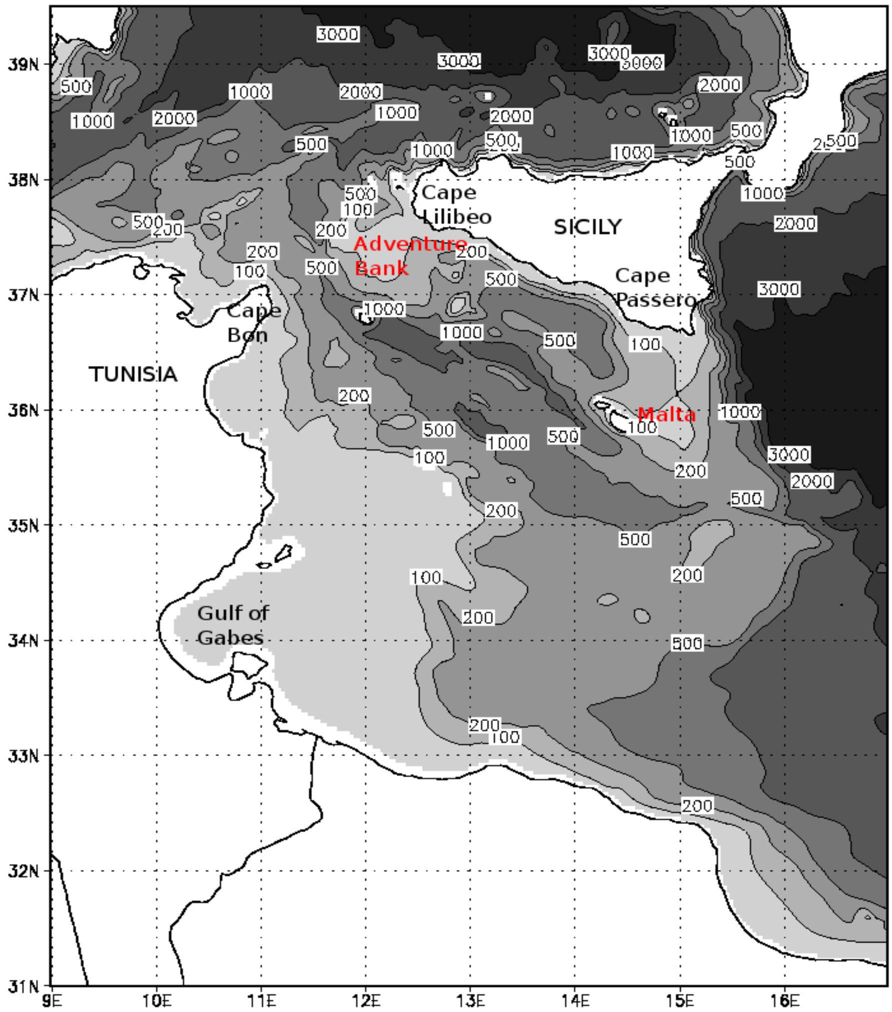


Figure 1. The bathymetry, in metres, of the Straits of Sicily shown in grey contours, from light (shallow) to dark (deep).

Flat-bottomed deep trenches are situated in the central part of this basin to the west of Malta, reaching depths of 1100-1200m off Pantelleria, 1300m off Linosa and 1650m in the Malta Graben. Owing to the nature of its different behaviour with respect to the two main Mediterranean sub-basins, it is generally considered as a third sub-basin: the central (or south-central) Mediterranean Sub-basin. On the southern coast of Sicily the shelf is bounded by two wide (approx. 100 Km) and shallow (100 m) banks on the western (Adventure Bank) and eastern extremities (Malta Channel area), while it narrows down considerably along its middle part. Along the eastern coast of Sicily and extending southward there is a narrow Ionian shelf break which is very steep to the east of Malta (known as the Malta Escarpment). The shelf break fans out to the south and broadens to a gentle slope to the north of Libya. The Tunisian and Libyan continental shelves are very wide and cover more than one third of the aerial extent of the Straits of Sicily area. In the Gulf of Gabes the bathymetry is shallower than 30 m for large stretches away from the coast. The Maltese Archipelago, consisting of a group of small islands aligned in a NW-SE direction, is located on the southernmost extremity of the Sicilian V4continental shelf. The topography of the shelf in this area is characterised by a plateau in the middle part, with an average depth of 150 m. The shelf is flanked by a submarine ridge which protrudes as a submerged extension of Cape Passero and embraces the shelf area along the eastern and southern perimeter. The Maltese Islands represent the emerged part of this ridge while the Hurds Bank to the northeast of Malta shallows to a depth of just over 50 m. To the southeast a series of relatively shallow areas, notably the Medina Bank, maintain an average depth of less than 300 m in the sea joining the Sicilian and Libyan continental shelves.

The strait between Cape Bon (Tunisian) and Cape Lilibeo (Sicily), hereunder referred to as "Straits of Sicily", constitutes the main exchange passageway for the superficial and intermediate water masses between the two Mediterranean sub-basins. It consists of a two-sill system. The first with a minimum depth of 365 meters oriented toward north-northwest, the second with a minimum depth of 430 meters oriented toward north (Frassetto, 1965). The major flux occurs through the narrower and deeper eastern passage close to the Sicilian shelf (Bethoux, 1980). The Straits of Sicily have not received the same attention as the Strait of Gibraltar although it has been suggested that its role is as important. The entrance of the LIW (Levantine Intermediate Waters) from the east occurs mainly at the Medina sill to the southeast of Malta.

3. General circulation and water masses in the south–central Mediterranean

The flow in the region is known to be characterized by a number of significant dynamical processes covering the full spectrum of temporal and spatial scales. The general circulation is mainly driven by the Mediterranean thermohaline circulation (depicted in Fig. 2), together with its mesoscale and seasonal variability. As a first approximation, the vertical structure consists of a two-layer flow with fresh Modified Atlantic Water (MAW) directed eastward in the upper layer, and a deeper westward salty Levantine outflow. The MAW is transported by the Algerian Current which, approaching the Straits of Sicily, splits in two branches. The branch passing the region of the Straits of Sicily constitutes an energetic and meandering stream known after Robinson *et al*. (1996) as the Atlantic Ionian Stream (AIS), while the southern branch is called the Atlantic Tunisian Current flowing along the Tunisian shelf break. Both branches are characterized by a strong seasonal variability, in terms of path and hydrological features.
At the intermediate depth the flow is characterized by a quasi-steady current flowing westward, the Levantine Intermediate Water (LIW). The MAW-LIW system constitutes the basin scale thermoaline core of the Mediterranean circulation, that in the Straits of Sicily can be used as indicator of climate change.

Observations in the south–central Mediterranean are sporadic, with a coarse horizontal resolution and mainly limited to the Italian seas. Generally, data is lacking over the Tunisian and Libyan continental shelves. Moreover, given that the Rossby radius over the shelf area is about 10 Km, the mesoscale phenomena, with periods from 3 to 10 days, cannot be detected and followed unless several observations are available with sufficient detail in both time and space. These constraints have restricted the definite description of the circulation and a sufficiently accurate estimation of the water masses exchange through the entire area of the Straits of Sicily. Furthermore, the interannual variability of the deep water masses, and the mechanisms governing it, has been poorly investigated mainly because of the scarcity of appropriate time series.

Available observations reveal that the vertical structure is more complex both in the horizontal and in the vertical direction. The horizontal circulation is further modified by strong mesoscale signals in the form of eddy, meander and filament patterns. Using satellite-tracked drifters, Poulain (1998) reports on Lagrangian measurements of surface currents between November 1994 and March 1997. The tortuous drifter trajectories are the result of both spatial and temporal variability and reveal the complexity of the sub-tidal surface

currents patterns. These mesoscale processes are triggered by the synoptic scale atmospheric forcing. Tidal, inertial, gravity, surface and continental shelf waves occur in the area. The time variability of the water mass properties, circulation and water transport have been discussed by several authors using hydrographic observations, sub-surface current meter data and lagrangian drifting buoys as part of various research projects (Robinson et al., 1999; Poulain, 1998; Astraldi et al., 1999, 2001, 2002; Vetrano, 2003).
CTD and XCTD profiles taken during a cruise in November 1994, Robinson et al. (1996), have identified seven water masses in the northern area of the Straits of Sicily and the northwest Ionian Sea.

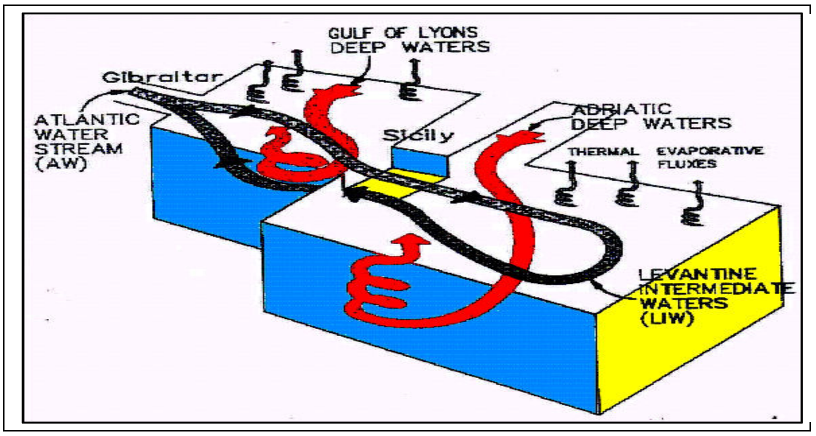


Figure 2. Schematic of the thermohaline circulation and deep-water formation in the Mediterranean. Relatively fresh Mediterranean Atlantic Water (AW) moves eastward as a surface flow.

The first detailed description of the water masses in the area of the Straits of Sicily was provided by Warn-Vargas et al. (1999). The horizontal distribution of these multiple water masses gives evidence to the strong mixing processes in action. The main water masses are:

(1) The upper (up to 100m depth) MAW (T=15-17 ^{o}C, S=37.2-37.8), which enters through the Straits of Sicily as an extension of the North African Algerian coastal current. It is described as a broad homogeneous layer that undergoes progressive modifications becoming warmer and saltier as it spreads eastward toward the Eastern Mediterranean basin (Manzella, 1994; Moretti et al., 1993). The signature of the MAW is seasonal and it is given by a salinity minimum (~ 37.2) that is found at about 50 meters during summer and near the surface during winter (Wust, 1961; Manzella, 1988). At the bottom part of the MAW there is a thin layer traced by means of a relative temperature minimum located between depths of about 100 and 200 m.

(2) The Ionian Water (IW: T=15-16.5 ^{o}C, S=37.8-38.4), residing as a subsurface layer (50-100 m depth) in the eastern extremity of the area, mainly south of Malta on the Malta shelf areas.

(3) The LIW, characterized by relatively high salinity and temperature and moving towards the west, residing at a depth between about 200 m and the bottom. The core of the LIW is indicated by a temperature and salinity maximum at an average depth of about 300 m, with T = 13.75-13.92 ^{o}C and S = 38.73-38.78 at the Straits of Sicily (Astraldi et al., 2002). The LIW has maximum salinity in the western and south-western approaches of Malta. The renewal time of the total LIW in the area of the Straits of Sicily is estimated to be 9 months, long enough to maintain a fairly constant salinity over the annual cycle. This also indicates that the characteristics of the LIW incident into the Straits of Sicily from the Eastern Mediterranean are also stable.

(4) The deeper Eastern Overflow Water (EOW), which represents the water incident from the eastern Mediterranean overflowing over the south–central Mediterranean ridge into the Tyrrhenian Sea. It consists of LIW and Eastern Mediterranean Deep Water (EMDW) which is colder and fresher than the LIW. Below the LIW there is a significant volume of transient EMDW (tEMDW) (Sparnocchia *et al*., 1999). The tEMDW originated from the Eastern Mediterranean Transient (EMT, Roether et al., 1996), during the mid-1990s and is the result of mixing between the LIW, the old EMDW and the new EMDW. In the Straits of Sicily area the tEMDW appears as a colder and fresher water mass with respect to the LIW, having a core characterized by a minimum temperature of 13.63^{o}C, a salinity of 38.73 and a density of 29.15 kg m^{-3} which is significantly higher than the deep-layer density in the Western Mediterranean (Astraldi et al., 2002).

4. Derivation of climatological fields

Numerical model simulations constitute an important tool in order to study and contribute to a better understanding of the multiscale circulation and its time variability. On the other hand high resolution models with horizontal numerical mesh sizes below 5Km, also able to simulate the mesoscale features and its variability, have been poorly used mainly due to computational constraints. This poses the need to nest a hierarchy of successively embedded model domains (Ocean Limited Area Model-OLAMs) for the downscaling of the large hydrodynamics basin scale from the coarse resolution model to finer grids in coastal areas through the nesting technique.

The use of OLAM at regional scale embedded into a coarse resolution ocean model represents an efficient solution to downscale the model solutions from the basin-scale (12.5 Km) to the regional scale (3.5 Km) through a one-way, offline nesting at the lateral open boundaries. This method was found to be computationally efficient and sufficiently robust to transmit information across the connecting boundaries without excessive distortion.

The climatological fields have been calculated in the form of monthly and seasonal averages from the daily output of a numerical model run over a period of five years (4th January 2000 – 27th December 2004). The numerical code used is that based on an application of the Princeton Ocean Model, POM (Blumberg and Mellor, 1987). The model runs with full atmospheric forcing and includes complete thermohaline dynamics. POM is a primitive equation, stratified and non-linear numerical ocean model that utilises the Boussinesq approximation and hydrostatic equilibrium. It uses the free surface, potential temperature and salinity, the three orthogonal components of velocity, the turbulence kinetic energy and the turbulence macro-scale as the prognostic variables. The model features a split mode time step and a sigma-coordinate transformation for the vertical grid. The bottom-following sigma layers allow the model to represent regions of high topographic variability accurately. The horizontal grid uses orthogonal coordinates and an ‘Arakawa C’ differencing scheme. The Mellor and Yamada (1982) turbulence closure scheme is used to calculate the coefficients of vertical mixing of momentum, the vertical eddy viscosity and the eddy diffusivity of heat and salt. Density is calculated by an adaptation of the UNESCO equation of state revised by Mellor (1991).

The model entirely covers the studied domain (10^{o} E - 17 ^{o} E and 31^{o} N - 38 ^{o} N) and covers GSAs 12, 13, 14, 15, 16 and 21. The U.S. Navy Digital Bathymetric Database (DBDB1) with a 1/60^{o} x 1/60^{o} resolution is used directly for the computation of depth at each grid cell using a bilinear interpolation method.

The model runs on a hierarchy of embedded models linking in a one-way offline nesting mode to the basin scale Mediterranean Ocean General Circulation Model from which analysis fields are used. The nesting techniques have been amply tested for robustness (Drago et. al, 2003; Sorgente et. al, 2003).

The model makes use of an asynchronous air-sea coupling scheme consisting in the use of a well-tuned set of bulk formulae for the computation of momentum, heat and freshwater fluxes at the air-sea interface where the heat flux components depend upon the state of the ocean directly. The atmospheric parameters used come from the ECMWF operational analyses, covering years 2000 to 2004, with a longitude and latitude resolution of 0.5 degrees. The temporal resolution is of 6 hours (0:00, 06:00, 12:00, 18:00 UTC).

The momentum flux used is given by:

$$\rho_0 K_M \left.\frac{\partial \vec{u}}{\partial z}\right|_{z=\eta} = \vec{\tau}, \tag{3.1}$$

where ρ_0 is the density and τ is the wind stress calculated from the surface winds with the Hellerman and Rosentein (1983) formula. The surface boundary condition for heat is interactive and is given by:

$$K_h \left.\frac{\partial T}{\partial z}\right|_{z=\eta} = \frac{Q_t}{\rho_o C_p} + \frac{C_1}{\rho_o C_p}(T^*_{z=0} - T_{z=\eta}), \tag{3.2}$$

where C_P is the specific heat capacity at constant pressure, T* is the monthly Med6 climatology for surface temperature, and Q_t is the surface total heat flux. The total heat flux (Q_t) consists of the solar radiation (Q_{sol}) minus the net long-wave radiation (Q_b) and the latent (Q_e) and sensible (Q_h) heat fluxes:

$$Q_t = Q_{sol} - Q_b - Q_e - Q_h, \tag{3.3}$$

The heat flux components are calculated using the Reed formula (Reed, 1977) for the short wave radiation flux (Q_{sol}) and the Bignami formula (Bignami et al., 1995) for long wave radiation (Q_b). The latent (Q_e) and sensible (Q_h) heat fluxes are given by the bulk aerodynamic formulae using the Kondo scheme for the turbulent exchange coefficients (KONDO, 1975).

$$\begin{aligned} Q_b &= Q_b(T_a, T_o, C, rh), \\ Q_e &= Q_e(T_a, T_o, rh, |W|), \\ Q_h &= Q_h(T_a, T_o, |W|), \end{aligned} \tag{3.4}$$

where T_a is the air temperature, C is the total cloud cover, rh is the relative humidity and W is the 10 m wind velocity modulus. The important concept is that T_o (the sea surface temperature) comes from the model integration itself, while all the other meteorological parameters come from the 6-hours operation ECMWF analysis.

For the salinity flux we consider:

$$K_h \left.\frac{\partial S}{\partial z}\right|_{\eta=0} = S(E-P) + C_2(S^*_{z=0} - S_{z=\eta}), \tag{3.5}$$

where S* is the monthly Med6 climatology of surface salinity, the evaporation rate E is expressed as the ratio Q_e/L_e, and precipitation P is obtained from monthly climatological values by Legates and Willmott, 1990.

The numerical model output is expressed as a time series of daily averaged currents, temperature and salinity fields for the five years. The fields for the GSA15 area were extracted and expressed at selected depths (1, 30, 90, 160, 200, 280 and 360 m) at each model grid cell with a spatial resolution of 1/32 degrees. The model thus offers a very detailed picture of the area under study by providing a full three-dimensional array of currents, temperature and salinity updated every day. The fields were subsequently averaged over time to produce monthly averaged fields over the five-year period (2000 – 2004).

The fields are: (i) temperature, (ii) salinity, (iii) U-component (east-west, east positive) total velocity, and (iv) V-component (North-South, North positive) total velocity. U and V components have been used to plot intensity and direction of the currents. Each field is expressed at each of the z-levels as well as at the sea bottom. The seasonal averages are defined as follows:

WINTER: from December to February;
SPRING: from March to May;
SUMMER: from June to August;
AUTUMN: from September to November.

The integration of previous knowledge and comparison of regional model outputs with satellite data has been chosen as a suitable approach to validate the model and to further investigate the climatological characteristics of currents and hydrology of the area with deeper insight.

It is important to note that the monthly and seasonal averaging of the fields filters out all the short-term variability that is certainly relevant when analyzing mesoscale processes. An idea of the daily and hi-frequency variability of T, S and (U, V) in the area can be obtained by following the 6-hour forecast fields issued currently by the PO-Unit of the IOI-Malta Operational Centre on www.capemalta.net\ MFSTEP\results.html, and the regional scale forecast produced by IAMC-CNR of Oristano can be consulted at http://www.imc-it.org/progetti/mfstep/mfs_SCRMresults.htm.

5. Climatological characteristics of hydrology and circulation

5.1. Surface Circulation

The general pattern of the circulation in the south-central Mediterranean is depicted in schematised form in Fig. 3. The inflow of MAW in the area of the Straits of Sicily comes through the Sardinia Channel (1900 m deep) as an unstable coastal boundary current, called the Algerian Current (AC), subject to significant mesoscale variability and quite a complex surface pattern due to the bottom topography. After which, guided by the topography, the AC separates into two branches at the start of the Straits of Sicily (Millot, 1987), one entering the Straits of Sicily (about 2/3 according to Bethoux, 1980) while the second one, following the northern coast of Sicily, enters the Tyrrhenian Sea, known as Biforcation Tyrrhenian Current.

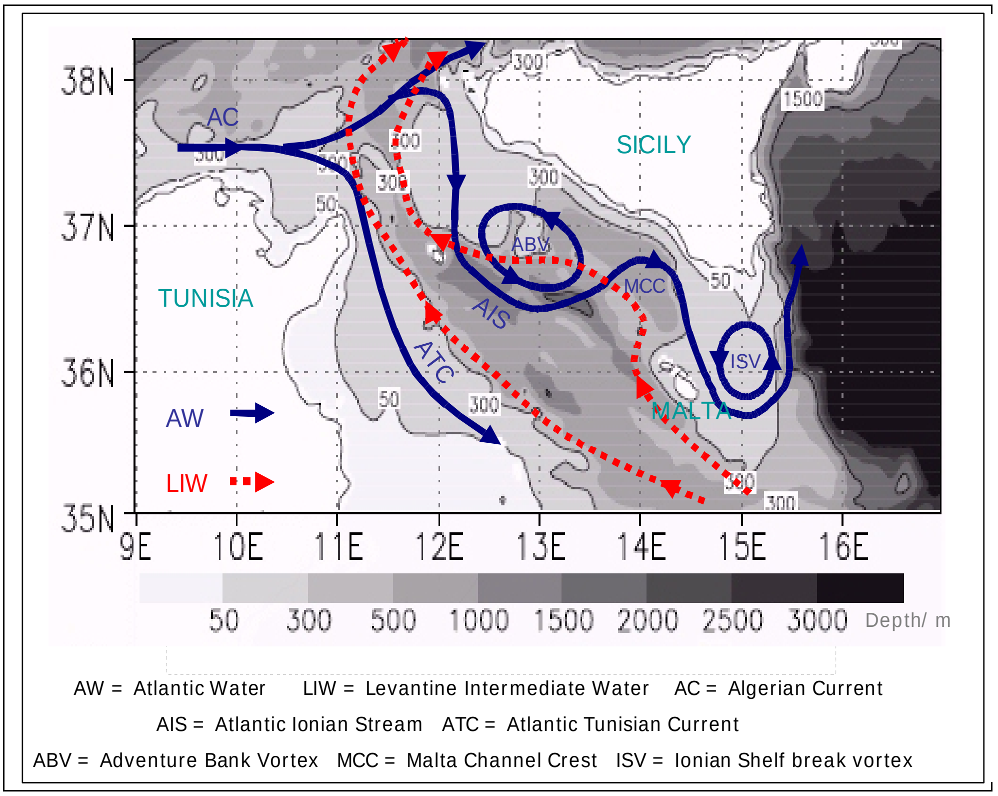


Figure 3. Scheme of the AW and LIW paths according to Astraldi et al. (2002) and Lermusiaux and Robinson (2001)

The MAW inflow into the Straits of Sicily consists of two other branches, as stated in section 2. This is also confirmed by observations conducted in summer and autumn 1996 (Robinson et al., 1999; Pierini and Rubino, 2001; Onken et al., 2003) and by the seasonally averaged model results (Fig. 4). The southern branch is the Atlantic Tunisian Current (ATC). The ATC is not well documented, and its long-term variability in space and time can be only inferred from surface drifters and SST satellite images or from numerical model studies (Beranger et al., 2004; Sorgente et al., 2003). From drifter trajectories between 1994 and 1997, seasonal average velocities have been computed (Poulain, 1998). Except in winter, when the drifter trajectories are scarce, it is clear that the ATC flows mainly along the 200 m isobath just off Lampedusa. South of Lampedusa, a part of the ATC separates and invades the Tunisian shelf in the Gulf of Gabes and recirculates anticyclonally on the shelf (Lacombe and Tchernia, 1972) while the rest becomes a coastal current along the Libyan coast.

The model results show that the ATC signature is weaker in summer, while in winter it is well developed (Figs. 4 to 7), in agreement with Manzella *et al*. (1990) and Grancini and Michelato (1987), both reporting that during winter the MAW is more steeply sloped toward the African coast. This is corroborated by analysis of the simulated climatological current fields (Fig. 4) which actually indicate an intensification of the ATC flow on the south-western side of the Straits of Sicily during autumn and winter (top left panel of Fig. 4). On the contrary in summer the ATC is weaker.

The northern branch of the MAW into the Straits of Sicily constitutes the energetic and meandering AIS moving eastward adjacent to the southern coast of Sicily as a free jet with complex and time variable patterns. The AIS moves towards the centre of the Straits of Sicily where it is constrained on one hand by the ATC and on the other hand by the presence of saltier waters related to upwelling along the southern coast of Sicily. Recent CTD observations show that in the eastern region of the Straits of Sicily a large IW spread stops the flow of the western streams. The model results depict a summer maximum of the current and the formation of typical summer features around the very well-known surface thermal semi-permanent, mesoscale cyclonic and anticyclonic features like the cyclonic Adventure Bank Vortex (ABV), the anticyclonic Maltese Channel Crest (MCC), the cyclonic Ionian shelf Break Vortex (ISV) and the intermittent cyclonic Messina Rise Vortex (Robinson et al., 1999; Hamad et al., 2005). This mesoscale meandering behaviour and the small summer features are obviously hidden in the figures by the seasonal climatological averaging process.

Intense increases in speed of the AIS are observed over the Adventure Bank and the Malta Plateau. In its movement towards the Ionian Sea the AIS can flow south-eastward or bifurcate northward in an anticyclonic loop, called the NAIS. It appears that the summer circulation pattern with this northward veering of the MAW over the Malta Escarpment is also common in both spring and fall. This is in contradiction with earlier studies such as by Tziperman and Malanotte-Rizzoli (1991) and by Ovchinnikov (1966), who conclude that on exiting the strait, the AW will predominantly proceed to the north during summer and to the south and south eastward during the remainder of the year.

Interannual changes are noticed in this behaviour (Marullo et al., 1999; Robinson et al., 1999; Korres et al., 2000; Buongiorno-Nardelli et al., 2001). For this reason seasonal model results cannot depict features like the NAIS and the NAISA (NAIS Antyciclonic eddy). The northward flow along the Ionian shelf break is predominant during summer, when the AIS is most intense and closely follows the Sicilian shelf break. The flow subsequently extends as a relatively strong velocity front into the north-western Ionian where the summer circulation is mostly anticyclonic. The contrast in temperature of the MAW exiting in the region of the Straits of Sicily with the warmer Ionian Sea produces the Maltese Front which constitutes a conspicuous thermal filament on sea surface temperature AVHRR maps. Interannual variations of this scheme and the preferred locations of these two branches cannot yet be well defined from the data available due to the lack of sampling.

Fluctuations of the upper layer currents are generally isotropic except on the Sicilian shelf where the coastal currents are characterised by a noticeable alongshore variability. The variability of the dynamic processes over the Sicilian shelf area is evidenced by the high current variance which is reported by Grancini and Michelato (1987) to have values in winter that are more than twice that of the surface flow in the central and southern areas of the strait. The kinetic energy is mainly in the tidal frequency band and is found to be dominated by the semi-diurnal and diurnal signals. The semi-diurnal currents do not exhibit significant seasonal changes in magnitude. Their consistency with depth reveals a dependence on the barotropic tide. On the other hand, the diurnal currents are baroclinic in nature and represent most of the current variability. They are reported by Grancini and Michelato (1987) to be confined mainly to the Sicilian shelf and to be particularly strong in the vicinity of Malta. The diurnal currents are stronger in summer. During winter they can completely disappear in some areas. During summer inertial currents occur throughout the section between Sicily and Libya. Inertial events, each with duration of about 10 days, occur in succession and give rise to inertial oscillations with periods between 20 and 21 h. Their amplitude can reach 25 cms^{-1} and persist for several days on the Libyan continental shelf. On the Sicilian-Maltese continental shelf the diurnal currents and the inertial oscillations co-exist and give rise to a distinctive diurnal-inertial spectral peak in summer.

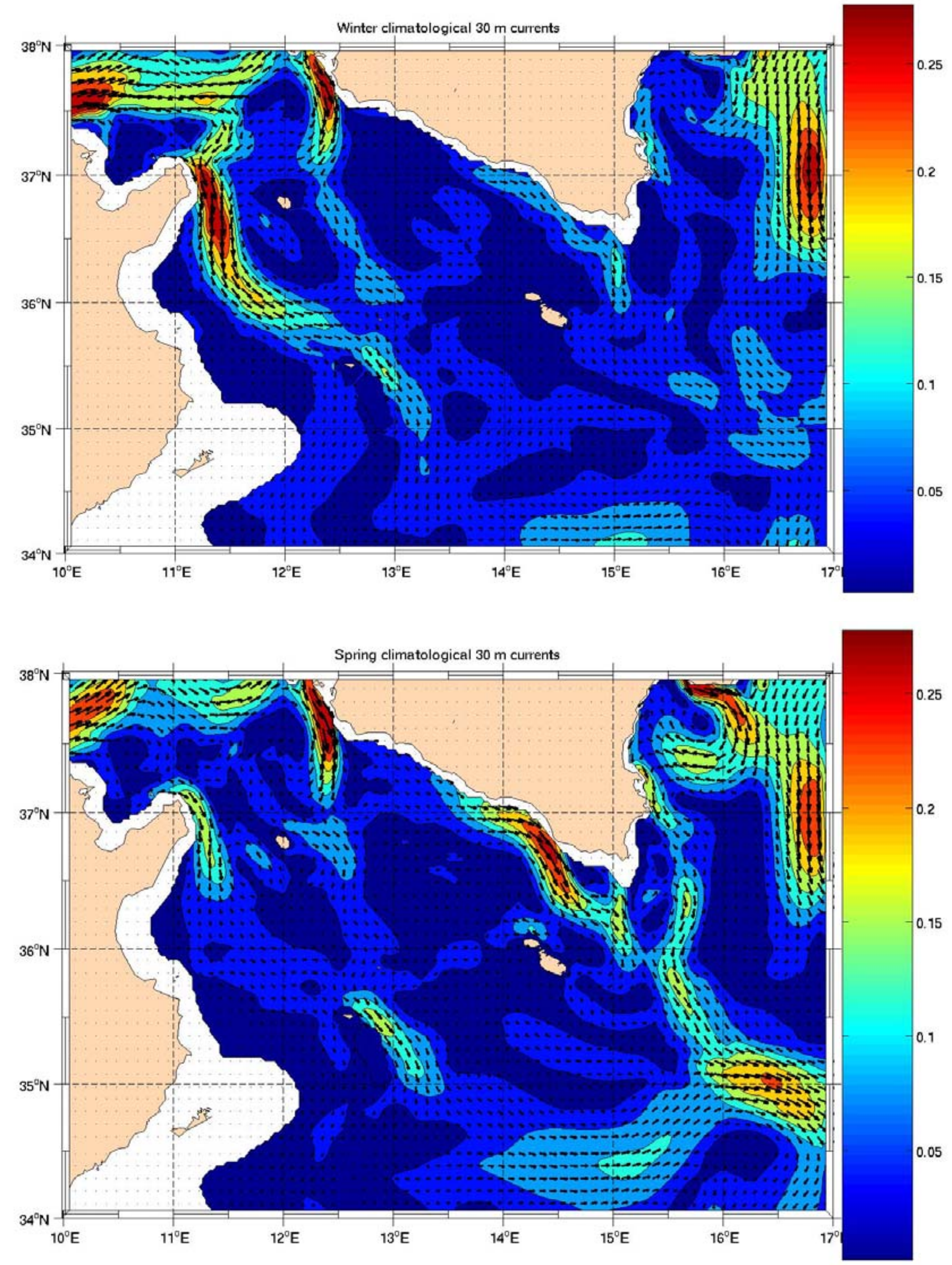


Fig. 4a. 30 m depth currents for winter (top) and spring (bottom). Zoom on AIS and ATC area

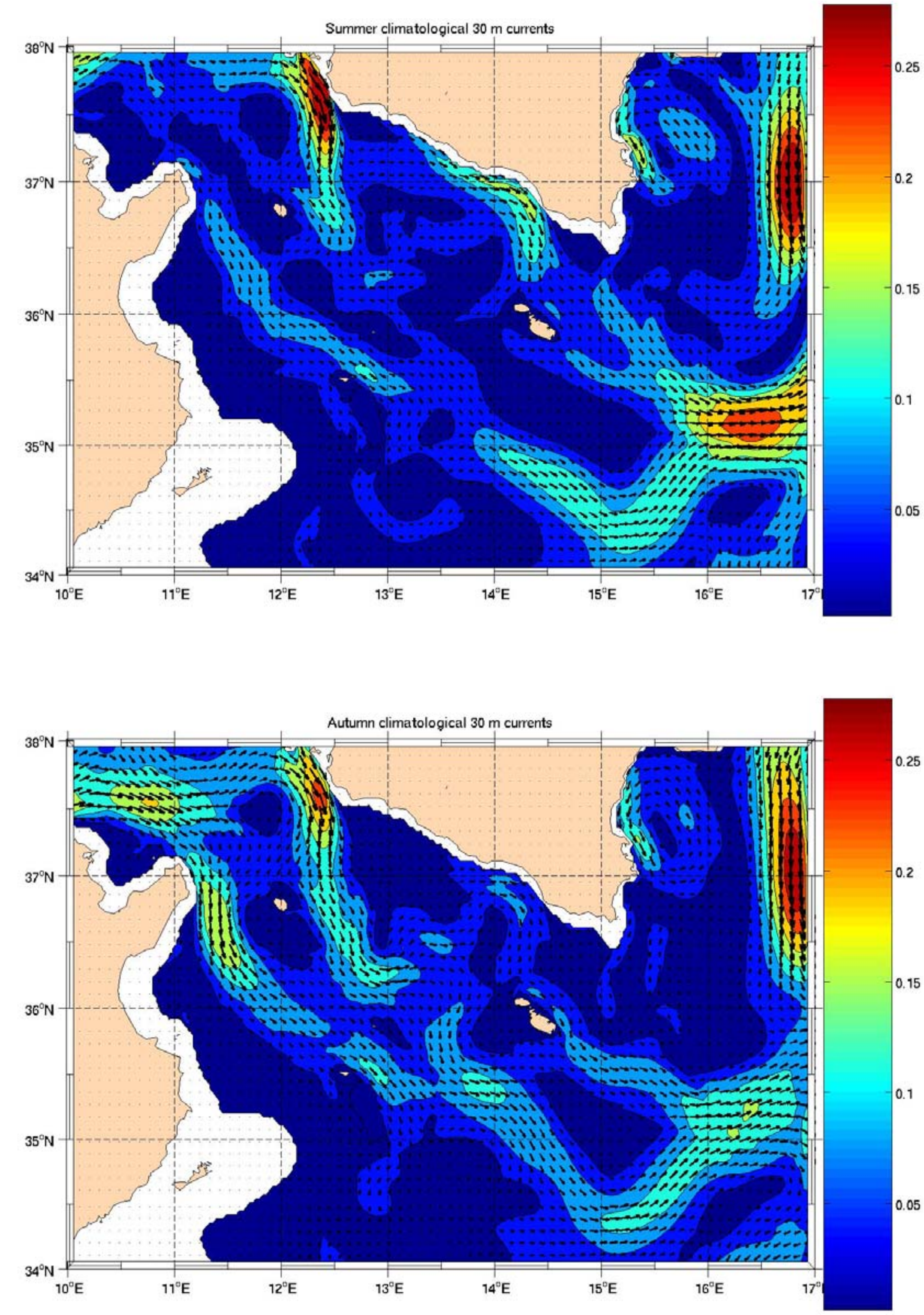
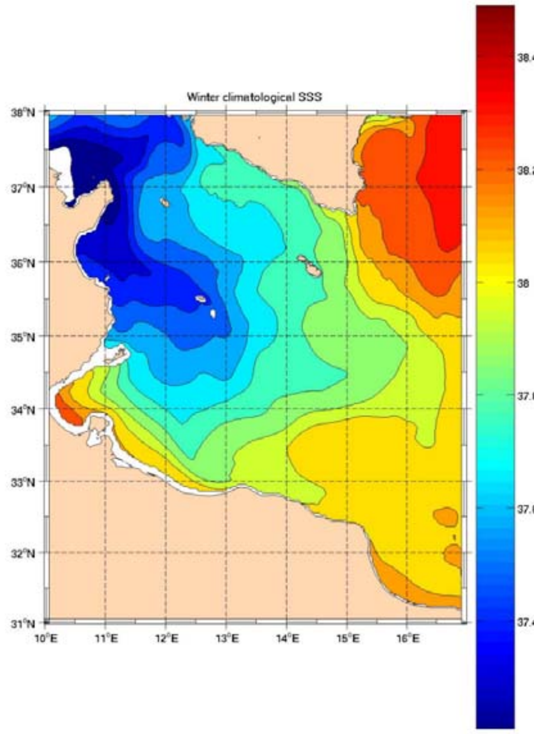


Fig. 4b. 30 m depth currents for summer (top) and autumn (bottom). Zoom on AIS and ATC area



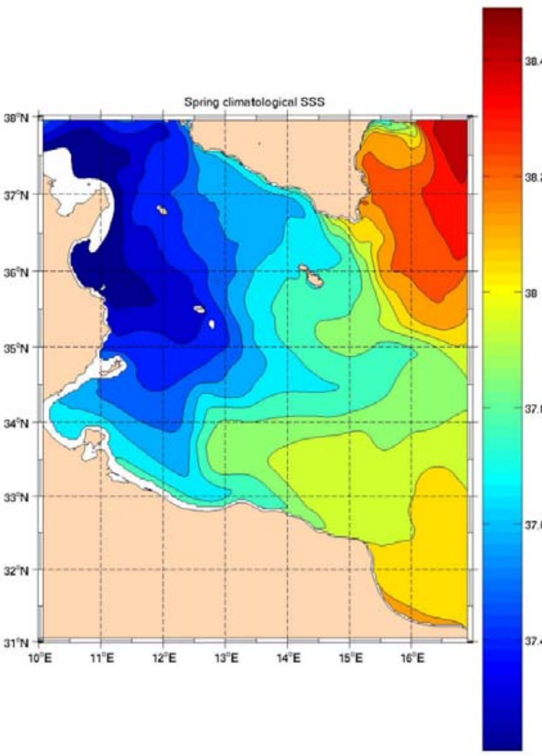


Fig. 5a. Surface salinity for winter (top) and spring (bottom)

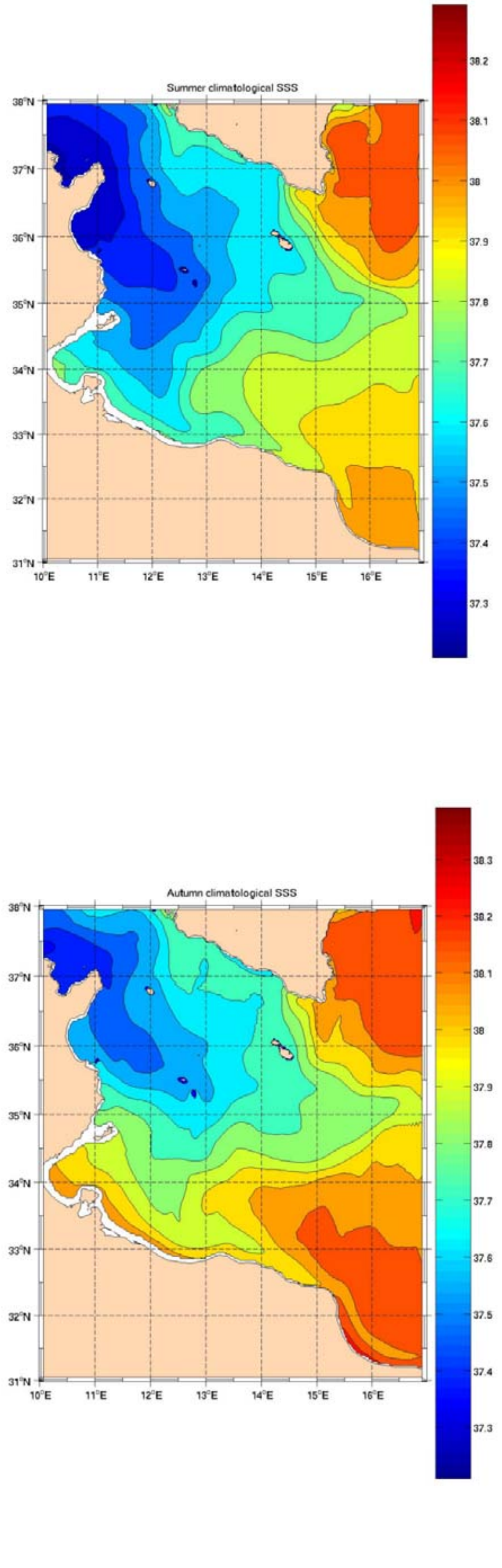


Fig. 5b. Surface salinity for summer (top) and autumn (bottom)

Current meter measurements made in the Straits of Sicily are predominantly in the channel between Cape Bon and Marsala. Measurements in the rest of the strait are generally lacking. The most comprehensive sea current data refers to the section between Sicily and Libya that was studied by the oil company AGIP, in the framework of the Libyan Offshore to Sicily Gas Transportation System Project conducted during July 1981- July 1982, and described by Grancini (1985). The array of moorings includes four stations on the Sicilian shelf, one of which situated to the east of Malta. On the basis of these measurements the current pattern across the vertical section between Sicily and Libya is reported to be rather complex, due to the presence of large continental shelves and deep trenches, to the variability of atmospheric disturbances and finally to the vertical density structure which couples with the wind stress producing barotropic and baroclinic responses of the current (Grancini and Michelato, 1987). On the Sicilian continental shelf the currents are characterised by a south-eastward steady flow of the order of 25 $cm\,s^{-1}$ throughout the year. Wind forcing increases the flow to 30 $cm\,s^{-1}$ during winter. This shows the temporal consistency of the AIS. In the vicinity of Malta the stream funnels out to a more southward direction with a reduced average steady flow of 10 $cm\,s^{-1}$. Further south, in the mid-section corresponding to the deep trench separating the Sicilian and Libyan continental shelves, the steady flow of AW in the upper layer is predominantly eastward, with an intensification to values of 10 $cm\,s^{-1}$ during winter and spring, especially in the vicinity of Medina Bank. During autumn this steady eastward flow is spread further to the south.

Low frequency current components in the strait are also remarkable. They are particularly energetic close to the Tunisian and Sicilian coasts as well as in the deep central areas of the strait. Their intensity is reduced over the shelves while they are hardly observed over the Libyan shelf. These low frequency currents can be very intense especially in winter, reaching up to 30 $cm\,s^{-1}$ and modulating the tidal oscillations with a mean periodicity of about 10-12 days. The relationship with meteorological forcing at these time scales is rather complex. Grancini and Michelato (1987) attribute the origin of the low frequency currents along the full extent of the Sicilian southern coast to the forcing by the local longshore wind. On the other hand, the low frequency variability within the Atlantic water flow is believed to be driven by larger scale non-local weather patterns. Local perturbations in the low frequency flow emanating from the region of the Straits of Sicily can result in the formation of mesoscale baroclinic eddies along the deeper central axis of the strait, and thus give rise to the low frequency clockwise rotating currents that are observed in these areas.

In summary, it could be said that the winter and spring cold periods are characterized by lower salinity very close to the surface, suggesting a significant eastward advection. Conversely during the other periods, the higher salt content and the more pronounced local circulation patterns suggest an enhancement of mixing and a weakening of the eastward advection (Beranger et al., 2004). These considerations are consistent with previous observations (Manzella et al., 1988). It is evident that the surface circulation in the Straits of Sicily is characterized by a large variability. The presence of the different water masses, their paths, and their interactions are the result of local (such as due to upwelling, meandering or eddy phenomena) and large-scale effects (such as the intrusion of IW).

5.2. Intermediate and deep circulation

At the intermediate and deep levels, between about 200m and the bottom depth, the Levantine Intermediate Water (LIW), and further below, the transitional eastern Mediterranean Deep Water (tEMWD), form the eastern Mediterranean Overflow Water (EOW).
The intermediate and bottom circulations from historical data as well as from surveys show almost stable situations, mainly shaped by topography. These water masses spread westward as an undercurrent and spill over the sills of the Straits of Sicily, partially compensating the transport of the upper flow and bringing salty and warm waters into the Western Mediterranean. The renewal time of the total LIW in the Straits of Sicily is estimated to be 9 months, long enough to maintain fairly constant salinity over the annual cycle. This also indicates that the characteristics of the LIW incident in the Straits of Sicily from the eastern Mediterranean are also quite stable. The LIW can be identified by the relative maximum in temperature and an absolute maximum in salinity at an intermediate depth, between about 200 and 600 m in the Straits of Sicily.
The Fig. 6 shows the LIW inflow into the Straits of Sicily through the narrow channel south-western of Malta, with a weak seasonal variability, together with an almost constant core depth along the 15° E section.
At the Straits of Sicily the LIW layer is thicker towards the Tunisian side, as shown by the model results (Fig. 7), reaching values of S=38.77. The thickness of the LIW layer changes substantially with the seasons, wider in fall-winter and thicker in spring-summer.
The transition layer is squeezed into a few tens of meters in fall and winter and is wider in spring and summer season, sloping up from south to north as is typical in a system with two layers flowing in opposite directions. Long-term time series of currents in the Straits of Sicily by Grancini and Michelato (1987) indicate that the Levantine water transport during winter is 2-3 times stronger than during summer. The LIW core depth varies seasonally, being deeper in winter (below 250 m) and closer to the surface in summer and autumn (up to 230 m) with a flux subject to seasonal variability (Manzella et al., 1988).

The tEMDW flows along the bottom of the Straits of Sicily into the Sardinia Channel and this water displays lower temperatures and salinity than the LIW (Astraldi et al., 2002). Our results indicate the presence of this water mass at about 300 m depth flowing along the African side. Due to the coarse resolution of the model in this region, the hydrological difference between this water masses at the exit of the Straits of Sicily the EOW, mainly composed of LIW, flows into the Tyrrhenian Sea.

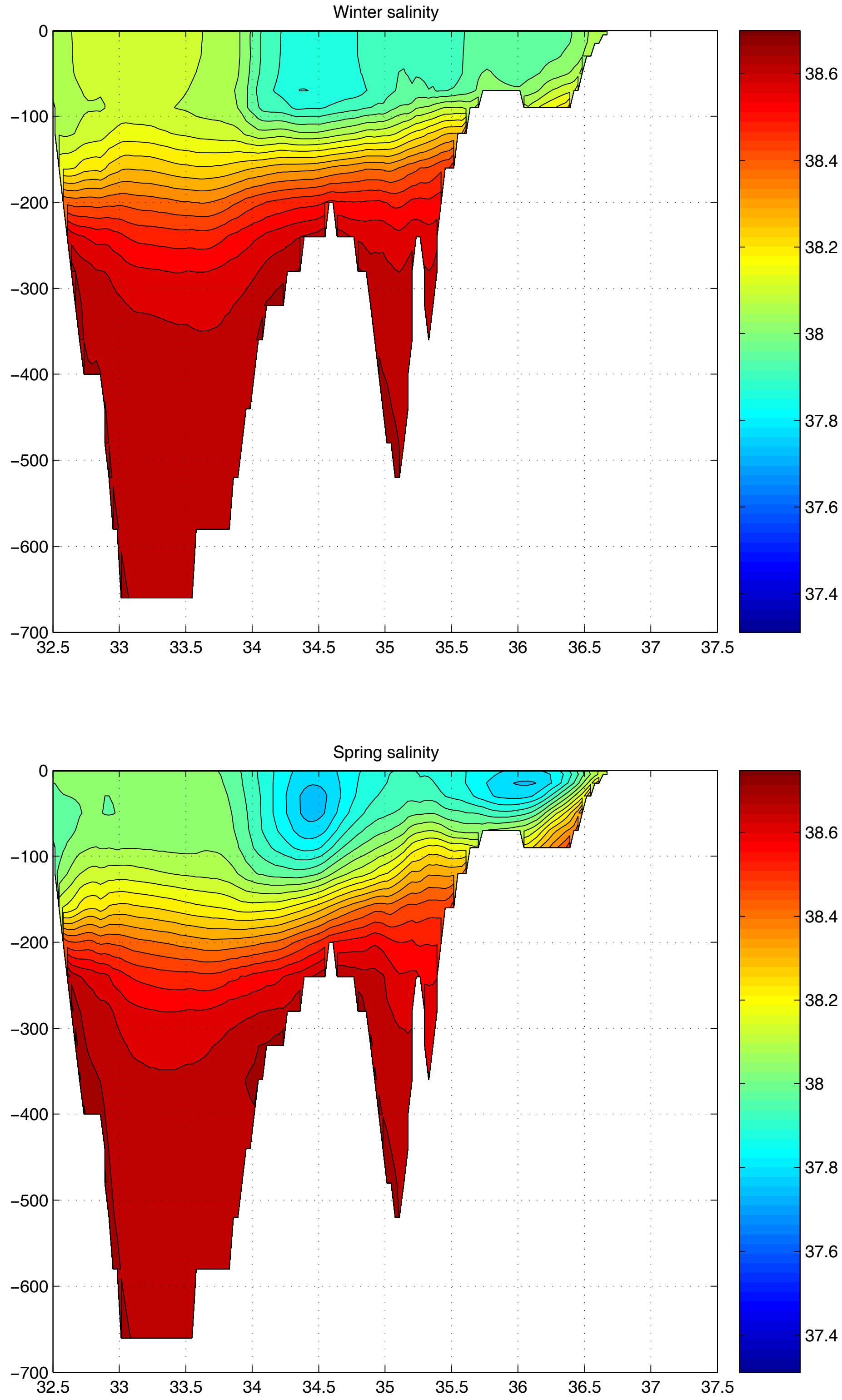


Fig. 6a. Salinity sections along 15° E of longitude for winter (top) and spring (bottom).

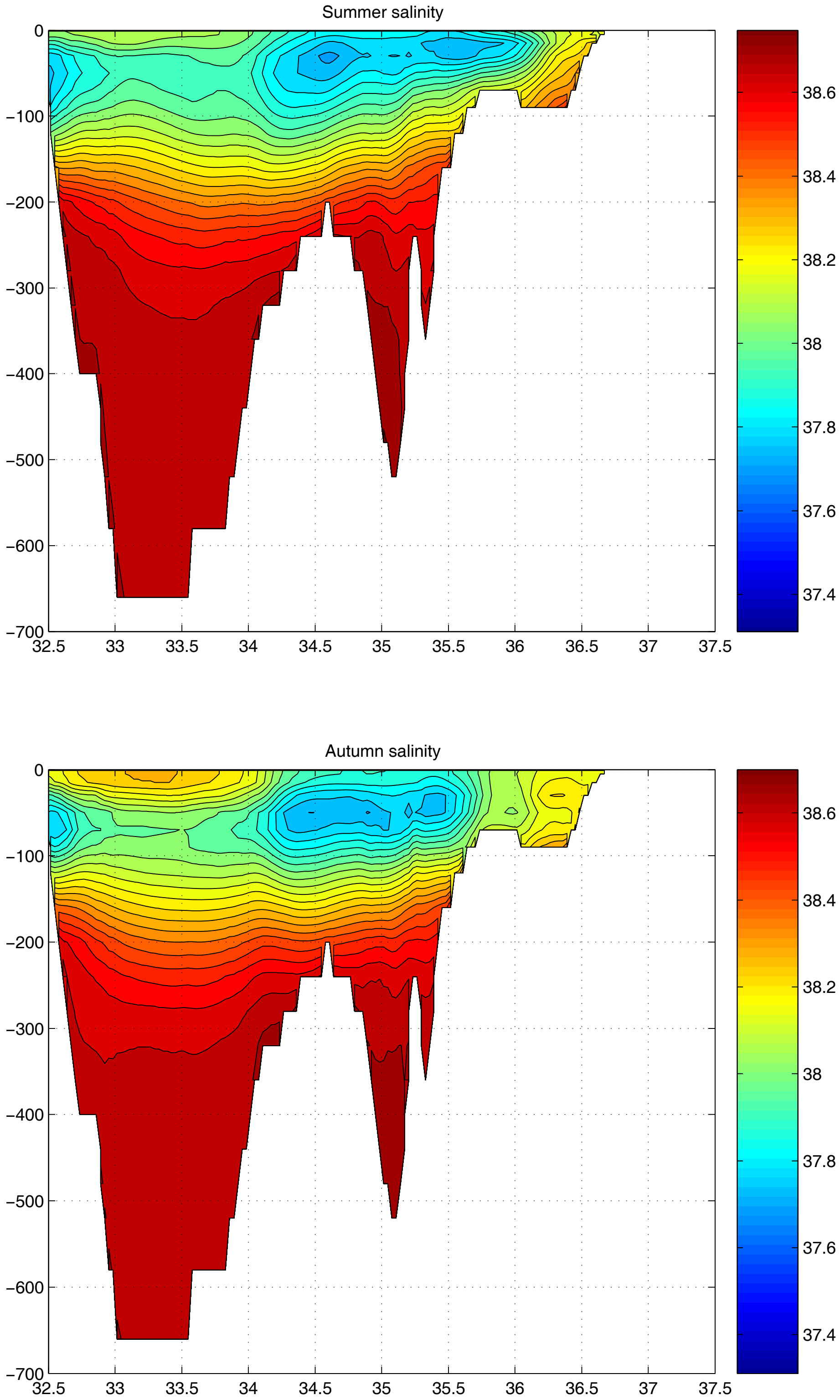


Fig. 6b. Salinity sections along 15° E of longitude for summer (top) and autumn (bottom).

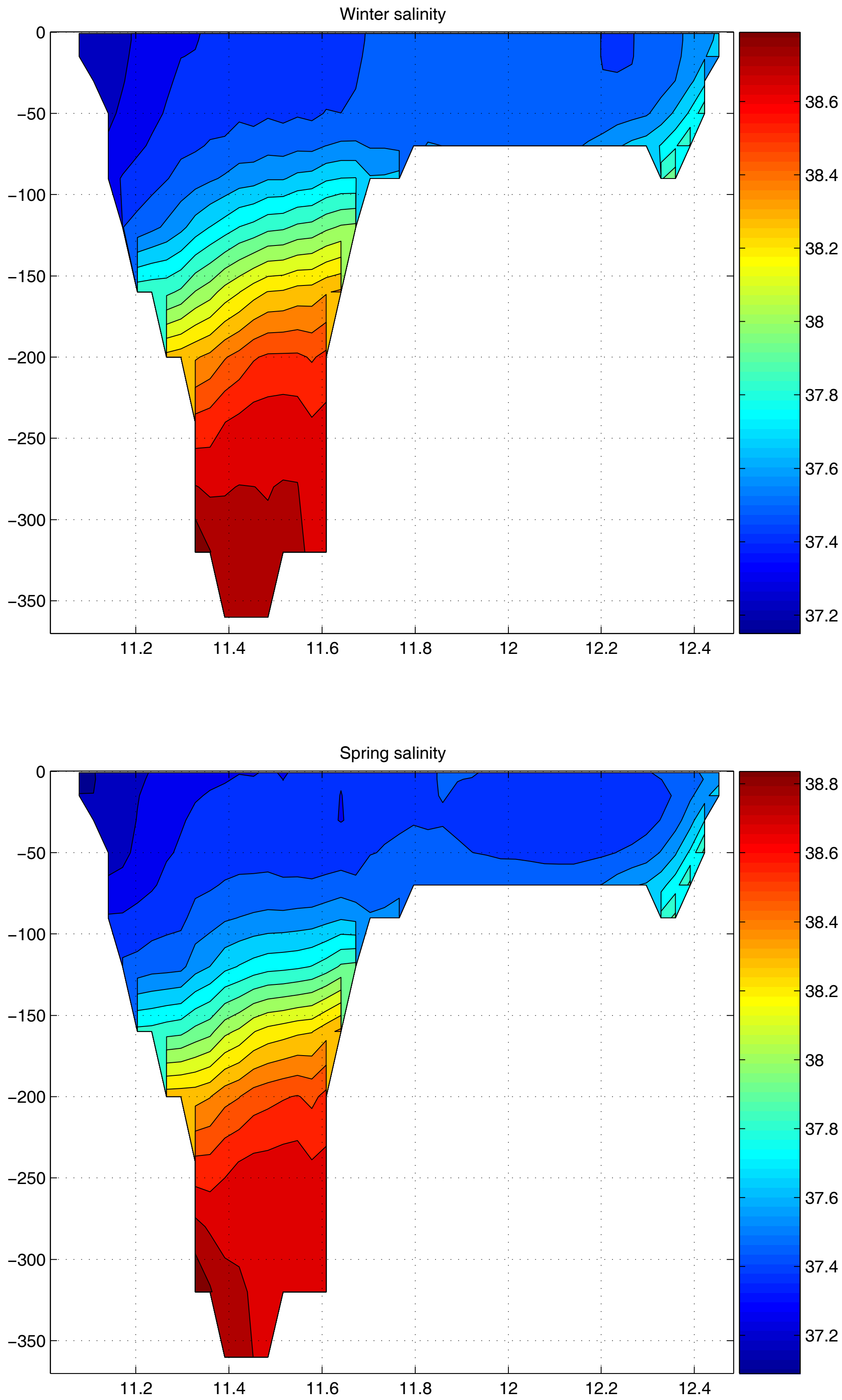
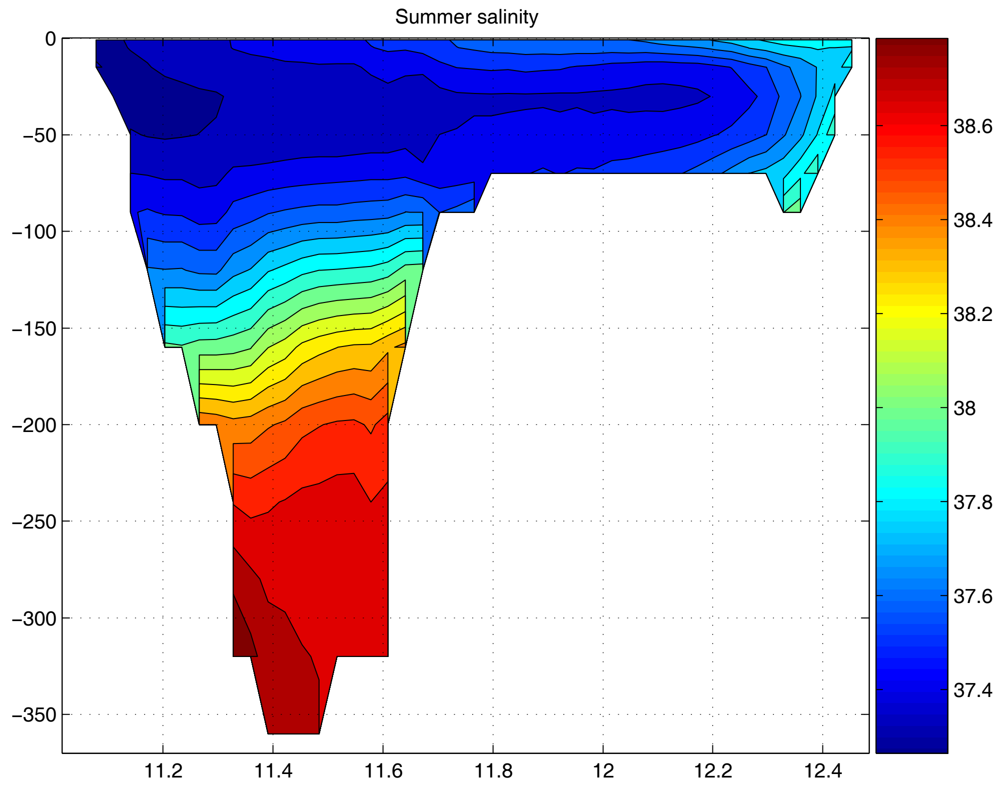


Fig. 7a. Salinity sections along the transect Cape Bon - Cape Lilibeo, for winter (top) and spring (bottom)



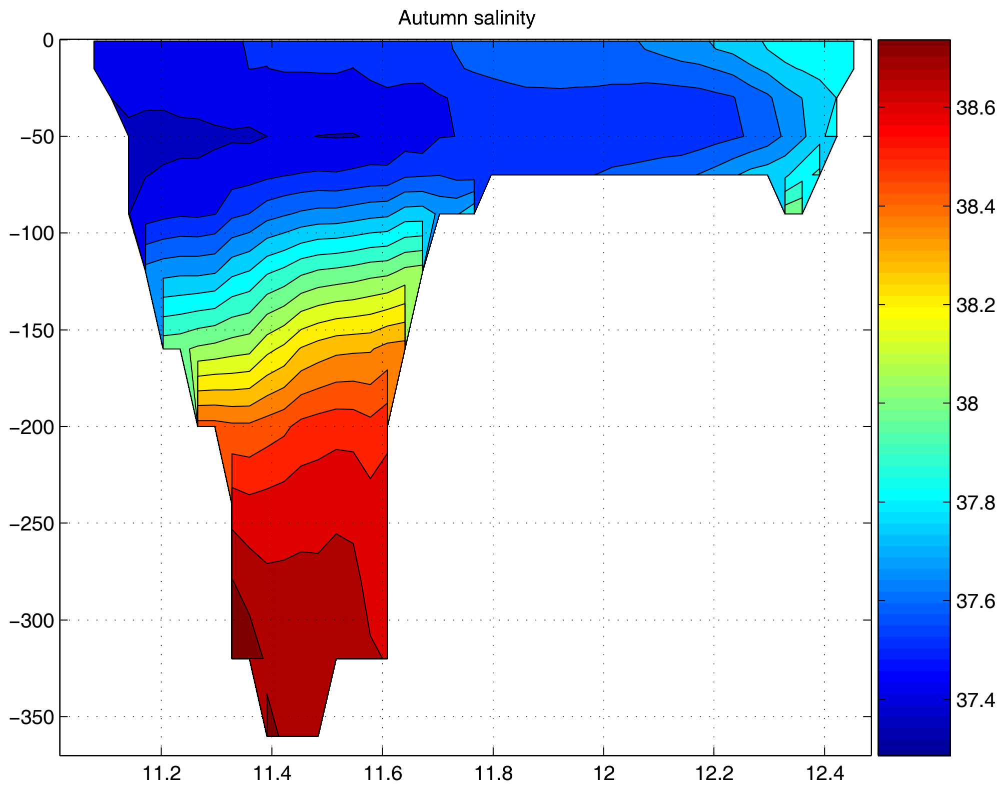


Fig. 7b. Salinity sections along the transect Cape Bon - Cape Lilibeo, for summer (top) and autumn (bottom)

5.3. Synoptic scale phenomena: the upwelling south of Sicily

In addition to the general circulation and its mesoscale variability, the Straits of Sicily and the Ionian shelf-break region are also influenced by a number of significant synoptic scale processes and phenomena. In particular, the phenomenology of the circulation is characterised by the frequent coastal upwelling events along the westward and southern coast of Sicily induced by westerly winds and by inertia of the isopycnal domes of the AIS meanders and cyclonic vortices. The upwelling in this area is relevant in an ecological sense because of the implications in the population dynamics of some commercially important small pelagic fishes, as stated for example by Garcia-Lafuente et al. (2002a, 2002b). Due to the presence of large mesoscale phenomena in the Straits of Sicily, the upwelling can extend its influence far offshore, as documented by infrared satellite observation (refer to Fig. 8).

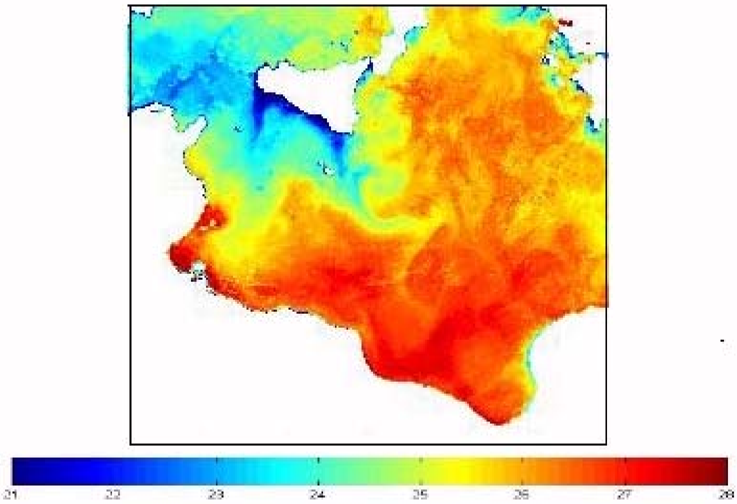


Figure 8. Sea Surface Temperature 22nd July 2002 Upwelling along the Southern coast of Sicily triggered by strong NW winds.

The upwelling zone extends over the whole southern coast of Sicily and is favoured by the north-westerly gusts that are numerous and can be particularly strong at any period of the year. The south-eastward advection of these cold patches in the form of long plumes and filaments are a very characteristic feature in the thermal IR images of the region.
During the colder months, surface cooling due to the influence of polar air masses can result in the formation of large patches of relatively cooler water that accentuate the latitudinal thermal gradients in the northern parts of the Straits of Sicily (top panels of Fig. 9), and enhance the contrast with the relatively warmer Ionian water at the Maltese Front.
The thermal signature of the upwelling is more evident in the climatological maps in summer and autumn (bottom panels of Fig. 9) than in winter and spring, due to the stronger contrast betwen upwelled waters and the upper, warm stratified layer. In summer the upwelling is probably enhanced by the action of the AIS.

Closer to the land perimeter, the incidence of coastal currents is very important. The Sicilian coastal current along the southern border of the island is wind driven and associated with local and remote storms. From thermal IR images, the vein of cold water along the Italian southern coast can often be followed down to Sicily. The penetration of cold Ionian water from the eastern coast of Sicily around Cape Passero over the shelf is favoured by the northerly winds and is often associated with the meandering frontal extension northward of the Maltese front.

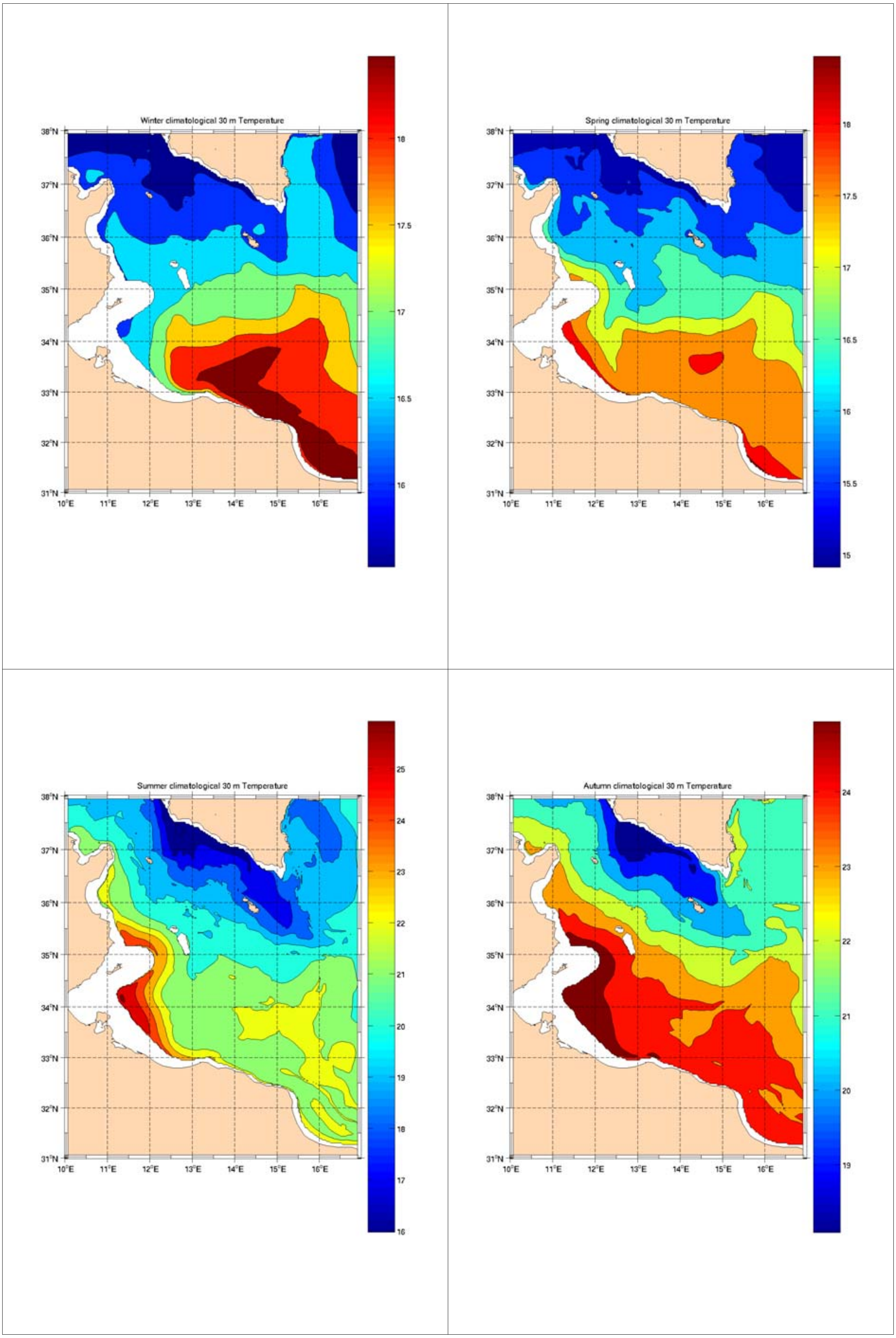


Fig. 9. Temperature, 30 m depth maps for (left-right and top-bottom) winter, spring, summer and autumn.

5.4. SST signatures and seasonal surface circulation

The availability of satellite-derived thermal infra-red images of the Mediterranean Sea with snapshots at several times daily, offers great potential in following the temporal evolution of surface flows as they are transformed by different meteorological and mixing conditions. Following the first studies by Champagne-Philippe and Harang (1982) and subsequent authors, it is now known that movements and phenomena inferred from thermal IR images, and in particular thermal fronts, do indeed represent real features found at sea. The utilisation of thermal image atlases (Le Vourch et al., 1992) is thus an indispensable tool to identify the characteristics and trends of oceanographic processes pertaining to a particular area. The interpretation of SST images can be particularly hard in this area due to the intense mixing, the upwelling events and the southern warming gradient. A correct interpretation of such satellite data needs previous knowledge coming from literature and can be well supported by *in situ* observations and modelling tools.

In the Straits of Sicily, the processes described in the previous section can all be practically followed by surface temperature signatures. The surface layer AW itself, and its characteristic lower sub-surface temperature, will lead to changes in SST as it undergoes large scale movements with the associated vertical mixing. The winter cooling and summer heating of shallow areas can also be followed from time series SST maps (Fig. 11 a,b,c). The dataset used to produce the maps of Fig 10(a,b,c) is the NOAA AVHRR Pathfinder V5 1985-2001 climatology. In this case we preferred to show the monthly climatology, instead of the seasonal one, in order to reduce the smoothing in the SST fields produced by the seasonal averaging and to show important features such as thermal fronts better.

In the area surrounding the Maltese Islands, various phenomena join to produce a very variable and complex SST field. The progression of the AIS and its eastward extension, the upwellings south of Sicily and the warming and cooling of the shallow continental shelf waters are amongst the main driving processes. The annual cycle is indeed rather complex and significant variability can be observed from one year to another, however the general features and characteristics described below are representative of the average background synoptic situation.

Starting from December, the winter structures are characterised by a front to the south of Malta. This front is commonly broad and long, often taking the form of a V-shape pointing north-westwards. It results from the contrast at the northern border of the warm Sidra gyre with the colder vein of AW that usually flows at these lower latitudes during this time of year. This front can occasionally be shifted northwards up to the shelf break in very close proximity to Malta. By contrast, the sea surface temperature on the shelf is cooler and commonly very homogeneous throughout winter. The Maltese Islands are thus very often situated within the frontal line, so that temperature differences between the northern and southern shores are appreciable.

In April the Sidra frontal zone is considerably attenuated and this month is usually without significant SST features. The end of May usually leads to the first summer features; the reduced surface cooling and the presence of stratification mark the onset of upwelling fronts. These fronts are very common in summer and show up as extensive plumes and tentacle-like structures which are advected by their interaction with the AIS. During major events of mistral winds the area of upwelled water can be extensive and actually engulf the whole shelf area. At the southernmost tip of Sicily and over the Malta escarpment a huge filament of cooler water is usually established against the warmer Ionian water to the north and the warmer Sidra water to the south (Champagne-Philippe and Guevel, 1982).

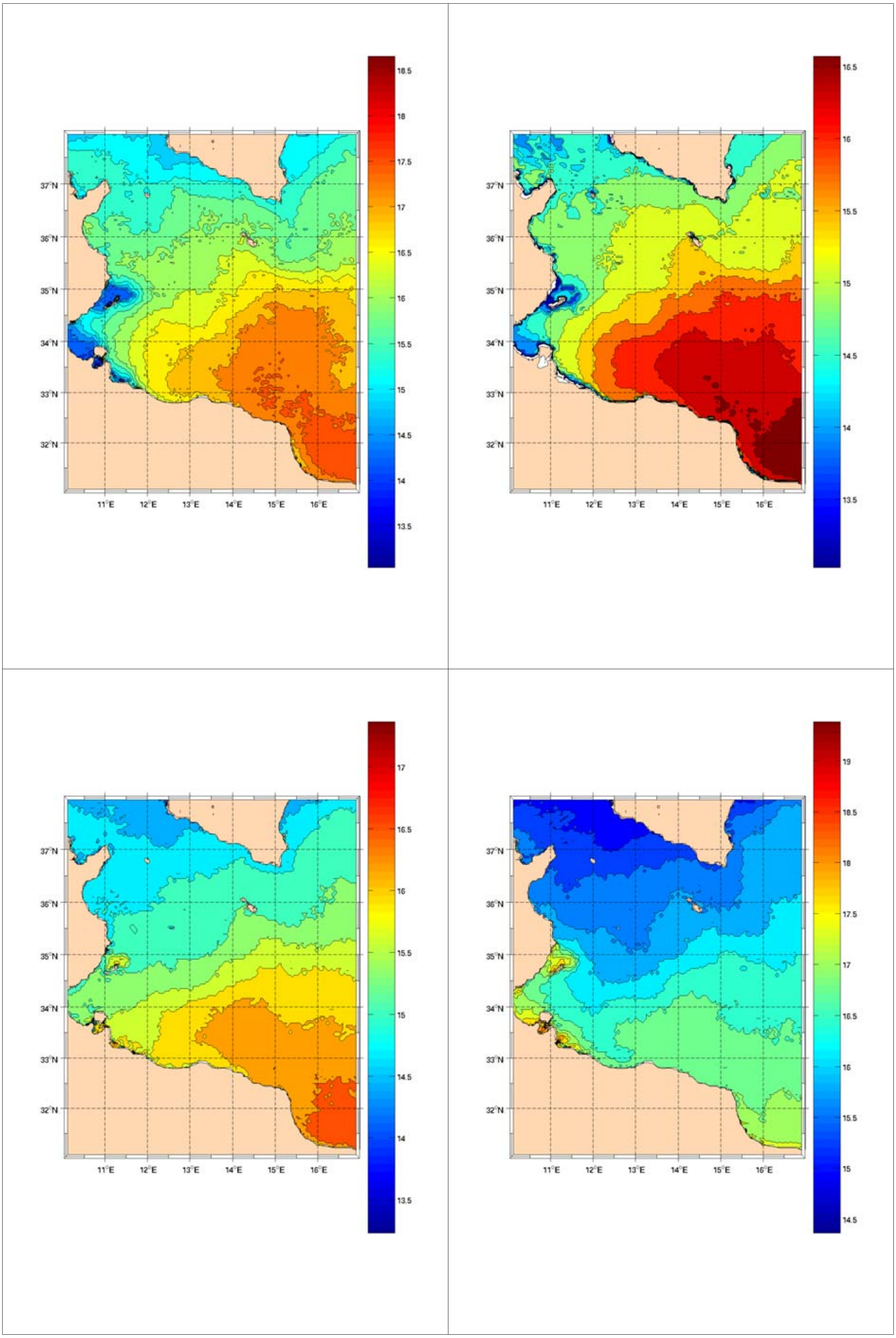


Figure 10a. Monthly averaged SST synoptic maps for January-April (left-right and top-bottom).

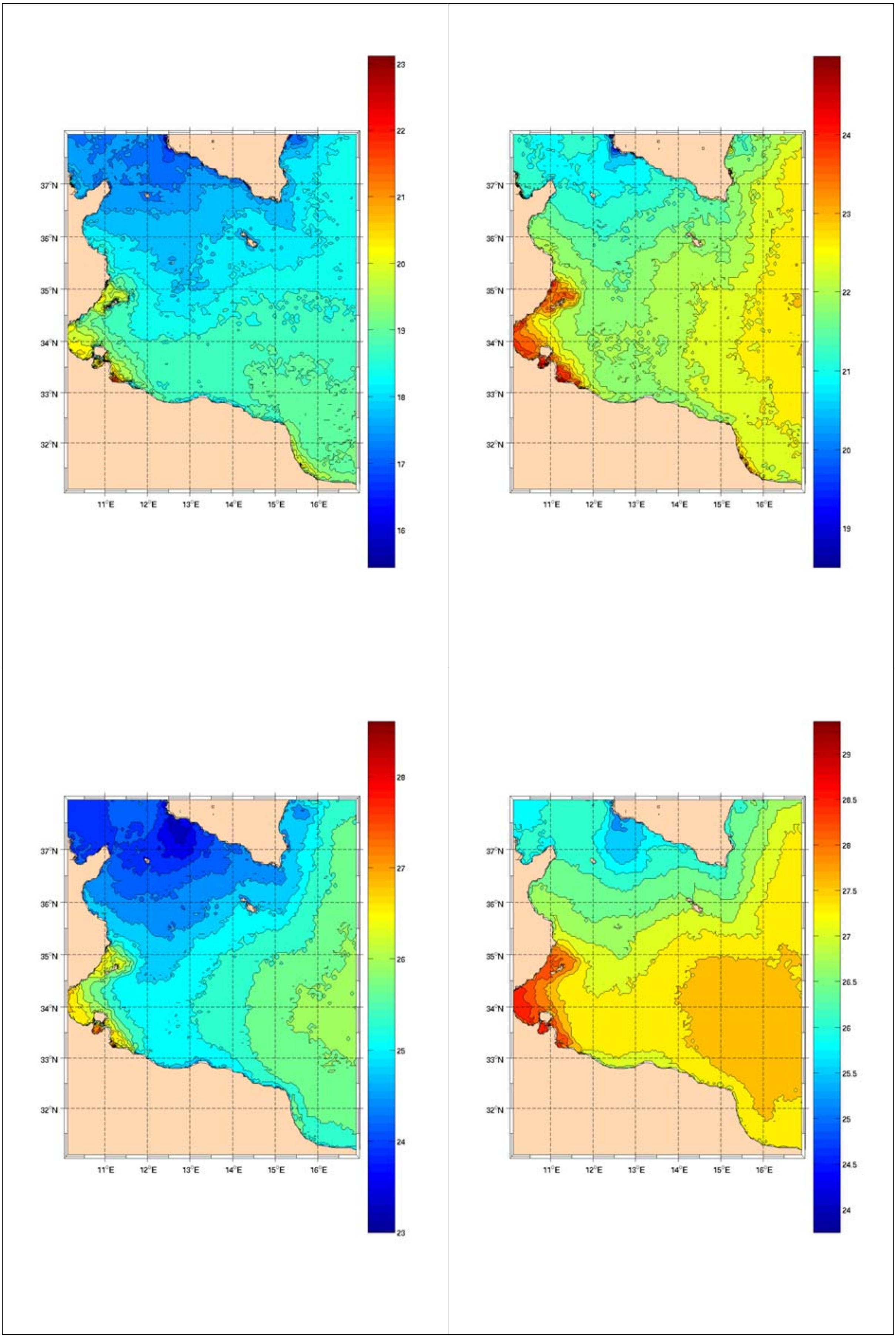


Figure 10b. Monthly averaged SST synoptic maps for May-August (left-right and top bottom).

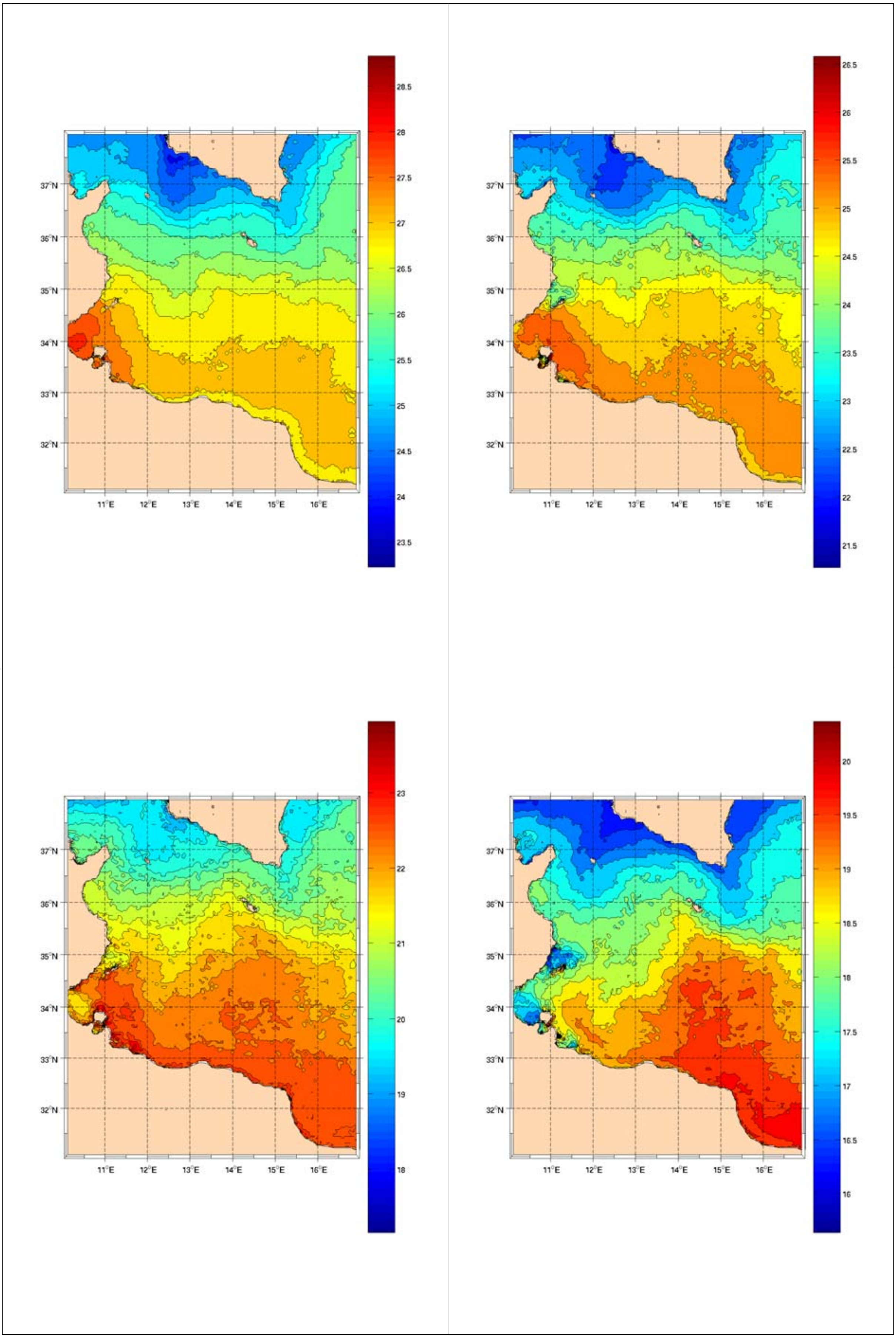


Figure 10c. Monthly averaged SST synoptic maps for September – December.

This Malta Front can protrude south-eastward to very long distances. On other occasions it is restricted to latitudes higher than 34^o N under the clear influence of the northward veering of the outflowing AIS. When upwelling events are interrupted a series of complex latitudinal fronts are established over the shelf in the Malta Channel. The cooler coastal current along the southern perimeter of Sicily often appears as a thin channel of cooler water. The autumn season presents the most complicated SST structures. The variability and the number of fronts is highest during this season. The thermal gradients are usually weaker than those in summer, but a mixture of thermal structures between those occurring in summer and winter can often be established. In October a new frontal zone appears off the coast of Tunisia. It can be either continuous from southern Sardinia to the Straits of Sicily or divided into two parts, one south of Sardinia and the other starting south of Cape Bon, delineating the northern border of the eastern Tunisian continental shelf warmer water. In October and November, this frontal system is superimposed on the persisting summer structures of southern Sicily.

5.5. Tides in the south-central Mediterranean

Tidal oscillations in the south-central Mediterranean are small in amplitude and are predominantly semidiurnal. The general tidal pattern for the Mediterranean Sea as a whole gives nodal locations in the Straits of Sicily and the magnitude of the tide in the region is thus generally small (Defant, 1961). The harmonic constituents for the main ports in the south-central Mediterranean are in most cases derived from short series of tidal measurements. The known longest historical sea-level data set in the region refers to the Grand Harbour in Malta. These chart records are kept at the British Hydrographic Office and cover the period 1876-1926 (Drago and Ferraro, 1994).

The tidal oscillations in the south–central Mediterranean are dominated by the semidiurnal constituents with supplementary contributions from the diurnal constituents especially on the North African coast. M_2, S_2, K_2, N_2, K_1 and O_1 are the only components greater than 1 cm (Purga et al., 1979). The higher frequency components are reported to be less than 1 mm on the Sicilian coast (Mosetti et al., 1983). Notwithstanding their small size, the tides in this region display particularly interesting behaviour. They are greatly connected with the hydrodynamics of the whole Mediterranean Sea and their development is related to the influence of tidal co-oscillations. The basin morphology also has important effects and the relatively shallow bathymetry on the African shelf results in the amplification of the tide. The syzigial excursions in the Gulf of Gabes reach 216 cm (Mosetti and Purga, 1989). As shown in Fig. 11, the M_2 tide alone has a remarkable amplitude of 51 cm in Gabes (Molines, 1991). In Fig. 11 the phases of the M2 tidal component through the Sicily Strait is also shown.

The diurnal tides are small and without nodes throughout the Straits of Sicily (Manzella et al., 1988). The amplitude of K_1 is uniform with values of 3.1cm at Gabes and 2.1cm at Cape Passero. On the other hand the influence of the rotation of the earth causes strong transverse (North-South) oscillations that transform the nodal lines of the semidiurnal components in the region into amphidromies *contra solem*. On the basis of semi-empirical considerations, Sterneck (1915) had prognosticated an M_2 amphidromic point close to Pantelleria even before tidal coastal data could provide a confirmation by means of field measurements. Numerical simulations of the barotropic tide have succeeded in reproducing these tidal features and elaborating on the associated hydrodynamics (Mosetti and Purga, 1989; Molines, 1991).

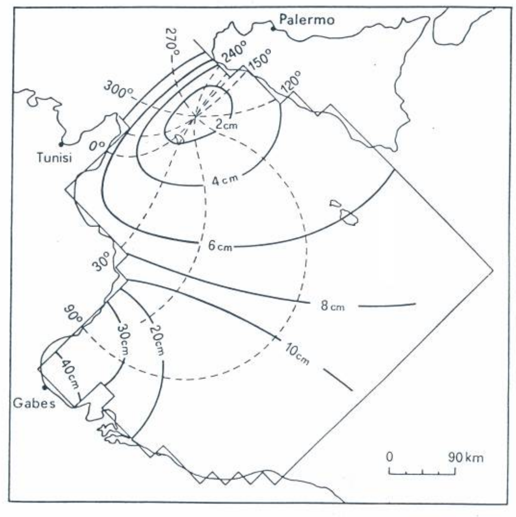


Figure 11. Amplitudes H (in cm) and phases g (in degrees) of the M2 tidal component through the Straits of Sicily. M2 tidal component in the south–central Mediterranean (derived from Mosetti *et al*., 1983)

A strong diurnal internal tide has also been detected at a station near the shelf break on Adventure Bank from time series of vertical temperature profiles (Artale *et al*., 1989). These sub-inertial oscillations of the thermocline are related to baroclinic flows with phase opposition between the upper and lower layers. They must be related to the same process of the trapping of energy at the diurnal frequency as that observed in the vicinity of Malta.

The presence of intense diurnal subsurface flows in the NW coastal area of Malta, have recently been confirmed from measurements obtained during a physical oceanographic survey carried out in summer 1992. These diurnal baroclinic currents are believed to be the expression of a topographically trapped wave that takes the form of an internal Kelvin-like waveform in the deeper sea, away from the shelf break and is accompanied by shelf wave modes propagating over the continental platform. An associated vertical oscillation of the thermocline in the form of an internal tide has been quantified to have a crest-to-trough amplitude of the order of 8 m (Drago, 1997). The free surface displacement accompanying this internal tide is estimated to have a semi-amplitude of approximately 1.2 cm. From sea level measurements in Mellieha Bay (Malta) covering a period of 42 months (1993 – 1996), Drago (1999) reports that the variability of the diurnal residual shows consistent peaks during the periods spanning mid–October to mid–January and mid–April to mid–July respectively. These sea level signatures reveal the temporal variability of the underlying dynamical processes. The semidiurnal residual does not exhibit this variability and except for sub-seasonal variations, it remains practically constant throughout the year. In particular, the semidiurnal can predominate over the diurnal residual during late winter and late summer.

Besides the influences of tidal origin, the sea level variability in the Straits of Sicily also depends on effects deriving from interference by the general circulation, from mesoscale eddies propagating on the Sicilian shelf, from fronts and in particular from meteorological factors. The annual and semi-annual components Sa (365.3 days) and Ssa (182.6 days) are rather strong. Values for these long period constituents at Porto Empedocle and Cape Passero, along the southern coast of Sicily, exhibit high spatial coherence and contribute to the sea level variations that are in phase with the annual variations in atmospheric pressure (Mosetti and Purga, 1982). A direct inverse barometric effect is thus excluded at this scale. The response of the sea level to atmospheric pressure is thus a complex one. The main influence is determined by the general synoptic situation over the whole Mediterranean basin, with horizontal gradients being produced by different pressure regimes between the Western and Eastern Mediterranean basins.

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Annex 1 - Assessment of model skill

A circulation model needs to be assessed in its ability to transfer results from a numerical to a physical domain. This can be done by comparing numerically generated fields with remote-sensed and *in situ* hydrographic observations, applying statistical analysis on model results and measurements. Statistical diagnostics comprise classical tools like comparison of local values, vertical sections or basin averages; calculus of anomaly and variance maps, and evaluation of root mean square error.

In the case of the Straits of Sicily Regional Model, Olita *et al*. (2007) have confirmed the convincing correlation of monthly averaged simulated SST with satellite data (SST from the 5-channel Advanced Very High Resolution Radiometers Oceans Pathfinder). The spatial distribution of the SST anomalies as well as their time-frequency location was similar for the remotely-sensed and simulated temperatures. Fig. 12 compares the time series of computed SST (domain averaged) with the satellite monthly data; the difference between the two time series turns out to be mainly in correspondence with extreme values, ranging from -0.5^{o} C to 1.3^{o} C, with the satellite monthly means being on average colder than model values by 0.4^{o} C.

In this study the model results are compared to hydrographical data collected during the Ansic03 cruise (11-21 July 2003) conducted in the area of the Straits of Sicily by M/V Urania. The 33 CTD profiles were collected along four transects: T1 and T2 perpendicular to the Sicilian coast; T3 parallel to the coast and T4 in Ionian over the Malta escarpment (refer to Fig. 13). For all the hydrographic stations the first (upper) datum is collected at approximately 5 m from the sea surface.

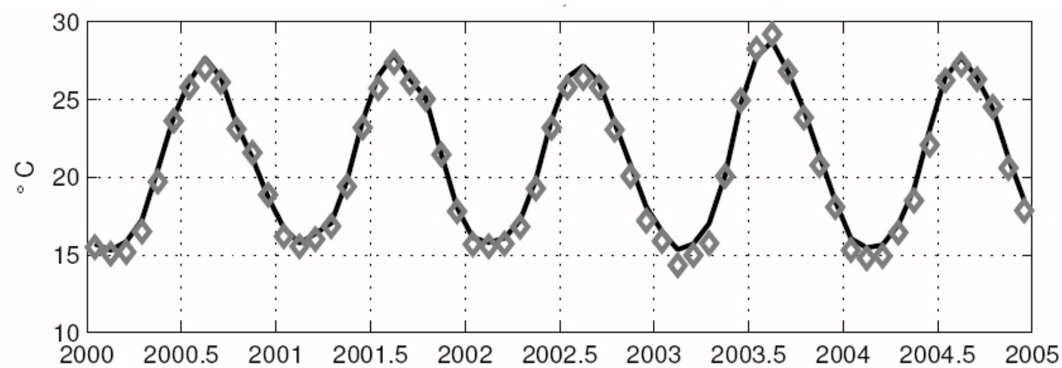

Figure 12. SST monthly time series (averaged on the entire domain) as output from the model (continuous black line) and as extrapolated from satellite data (grey diamonds)

The comparison with the CTD data assesses the capability of the model to reproduce the main hydrodynamic features at least during the period of the observations. The composite TS diagrams (Fig. 14) show good agreement between the simulated TS and the measurements, although the absolute minimum of salinity is underestimated. The main water masses crossing the area (AW and LIW) are well reproduced from the model. The Root Mean Squared Error (RMSE) between modelled and measured temperature and salinity offers a quantified measure of the skill of the model for each profile. The RMSE was computed using the CTD values at depths matching the model sigma levels, without any interpolation on zeta. The RMSE of temperature ranges from +0.2 ^{o}C to 1.5 ^{o}C with a mean of 0.94^{o}C, while for the salinity the averaged value is 0.199. Considering only the temperatures of the first 100 m, the modelled profiles show a good correspondence with the *in situ* data (Fig. 15). The main difference comes from the underestimation of the mixed layer depth, while the thermocline zone and the general trend of the temperature are well reproduced. The model has thus a good skill to reproduce the main water mass characteristic in the subsurface layer. This provides enough confidence to assume that the model is able to reproduce the hydrodynamic features and water mass structure in the area.

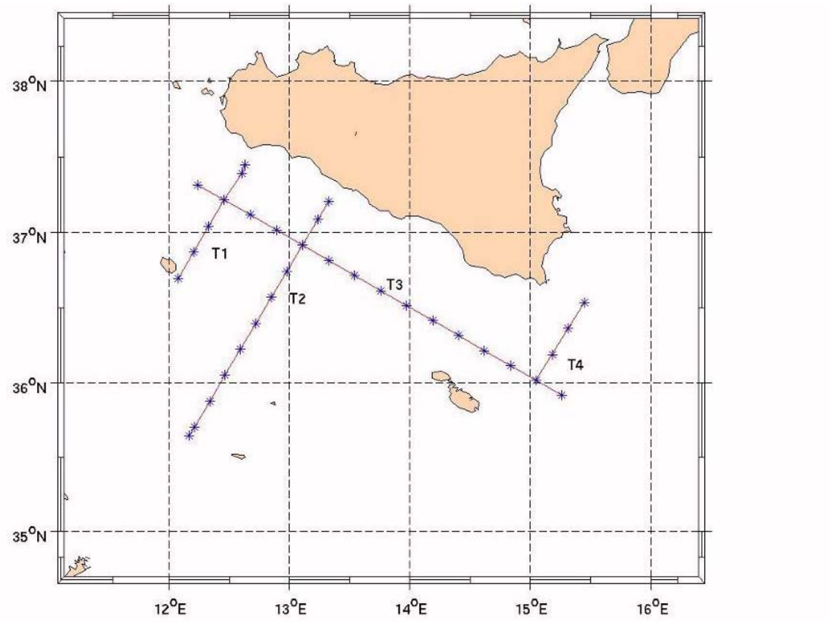

Figure 13. CTD sampling points collected during the ANSIC2003 survey (11-21 July 2003) model data were prepared for comparison by interpolating from the sigma coordinates to the zeta coordinates coinciding to the depths of the respective CTD stations, thus allowing a direct comparison at the same depth levels. A bilinear interpolation between the four points around each observed station data point was used to obtain the model profile of temperature and salinity in coincidence with the station position.

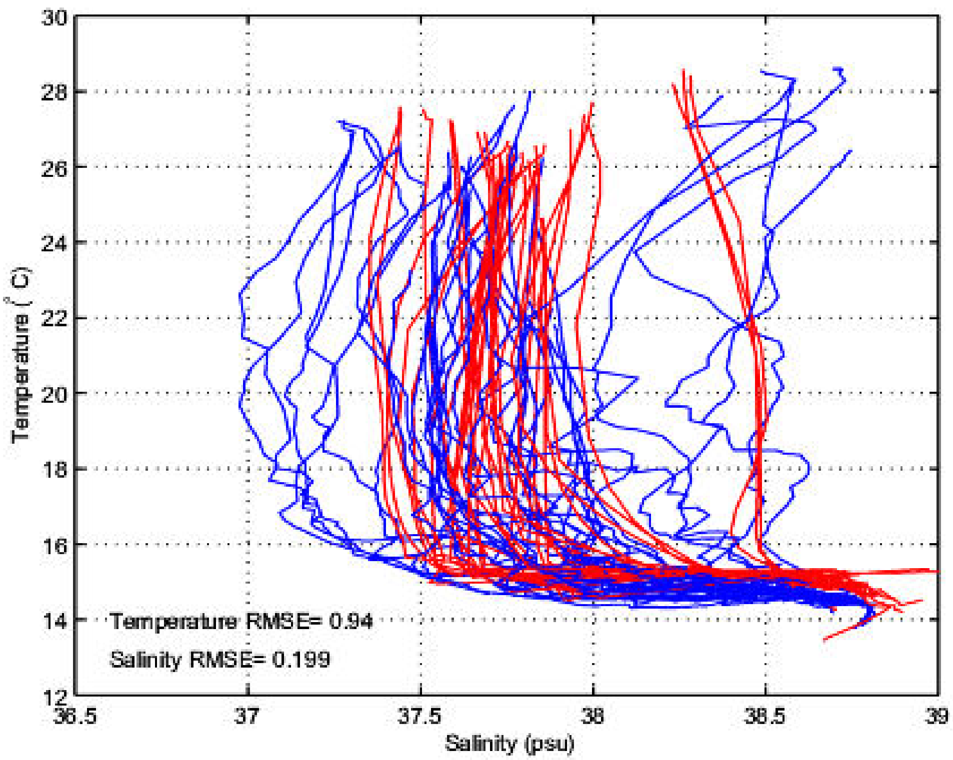

Figure 14. Comparison TS diagram between model (red) and *in situ* data (blue). The averaged Root Mean Square Error (RMSE) of salinity and temperature are indicated

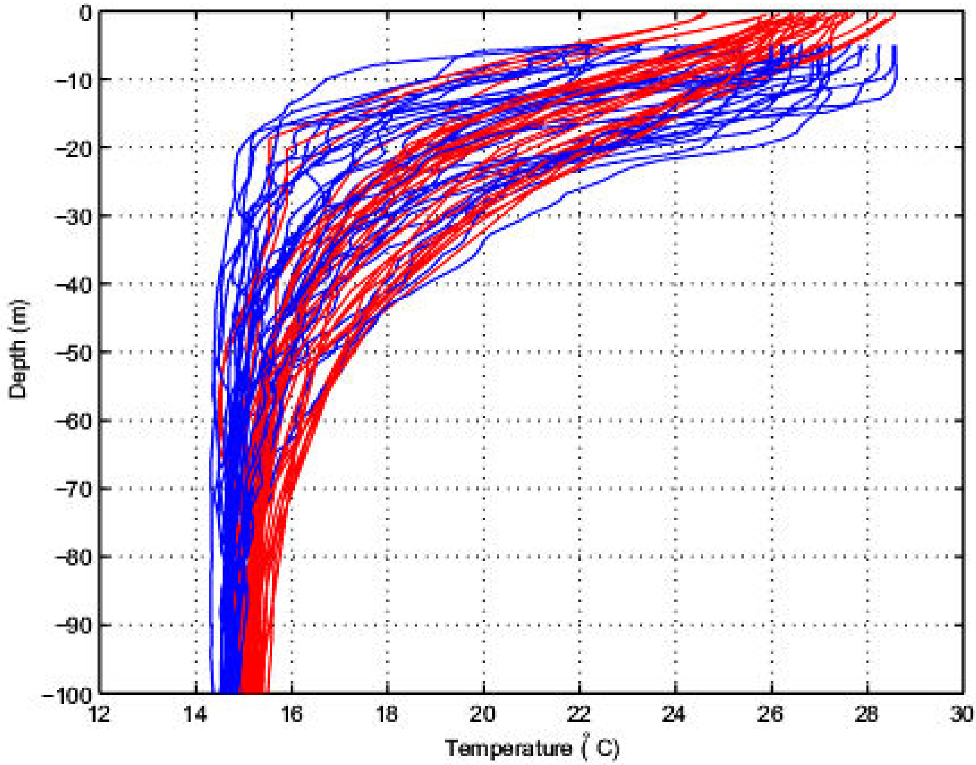

Figure 15. Comparison of Temperature profiles between model (red) and *in situ* data (blue)