Deep-Sea Research I 63 (2012) 65–81

Contents lists available at SciVerse ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

Water masses exchanged through the Channel of Sicily: Evidence for the presence of new water masses on the Tunisian side of the channel

Sana Ben Ismail [a], Chérif Sammari [a], Gian Pietro Gasparini [b], Karine Béranger [c], Mouldi Brahim [a], Lotfi Aleya [d,*]

[a] Institut National des Sciences et Technologies de la Mer (INSTM), 28 rue 2 mars 1934 Salammbô, 2025, Tunisia
[b] CNR – ISMAR/Sezione della Spezia, Forte Santa Teresa, 19036 Pozzuolo di Lerici, Italy
[c] Unité de Mécanique, ENSTA-ParisTech, Chemin de la Hunière, 91761 Palaiseau Cedex, France
[d] Université de Franche-Comté, Laboratoire de Chrono-Environnement, UMR CNRS 6249, Place Leclerc, F-25030 Besançon Cedex, France

ARTICLE INFO

Article history:
Received 22 February 2011
Received in revised form
19 December 2011
Accepted 24 December 2011
Available online 25 January 2012

Keywords:
Mediterranean
Mesoscale variability
Geostrophic transport
Atlantic Tunisian Current
Channel of Sicily

ABSTRACT

Studies of water masses present in the Channel of Sicily are relevant to understanding not only the overall Mediterranean circulation but also the Tunisian coastal shelf circulation. This study attempts to clarify the dynamics of water masses exchanged through the channel and its variability using data collected during six hydrographic cruises in the western half of the Cap Bon – Mazara del Vallo section during 2003.

Hydrographic measurements clearly show the signature of the Atlantic Tunisian Current along the Tunisian coast characterized by important mesoscale variability. Computation of a normalized temperature and salinity standard deviation makes it possible to distinguish areas of high temporal variability located in the transitional layer between the Atlantic Water and the Levantine Intermediate Water. This transitional layer is created by the presence of both Western Intermediate Water and Ionian Water. In addition to highlighting the relevance of the mesoscale activity, a comparison between direct current measurements and adjusted geostrophic currents produced a more confident estimate of the surface and deep transports through the western part of the channel. Our conclusions on seasonal and mesoscale variability are confirmed by a high resolution numerical simulation.

1. Introduction

The Channel of Sicily (CS) is located at the junction between the eastern and the western Mediterranean. At depth the CS is composed of two narrow passages, the Tunisian passage to the west and the Sicilian passage to the east, which have a depth of approximately 300 m and are separated by sub-marine mountains. Near the coasts are several wide continental shelves. The large scale circulation in the CS is mainly driven by the thermohaline circulation of the Mediterranean Sea, modulated by mesoscale dynamic processes, wind forcing, complex topographic constraint and mixing processes (Stansfield et al., 2003). The Mediterranean thermohaline circulation is prone to known interannual variations, like the Eastern Mediterranean Transient in the eastern Mediterranean (EMT, 1991–1993; Roether et al., 1996) and the Western Mediterranean Transition in the western Mediterranean (WMT, 2004–2006; Schroeder et al., 2008). The thermohaline circulation of the eastern Mediterranean is driven at surface by the eastward path of Atlantic Water (AW) through the CS. The AW then flows in a cyclonic path around the eastern Mediterranean (Millot and Taupier-Letage, 2005). At intermediate depths in the eastern Mediterranean, two water masses are formed during winter convection events, the Levantine Intermediate Water (LIW) in the Levantine Basin and, since 2002, the Cretan Intermediate Water (CIW) in the Cretan Sea (Theocharis et al., 1999). At deeper levels is found the Eastern Mediterranean Deep Water (EMDW), alternatively composed of Adriatic Deep Water before the EMT and, of Cretan Deep Water after the EMT. These water masses are spread and mix in the Ionian Basin before partly overflowing into the Tyrrhenian Sea when they reach the CS. The large scale circulation in the CS can be thus schematized as a two-layer system (Fig. 1) composed of a surface layer of fresher water flowing eastward (mainly composed of AW) and a salty bottom layer (mainly composed of LIW) flowing westward (Garzoli and Maillard, 1979; Manzella et al., 1988, 1990; Astraldi et al., 1999; Robinson et al., 1999; Sammari et al., 1999). The surface circulation in the CS consists of two main branches (Herbaut et al., 1998), the first being an AW jet called the Atlantic Ionian Stream (AIS) which flows along the southern Sicilian coast (Robinson et al., 1999) and whose path in summer is well documented. In fact, the AIS meanders around

* Corresponding author. Tel.: +33 3 81 66 57 64; fax: +33 3 81 66 57 97.
E-mail address: lotfi.aleya@univ-fcomte.fr (L. Aleya).

0967-0637/$ - see front matter
doi:10.1016/j.dsr.2011.12.009

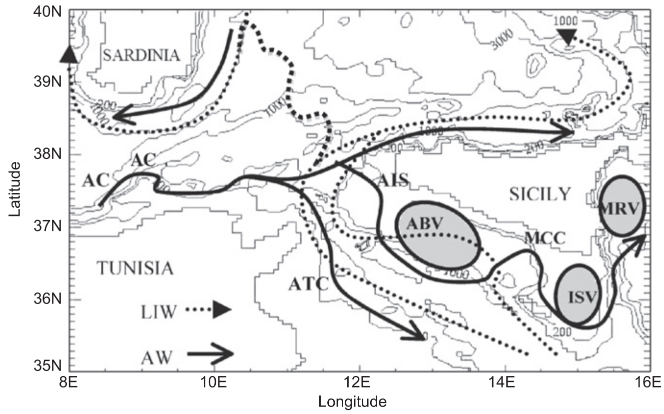

Fig. 1. Scheme of the pathways of surface (AW) and deep (LIW) waters in the Central Mediterranean region according to Lermusiaux and Robinson (2001), Astraldi et al. (2002), Sorgente et al. (2003, 2011), Béranger et al. (2004) and Ciappa (2009). The main branches of AW are: AC, Algerian Current; ATC, Atlantic Tunisian Current; AIS, Atlantic Ionian Stream; BTC, Bifurcation Tyrrhenian Current. The mesoscale features are: ABV, Adventure Bank Vortex; MCC, Maltese Channel Crest; IBV, Ionian shelf Break Vortex.

the Adventure Bank Vortex (ABV, Fig. 1) and turns southward again when reaching the Maltese Channel Crest (MCC, Fig. 1) to finally turn around the Ionian Shelf-break Vortex (ISV, Fig. 1) (Lermusiaux and Robinson, 2001). The less well-known second branch is the Atlantic Tunisian Current (ATC) (Sammari et al., 1999; Poulain, 1998) flowing along the Tunisian coast whose path is more clearly-marked in winter (Sorgente et al., 2003, 2011; Béranger et al., 2004) though less so in summer. Among the few existing reports on this second AW branch some have dealt with its spatio-temporal variability due to near-surface drifter trajectories (Poulain and Zambianchi, 2007) or its Sea Surface Temperature (Hamad et al., 2006) or Chlorophyll surface signatures (Ciappa, 2009). However, these studies have not addressed the subsurface thermohaline characteristics and the current's dynamic patterns. The transitional waters between AW and LIW are characterized by intermittent signatures (Sammari et al., 1999; Lermusiaux and Robinson, 2001) composed mainly of two main water masses, the Western Intermediate Water (WIW) and the Ionian Water (IW). The WIW forms during winter in the northwestern Mediterranean Basin due to the surface cooling of AW (Salat and Font, 1987; Gasparini et al., 1999) and has been recorded in the Algerian Basin by Benzohra and Millot (1995), flowing eastwards below the AW in the Algerian Current through the Channel of Sardinia. The WIW is characterized by a relative minimum potential temperature located between 100 and 200 m depth. The circulation of WIW has been investigated only in the Algerian Basin and there is speculation that it follows the same flow paths as the overlying AW (Millot, 1999). The Ionian Water (IW) flows in the other direction, above the LIW towards the Tyrrhenian Sea, and is characterized by a relatively warm temperature close to the Sicilian shelf (Lermusiaux and Robinson, 2001; Gasparini et al., 2005). Two estimates of the thickness of this transitional layer located between AW and LIW give values ranging from 30 m in winter to 100 m in summer (Morel, 1972) and from 120 to 270 m (Warn-Varnas et al., 1999). However, such studies are scarce or absent in the western section (i.e., the Tunisian section) of the CS, hence the interest in investigating the water masses there. The intermediate and deep circulations (Fig. 1) are mainly represented by the LIW westward path around the submarine mountains of the eastern Mediterranean before crossing the channel through the sill of Malta at a depth ranging from 250 to 350 m. The LIW then ultimately crosses the western sills of the channel to enter the Tyrrhenian Sea (Stansfield et al., 2003) a part of it perhaps being directly advected towards this channel following a cyclonic circulation (Sorgente et al., 2003) or perhaps being trapped by mesoscale eddies (Béranger et al., 2004). The LIW then passes through the Channel of Sardinia to stream northward along the island's western coast (Millot, 1987; Send et al., 1999; Millot and Taupier-Letage, 2005). Finally, for the outflowing dense water mass characteristics in the CS, interannual changes have been recorded (Gasparini et al., 2005). In particular during the EMT, a part of EMDW has been uplifted and was able to overflow into the Tyrrhenian Sea (Klein et al., 2004). This water mass was then called transitional EMDW (tEMDW). The tEMDW is characterized at the bottom of the channel by a minimum potential temperature (Gasparini et al., 2005), in particular in the Tunisian Passage (Sammari et al., 1999; Astraldi et al., 2002). Transport through the CS has been estimated either from climatological datasets (Morel, 1972; Béthoux, 1980; Hopkins, 1985), or from direct current measurements (Molcard, 1972; Astraldi et al., 1999, 2002), or with geostrophic computation from hydrographic transects (Garzoli and Maillard, 1979; Molcard et al., 2002). Estimates of LIW transport range from 0.5 to 1.5 Sv whereas those for AW transport range from 0.8 to 1.4 Sv (see Béranger et al., 2004). We have noted that to counter the lack of *in situ* velocity measurements, which cannot be taken simultaneously in both the Tunisian and Sicilian passages, Astraldi et al. (1999) suggested that the LIW transport value would be approximately the same in each passage.

With the aim of improving knowledge of water mass characteristics along the CS, and due to complex bathymetry and presence of sills there, particular attention should be devoted to conducting a high resolution sampling to be compared to the results of previous studies in this region where only 2.5 miles have been screened (Sammari et al., 1999). In this study, we attempt to describe, on the basis of data collected via high resolution, the hydrographic properties of water masses exchanged in the Tunisian passage in 2003, i.e. the westernmost part of the CS. To assess the mesoscale and seasonal variability of these water masses, we compare the data to a high resolution numerical simulation of circulation in the Channel of Sicily. Section 2 gives a description of the *in situ* data and the numerical simulation. The hydrographic characteristics of the identified water masses are then detailed in Section 3. Transport estimates across the Tunisian passage are given in Section 4 according to both geostrophic computation and current meter measurements. The results are discussed in Section 5 before the conclusions stated in Section 6.

2. Datasets and methods

2.1. Sampling and CTD data

Data were obtained from six hydrographic cruises carried out monthly (March, April, May, July, August and October) on board the R/V Hannibal in 2003 along the section Cap Bon–Mazara del Vallo, at 12 stations, with the exception of the March cruise when, due to severe weather conditions, only 10 stations were screened (Fig. 2). The CTD data from these cruises were collected with SBE 911plus sensors allowing an accuracy of 0.005 °C for temperature and 0.002 psu for salinity.

2.2. Mooring data

A current-meter mooring equipped with two Acoustic Doppler Current Profilers (ADCP) was deployed by the CNR/ISMAR (La Spezia) between 37°17.14′N and 11°30.04′E near the western sill of the CS, very close to the two easternmost hydrographic stations (e.g., stations 11 and 12, Fig. 2) from April 1, 2003 to January 12, 2004 (no adjustments for transport were made for the March cruise for the reasons given previously). The first ADCP was used to assess the sea current at near-surface (24–128 m depth),