

The drift of Modified Atlantic Water from the Alboran Sea to the eastern Mediterranean*

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SUMMARY: The Algerian basin is a region of the western Mediterranean with a highly variable circulation structure, including the eastward transport of Modified Atlantic Water (MAW) in its surface layer. An experiment with satellite tracked Lagrangian drifters was performed in 1996-97 to analyse the mesoscale circulation of the Algerian current. The complete trajectories of 18 drifters indicate that, at basin scale, all the surface flow occurred along the coast from the Alboran Sea to the strait of Sicily. At that time, no portion of the inflowing MAW was driven to the central or northern regions.

Key words: western Mediterranean circulation, Algerian basin, Lagrangian drifters.

INTRODUCTION

Modified Atlantic Water (MAW) is initially made as a result of the mixing of comparatively fresh Atlantic water ($S < 36.5$) flowing via the strait of Gibraltar into the Mediterranean Sea with the surface waters of the Alboran Sea (Gascard and Richez, 1985). The resulting water mass occupies the southern part of Alboran Sea and, entrained by an intense jet coupled to a wave-like front (La Violette, 1990; Viúdez *et al.*, 1996), exits the eastern end of this sub-basin either along the African coast (Viúdez and Tintoré, 1995) or along the Almeria-Oran front (Tintoré *et al.*, 1988). Near Oran, the MAW jet forms the Algerian Current (Millot, 1985; Arnone and La Violette, 1986) that flows eastward along the African continental slope, and is one of the most important and less known current systems in the western Mediterranean. At basin scale, MAW

driven by the Algerian Current both penetrates into the eastern Mediterranean through the strait of Sicily, and circulates cyclonically all around the western basin (Millot, in press). In its cyclonic circulation in the basin, it can be identified by a surface salinity minimum that is progressively smoothed by mixing with surrounding waters. In fact, all the basin surface layer (100-200 m) is occupied by the minimum salinity MAW whose minimum is dependent on the different degrees of mixing due to residence times, until reaching salinities above 38.0 in the open sea of the northwestern region. López-García *et al.* (1994) named the fresher MAW found in the Alboran Sea and along the Algerian coast as "recent MAW" to distinguish it from older MAW occupying the western and central regions of the western basin.

Thus, the traditional picture of a widespread eastward and northeastward flow in the Algerian basin (Ovchinnikov, 1966), has been replaced by the image of an alongslope coastal current subject to very intense mesoscale activity (Millot, in press).

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However, some climatological and numerical studies (e.g. Tzipermann and Malanotte-Rizzoli, 1991; Pinardi and Navarra, 1993) still indicate the existence in the western Algerian basin of a widespread flow to the northeast (to the Balearic islands). This, despite the strong indication by satellite images evidence that the presence of recent MAW in this northern areas is not due to a general smooth flow of the Algerian Current, but to the interaction of the current with strong mesoscale eddies (Taupier-Letage and Millot, 1988; López-García *et al.*, 1994). The lack of hydrographic and current data in the Algerian basin with adequate horizontal and vertical resolution has till now prevented a complete explanation of this dynamical process.

To help in overcoming this deficiency, two projects have been instigated. The first one - "ALGERS: the use of ERS sensors for the study of the dynamics of Modified Atlantic Water in the Algerian basin (western Mediterranean sea)" - is a research project that utilizes data from the European Space Agency ERS satellites, and includes, as one of its objectives, the investigation of the drift of MAW in relation to the regional mesoscale eddies. The second project - "MATER: mass transfer and ecosystem response" - is the second phase of the Mediterranean Targeted Project of the European Union Marine Science and Technology (MAST) program. One of the MATER tasks is to study the mesoscale circulation in the Mediterranean using surface Lagrangian floats released at the Alboran's eastern boundary.

As a contribution to ALGERS and MATER, a surface drifter experiment was initiated as part of the ALGERS'96 cruise aboard the Spanish research vessel Hespérides in October 1996. We present here the first general results of this experiment, with the trajectories of all the drifters tracked by satellite for the several months they were operative.

THE LAGRANGIAN DRIFTERS

Two models of drifters were used (A111 and A104), both manufactured by Brightwaters Instrument Co., New York, USA. Model A111 is a simple cylindrical drifter that contains an ARGOS transmitter, an antenna and batteries, with a small wheel on top as floatation element. Only the antenna emerges from the sea surface, which minimises the wind drag effect. A secondary surface float attached to the drifter gives the necessary buoyancy for the

subsurface drogue. This was a TOGA-WOCE standard holey sock, 10 m long with a 5 m tether, so the main drag was centred at 10 m below the surface with a subsurface-surface drag ratio close to 70. Model A104 is a bigger drifter, with a mechanical structure based on the popular Davis surface drifter (Davis *et al.*, 1982), that besides the ARGOS tracking equipment hosts a GPS (Global Positioning System) receiver and antenna, with both internal recording and data transmission through ARGOS. A temperature sensor is also included. Only the two antennas and the top of five small floats emerge from the sea surface. The A104 drifters also carried the same model of sock drogue, with dimensions adapted to produce a similar drag ratio as the A111. In all, 15 units of A111 and 3 units of A104 were deployed during the experiment. The A104 units were programmed to record the GPS position every 30 minutes. All the drifters were located by ARGOS on average 6-8 times a day.

THE DRIFTERS EXPERIMENT

The ALGERS'96 cruise aboard the RV Hespérides in October 15-21, 1996 was carried out in the western Algerian basin, close to where the Algerian Current is normally formed. The main objective of the cruise was to exhaustively sample the three-dimensional structure of a mesoscale instability of the Algerian Current from the dynamical, geochemical and biological point of view.

In the period prior to the cruise, satellite infrared imagery was used to identify the specific area to be sampled. By the end of September 1996, the satellite imagery indicated a mesoscale instability of the Algerian Current developing near 1°E, close to the eastern boundary of the Alboran Sea. The instability appeared as a meander of the current surrounding a coastal anticyclonic eddy, and associated with a secondary cyclonic eddy, upstream and seaward from the crest of the meander (Fig. 1). This mesoscale feature was chosen as the instability to be studied during ALGERS'96. To maintain continuity between the features seen in the satellite images and ship's cruise work, a Sea Space portable satellite receiving station (Terascan TS-300 system) was installed aboard the Hespérides. This station provided the shipboard scientists with NOAA AVHRR infrared imagery four times a day. This continuous remote sensing monitoring was critical in guiding the in situ sampling, by daily updating the location

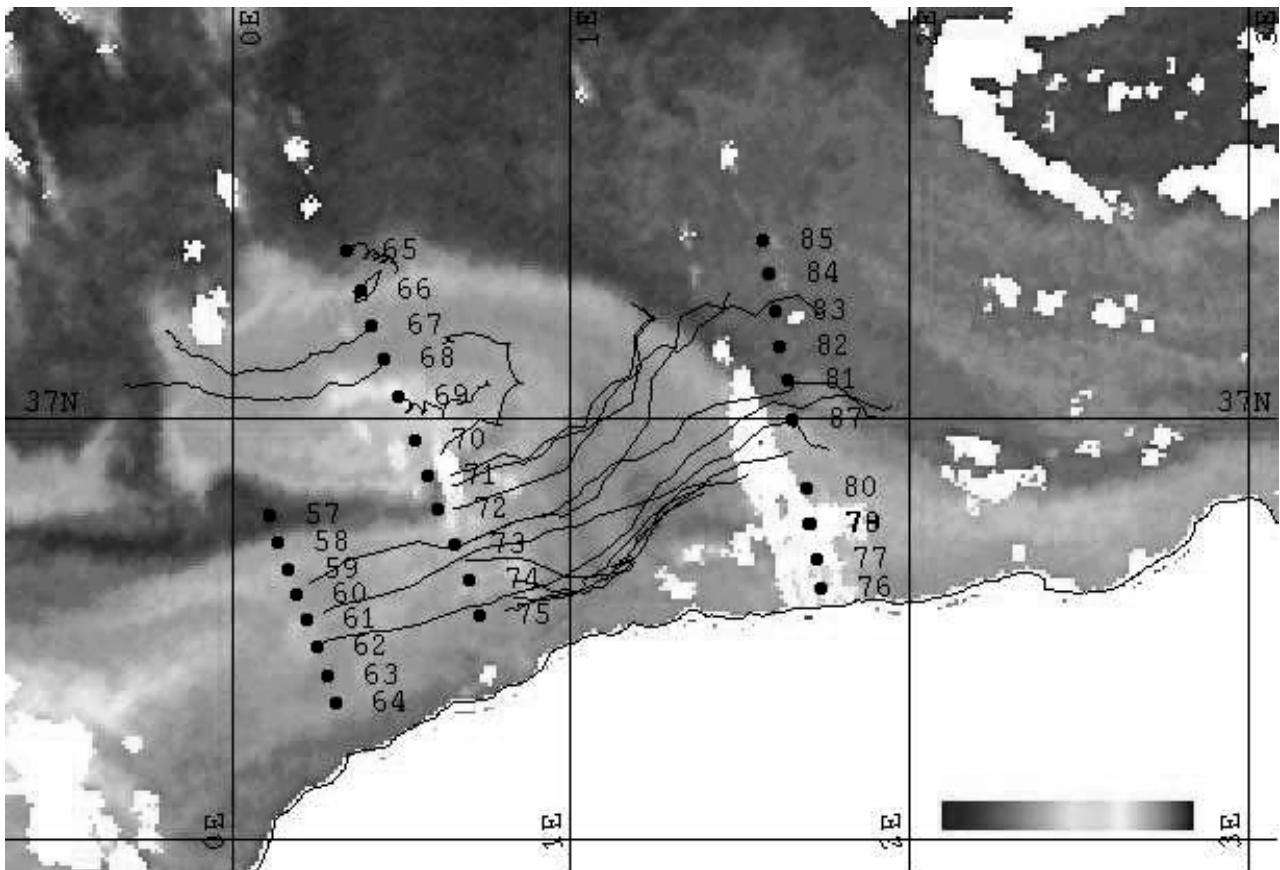


FIG. 1. – NOAA AVHRR image of the ALGERS'96 area on 16 October 1996, with the location of several CTD stations and trajectories of the 18 Lagrangian drifters until 21 October. The trajectories illustrate precisely the alongslope current and its offshore displacement to contour the coastal anticyclonic motion appearing between 1° and 2°E, that was growing and slowly migrating eastwards. The six outer drifters followed the motion of the cyclonic eddy, that was rapidly deforming, elongating to the west.

of the main thermal gradients and hence the position of the boundaries of the evolving instability.

The deployment pattern and specific positions of the drifters discussed in this paper were derived from a coupled analysis of this satellite data and in situ underway measurements: surface temperature and salinity (SeaBird SBE21 thermosalinograph) and vertical profiles of temperature (expendable XBT probes Sippican T-7) and velocity (Acoustic Doppler Current Profiler RD Instruments VM0150).

During the early hours of 17 October 1996, the A104 drifters were launched at three consecutive hydrographic stations, five nautical miles apart, in the core of the Algerian current upstream from the coastal instability (see Fig. 1 and Table 1). It was planned to leave these drifters at sea for a few days for small scale measurements related to the evolution of the coastal structure, and recover them before the end of the cruise. Because of an unexpected reduction of cruise length due to technical problems, the drifters were not recovered and they were

left to drift till the end of their battery life. The following day (18 October), the 15 A111 drifters were released at intervals of 5 miles, or 2.5 miles in the core of the current, along a straight line across the coastal current and the centre of the well developed cyclonic part of the instability, offshore the meander (Fig. 1 and Table 1). The shipboard satellite receiving station, when receiving NOAA data, could retrieve the positions of the ARGOS transmitters located by the satellite during each overflight. In this manner, the drifters trajectories were tracked throughout the cruise. After the cruise, a daily on-line access to the ARGOS system was used to derive the complete trajectories of the drifters.

The drifters experiment was planned to last 12 months, and the batteries of the instruments (except for the three A104) were sufficient for the platforms to transmit during 400 days. However, they ceased to transmit much more rapidly than expected, in most cases near the coast. We believe the high failure rate in these regions was due to the instruments,

TABLE 1. – Deployment information and last localisation for the three A104 (ID 20700 series) and the 15 A111 (ID 18700 series) Lagrangian drifters used for the experiment

Drifter PTT ID	Launch date	Time	Launch position (N-E)	End position (N-E)	End date	Days tracked
20779	17/10/96	02:52	36.61-00.22	37.13-11.24	18/11/96	31
20780	17/10/96	04:06	36.52-00.22	36.78-02.02	24/10/96	6
20781	17/10/96	05:48	36.45-00.25	36.73-02.67	26/10/96	8
18724	17/10/96	20:53	37.39-00.34	38.08-14.45	18/02/97	124
18723	17/10/96	22:58	37.30-00.38	36.70-01.97	11/11/96	24
18715	18/10/96	02:01	37.21-00.41	32.53-14.65	31/03/97	165
18717	18/10/96	03:42	37.13-00.44	36.95-11.11	30/01/97	104
18725	18/10/96	06:44	37.04-00.49	37.21-09.18	02/12/96	45
18719	18/10/96	09:01	36.93-00.55	38.76-07.16	24/12/96	67
18722	18/10/96	12:20	36.86-00.63	38.10-12.70	12/01/97	86
18718	18/10/96	12:40	36.83-00.62	37.46-07.22	13/01/97	87
18721	18/10/96	14:49	36.78-00.64	37.66-12.51	07/01/97	81
18716	18/10/96	15:39	36.74-00.64	36.94-01.14	19/10/96	1
18727	18/10/96	18:08	36.70-00.67	37.03-06.31	01/12/96	44
18713	18/10/96	18:30	36.66-00.67	35.84-14.54	14/03/97	147
18714	18/10/96	19:58	36.62-00.70	37.03-08.92	03/12/96	46
18726	18/10/96	20:18	36.57-00.71	43.20-10.53	18/02/97	123
18720	18/10/96	20:39	36.53-00.73	37.14-04.36	18/11/96	31

or at least their antennae, being damaged on reaching the shore line. The life lengths of the 18 drifters span from 1 day to 5.5 months, as also detailed in Table 1. After the last position indicated in the table, drifter #18715 still continued to transmit for an addi-

tional eight weeks near the coast of Libya, but the localisations were scarce and were of poor quality. Figure 2 presents the whole set of drifters trajectories from their release points near 0° - 1° until their last ARGOS localisation.

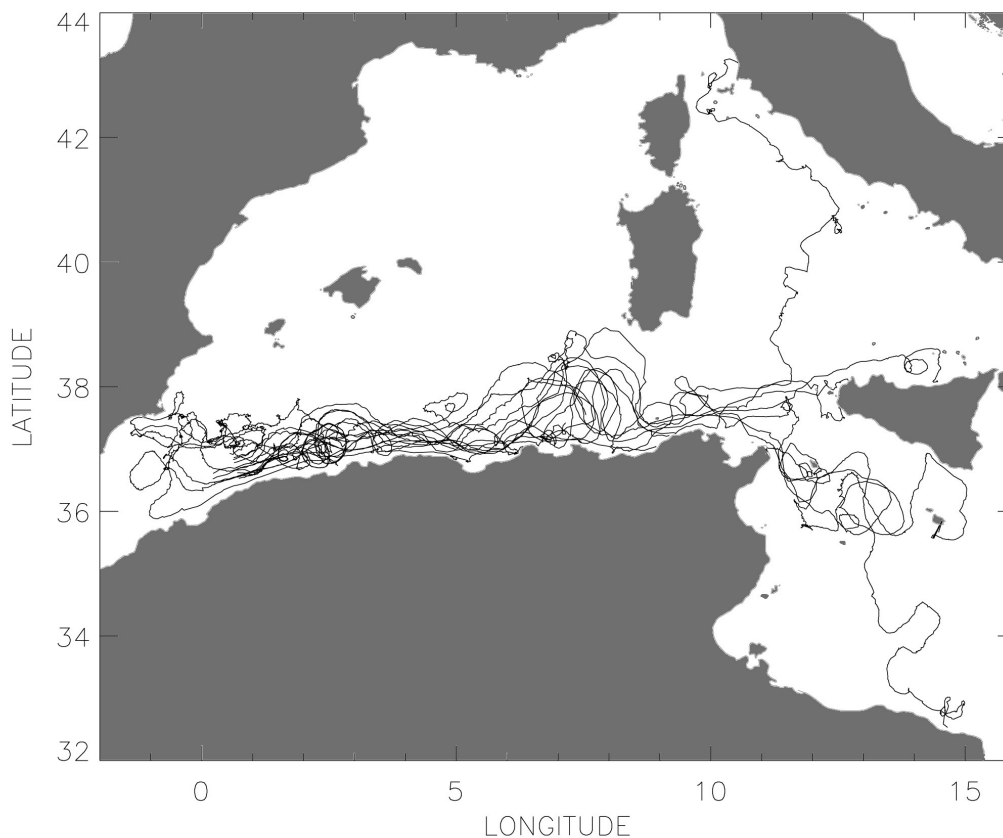


FIG. 2. – Complete trajectories (consecutive ARGOS locations) for all the Lagrangian drifters from October 1996 to March 1997. The release zone is between 0° and 1°E, 36°30' and 37°30'N, near the western limit of the Mediterranean area included in this figure.

RESULTS AND DISCUSSION

The experiment strategy was to deploy the Lagrangian drifters in an area influenced by the MAW jet outflowing from the Alboran Sea, and then to track them as they drifted about the Mediterranean basin (Fig. 2). Besides characterising the mesoscale motion in the Algerian basin, the information would be used to study the MAW drift at large scale. An analysis of several portions of drifters trajectories in conjunction with satellite infrared imagery is being completed, in a separate study (Salas *et al.*, 1998), as a first contribution to the primary objective of the experiment, the mesoscale circulation study.

The first relevant result to be noticed in Figure 2 is that all of the drifting buoys drifted eastwards in the southern part of the Algerian basin. This included those that were deployed in the cyclonic part of the meander and that initially drifted to the west almost reaching the Spanish coast. In spite of the strong mesoscale variability, as indicated by the numerous loops in the individual tracks (Fig. 3), none was deflected to the north. We conclude therefore, that there was no widening or smoothing of the Algerian Current during the period of the experiment. We further conclude that no portion of the recent MAW went directly to the Balearic basin due to mesoscale motion. In essence, all the surface water that was leaving Alboran in October 1996 flowed to the east and with at least a portion reaching the Sardinia Channel by the end of December at a mean speed of almost 10 km/day.

The drift pattern disclosed by these 1996 drifter trajectories is very different from the one observed in an earlier drifter experiment in the same area (Millot, 1991). In June 1986, four surface floats were released in the Algerian Current (1°50' and 4°E) and, after drifting eastward, were abruptly entrained to the north near 5°E. None of these 1986 drifters progressed east of 5°40', and all either ceased transmission in the Algerian basin or reached the Ligurian Sea after drifting between the Balearic islands. This disruption of the alongslope flow indicated by these 1986 drifter trajectories appears to have been related to a big offshore anti-cyclonic eddy noted by concurrent satellite images and current measurements. The joint analysis of both Lagrangian data sets supports the hypotheses that the presence of recent MAW in the Balearic area (Font *et al.*, 1988; Pinot *et al.*, 1994) has to be due to the interaction of the alongslope Algerian Current with energetic mesoscale eddies, as documented by López-García *et al.* (1994) and other satellite imagery sets, and not to a permanent branching of the current from its beginning. A similar explanation could account for the presence of MAW in the western Corsican Current.

All these facts emphasize the need for an effective implementation of mesoscale motion (eddy-resolving) in the Mediterranean general circulation models, to reproduce a realistic time evolution of the main features and to find dynamic explanations for the mean current-eddy interactions.

Another relevant result of our experiment is that all the drifters that crossed the Sardinia Channel,

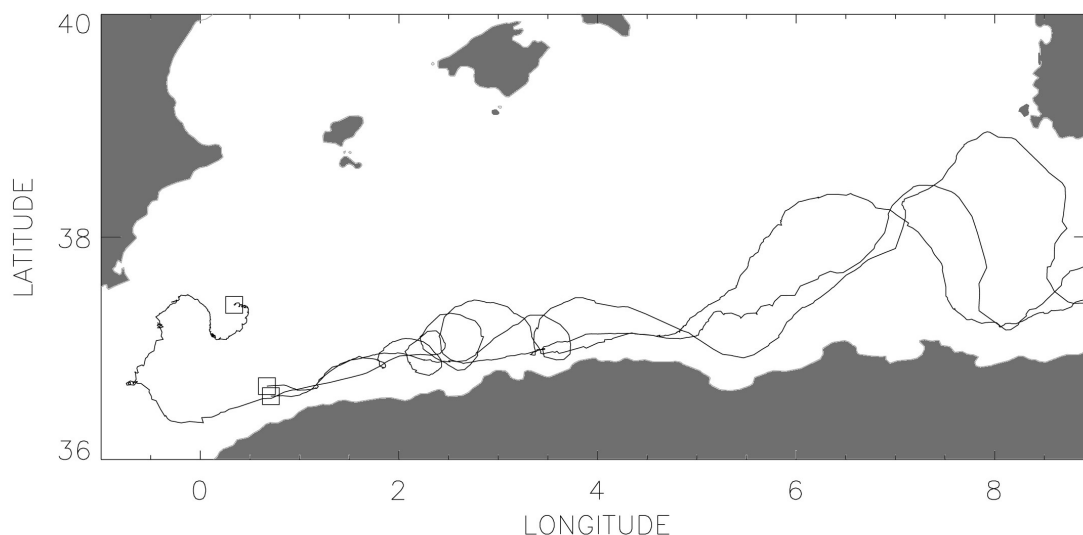


FIG. 3. – The trajectories of three of the ALGERS'96 drifters from their release location until they crossed the Sardinia Channel show how, despite any mesoscale perturbations, the net MAW drift is to the east along the Algerian coast.

the seven of them that were still transmitting after the first week of January 1997, did so close to the Tunisian coast. That is, the Algerian current was still an alongslope flow at that longitude (9° E), after having been subject to intense eddy motion southwest of Sardinia (Salas *et al.*, 1998). This situation is similar to the one that has been recorded for several months in 1993-94 during the first phase of the Mediterranean Targeted Project (Bouzinac *et al.*, in press).

All these surviving Lagrangian drifters continued eastwards as far as the Strait of Sicily, where two of them went ashore on the westernmost coast of the island. Three other drifters passed through the strait into the eastern Mediterranean, and finished their trajectories in different locations of the western Ionian sea after having initially circulated following a southeastward path. This coincides with what Moretti *et al.* (1993) describe as a jet-like meandering flow in an analysis of several years of hydrographic data, and with trajectories of Lagrangian drifters released in several occasions in this region (Poulain, 1998). The remaining two drifters meandered into the Tyrrhenian sea, indicating a high variability of the MAW flow in the entrance of the strait. One of them initiated a cyclonic path along the slope, but went ashore in the north-eastern coast of Sicily. The last one crossed the southern Tyrrhenian and then followed the Italian peninsula slope as far north as the Corsican Channel (Fig. 2).

The complete trajectories are now offered to the whole MATER community through the MATER www server (<http://www.cetiis.fr/mtp/mater/>), and can be used by the different teams working in the Algerian, Tyrrhenian and Ionian regions.

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