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Algerian Eddies lifetime can near 3 years

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Abstract

The Algerian Current (AC) is unstable and generates mesoscale meanders and eddies. Only anticyclonic eddies can develop and reach diameters over 200 km with vertical extents down to the bottom (~ 3000 m). Algerian Eddies (AEs) first propagate eastward along the Algerian slope at few kilometers per day. In the vicinity of the Channel of Sardinia, a few AEs detach from the Algerian slope and propagate along the Sardinian one. It was hypothesized that AEs then followed a counter-clockwise circuit in the eastern part of the basin. Maximum recorded lifetimes were known to exceed 9 months. Within the framework of the 1-year Eddies and Leddies Interdisciplinary Study off Algeria (ELISA) experiment (1997–1998), we exhaustively tracked two AEs, using mainly an ~ 3-year time series of NOAA/AVHRR satellite images. We show that AEs lifetimes can near 3 years, exceeding 33 months at least. We also confirm the long-lived AEs preferential circuit in the eastern part of the Algerian Basin, and specify that it may include several loops (at least three).

Keywords: Algerian Current; Mesoscale; Eddies; Remote sensing; NOAA/AVHRR

1. Introduction

The Algerian Basin is a key-area for the general circulation of water masses in the Western Mediterranean (see Millot, 1999 for a review). The Algerian Current (AC), named as the flow of Modified Atlantic Water (MAW), along the Algerian slope, is unstable. The general structure of an AC instability, as far as MAW is concerned, is depicted from the available in situ and laboratory experiments as rather complex (Obaton et al., 2000). Basically, instead of flowing steadily alongslope, the AC meanders. Part of the MAW then recirculates inside the meander, so that a surface anticyclonic eddy is created, embedded between the crest of the meander and the continental slope. Transient (few days) surface cyclonic circulations (CC) are also frequently observed on satellite images upstream from the meander crest, and have been evidenced in situ by drifting buoys trajectories (Font et al., 1998a) and hydrology (Moran et al., 2000). However, only anticyclonic eddies can develop, and given in this paper are the generic name of Algerian Eddies (AEs). The generation of AEs is observed from ~ 0° to ~ 8°E. AEs trajectories begin with an alongslope-downstream propagation at few kilometers per day, while within their embedding meander, the water typically flows at ~ 50 km/day. AEs diameters vary during their course between 50 and 150 km up to ~ 250 km. AEs lifetimes range from few weeks to several months. The maxima reported up to now are at least 6 months, with in situ observations (Millot et al., 1997), and at least 9

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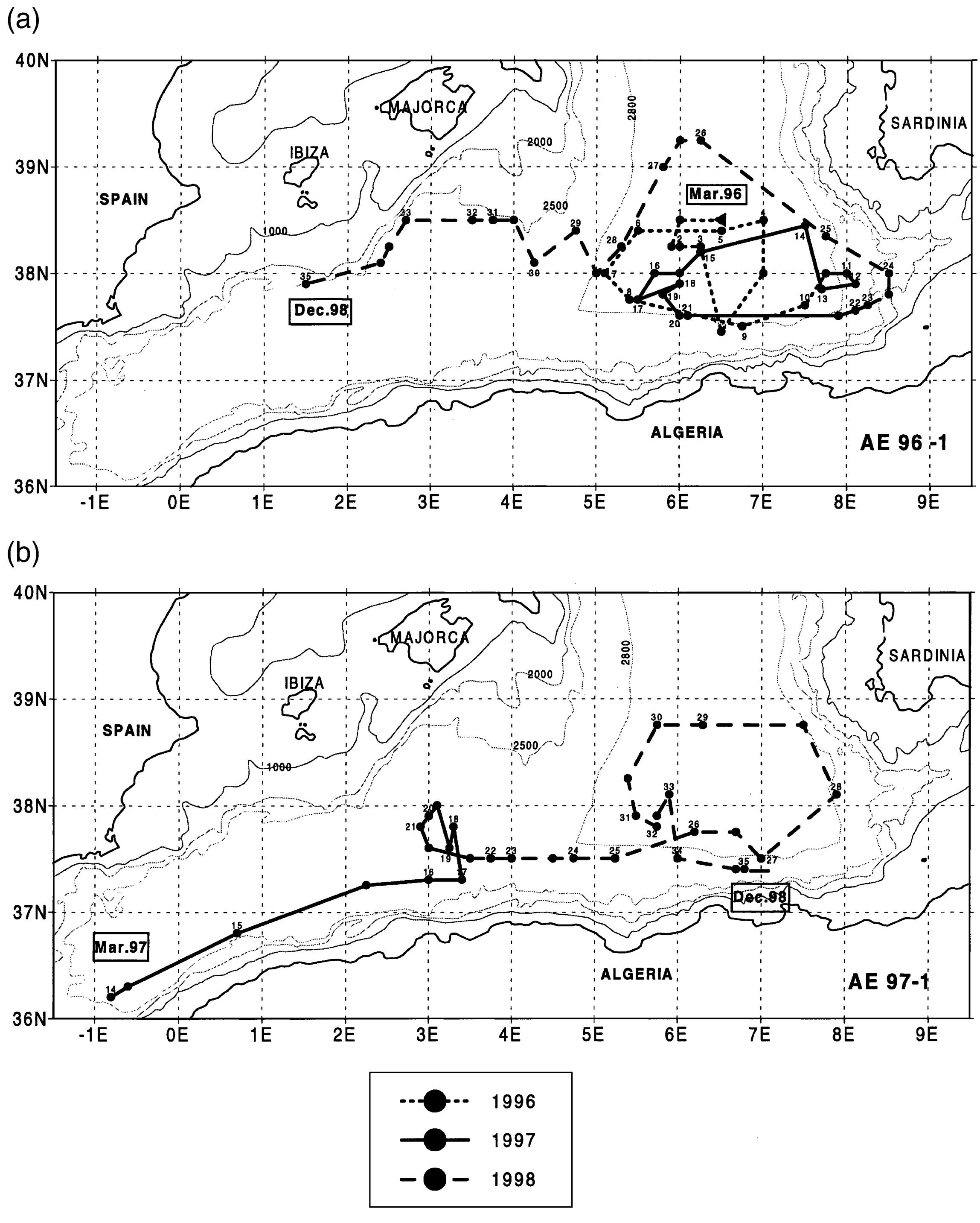


Fig. 1. Trajectories of Algerian Eddies: (a) 96-1, (b) 97-1, in 1996 (dotted line), 1997 (solid line), and 1998 (dashed line). Numbers refer to images on Plate 1. Bathymetry in m.

months, with satellite images (Taupier-Letage and Millot, 1988).

The AEs alongslope-downstream propagation usually ends in the Channel of Sardinia, where AEs dramatically interact with the bathymetry (see Fig. 1). Most of them (the less energetic?) collapse and release MAW that continues to flow through the channel (Sammari et al., 1999). A few AEs per year (the most energetic? called "events" by Millot et al., 1997) follow the deep isobaths northward across the channel and detach from the Algerian slope, which implies a deep structure. It is now confirmed that these AEs can be anticyclonic coherent structures down to the bottom (~ 3000 m, Ruiz et al., 2002). Additional complexity arises, however, from recent observations showing that this vertical coherence down to the bottom is not permanent (ELISA data, unpublished). AEs detached from the Algerian slope then drift northward along the Sardinian one, as confirmed by Vignudelli (1997), Iudicone et al. (1998), and Bouzinac et al. (1998). Before reaching ~ 40°N, AEs detach from the Sardinian slope and propagate in the open basin (where an AE was sampled for the first time by Katz, 1972). Some AEs come back eventually close to the Algerian slope, where they interact with their parent current. The pooling of several-month-long trajectories of different AEs on different years led Fuda et al. (2000) to hypothesize a preferential counter-clockwise circuit in the eastern part of the Algerian Basin. Now, interactions between the AC and AEs, and/or between AEs themselves, can substantially modify this general scheme. This leads, e.g. to offshoreward deviation of the AC path or of upstream AEs, to the interruption of the AEs alongslope-downstream propagation, up to AEs destruction (Taupier-Letage and Millot, 1988).

The relative complexity of the mesoscale phenomena and the important variability associated with AEs explain why the Algerian Basin, a key-place for the circulation of the water masses in the Western Mediterranean, is paradoxically poorly known for such a close area. This dictated, within the framework of the European program MAST-3 MAss Transfer and Ecosystem Response (MATER), the Eddies and Leddies Interdisciplinary Study off Algeria experiment (ELISA) in the eastern part of the basin (Taupier-Letage et al., 2001). Intensive field work was carried out between July 1997 and July 1998, involving the 1-year deployment of a nine-mooring network and four main cruises. ELISA's aims were to study (1) the general circulation of the water masses, (2) the origin, structure and trajectories of AEs, (3) the biological response associated to mesoscale dynamical phenomena, and (4) the biological consequences of the mesoscale activity on the functioning of the Algerian Basin. It was thus of the utmost importance to know the history and trajectory of the AEs sampled. The aim of this paper is to present the results of the thorough NOAA/AVHRR satellite images analysis from early 1996 to late 1998 that we conducted, in order to achieve AEs tracking. The methodology is briefly described in Section 2. The main results about AEs lifetime and preferential trajectory are detailed in Section 3, and we take this opportunity to further document and characterize AEs. In Section 4, we point out questions raised by these results.

2. Method

The most efficient (and cost-effective) way to track AEs over long term is to use satellite data such as images from NOAA/AVHRR thermal infrared channels, as they provide a spatio-temporal cover (~ basin and ~ day) adequate to study such mesoscale phenomena[1] (e.g. Arnone and La Violette, 1986; Le Vourch et al., 1992). The complementary use of altimeter data (from ERS and TOPEX/POSEIDON, e.g. Ayoub et al., 1998; Iudicone et al., 1998) helps to fill the gaps when cloud cover is important, and when thermal gradients weaken, as the temperature difference between MAW and resident water reverses by springtime and fall.

Previous studies have shown the coherence between AEs signatures on satellite images and contemporaneous in situ observations, definitely validating the use of satellite superficial signatures to track AEs (e.g. Millot, 1991; Millot et al., 1997; Benzohra and Millot, 1995a,b; Font et al., 1998a,b; Bouzinac et al., 1999; Sammari et al., 1999; Fuda et al., 2000). In order to

[1] Ocean color satellites such as SeaWiFS are also extremely efficient, however, image processing is more complex and availability is more problematic.

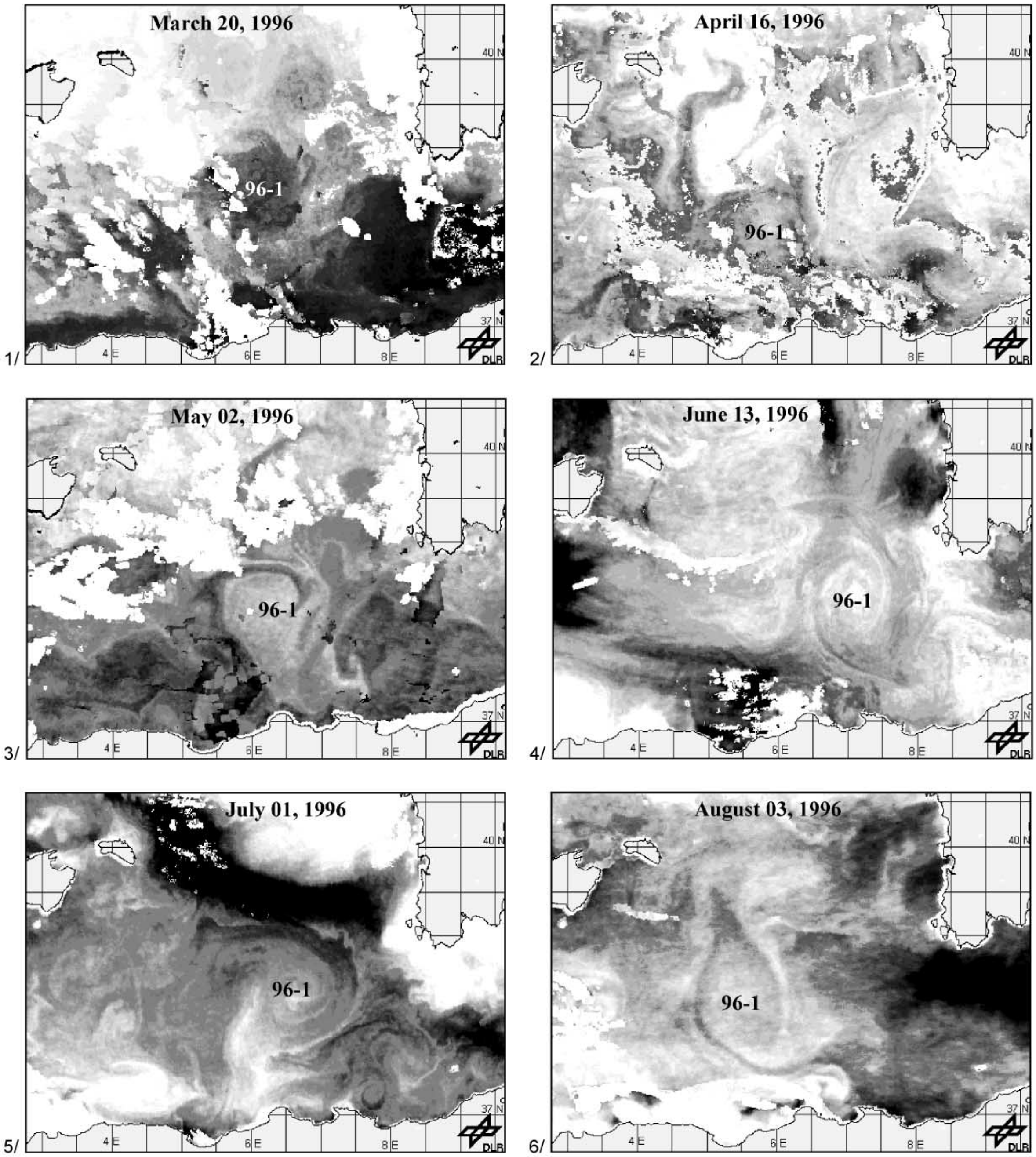
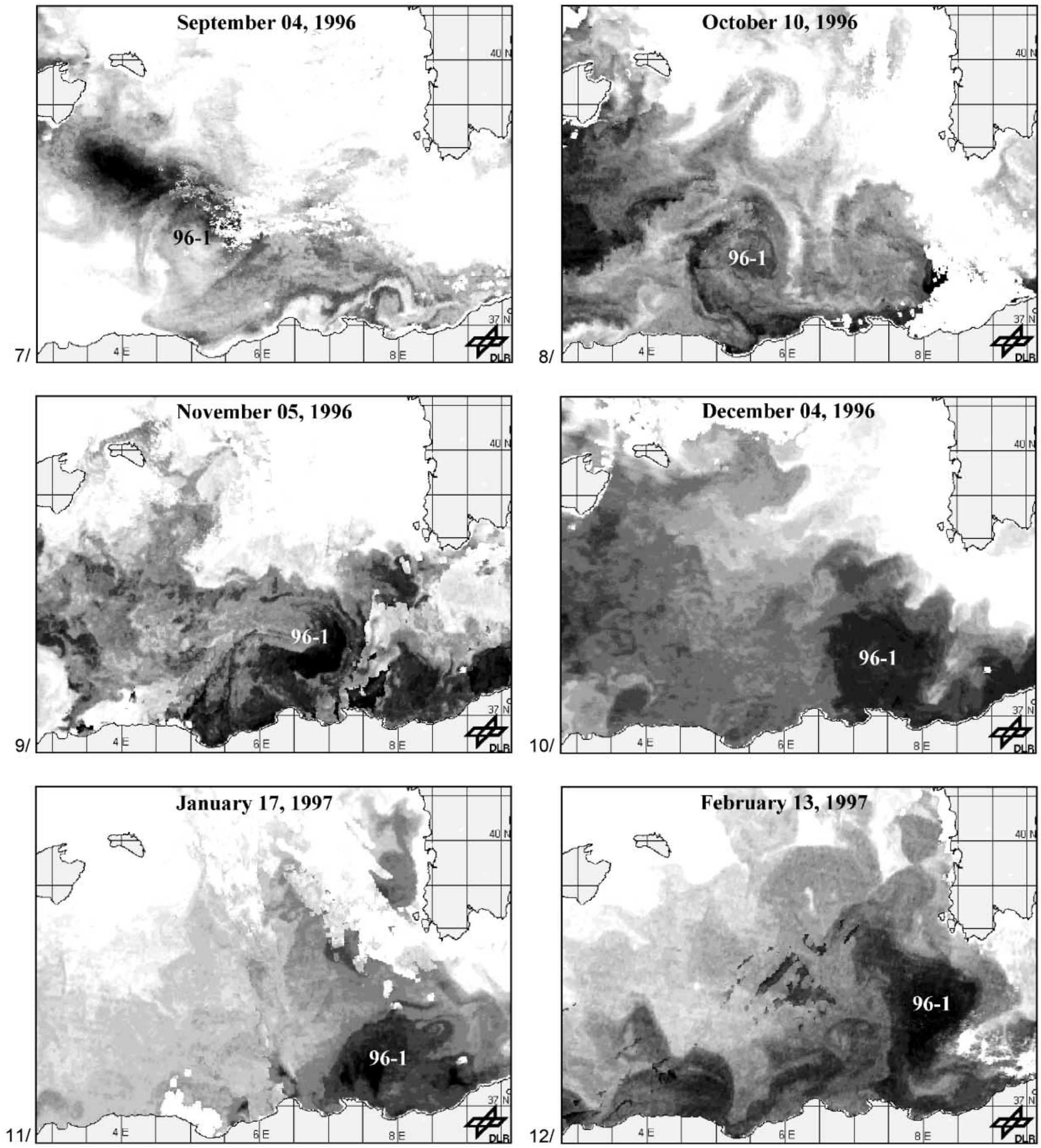


Plate 1. (1–35): NOAA/AVHRR images time series showing the AEs 96-1 and 97-1 successive positions. Contrast is specifically adjusted for each image so that greyscales are not to be compared. Temperature increases from white to black.



identify AEs throughout time and papers, we will use a notation close to that used for the Gulf Stream rings, associating the year the AE appeared with an incrementing number. In an ideal situation, numbers correspond to the rank the AEs appeared. However, as it is unlikely that any exhaustive study of all contemporaneous AEs will be performed, only those AEs picked up for specific features will be numbered.

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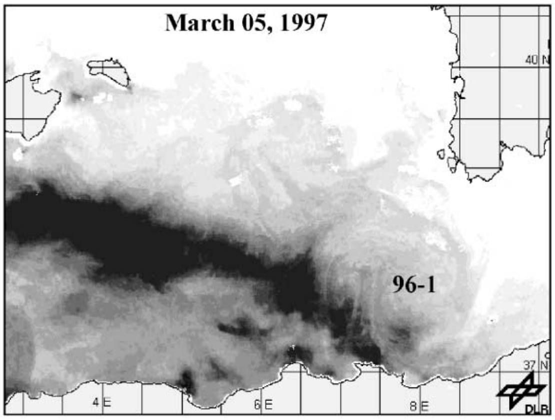

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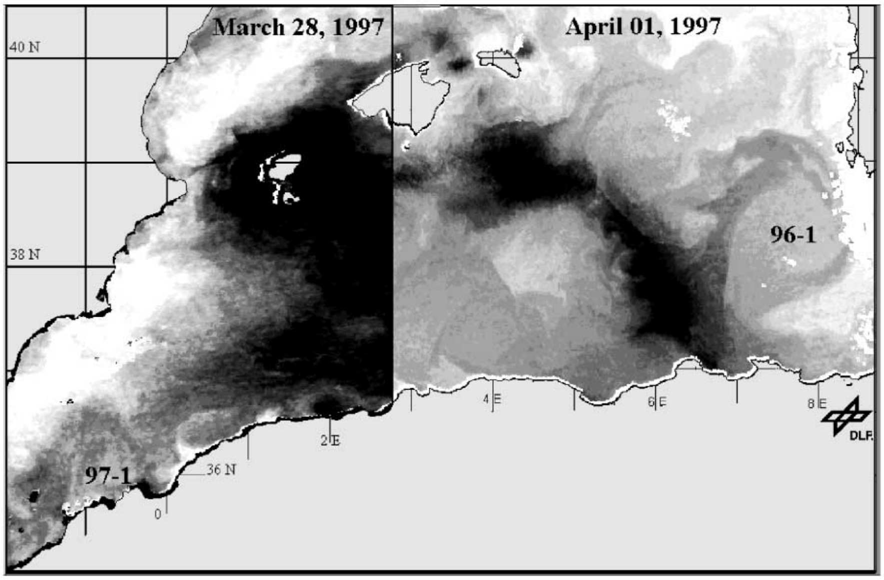

Plate 1. (1-35) (*continued*).

We used NOAA/AVHRR Sea Surface Temperature (SST) daily composites from February 1996 to late December 1998 from the ISIS DLR data base, and NOAA/AVHRR channel 4 (brightness temperature) images (three to six passes per day) from late June 1997 to late December 1998. As no automatic method is available so far to track AEs automatically (most often, there is no thermal gradient associated with the AC, and the AE signature is only partially visible; see details Taupier-Letage et al., 1998), position and diameter estimates were deduced from the visual analysis of AEs thermal signatures. AEs tracking was backed with TOPEX/POSEIDON/ERS Sea Level Anomalies (SLA) maps from January 1998 to early 1999, as well as with the ELISA currentmeter time series on the nine moorings from mid July 1997 to early July 1998. The variability of the AEs thermal signatures, added to the seasonal temperature reversal of the water masses (see Section 3.6), prevents from keeping a constant color to temperature palette. Hence, contrast was adjusted specifically for each image, and colors are not to be compared between images.

Due (i) to the amount of satellite data (more than 2000 AVHRR images and 350 SLA objectives analyses) and (ii) to the duration of the survey, we restrict illustration to ~ 1 image/month (Plate 1), and pro-

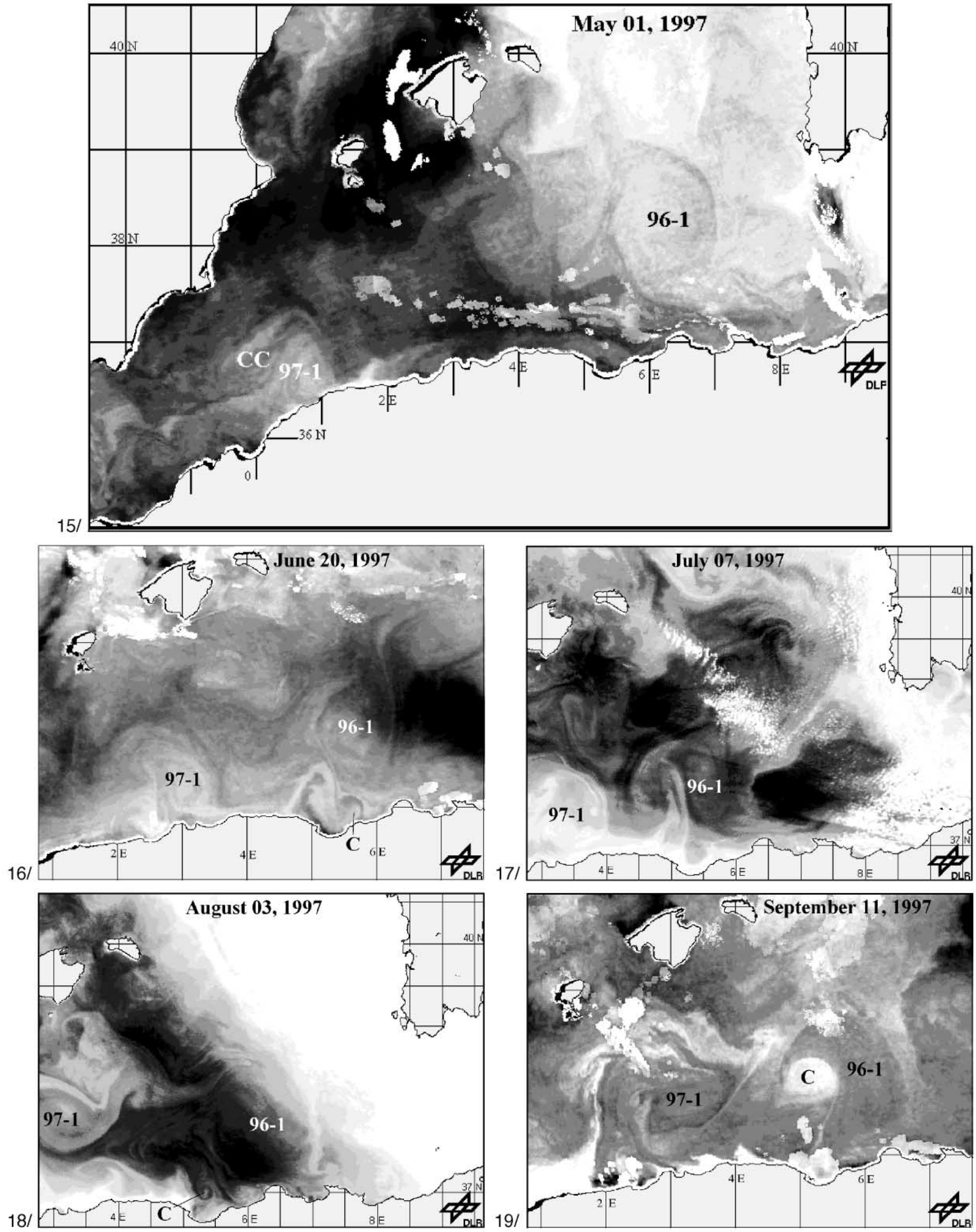

Plate 1. (1-35) (*continued*).

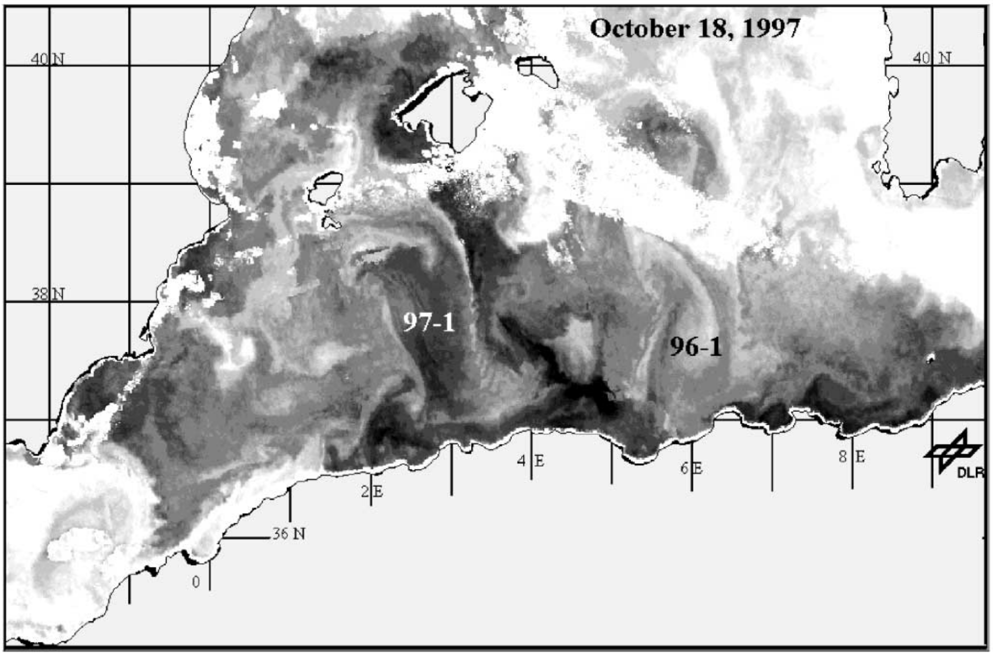

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Plate 1. (1-35) (*continued*).

vide monthly (at least) positions with trajectory schematics in Fig. 1.

3. Observations

Two AEs, called 96-1 and 97-1, dominated the eddy field during the ELISA period and have been thoroughly tracked during most of their lifetimes. Other AEs have been temporarily tracked, for instance when in the vicinity of, or interacting with, 96-1 and 97-1, but will not be detailed here.

As discussed in Section 3.1, we think that the image time series presented in Plate 1 is self-explanatory, so that a tedious chronological description of AEs positions (Fig. 1) can be avoided. Now, we take benefit from this time series to further document different phases and aspects of AEs' life.

3.1. Lifetimes

We could definitely track the AE 96-1 from early March 1996 (earlier positions could not be determined with confidence, since cloud cover was important and no altimetric data were available to us). At that time (Plate 1:1), 96-1 was already located offshore, which means that it was independent from an AC meander, and hence, most probably several months old. It has been tracked till December 1998 (Fig. 1a). As confirmed by both altimetric (not shown) and thermal vanishing signatures, it was decaying, appearing as warmer water swirls South of Ibiza (Plate 1:35). This yields a lifetime exceeding 33 months. 97-1 has been tracked from late March 1997, when it was a few days old (Plate 1:14) in the AC, till the end of December 1998 along the Algerian slope in the vicinity of the Channel of Sardinia (Plate 1:35, Fig. 1b). This yields a lifetime exceeding 21 months (tracking was interrupted only because no more data were available to us). Among the few other AEs we tracked, lifetimes ranged from 3 to 13 months.

3.2. AC instability

On Plate 1:15, 97-1 displayed the classical features of a recent AC instability, with a well-developed surface cyclonic circulation (CC). About 1 month later, the cyclonic circulation had decayed (Plate 1:16). The continuity between the AC meander flow (leaving the coast near 2°–2°30′ E and coming back

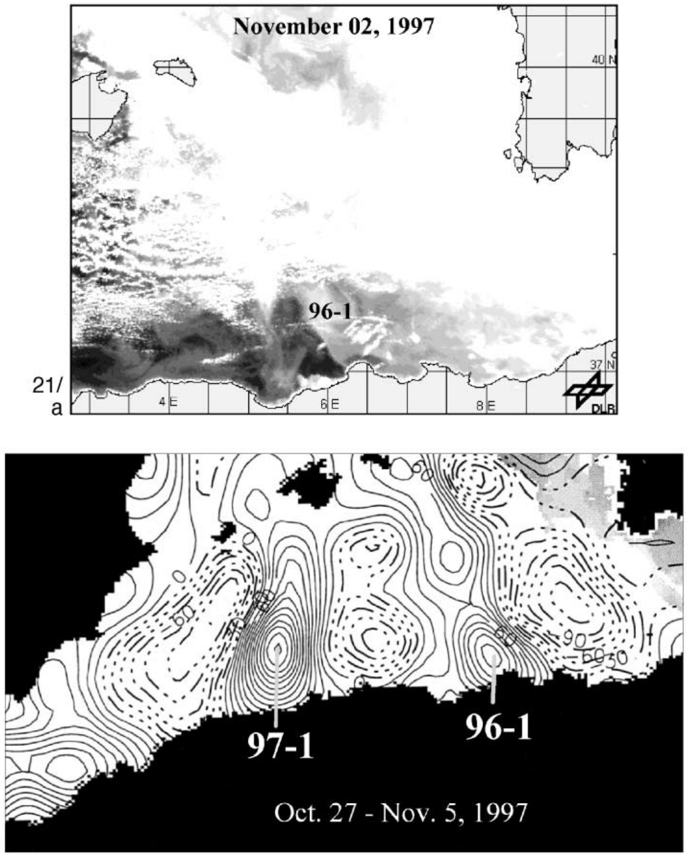


Plate 1. (21) (a) NOAA/AVHRR image. (b) Sea Level Anomaly (SLA) map (courtesy of P.-Y. Le Traon). Solid lines indicate positive SLA, corresponding to anticyclones.

alongslope near ∼ 3°30′ E) and the recirculating part that defined 97-1 appeared extremely clear. About 3 months later (Plate 1:19), the meander size had increased. The meander no longer came back straight alongslope downstream from 97-1, due to interactions with 96-1. Thermal signature continuity suggested that part of the AC water was skirting 96-1 offshore before coming back shoreward near ∼ 7°E, that is downstream from 96-1, in a paddle-wheel-like effect. An analogous situation happened on Plate 1:26, when part of the meander flow embedding 97-1 was relayed northward by 96-1.

Individualizing the AC meander water from the basin resident one, however, is generally not easy, especially as mixing on edges can weaken thermal difference. Moreover, as water is upwelled where the meander leaves the slope, cooler inside-spiraling isotherms clearly materialize the recirculation, so that the most visible part of an AC instability — when not the only one — is usually the embedded eddy (e.g. 98-2 in Plate 1:29). Considering that open-sea AEs can come back subsequently along the Algerian slope, it is thus most often impossible, using thermal signatures on short term only, to discriminate between embedded AEs and open-sea ones.

3.3. Trajectories

Pooling all observed trajectories yields what we regard as the AEs preferential path. AE generation occurs along the Algerian slope. In most cases, it is in the western part of the basin, such as 97-1 near 0° (Plate 1:14), but it can also be further east, as in the case of 98-2 generated early May 1998 near 5°–5°30′ E. Then, AEs propagate eastward alongslope (3–5 km/day), as shown by 97-1 positions on ∼ 1°E

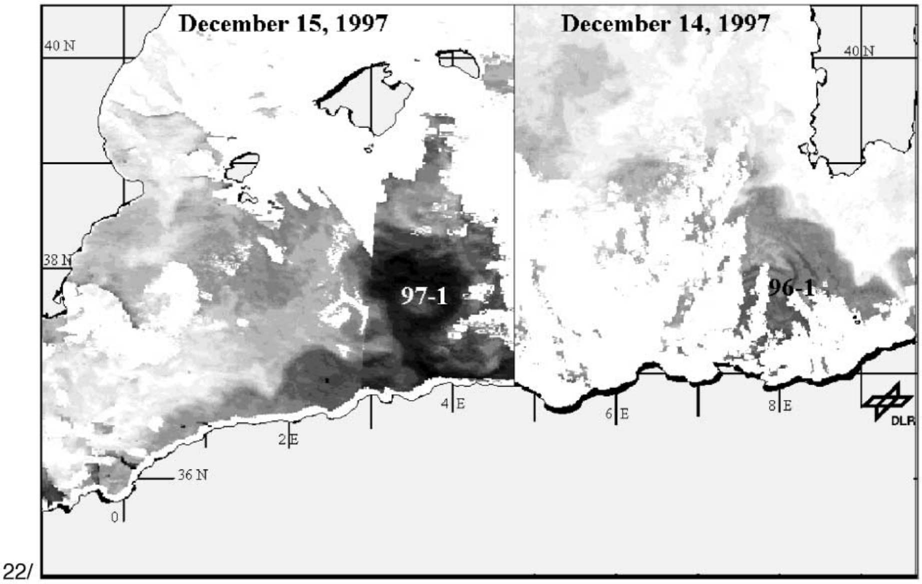


Plate 1. (1-35) (*continued*).

in May 1997 (Plate 1:15) and on ~ 3°E about 1 month and a half later (Plate 1:16). AEs can also remain without propagating for months, as 96-1 between early July and late October 1997 (Plate 1:16–20; Fig. 1a), and 97-1 between early July and early December 1997 (Plate 1:17–22; Fig. 1b). The use of the SLA maps (Plate 1:21-b) during this period enabled in most cases to track AEs even during cloudy periods. At the entrance of the Channel of Sardinia, a few AEs detach from the Algerian slope. Then, they propagate along the Sardinian slope (96-1 on Plate 1:23–25, 97-1 on Plate 1:27–29). Before reaching ~ 40°N, AEs detach from the Sardinian slope and drift in the open basin (96-1 on Plate 1:25–26, 97-1 on Plate 1:28–29). From Fuda et al. (2000) and these ~ 3-year observations, it seems that AEs preferentially come back to the Algerian slope, and preferentially near ~ 5–6°E (Fig. 1). AEs thus describe a counter-clockwise circuit in the eastern part of the basin. This circuit possibly includes several loops: 96-1 described at least three loops, 97-1 described at least one.[2] Due to such a path, different eddy fields can appear similar. This was the case of the 3-month-apart Plate 1:26 and 29: the two AEs aligned on a North–South axis were 96-1 and 97-1 in the former, and 97-1 and 98-2 in the latter.

Now, due to interactions with the AC or with other AEs, departures from this general scheme are observed, for instance early detachment from the Algerian slope. This was the case of the AE 98-1 (not shown) sampled during the ALGERS-98 campaign (Ruiz et al., 2002), which described a shorter counter-clockwise circuit in the western part of the basin. As well, the looping scheme can stop: 96-1 for example went drifting to the northwest and reached the Balearic slope by summer 1998 (Plate 1:26), where its trajectory seemed then closely constrained by the bathymetry.

3.4. AEs diameter and drift speed

AEs diameter varies during their course, as shown by 97-1 between Plate 1:16 (~ 110 km), 19 (~ 170 km), 25 (~ 110 km), and 26 (~ 150 km). The entrance of the Channel of Sardinia seems to be a critical place in this regard. This region is a barrier for large and deep AEs, which often remain there for a few months (Fig. 1a). Interactions with the bathymetry (northward-leading) and with the AC (eastward-lead-

[2] We have indications that 97-1 might have been undertaking another loop, as isolated images show a coherent AE signature near 7°30′ E on December 27, 1998, and near ~ 8°15′ E on February 21, 1999.

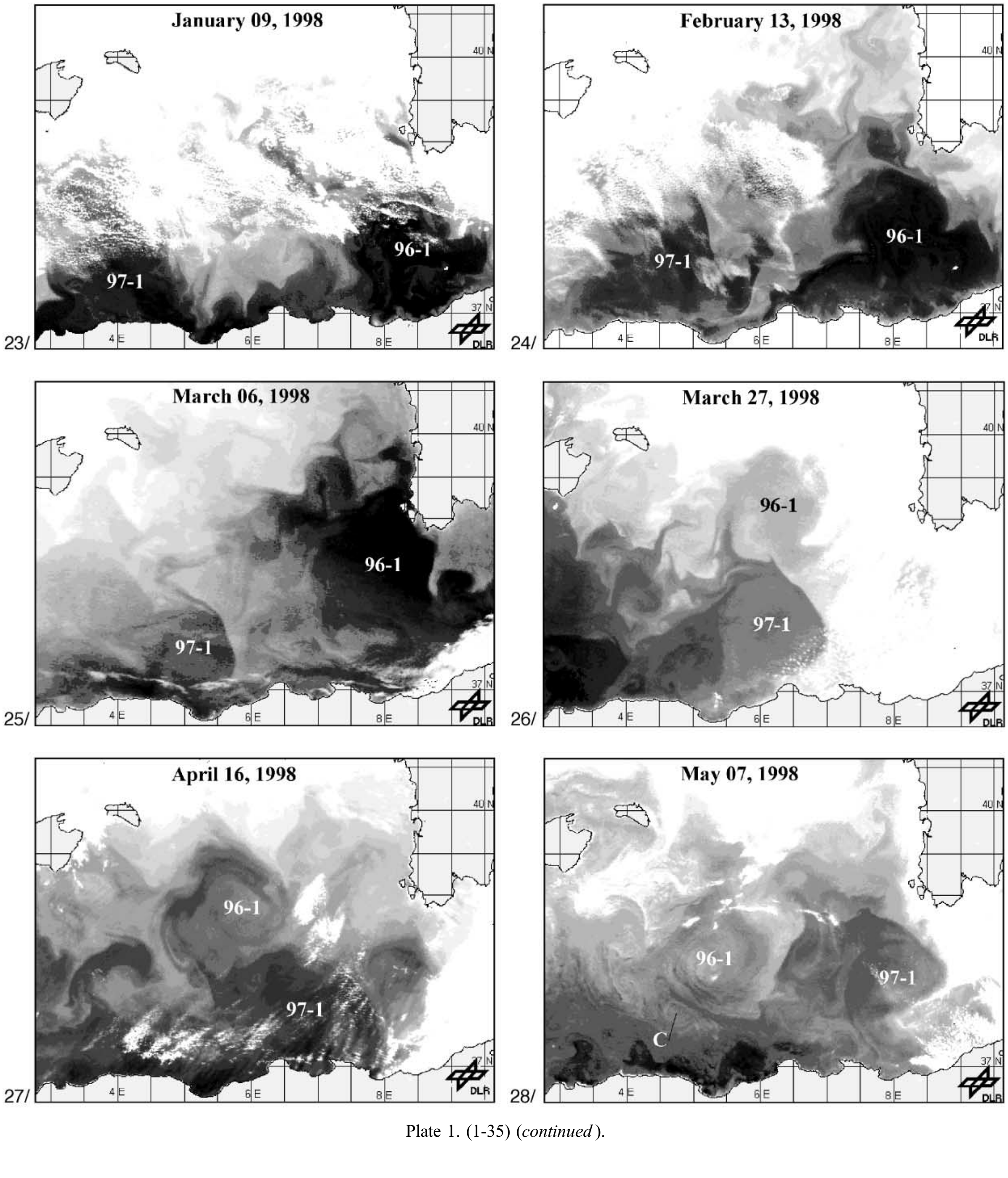


Plate 1. (1-35) (*continued*).

ing) result in dramatic changes of shape and diameter. Drift speed varies too, from the usual value of few kilometers per day to the seldom-recorded one of ~ 10 km/day observed for 96-1 during March 1998 (Plate 1:25–26, Fig. 1a). AEs can also remain there motionless, sometimes for months, as shown with the above-mentioned observations in the Channel of Sardinia and in Section 3.3.

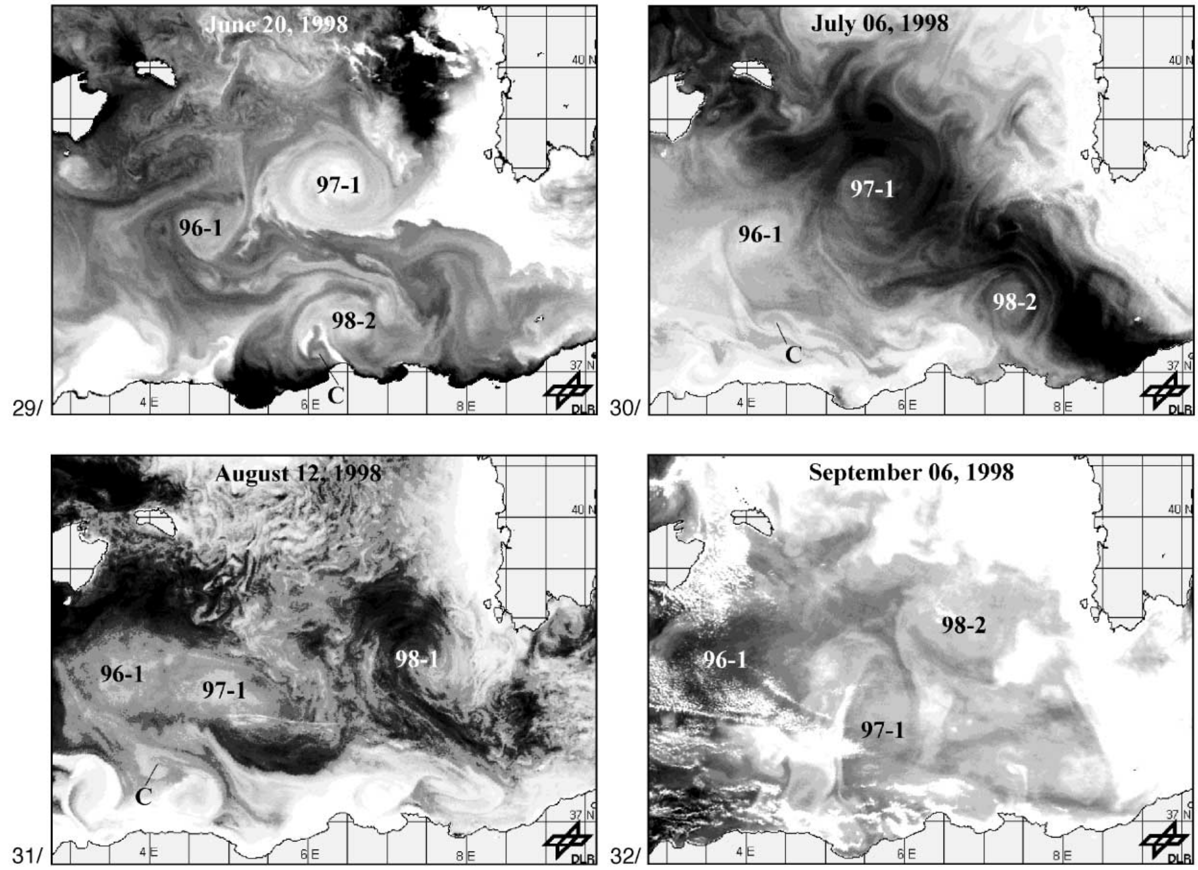


Plate 1. (1-35) (*continued*).

3.5. AE-induced secondary phenomena

When close to the Algerian slope, AEs interact with the AC. This results most often in the seaward spreading of recent MAW, as for instance on Plate 1:14 where MAW skirted around 96-1 before entering the Channel of Sardinia, in a paddle-wheel-like effect. Although the thermal signature of such AC–AE interactions is very close to that of an AC instability, mechanisms beyond are fundamentally different.

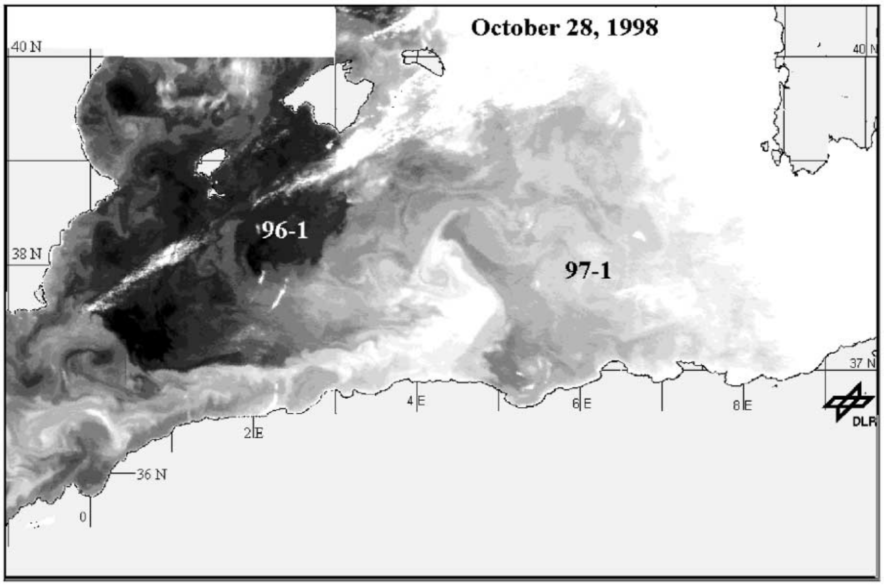
The shear induced by AEs either at coastline prominent breaks or between AEs sporadically generates small-scale shear cyclonic eddies ("C" on Plate 1:16, 18, 19, 28, 29, 31). The latter are usually a few tens of kilometers in diameter, and last only for a few days to a few weeks. On Plate 1:19, however, the shear eddy C is by far the largest we have observed up to now (diameter ~ 40 km, lifetime > 3 weeks).

3.6. Seasonal cycle of surface temperature

By late summer, surface resident water is much warmer than MAW. Hence, the AC appears colder (Plate 1:29, near 3–4°E), as well as the AEs signatures (Plate 1:29: 96-1, 97-1 and 98-2). Fall is usually the period of maximum thermal gradient, as shown by the intense AC signature on Plate 1:33. Now, in winter, MAW is warmer (~ 16 °C) than resident water (~ 13 °C), and the AC appears warmer on Plate 1:35, as well as AEs (e.g. Plate 1:23–25).

4. Discussion

Lifetime of AEs can thus reach unexpected length. Considering the 96-1 eastward and offshore position in March 1996, it is legitimate to infer a



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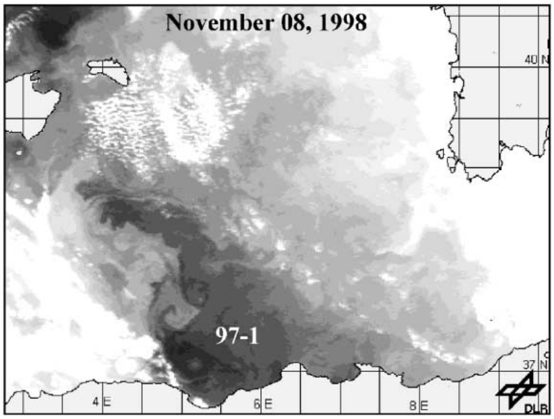

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Plate 1. (1-35) (*continued*).

lifetime of ~ 3 years at least. In the same way, as 97-1 was still very well signed by December 1998, it is legitimate to infer a lifetime of ~ 2 years at least. We see no objective reason to say that exceptional environmental conditions prevailed during this period, nor that 96-1 and 97-2 were exceptional AEs either. We even expect that further easy access to high temporal resolution satellite data (including ocean color), and additional thorough analyses, will allow to show that AEs maximal lifetimes do go beyond 3 years. Now, it is obvious that contemporaneous AEs must have shorter lifetimes. Indeed, as space is limited in the basin, such AEs persist at the expense of newly generated AEs: the number of simultaneous long-lived AEs must be limited to a very few. Why and how AEs can last for so long is beyond the reach of observations. Nevertheless, as isolated eddies cannot gain energy while energy is permanently available from the AC, we suspect that the frequent interactions between AC and AEs allow to transfer energy to the latter.

We can now be precise of the archetypal AE trajectory, from the AE generation in the western part of the basin to the entrance of the Channel of Sardinia, to one or more counter-clockwise loops in the eastern part of the basin. However, proper identification of

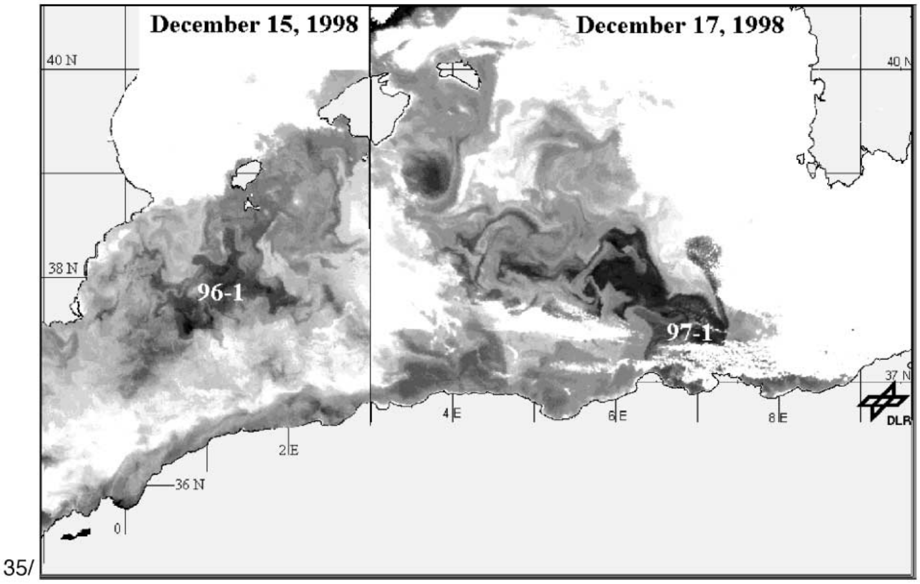

Plate 1. (1-35) (*continued*).

AEs definitely requires very high temporal resolution analysis and possibly cross-check with complementary data sets. Indeed, the variability of the AC signature precludes from discriminating between embedded and older AEs from isolated images only, as does the similarity between AC instability and AC–AE interaction signatures. Moreover, the variability of diameter, propagation speed, and trajectory may result in similarly looking eddy fields, actually involving different AEs. Together with the seasonal temperature difference reversal, these are further obstacles to automated AE detection and tracking methods. Some trajectory segments are clearly constrained by the bathymetry (along Algerian, Sardinian and Balearic slopes). Why open-sea AEs leave the Sardinian slope before reaching ~40°N and why they drift southward near 5–6°E is also beyond the reach of observations.

Few numerical studies of the AC have been elaborated. The most recent one (Gervasio et al., 2000) considers a more or less complex stratification with a rectilinear slope (vertical in its upper part and variable at depth) and a schematized basin. While the instability structure in the MAW surface layer (basically an anticyclone) is in pretty good agreement with both in situ and laboratory experiments (Obaton et al., 2000), there are marked discrepancies at depth (below the MAW layer down to the bottom): the numerical study simulates there an out-of-phase cyclone (i.e. the classical baroclinic structure), while the experiments depict an in-phase anticyclone. Other AEs characteristics, which are not correctly reproduced yet, are the fact that AEs detach preferentially at the entrance of the Channel of Sardinia, and the fact that the counterclockwise loop is generally closed by a southward segment. Now, issues such as AEs long lifetimes and, correlatively, AC–AE interactions, will also have to be addressed. AEs appear as a case study for interactions between observers and modelers.

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