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**Rapid subduction in
the deep North
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Mediterranean**

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An Acoustic Doppler Current Profiler (ADCP) moored at the deep-sea ANTARES neutrino telescope site near Toulon, France, measured downward vertical currents of amplitudes up to 0.03 m s^{-1} in spring 2006. The currents were accompanied by enhanced levels of acoustic reflection by a factor of about 10 and by horizontal currents reaching 0.35 m s^{-1} . These observations coincided with high levels of bioluminescence detected by the telescope. Although during winter 2006 deep dense-water formation occurred in this area, episodes of high levels of suspended particles and large vertical currents continuing into the summer are not direct evidence of this process. It is hypothesized that the main process allowing for particles to be moved across the entire water column (2500 m) within a few days, is local convection, triggered by small-mesoscale phenomena, such as meanders including a bipolar vortex, linked with boundary current instabilities.

1 Introduction

The ANTARES detector is designed to search for high-energy neutrinos coming from galactic and extra-galactic astrophysical sources. The detection principle is based on the collection of Cherenkov photons induced by relativistic charged particles, produced in neutrino interactions, using a 3-D-array of about 900 sensitive optical sensors, Photo-Multiplier Tubes (PMTs) (Amram et al., 2002). The PMTs, together with electronics, are integrated into Optical Modules (OMs) on 12 mooring lines between about 1900 and 2400 m in the Mediterranean Sea. An extra line is used for seismic and oceanographic observations including those on water motions, marine biology and sedimentology. The telescope is at great depths, mainly to have the water act as a shield for sunlight and cosmic rays, and also to avoid large levels of bioluminescence. In general, bioluminescent organisms are progressively less abundant at greater depths (Vinogradov, 1961). Their presence in the Mediterranean Sea is a factor of about 10 less abundant than,

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e.g., parts of the North-Atlantic Ocean. In the Mediterranean values may differ by more than a factor of 10 as a function of time, location and depth (Priede et al., 2008).

The ANTARES site is off the French Provençal coast, close to the base of the steep continental slope (Fig. 1). A 40 km long electro-optical cable provides power and the connection for data transmission to and from a shore station (Aguilar et al., 2007). The Northern Current (NC) flows counter-clockwise along the boundary slopes of the Ligurian and Provençal subbasins and is $O(10)$ km wide. As the NC is meandering, its rim skims over the ANTARES site. The NC borders the area of dense water formation in the subbasin (Crépon et al., 1982, 1989). As a result, this site offers oceanographers excellent opportunities to study details of water motions, sediment transport and marine biology for long periods of time in the sea interior just off a continental slope. Here, we report on Acoustic Doppler Current Profiler ADCP-data (RDI, 1992) measuring echo intensity and current in all three Cartesian components: East-West (u), North-South (v), vertical (w), including periods of large persistent downward w , “subduction”.

In the western basin of the Mediterranean, two physical processes can exist, characterized by downward w having $O(10^{-2} \text{ m s}^{-1})$ surface-to-bottom amplitudes (Millot, 1999). Both can affect the ANTARES site: i) deep dense water convection due to evaporation and cooling of near-surface waters mixing with intermediate waters below, which is predominantly known to occur off the shelf of the Gulf of Lions (GoL), in the Provençal subbasin, “MEDOC”-area, and in the Ligurian subbasin (e.g., Voorhis and Webb, 1970; Gascard, 1973), ii) convection due to frontal zones and mesoscale eddies, such as occurring in the Algerian subbasin (van Haren et al., 2006). In both processes, the larger amplitude downward motions are found in areas of smaller horizontal extent than those of the upward motions. The former are typified by $O(10^2 - 10^3 \text{ m})$ horizontal radius for downward motion “plumes” and 10–100 times larger upward motion areas (Marshall and Schott, 1999). The latter are typified for $O(10^5 \text{ m})$ radius mesoscale eddies by strong downward currents in an $O(10^3 \text{ m})$ wide rim around its perimeter (van Haren et al., 2006). So far, no direct observations have been reported of the effects on deep biomass by such vertical currents, but a patch of elevated bioluminescence was

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observed at about 1000 m underneath a mesoscale eddy in the Atlantic (Heger et al., 2008).

In the Ligurian subbasin, water motions show a seasonal variation, with mesoscale horizontal current speeds up to 0.5 m s^{-1} in winter compared to $O(10^{-2}) \text{ m s}^{-1}$ in summer (Taupier-Letage and Millot, 1986). The larger-scale NC is directed counter-clockwise and driven by buoyancy and Coriolis forces (Crépon et al., 1989). Generally in January, the NC can become baroclinically unstable with intense mesoscale activity reaching from the surface to the bottom. The NC forms waves of typical horizontal extent $O(10^4 - 10^5 \text{ m})$ with a phase speed relative to the upper layer flow $O(10^{-1} \text{ m s}^{-1})$ or less. Due to coupling with lower layer motions the wave propagation is almost stationary with respect to the continental slope (Griffiths and Pearce, 1985). Along the NC-border, enhanced levels of near-surface phytoplankton grow in spring and may be transported downward along the front, although evidence was so far limited to the upper few 100 m (e.g., Boucher et al., 1987; Gorski et al., 2002). Presently unknown is the influence of the NC in transporting downward other suspended materials including zooplankton to great depths. The NC can also cause variability in horizontal motions of water masses past the ANTARES site.

2 Data

In spring 2005, the ANTARES Collaboration deployed and operated a so-called Mini Instrumentation Line equipped with Optical Modules (MILOM) at the site $42^\circ 48' \text{ N}$, $06^\circ 10' \text{ E}$, 2475 m water depth (Aguilar et al., 2006) (Fig. 1). In March 2006 the first detector line became operational (Ageron et al., 2009). The MILOM consisted of an instrumented releasable anchor and of three storeys located at 100, 117 and 169 m above the sea bed. It was equipped with four OMs: a triplet of OMs on the middle storey and a single OM on the upper storey. A downward-looking 300 kHz, four-beam Teledyne RDI-ADCP was mounted on the upper storey. In this apparatus the beam slant is 20° to the vertical. This leads to current estimates that are averages over

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horizontal beam spreads of 3–80 m as a function of the vertical range. As the ADCP operates a redundant 4th beam, it offers an extra “error” velocity (e) that is composed of the difference between two w 's estimated from the independent beam pairs. Thus, reasonable estimates are obtained for errors in w that include horizontal current inhomogeneities over the beam spread and effects of ADCP's tilt- and heading variations.

As ADCPs rely completely on the reflection of sound on “particles” in the water, larger than about 0.003 m at 300 kHz (RDI, 1992), they sample variations in these reflections as “echo intensity” (I). Part of the I -variation with depth is the inevitable acoustic energy loss in water. A simple method to correct for sound loss is the computation of a “relative echo intensity”, $dI = I - I_{\min}$, by subtracting the minimum I_{\min} from the original signal at each depth. A single-frequency instrument cannot be used to distinguish the cause of variations in dI with time. The origin of variations ranges from changes in shape and species to number of particles. Most often however, variations in dI imply variations in the number of particles passing through the beams. A 300-kHz ADCP is sensitive to particles like large suspended flocs of material and especially zooplankton that have sizes $> 10^{-3}$ m, or larger animals. It is not sensitive to bacteria and phytoplankton, which have typical sizes $O(10^{-5} - 10^{-4})$ m or less.

The ADCP sampled data-ensembles in 50 vertical bins of 2.5 m every 10 min. The shoreward data-transport was frequently interrupted (Fig. 2) especially in the first year.

3 Observations

In March 2006, the PMTs counting rates, which at low levels are mainly due to ^{40}K -decay and to bioluminescent bacteria, suddenly increased by a factor of 10 or more (Fig. 2a). Low levels are observed before day 69 and after day 170. Sudden increases are apparent for 30 days after day 69 and high levels are maintained until about day 170. Similar observations were made using different PMTs on MILOM and line 1 (Ageron et al., 2009). An increase in counting rate is usually attributed to larger levels of bioluminescence.

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The ADCP's dl suddenly increased by a factor of about 10 on day 69 (Fig. 2b). Relatively large acoustic reflections occurred until day 190, and episodically later in the year. However, it is noted that optical and acoustic data may imply variations of different origin. The former are sensitive to variations due to distributed light sources, such as luminescent bacteria or zooplankton species. The latter is mostly sensitive to echos due to accumulation of zooplankton and higher order species, not necessarily light-emitting objects. Associated with the increase in dl are: a doubling in current amplitude, $|U|$, (Fig. 2c) and a large downward w (Fig. 2d). Aside from the period between days 70 and 100 of enhanced dl , large negative w and large $|U|$, periods of typically 10–30 days of similar but slightly weaker absolute values are observed later in the year as well, e.g., days 220–230 and 285–300. Variations with time may be more clearly seen in series from a particular depth (Fig. 3). Large negative w and larger dl and $|U|$ are occasionally accompanied by increases in temperature, but the correlation is ambiguous despite the tendency of large $|U|$ with small T (Fig. 3a). The measurement of e shows that it has a mean of about zero and standard deviation of noise of 0.002 m s^{-1} (Fig. 3c). The observed w are systematically negative throughout the year. As a result, current inhomogeneities over the beam spread are not causing any negative bias in w and its apparent noise is mostly due to high-frequency internal waves and small-scale convection.

Focusing on the first half of 2006, it is seen that variations in negative w and increased dl and $|U|$ also occur at shorter periods of 1–10 days (Fig. 3). From day 70 to 80, the mean downward motion was about 0.01 m s^{-1} and regularly exceeded 0.025 m s^{-1} , or 2000 m day^{-1} . Particles can be transported from the surface to the bottom within 1–3 days by this subduction if extrapolated over the water column, due to its persistence with time. The w contain a lot of high-frequency variations that are not noise, but internal waves near the buoyancy frequency. It is noted that these w are measured close to the sea bottom and larger amplitudes are expected higher-up. Such large downward motions cannot be associated with sinking particles like heavy diatoms and faecal pellets, whose speeds are 1–2 orders of magnitude smaller (Passow, 1991;

Lampitt et al., 1993). Also they cannot be associated with zooplankton migration, which has the following characteristics. It moves at such speeds, but down and up, in various cycles including a diurnal and a seasonal cycle, in the latter going up in spring (van Haren, 2007).

5 Similar, although less intense, variations later in the record also can cause vertical transports across at least 1000 m and maybe the entire water column, assuming continuity of vertical currents. Due to warming from May onwards the stratification prevents any deep convection, so that this process definitely cannot explain large autumnal downward currents. Similarly, cascading events in nearby canyons transporting
10 debris down are not expected other than in winter and during short periods O(days) (Khripunoff et al., 2009).

Progressive Vector Diagrams (PVDs) constructed via time integration of horizontal particle velocities using the deep ADCP data show predominant westward “displacement” between days 69 and 79, preceded by northward and followed by southward
15 displacements (Fig. 4a). Although ambiguous, this could be interpreted as due to the passage of a mesoscale meander or clockwise eddy passing with its core between the ANTARES site and the coast during westward propagation with the prevailing NC, such as observed previously (Crépon et al., 1982). Generally, the baroclinically unstable, meandering NC passes inshore of the ANTARES site (e.g., Fig. 4b). Particularly
20 on day 69 we observe a strong baroclinic instability forming a vortex pair or dipole just to the East of the ANTARES site (Fig. 4b), with a seaward jet. The dimensions are 40×80 km, about twice the amplitude and wavelength of typical NC-instabilities that are visible to the West of the dipole and which occur at 10–20 days intervals. The size of the dipole compares well with previous observations affecting surface plankton in
25 the Atlantic Ocean (Gower et al., 1980). Due to cloudiness not many good satellite images were obtained the following days, but the seaward flowing jet seemed more or less stationary over the ANTARES site for at least a fortnight. In addition, the active dipole developed connection with a surprisingly northward extent of mesoscale eddies in the central basin that finally touched the NC at the ANTARES site (Fig. 4c).

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Our observations compare to some extent with models on dipoles, which have near-zero phase speed due to their interaction with the sheared current deep below (Griffiths and Pearce, 1985; Crépon et al., 1989). As a result, a particular area can receive persistent vertical flux of material during the lifetime of a jet or mesoscale meander or eddy. Later in the ADCP-record indication is found for more meanders or eddies, associated with times of large downward vertical currents. The PVDs show eddies of a clockwise nature, but it is noted that eddy interpretation from PVD can be ambiguous when no other information is available.

4 Discussion

The beginning of 2006 was characterized by particularly strong convection observed in the GoL- and MEDOC-areas during two major periods, January and March/April, and which lasted well into spring (Durrieu de Madron, personal communication, 2008). However, although MEDOC-dense water formation may extend to the East into the Ligurian subbasin, it is unlikely that the present observed rapid subduction is directly associated with either of these water masses and even with local deep convection, for a number of reasons: i) GoL dense water cascading downwards from the shelf will follow the Spanish coast towards the Balearic Islands due to deflection by the rotation of the earth and hampered by deep convection in the MEDOC region above the abyssal plain, ii) deep convection occurs also in the Ligurian subbasin which showed anomalous high salinity and temperature in 2006 (Schroeder et al., 2008; Smith et al., 2008) whilst no persistent T-excess is found in the present record, iii) downward motions are observed throughout the year, not only in winter/early spring. The NC is a permanent current, as is its meandering activity, although modulated by seasonal variation and (re)inforced by dense water formation (Crépon et al., 1989). The meandering NC-front is a good candidate to cause temporal variations in current and dl at the ANTARES site all year long, when forced to great depths.

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As a result, and given the support by sea-surface satellite images, active mesoscale motions could cause the observed large downward motions. As such motions are generated via instabilities of the coastal NC-system in response to atmospheric forcing above the deep open subbasin, they follow periods of exceptional dense water formation and last for months.

The present acoustical observations support the optical observations of the ANTARES array that large amounts of particles are transported downward from higher up, possibly from the surface to the bottom, resulting sometimes in particularly high counting rates in the PMTs. As both acoustics and optical sensors respond at the same time and because acoustics are insensitive to bacteria, an important contribution to bioluminescence can be ascribed to crustacea and zooplankton, or, perhaps though unlikely, to large suspended material carrying luminescent bacteria. This provides unique indications that the sea replenishes fresh organic material to the abyssal plains when mesoscale meanders or eddies appear, not just over the ANTARES site, but anywhere where unstable currents occur.

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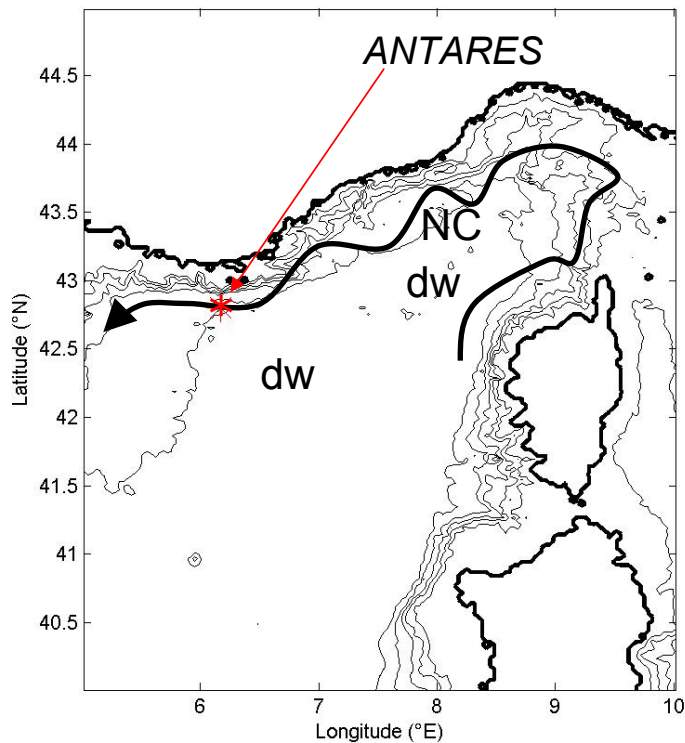


Fig. 1. ANTARES site (red star) on the northern part of the Ligurian subbasin, western basin Mediterranean, with a sketch of the Northern Current NC (solid line) and areas of dense-water formation (dw). Isobaths every 500 m between $[-500, -2500]$ m.

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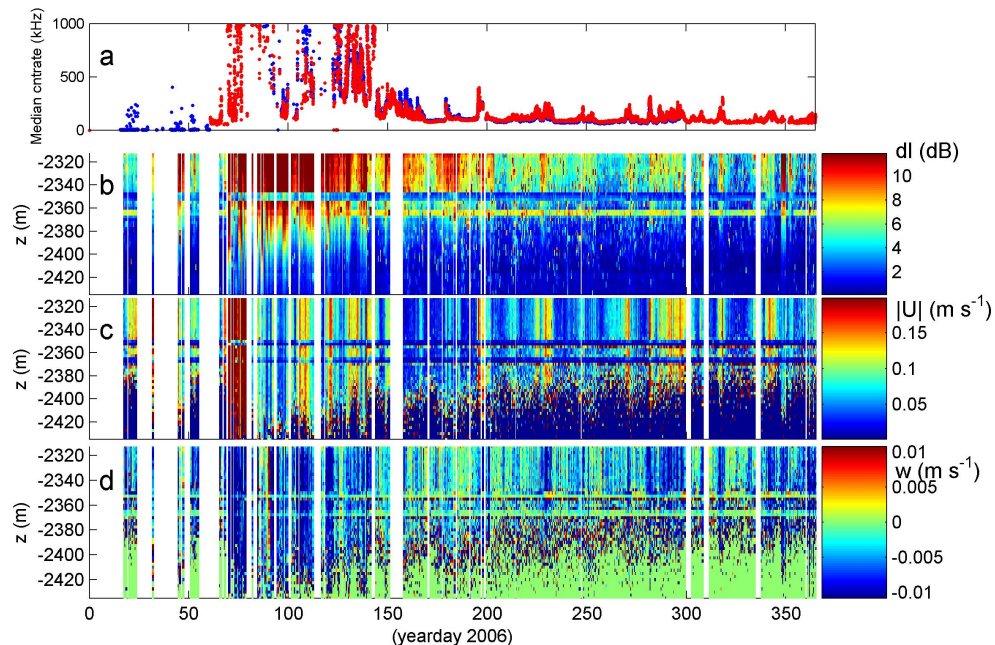


Fig. 2. (a) Optical counting rate observed 50 m below the ADCP at MILOM (blue) and on Line 1 (red) as a function of time. (b–d) Raw MILOM-ADCP data, time-depth series. In all panels the vertical white lines indicate absent data. The two horizontal lines at 2350 and 2365 m are direct sound reflections from two storeys below the ADCP. (b) Relative echo amplitude from a beam, limited to [0, 12] dB. (c) Current amplitude, between [0, 0.2] m s⁻¹. (d) Vertical current, between [-0.01, 0.01] m s⁻¹. In (c, d) useful data are available down to about 2390 m, and to about 2420 m between days 70 and 100 when echos are large. The time convention is 1 January, 12:00 UTC = day 0.5, 2006.

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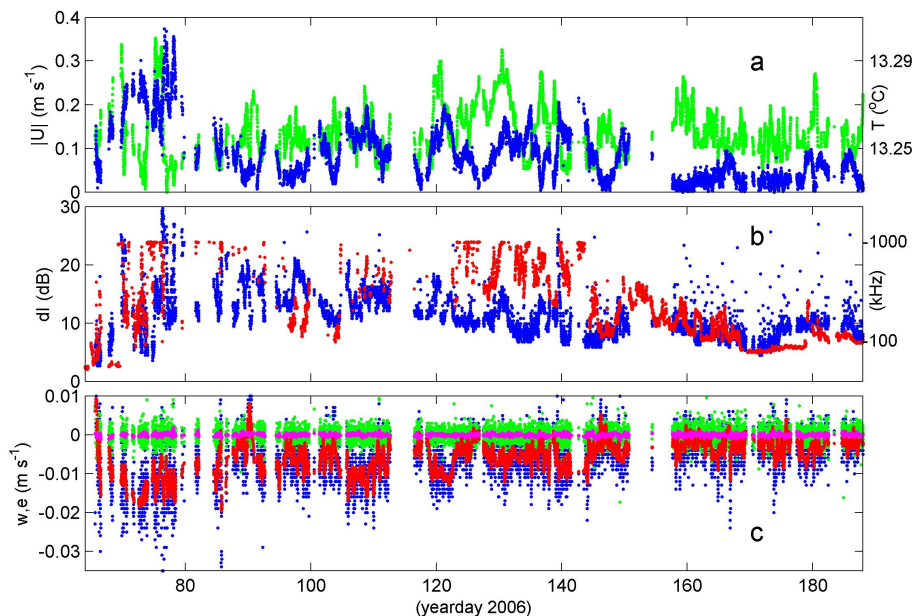


Fig. 3. (a) Horizontal current amplitude at 2320 m (blue; raw data) and temperature (green; smoothed) measured at the ADCP. (b) Relative sound-echo amplitude (blue; smoothed) and PMT baseline data from 2350 m (red). (c) Vertical current (blue: raw data; red: smoothed) and error velocity (green: raw data; purple: smoothed). Applied smoothing is using a 20-points running mean.

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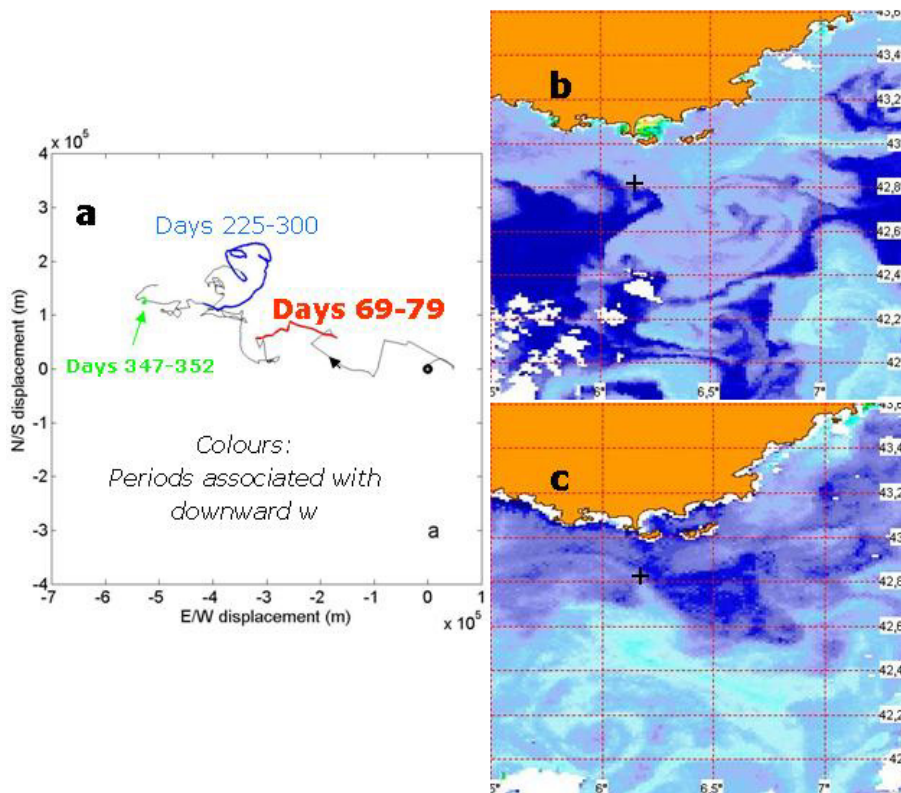


Fig. 4. (a) Progressive Vector Diagram of integrated Eulerian horizontal currents observed at 2320 m. In black the total 2006-time series that start at (0,0), in colours portions between the days indicated. (b) Satellite image of false-coloured near-surface chlorophyll-*a* on day 69. (c) As (b), but for near-surface suspended particulate matter on day 88. In (b) and (c) the ANTARES site is marked by a cross. Note the images are used qualitatively for pattern recognition.

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