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Manifestation of two meddies in altimetry and sea-surface temperature

I. Bashmachnikov[1,2], **D. Boutov**[1], **and J. Dias**[1,2]

[1]Centro de Oceanografia, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal
[2]Departamento de Engenharia Geográfica, Geofísica e Energia (DEGGE), Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal

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Correspondence to: I. Bashmachnikov (igorb@fc.ul.pt)

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Abstract

Two meddies were identified in the Iberian Basin using shipboard ADCP (Meddy 1) and ARGO float (Meddy 2) in contrasting background conditions. Meddy 1 was observed while interacting with the Azores current (AzC) while Meddy 2 was observed rather far north from the AzC jet, in much calmer dynamical background. In both cases the meddies produced a clear anticyclonic surface signal, detectable in altimetry as well as in sea-surface temperature (SST).

Analysis of the in-situ observations of the dynamic signal over Meddy 1 showed that the signal, generated by the moving meddy, dominated the AzC dynamics at least up to the base of the seasonal thermocline even at the late stages of its interaction with the jet. The center of rotation of the surface signal was shifted south-westward from the axis of the meddy by about 18 km, and its dynamic radius was 2 times bigger than that of the meddy.

The SST anomalies in the core of the surface signals were negative in contrast to the positive SST anomalies in surface anticyclones generated by meandering surface currents. The later difference gives ground for identification of meddies (as well as other sub-surface anticyclones) using coupled altimetry – SST remote sensing data. An identification of Meddy 1 previous to the shipboard ADCP measurements was the first successful experience. At the same time, SST anomalies over both meddies were rather weak, often unstable and statistically significant only over periods of months.

1 Introduction

In the pioneering work of Käse and Zenk (1987) the existence of surface anticyclonic signals over meddies was first identified using surface drifter trajectories. Since then a number of observations of meddy dynamic signal reaching the sea-surface with significant intensity were obtained (Pingree and Le Cann 1993a, b; Paillet et al. 2002, etc., see also a review in Bashmachnikov et al., 2009a). Some of the in-situ surveys were combined with successful experiences of comparatively long-term tracking of meddies with altimetry data (Stammer et al. 1991; Pingree and Le Cann, 1993a; Pingree, 1995), but the first consistent study of meddy surface signals appeared only recently (Bashmachnikov and Carton, 2012). The results suggest that in the Subtropical Atlantic moving meddies with the diameter of more than 15–20 km generate a rather stable surface anticyclonic structure, although the intensity of their signals varies in time. Two situations were identified when meddies temporary loose their surface signals: after they have crossed a strong jet current, as the Azores Current (AzC), and when they enter in a close interaction with a surface cyclone (Bashmachnikov et al., 2009a; Carton et al., 2010).

In this paper we describe observational evidences of meddies forming a specific signature in sea-surface temperature (SST), which may further be exploited into remote sensing methods for identification of meddies as well as other deep eddies. The observational part of the work results from a successful identification of a meddy (Meddy 1) with a combined altimetry and SST satellite data in the Iberian basin, which has been later confirmed with in-situ observations. This meddy was observed in a complex situation of interaction with the AzC. For comparison, we also give an example of another meddy (Meddy 2) observed in a comparatively dynamically calm situation.

The theoretical and model-experimental basis of a meddy interaction with a jet flow is described in a number of studies. In particular, it has been found, that a large-scale background current of zonal direction, either barotropic (Van Leeuwen, 2007) or a baroclinic one (Vandermeirsch et al., 2001), do not have a significant advective effect on the drift characteristics of a meddy. This is attributed to formation of "β-gyres" as a result of adjustment of the mass field inside the meddy. Meanwhile, a southward background current may be efficient in translation of a meddy, since for such flows baroclinic β-effect adds to the translation of an anticyclonic eddy in the direction of the mean flow (Dewar and Meng, 1995; Morel, 1995). The mechanism of translation of a zonal jet by a meddy approaching from the north, lies in generation of an anticyclonic-cyclonic vortex pair in the current (Vandermeirsch et al., 2003). The anticyclonic meander moves north-eastwards and overlays the meddy, whereas a cyclonic vortex to the southeast of the meddy simultaneously intensifies. It is this cyclonic vortex which forces the meddy to travel south, crossing the jet. The crossing takes place only if its peak relative vorticity exceeds at least 1.3 times the maximum horizontal shear in the jet.

2 Material and methods

Oceanographic survey onboard of RV "Almirante Gago Coutinho" in the Iberian Basin took place during the period of 24–28 August 2010. Almost during all the campaign, a 75 kHz shipboard ADCP data on ocean currents down to 800 m depth with a bin size of 32 m were collected. The data were initially processed using VmDAS Teledyne RD Instruments software (http://www.rdinstruments.com/). To reduce the small-scale noise, the components of the ADCP derived current velocity were smoothed in horizontal and vertical directions by applying the 2nd order Savitzky-Golay filter with the smoothing window sizes of 5 km and 100 m, respectively. The barotropic tidal current in the region is less than 3 cm s^{-1} (Egbert and Erofeeva, 2002), an order of magnitude smaller than the observed meddy signal, and its effect was neglected.

Using AVISO altimetry data, the meddy observed during the cruise (Meddy 1) was tracked forward and backward in time by following the surface anomaly of relative vorticity. Efficiency of tracking eddies with their anomalies of relative vorticity, as compared with those of the sea-level elevations, was brought in by Isern-Fontanet et al. (2003), and successfully tested for meddies in Bashmachnikov et al. (2009a): the anomalies in relative vorticity are less often masked by merging with other surface dynamic structures than those of sea-level.

Another meddy (Meddy 2) was detected with an ARGO float. The data were obtained from the Coriolis operational data center (ftp://ftp.ifremer.fr). The float was considered to be within a meddy, when in its vertical profiles the mean salinity anomaly in the 800–1500 m layer exceeded 0.25. The vertical profiles of World Ocean Atlas climatology (WOA09) were taken as reference. The float was trapped within the meddy near

Setubal canyon and left the meddy after passing the Josephine seamounts. In total, 39 successive vertical profiles, from October 2005 to May 2006, were considered.

The surface signatures of the selected meddies were studied using the gridded AVISO altimetry data with the spatial resolution of about 30 km and weekly temporal resolution (AVISO). The data-set proved to be a reliable measure of the upper ocean circulation with claimed sea-level error of less than 3–4 cm (Fu and Cazenav, 2001). The fields of sea-level height were transformed to those of the sea-surface current velocity and relative vorticity, under the geostrophic approximation. To reduce the measurement noise the 7-point stencil width was used, as recommended in Arbic et al. (2012). The along-track data were provided by Radar Altimeter Database System (RADS) with 5–7 km along-track resolution and the claimed altimetric measurement error of less than 2 cm.

The Multiscale Ultra-high Resolution sea-surface temperature data base (MUR) was used to obtain SST anomalies over the meddies. The results were based upon the merged nighttime measurements of infrared and microwave sensors (AVHRR, MODIS and AMSR), combined with surface observations from ships and buoys to obtain so called foundation temperature, i.e. the upper ocean temperature below the surface skin layer. The spatial resolution of the final product is 1.1 km and it has daily temporal resolution. The algorithm of merging SST images from various sensors incorporates the Parameter Matrix Objective Analysis (Mariano and Brown, 1992), which compensates for motion of mesoscale structures during the period of merging. This keeps frontal boundaries as sharp as in the original images.

2.1 In-situ observations of Meddy 1 and its surface signals

The in-situ ADCP observations along the transect 2 (Fig. 1a) show that the transect crosses a deep anticyclonic eddy. The profiles of the current velocities suggest that the deep eddy was crossed slightly north of its center, at approximately 80 km from the western part of the transect 2 (Fig. 1b).

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The dynamic core of the eddy is situated in the Mediterranean water (MW) layer and its characteristics are typical for a meddy in the Iberian basin: the dynamic radius was 10–15 km and the maximum rotation velocities of 30–40 cm s^{-1}. In the study region no other deep anticyclonic vortexes with comparable size and intensity were registered in the MW layer. Therefore, we claim that the observed vortex is a meddy, although no direct temperature-salinity measurements are available during the time of the cruise. Some indication may be obtained from two vertical profiles of an Argo float (Fig. 1a). In particular, presence of a meddy is indicated by a vertical profile near the northern edge of the tracked surface vorticity signal a bit later, during mid-September 2010: in 800–1100 m layer the registered salinity and temperature anomalies relative to WOA09 were 0.2 psu and 0.5 °C, respectively.

Figure 1a gives evidence that the surface currents derived from AVISO data-set well correspond to the in-situ ADCP measurements. The altimetry derived currents showed that during the cruise the ship crossed the AzC 3 times. In the easternmost part of transect 2 the AzC axis is directed 120°, clockwise from north, and is affecting the current structure in the vicinity of the meddy. For further estimates of characteristics of the dynamic signal of the meddy, we separate the circulation related to the meddy from the one related to the AzC. This can be done since current velocity along the transect 2 is clearly dominated by the meddy dynamics (Fig. 1b). Using the ADCP information at the transect 1, were the AzC is not affected by the meddy, we come up with a model of the AzC: the velocity linearly decreases from its maximum at the jet axis to zero at distances of 700 m in vertical and 60 km in horizontal (Fig. 1c). The ADCP current in transect 2 with the AzC contribution removed is presented in Fig. 1d. As expected, the filtering did not change the structure of the meddy signal, but the meridional current velocities in the upper ocean became more symmetric relative to the meddy axis. The westernmost part of transect 2 is also influenced by the northward directed AzC (cf. Fig. 1a), but the AzC was not filtered out since it does not affect the circulation around the meddy.

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The module of velocity for each ADCP bin along the transect 2, with the AzC removed, is presented in Fig. 2a. The upwards decrease of the dynamic eddy intensity is similar to previously observed over meddies and is identified as the "meddy surface signal" (Pingree and Le Cann, 1993b; Paillet et al., 2002, etc.). Those signals are generated as a result of the potential vorticity conservation of the upper part of the water column compressed by a moving meddy (Paillet et al., 2002; Bashmachnikov and Carton, 2012).

Altimetry sea-level height fields also show a week anticyclonic circulation west of the meddy (Fig. 1a). Comparing to the ADCP sections, the srtructure with high degree of confidence can be related only to the meddy surface signal. The westward position of the center of the satellite derived vortex relative to that derived from ADCP measurements apparently is due to spatial-temporal smoothing of the gridded altimetry products (Fu and Cazenav, 2001).

The position of a vortex axis at a given depth level in zonal (along-transect) direction is obtained from the location of points of minimum velocity between two maxima, x_w and x_e, (dashed lines in Fig. 2a). We express this measure in term of the distance of the eddy centre to the beginning of the transect as x_c (Fig. 2b). To define the meridional position of the eddy centre relative to the transect line (y_c), we use the current directions ($\alpha_{\mathrm{w,e}}$) at x_w and x_e, respectively (as before, w identifies the western and e - the eastern extrema). Those points are selected since there the eddy signal is less affected by the background noise. Assuming the eddy is circular, from geometrical considerations we make the two estimates of y_c: $y_{c\mathrm{w}} = y_\mathrm{w} - (x_c - x_\mathrm{w})\tan(\beta_\mathrm{w})$ and $y_{c\mathrm{e}} = y_\mathrm{e} - (x_c - x_\mathrm{e})\tan(\beta_\mathrm{e})$, where $\beta_{\mathrm{w,e}} = 90 - \alpha_{\mathrm{w,e}}$. The dynamic radius of the vortex is estimated as: $R_\mathrm{w} = \sqrt{(x_c - x_\mathrm{w})^2 + (y_c - y_{c\mathrm{w}})^2}$ and $R_\mathrm{e} = \sqrt{(x_c - x_\mathrm{e})^2 + (y_c - y_{c\mathrm{e}})^2}$. The final distance y_c and the dynamic radius of the vortex R represent the mean of the two estimates (Fig. 2b).

The results permit identifying two dynamic layers: the meddy itself, from 650 to 800 m, and its surface signal, above 550 m (Fig. 2b). The axis of the meddy is situated at $x_c = 83$ km and $y_c = -5$ km, south of the transect line. The meddy dynamic

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radius is 12 km, which is about the second baroclinic Rossby radius of deformation and comparable with that observed by Pingree and Le Cann (1993b) or Pailet et al. (2002). The axis of the meddy surface signal is shifted in average 18 km south-westward from the meddy axis. The dynamic radius of the former gradually increases upwards and in average is around 25 km, close to the first Rossby baroclinic radius of deformation. The transition between the meddy and its surface signal at 500–600 m depth is characterized by the maximum vertical gradient of the horizontal velocity, abrupt shift of the centre of the vortex and a rapid increase of the dynamic radius by about 7 km. This suggests that we are dealing with two connected, but different eddies.

In the upper 200-m layer the computed central positions, y_{cw} and y_{ce}, diverge and in the 100-m layer the mean of the two (y_c) changes significantly. Rather weak meddy dynamic signal (5–10 cm s^{-1}) in the upper layer may be distorted by wind current. During the ADCP observations along transect 2, the wind speed increased from 1 to 8 m s^{-1}. Thus, the Ekman layer at the eastern end of the transect should reach at maximum 40 m, and the drift current at the base of the Ekman layer should be at maximum 5 cm s^{-1}. This may affect only the uppermost ADCP bin. It more plausible that characteristics of current velocity of the meddy surface signal in the uppermost layer are distorted by sub-mesoscale surface eddies. Therefore, when estimating the mean characteristics of the meddy surface signal we disregard the uppermost 100 m layer.

2.2 Tracking surface signal of Meddy 1 with altimetry

Relatively to the period of the in-situ measurements, the meddy was tracked forward and backward with the gridded AVISO altimetry data (Fig. 3a). The possibility of obtaining uninterrupted surface tracks of meddies during the initial period of their crossing of the AzC, was successfully tested by tracking the relative vorticity surface signal of meddies followed with deep RAFOS floats (Bashmachnikov et al., 2009a). In this case as well, from the time of observations and at least back to April 2010, the surface structure can be followed through sequential positions of the sea-surface relative vorticity minima. During these 4 months the surface signal was travelling south-south-west,

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approximately along the 137 pass of Jason 1. This made it easy obtaining a complementary study of the meddy surface signal with high resolution unsmoothed along-track sea-level anomalies (SLA) obtained from RADS. The local reference level in RADS data-set changes with time and the positive anomaly forced by the meddy at the sea-surface was taken relative to the closest SLA minima (Fig. 3b).

In both data-sets the surface anticyclonic structure can be continuously followed, suggesting that we are following the signal of the same meddy. The along-track data show that from April to May 2010 the surface signal of the meddy varied in strength typically between 5–10 cm in SLA (see also Oliveira et al., 2000) and 0.2–1.1 $10^{-5}\,s^{-1}$ in relative vorticity, clearly distinguishable from the background noise.

In the beginning of the registered journey, from April to May 2010, the SLA decrease in RADS data-set (Fig. 3b) was due to the meddy moving away from the Jason 1 pass 137. The process of crossing the AzC by the tracked vorticity surface structure closely follows that of a meddy crossing a zonal jet flow (Vandermeirsch et al., 2003). In June 2010, as the tracked surface signal approached the AzC, formation of an AzC meander was initiated. Then the tracked signal began merging with the meander, while a cyclone is generated and intensified to the southeast (Fig. 3a–b). During the merge the intensity of the signal increased drastically. During July 2010, a rather short period of perfect alignment with the AzC meander, the signal reached 15–20 cm in SLA and 0.6 $10^{-5}\,s^{-1}$ in relative vorticity. After that, as the meddy, forced by an intensive cyclone to the northeast, was travelling south, the intensity of its surface signal gradually decreased. In September 2010, as the meddy ran southeast on the Ampere seamount, the signal split into 2 parts. This may result from the meddy splitting by the seamount into 2 vortices (Cenedese, 2002; Richardson et al., 2000), but may also be a result of the AzC detaching the surface signal from the meddy and transporting it southwestward, while the meddy passed west of the seamount and formed a new surface signature. The decrease and loss of the meddy surface signal during September 2010, also observed in the AVISO altimetry maps, may partly result from interruption of the pass 137 in-between 34.5–35.5° N during this month (Fig. 3b). This has implication on apparent variation of intensity of a meddy surface signal derived from AVISO data-set as a result of variation of the meddy position relative to the closest available satellite track.

2.3 Surface signal of two meddies in SST

The SST field obtained for the time of the cruise gives evidence of a cold anomaly near the meddy (Meddy 1, Fig. 4a). The in-situ data, obtained with the shipboard ADCP thermometer, confirms the remote sensing results (Fig. 4b). The ship-based near-surface temperature is presented in terms of temperature anomaly over short segments of the ship trajectory (5–8 h or around 150 km along the ship track) with the linear trend excluded. The resulting anomalies highlight the mesoscale variation of temperature, largely removing the mean SST gradient and the temporal variations due to the diurnal cycle. The results clearly show that the sign of the surface temperature anomaly over the meddy is opposite to that of the anticyclonic meander, observed 100 km northwest of the meddy (Fig. 4a–b).

At the same time, the centre of the cold SST anomaly is situated south of the meddy position. This may result from advection of the SST anomaly by the AzC with a higher speed than the translation speed of the meddy. The later may happen when the meddy signal at the surface is week as compared to the background advection. This condition is verified by the end of July 2010, after the meddy had separated from the AzC meander. During 25 days (up to the time of the cruise), the surface dynamic structure associated with Meddy 1 travelled 100 km south-southeast with an average speed of 4.5 $cm\,s^{-1}$. If travelling with the locally observed speed of the AzC (12 $cm\,s^{-1}$), the SST anomaly during the same period should be advected 1.3° further south. This estimated separation between the meddy centre and the centre of the cold plume is only about 30 km bigger than the observed one.

When the meddy surface signal dominates the background circulation the negative SST anomaly coincides with that in relative vorticity (Fig. 5). During the initial interaction of the AzC with Meddy 1, the AzC later developed a meander which further aligned

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with the meddy (Vandermeirsch et al., 2003). During this process an intensification of a cold SST anomaly over the meddy was observed, as the meddy surface signal was now surrounded by a warm ring of the AzC water. This reaffirms the dynamic dominance of the meddy during the interaction. When a meddy interacts, but does not cross the jet, the warm ring remains attached to the meddy as it separates from the jet (Bashmachnikov et al., 2009a).

The radial structure of the surface signal of Meddy 1 and the associated negative SST anomaly were studied by averaging the SST values over concentric rings extending 0–25 km (SST_{25}), 25–50 km (SST_{50}), 50–75 km (SST_{75}) and 75–100 km (SST_{100}), relatively to the centre of the dynamic surface signal of the meddy, i.e. relative to the peak negative anomaly in relative vorticity. The SST anomalies, computed as SST_{25}–SST_{100} and SST_{50}–SST_{100}, are presented in Fig. 6a. The results showed that, during the 5 months of observations, negative SST anomaly overlaid the meddy 80 % of time and in average was −0.11 °C, with the 95 % confidence interval of the mean of 0.06 °C (Emery and Thomson, 1997). The decrease of the SST anomaly over the meddy in July–August 2010, coinciding with the decrease of the relative vorticity anomaly, corresponds to the time of differential southward translation of the meddy and of its SST signal.

The negative SST anomaly over Meddy 1 contrasts with the positive SST anomalies characteristic for anticyclones formed as a result of instability of the upper ocean flows. As an example, the AzC meander (Fig. 4a, transect 1) was tracked for nearly 3 months after the meddy has separated from it. The analysis showed that 85 % of the time the meander was associated with a positive SST anomaly, in average of 0.08 °C, with the 95 % confidence interval of 0.06 °C (Fig. 6b).

The obvious drawback of the previous analysis lies in the indirect observations of the path of Meddy 1. To obtain further proof, SST anomalies over another meddy (Meddy 2), tracked in-situ with an ARGO float were studied (Fig. 7a). The meddy was identified in ARGO vertical profiles as a strong salinity anomaly above 0.3, in the 750–1500 m layer relative to WOA09 climatic data. The AGRO float followed the meddy for

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7 months (November 2005 to May 2006) from the very time of its generation near the Lisbon canyon. During the time of observation the meddy propagated south-west in a dynamically calm area to the north of the AzC jet. At the sea-surface the meddy could be continuously followed as a pronounced negative anomaly in relative vorticity (Fig. 7b). It was also associated with a negative anomaly in SST during 75 % of the time of observations (in average −0.15 °C, but which at times reached −0.20 °C, with the 95 % confidence interval of 0.05 °C). Positive correlations of the peak vorticity of the meddy surface signal with the time-delayed SST anomaly in the 0–25, 25–50, 50–75 km rings surrounding the points of surfacing of the ARGO float (which also corresponded to the central part of the anticyclonic surface signal) were obtained. With the monthly delay the correlations were the highest (0.7–0.8) at the distances 25–75 km, while in the central 25-km ring they were 0.5, although also significant. With the 1.5 month delay the correlations were the highest (0.7) in the central 50-km ring, while at the 50–75 km they decreased to 0.5. With the 2 month delay the correlations were significant (0.5) only in the central 25-km ring. Therefore, negative SST anomaly in the centre of the meddy surface signal enhances following the increase of the anticyclonic circulation at the sea-surface with an approximately 1.5 months delay.

From the analysis above it follows that intensification of negative SST anomaly over a meddy is rather a result of entrainment of colder water towards the centre of the meddy and wrapping of warmer water around. The process can be observed in the consequent SST fields over Meddy 1 (Fig. 5). The similar structures were observed over Meddy 2 (not presented). Intensification of the anticyclonic surface signal of a meddy should generally lead to intensification of the surface water convergence. In a quasi-geostrophic vortex we can assume the radial velocities to be an order of magnitude less than the azimuthal ones. The azimuthal velocities in Meddy 2 were around 10 $\mathrm{cm\,s^{-1}}$ and the dynamic radius of its surface signal was in average 50 km. Thus, taking radial velocities in Meddy 2 of order of 1 $\mathrm{cm\,s^{-1}}$, we get that the surrounding water, entrained by intensification of the surface convergence, should reach the vortex centre in a 2 months time. This is close to the delay obtained from observations.

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3 Discussion and conclusions

In the previous works it was shown that sufficiently large meddies generate a dynamic signal at the sea-surface detectable by satellite altimetry (Bashmachnikov and Carton, 2012) and rather persistent in time (Bashmachnikov et al., 2009a). The observations of Meddy 1 confirms the previous suggestion that the dynamic surface signal represents a stand-alone vortex, the axis of which can be shifted from the axis of the meddy and the radius is approximately twice of that of the meddy (see also Paillet et al., 2002). Combination of altimetry and in-situ dynamic section across Meddy 1 gives evidence that the surface dynamic signal of the meddy was sufficiently strong to be detected with AVISO altimetry as a close anticyclonic structure and at times dominate the respective signal of an anticyclonic meander of the AzC at different stages of meddy-current interaction. This, however, may not be true west of the area of study where the AzC is stronger.

In this paper we also show that meddies may produce a statistically significant anomaly also in SST. Furthermore, while the dynamic surface signal of meddies detected in satellite altimetry is not principally different from the one generated by instability of surface currents, the sign of the SST anomalies over meddies is negative, contrasting to positive SST anomalies associated with surface anticyclones. This gives ground for identification of meddies (or other deep eddies) in remote sensing data. As an example, Meddy 1, described in this paper, was remotely identified previous to the cruise as an anticyclonic vortex which had a negative SST anomaly in the core.

Negative SST anomalies over the two studied meddies were less stable than their surface dynamic anomalies, nevertheless the former were observed for 70–80 % of the time of tracking of the meddies. Lower stability of the SST anomaly may partly lie in their rather small absolute values, at the limit of the precision of actual SST products. The patchy remnant cloud effects add additional noise to the results. At the same time, the average SST anomalies over the period of several months proved to be statistically significant.

Lower SST over a meddy may result from two processes. The first one consists in rising of isopycnals by a moving meddy. For example, observations at the Kiel-276 mooring (Siedler et al., 2005) showed that as a meddy was passing across the mooring, the upper current meters (at 200–500 m levels) registered cold temperature anomalies. Examples of vertical profiles of temperature and salinity showing the uplift of isopycnals above a meddy compared with the surrounding ocean, as presented in Fig. 8 (the meddy is observed near Madeira island and is described in detail in Bashmachnikov et al., 2009b). At the sea-surface, though, the SST signal may be masked by the seasonal thermocline and appear sporadically during the periods of strong vertical mixing.

Another mechanism consists in formation of the negative SST anomaly as a result of differential fluid entrainment: the colder fluid (entrained from the north) is advected towards the centre of a meddy surface signal, while the warmer fluid (entrained from the south) is wrapped around the cold core. The process is clearly visible while Meddy 1 interacted with the frontal interface of the AzC (Fig. 5). The entrainment process seems to be the most plausible mechanism of formation of the cold anomaly also over Meddy 2: soon after the relative vorticity of its surface signal has intensified, the gradual progress of the negative SST anomaly towards the centre was observed. Consistent with a coarse estimate of radial velocities, the cold SST anomalies reached the central area of the meddy surface signal in about 1.5 months. This differential entrainment mechanism may also be a consequence of isopycnals doming over a meddy: in horizontal plane the associated density gradient favours lateral entrainment of colder (denser) water towards the centre of the meddy surface signal while warmer (lighter) water stays at its periphery. With this later mechanism in action, the SST anomaly over meddies should deepen not only as the upper ocean stratification weakens or the sea-surface dynamic signal over a meddy intensifies, but also as the background horizontal SST gradients increase. Therefore, in the subtropical Northeast Atlantic meddies during winter and spring seasons may have stronger signal in SST.

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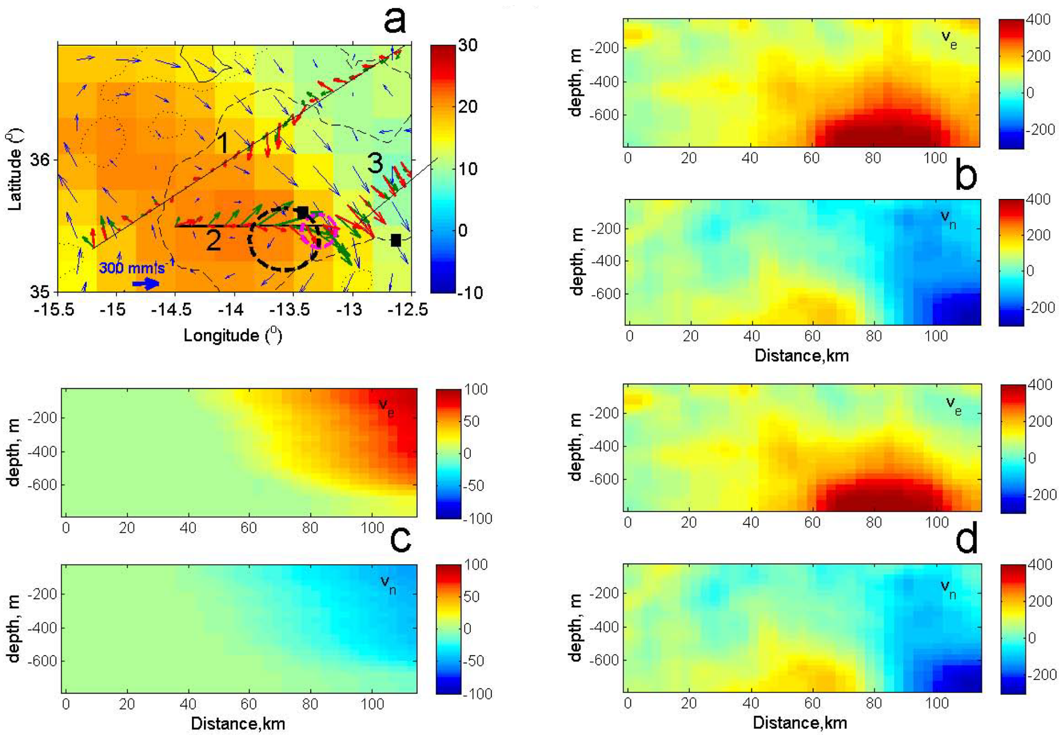

Fig. 1. **(a)** AVISO altimetry currents 24 August 2010 (blue arrows) overlaid on the sea-level height anomaly (cm, colour scale). ADCP currents 27 August 2010 at 100 m (red arrows) and at 700 m (green arrows). Magenta and black circles mark the positions of the meddy and its surface signal respectively, derived from the ADCP data. The black squares mark 2 positions of the vertical profiles of an Argo float, where the meddy-like anomaly was registered. Depth contours of 2000 (black dot line) and 4000 m (black dash line) are shown. **(b)** Present east (V_e) and north (V_n) velocity components (mm s^{-1}) obtained by shipboard ADCP 27 August 2010 along the Sect. 2. **(c)** Present the modelled contribution of the AzC. **(d)** The same as **(b)**, but after subtraction of the AzC contribution.

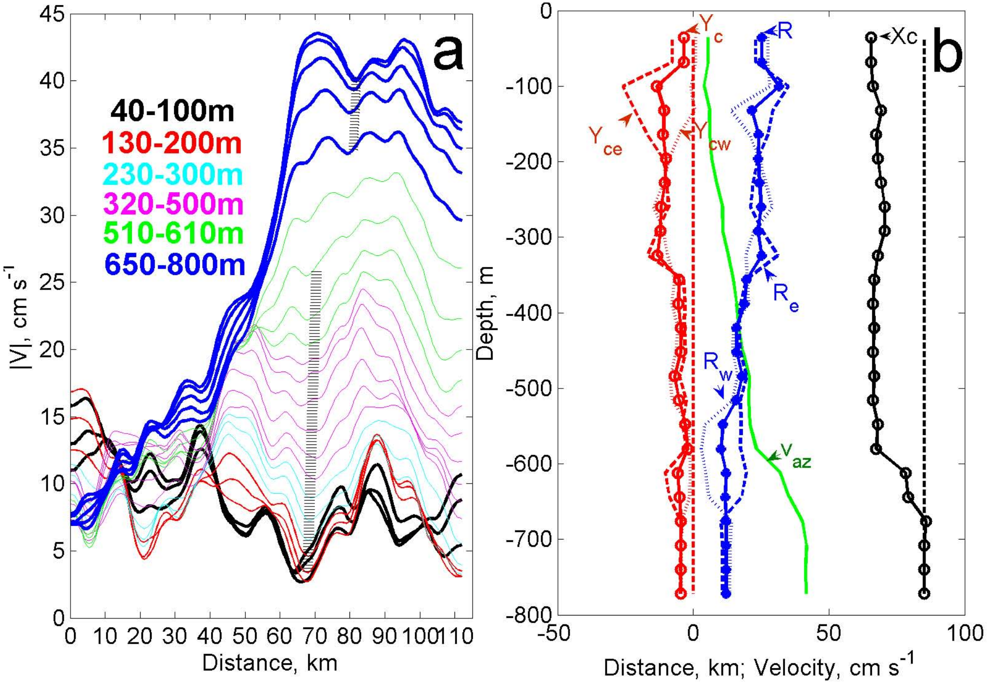

Fig. 2. (a) Velocity magnitude (cm s^{-1}) along transect 2 for each of the ADCP bins, after the AzC is removed. Black – 40–100 m levels, red – 130–200 m, cyan – 230–300 m, magenta – 320–500 m, green – 510–610 m, blue – 650–800 m. The vertically aligned black dashes identify the centres of the meddy (upper line) and of its surface signal (lower line). **(b)** Maximum azimuthal velocity of the eddy (V_{az}, cm s^{-1}, green), zonal distances of the eddy centre relative to the beginning of the transect line (x_c, km, black), meridional distances of the eddy centre relative to the transect line (y_c, km, red), and radius of maximum velocity relative to (x_c, y_c) (R, km, blue). The dash and dot lines are the estimates of the corresponding parameters using only western or only eastern maximum of current velocity. Strait vertical dash lines are given as a reference frame.

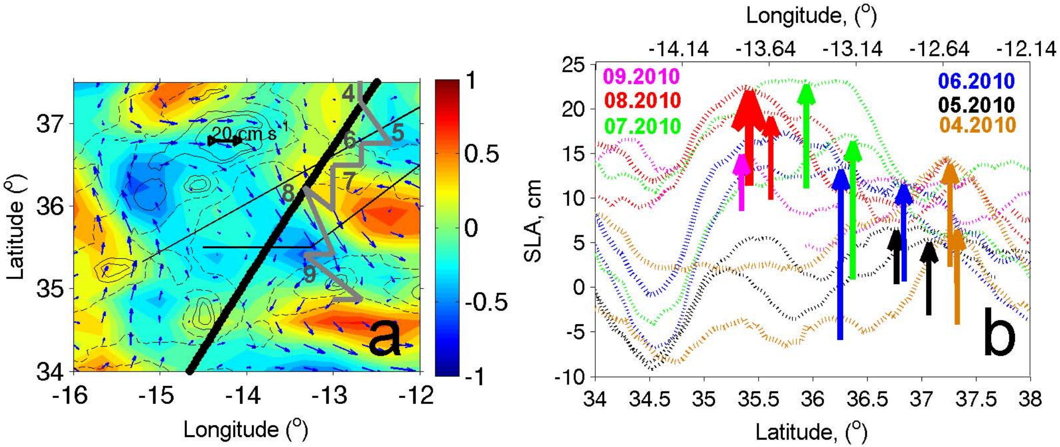

Fig. 3. (a) Relative vorticity ($10^{-5}\,s^{-1}$) and geostrophic currents ($cm\,s^{-1}$) at 24 August 2010 computed from AVISO altimetry. Pass 137 of Jason-1 (thick black line), the ADCP sections (thin black lines) and the meddy track (thick grey line, the numbers near the track mark the beginning of the respective month) are overlaid. Depth contours of 1000 and 1500 m (solid lines), 3000 and 4000 m (dash lines) are shown. **(b)** Sea-level anomalies (SLA, cm) of Jason-1 (pass 137) from April to September 2010, from RADS data-set. SLA of different months is presented with different colour. Arrows mark the centres of the tracked meddy signal and their length represent the difference of the SLA over the meddy and the closest SLA minimum; thick arrow marks the position of the centre of the meddy at the time of the cruise 24–27 August 2010.

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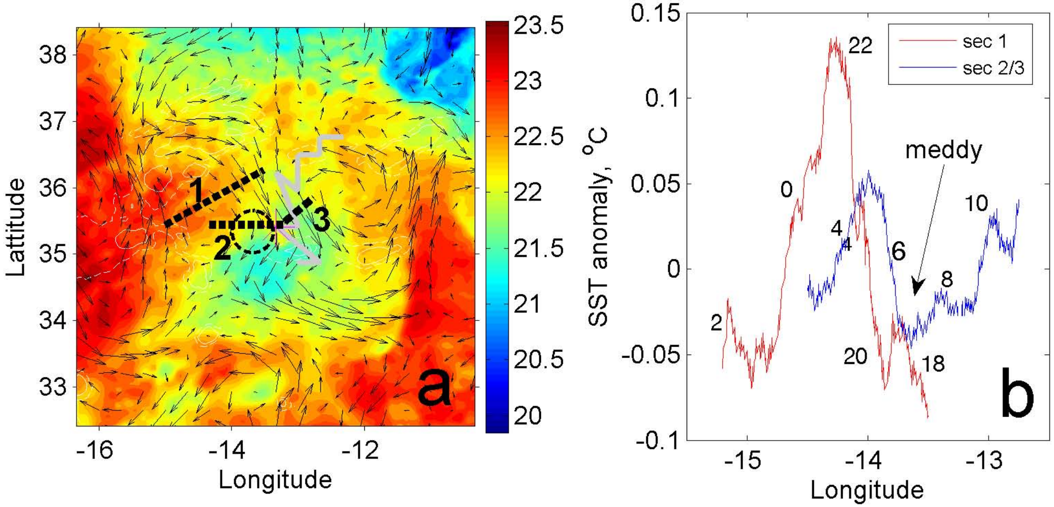

Fig. 4. (a) SST (°C) at 24 August 2010. The segments of the cruise tracks 1 and 2–3 are shown. The thick grey line marks the meddy track; the position of the surface signal of the meddy at 24 August 2010 is marked with a dashed circle. AVISO altimetry currents are overlaid. Thin grey contours show bottom topography with 1000-m interval. **(b)** Temperature anomalies from the ADCP incorporated thermometer at 4-m depth along the sections 1 and 2–3, as shown in **(a)**. Linear trends along the segments of the sections are removed. The numbers represent the time (hours of day) of temperature acquisition.

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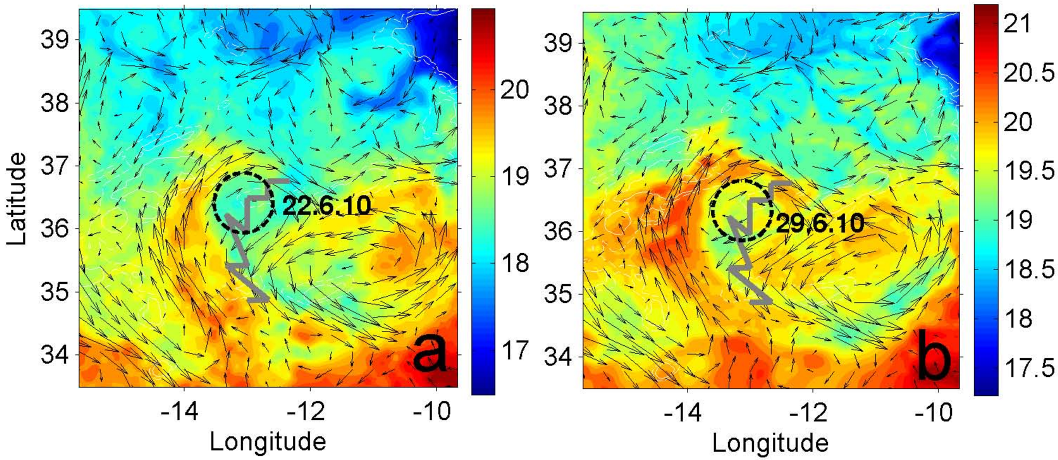

Fig. 5. SST field (°C) around Meddy 1 (marked as the dash circle) backtracked with surface vorticity at 22 **(a)** and 29 **(b)** of June 2010. AVISO altimetry currents are overlaid. The thick grey line marks the meddy track; thin grey contours show bottom topography with 1000-m interval.

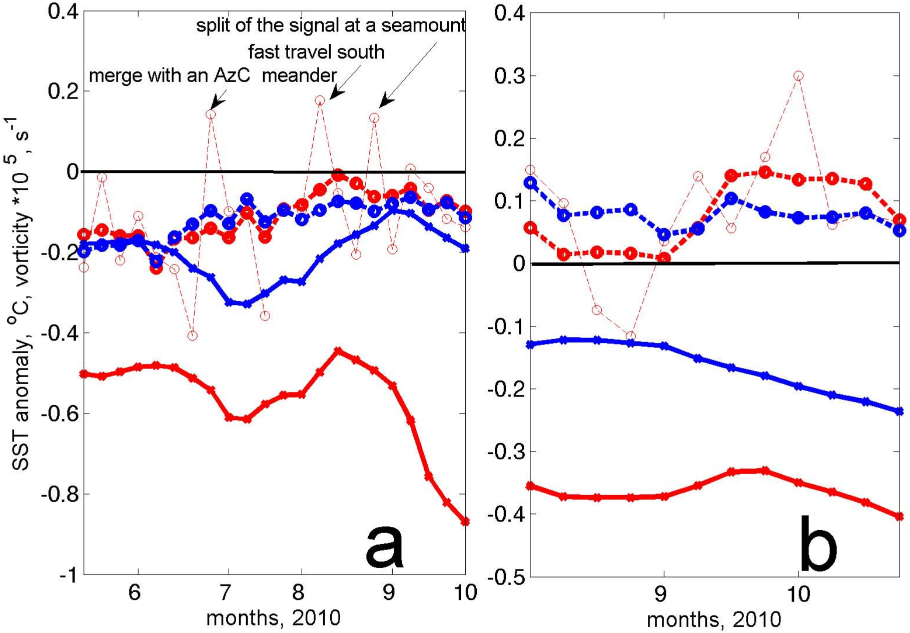

Fig. 6. Monthly running means of SST anomaly (˚C, thick dashed lines) and relative vorticity (10^{-5} s^{-1}, solid lines) in the surface signal of Meddy 1 **(a)** and in the AzC meander **(b)**. The red lines are SST_{25}–SST_{100} and mean relative vorticity in the 25-km circle around the vortex centre; the blue lines are SST_{50}–SST_{100} and mean relative vorticity in the 25–50 km ring around the vortex centre. The SST_{25}–SST_{100} with original (weekly) temporal resolution is also shown as a thin dashed red line.

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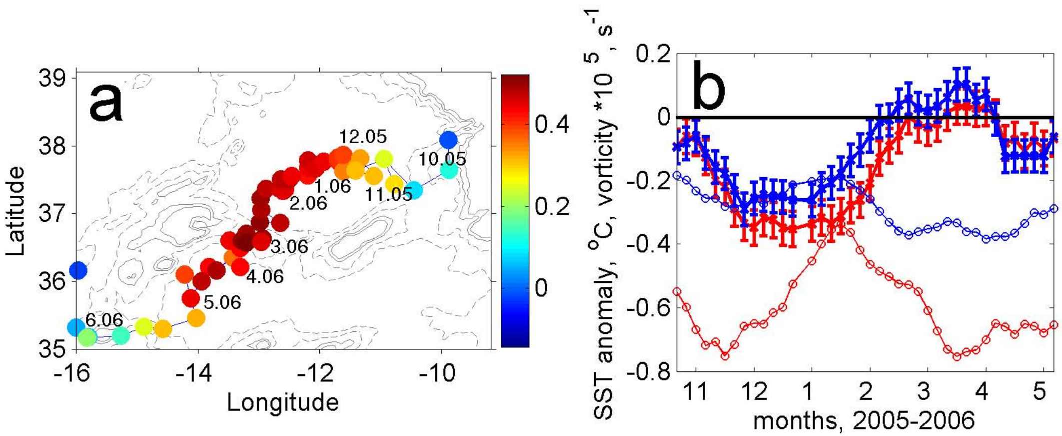

Fig. 7. (a) Mean salinity anomalies relative to WOA09 climatic data in the 700–1500 m layer for the consequent ARGO vertical profiles (Meddy 2). Thin grey contours show bottom topography with 1000-m interval. **(b)** Monthly running means of SST anomaly (SST_{25}–SST_{100}, °C, red lines with errorbars) and relative vorticity in 25-km central ring (10^{-5} s^{-1}, thin red lines with circles). The respective blue lines are SST_{50}–SST_{100} and mean relative vorticity in the 25–50 km ring around the vortex centre. The errorbars represent the mean error in calculation of the SST anomalies.

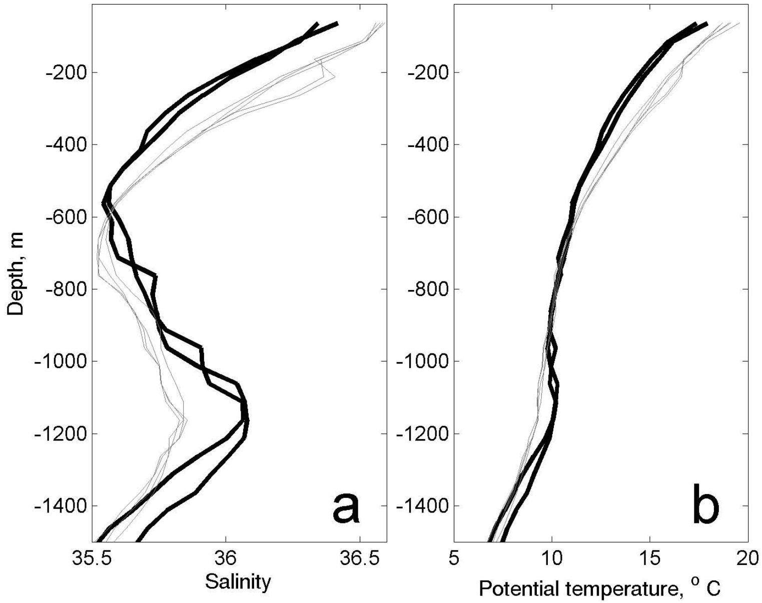

Fig. 8. Vertical profiles of salinity **(a)** and potential temperature **(b)** north-east of Madeira island in July 2004. Thick black lines are the casts through a meddy and thin grey lines are the casts around the meddy.

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