Hydrography, Circulation, and Mixing at the Calypso Deep (the Deepest Mediterranean Trough) during 2006–09

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ABSTRACT

The mass and flow fields from June 2006 to May 2009 in the Calypso Deep (bottom depth ~5.2 km) are investigated using eddy-resolving surface-to-bottom hydrography (station grid spacing ~0.2°) and two tall moorings yielding current-meter records at depths from 700 m to near bottom. A salty warm lens (excess core salinity and temperature are ~0.01 and 0.025°C relative to the surrounding water) of Cretan Deep Water with a core at ~3000 m and a horizontal (vertical) scale of ~50 km (1.5 km) is identified in June 2006 to be locked over the trough. The lens coincides with local maxima in dissolved oxygen. In October 2006 the salinity content of the lens and of all deeper layers is increased; the oxygen maxima are shifted to the bottom layers, indicating an episodic intrusion of higher-density ventilated Adriatic water. The circulation changes from anticyclonic at all depths in June 2006 to cyclonic below ~2.5 km in October 2006, whereas after January 2007 it is cyclonic at all instrumented depths. The measured currents are weak (mean speeds < 5 cm s⁻¹) and persistent in direction, being mostly along the bottom topography at all current-meter depths. After October 2006, the lens erodes due to salt/heat loss caused predominantly by lateral (intrusive) mixing, which works from the outside toward the lens center. The horizontal diffusivity is on the order of ~10 m² s⁻¹, near the center of the lens, and ~10² to 10³ m² s⁻¹, at its periphery, with an average error ~15 times the diffusivity value. In the deepest part of the trough and in periods of predominance of vertical mixing the vertical diffusivity at 4400 m is ~4 × 10⁻³ m² s⁻¹.

1. Introduction

The existing knowledge about the deep eastern Mediterranean relies basically on coarse sampling over long transects that concern only the mass field in studies dealing with the deep thermohaline circulation (Roether at al. 1996; Malanotte-Rizzoli et al. 1997; Klein et al. 1999). Information on deep circulation structures, such as can be derived by smaller-scale eddy-resolving
Hydrography or even more by direct current observations, is scarce if not unavailable at all. The overall absence of current measurements in the eastern Mediterranean is also vital with respect to the assessment of the mixing processes. Most of the existing direct current observations are from surface drifters (Gerin et al. 2009; Menna et al. 2012) or current-meter moorings deployed in areas of sea straits (Astraldi et al. 1999; Kontoyiannis et al.)

Fig. 1. (a) A part of the eastern Mediterranean including the southern Ionian Sea, with the tentative neutrino telescope areas, NESTOR and NEMO, and the Cretan Straits (i.e., the narrow sea passages to the northwest and northeast of Crete). Our study area is within the rectangle. Colored lines are bathymetric contours as indicated in the lower part. (b) A focused view of the study area with positions of hydrographic/CTD (conductivity, temperature, depth) stations and current-meter moorings. The thick black line indicates a repeated hydrographic section during the various surveys in the study area. Bathymetric contours are in meters. The 4400-m isobath is the dashed red line and the 5000-m isobath is shown in black around station NESTOR 5.2.
Deep current-meter measurements have been obtained off the coast of Libya at depths of 2000 m (www.ifremer.fr/lobtn/EGYPT) and offshore from southeast Italy in the early 2000s at depths near 3000 m (Rubino et al. 2012). The present work investigates the deep mass field and flow conditions in the deepest area of the Mediterranean Sea, the so-called Calypso Deep or Vavilov Deep, which is a circle-shaped bottom trough with a diameter near 50 km and depths greater than 4000 m.

Figure 2. (a) Profiles of potential temperature (curve 1), salinity (curve 2), percent light transmission for red light (curve 3), normalized dissolved oxygen, i.e., in situ dissolved oxygen divided by the profile minimum value, (curve 4), and potential density $\sigma_0$ (curve 5) at station NESTOR 5.2 in May 2007. Deep water masses are indicated on the salinity profile. (b) Profiles of potential temperature, salinity, and potential density south of the east Cretan Straits (34.38°N, 26.0°E) in April 2008. (c) The $\theta$/$\sigma$ diagrams for the deep part of the temperature and salinity profiles at site NESTOR 5.2 in May 2008 (curve 1) and of the profiles south of the Cretan Straits in (b) (curve 2).
4 km to the southwest of the Peloponnesus at the southern part of the Hellenic mainland (Figs. 1a,b). The Calypso Deep has a moderate bottom slope ($2.6 \times 10^{-2}$) for most of its extent, while it reaches a maximum bottom depth of 5267 m in the northwest where the bottom slope increases to values around $2.0 \times 10^{-1}$. The interest in this area is also associated with plans for installing therein a deep-sea neutrino telescope system called NESTOR.
The contribution of physical oceanography to the neutrino telescope site characterization (i.e., to the investigation of the appropriateness of a site and the area around it for the neutrino telescope operation) has been to provide the description and insights on the deep physical water characteristics and flow conditions along with their variability.

The wider oceanic area to the southwest of the Peloponnesus was surveyed several times in the period from the mid-1980s to the mid-1990s during the Physical Oceanography of the Eastern Mediterranean (POEM) program, which has conducted most of the large-scale hydrographic surveys in the eastern Mediterranean (Robinson et al. 1991, 1992). The POEM surveys sampled the upper ~2 km of the water column on a dense grid of hydrographic stations. A basic outcome was to provide the description and insights on the deep physical water characteristics and flow conditions along with their variability.

The present work fills this knowledge gap for our study area which is of limited extent compared to the POEM surveys. Nevertheless, the employed dataset consists of half-yearly surface-to-bottom CTD (conductivity, temperature, and depth) casts in the period 2006–09 and current measurements derived from deployments of tall current-meter moorings during the same period. It therefore reveals previously unknown information on the flow dynamic structures and variability throughout the entire water column, the role of the bottom topography on the local flows, and the mixing processes in the deep layers.

2. Field work and data

From February 2006 through May 2009, eight research cruises were conducted by the Hellenic Centre for Marine Research (HCMR) on board the R/V Aegaeo in the NESTOR area located to the southwest of Peloponnnesos (Fig. 1b). In these cruises, hydrographic CTD work was carried out at several sites shown in the station grid of Fig. 1b. The entire grid was not sampled in all of the cruises. The CTD section in Fig. 1b was conducted on five (June 2006, October 2006, May 2007, April 2008, May 2009) out of the total eight cruises, whereas stations south of the CTD transect were visited in four cruises and therefore deep dynamic height maps over the Calypso Trough, as depicted by the 4000-km isobath, can be constructed only for those four cruises (June 2006, October 2006, April 2008, May 2009).

A Sea-Bird SBE-9-plus unit was used for the CTD casts and the salinity readings were checked by employing corresponding salinity measurements on water samples with the use of a Guildline 8400B Autosol salinometer. The salinity corrections, when applied, agreed to the results on conductivity-sensor drift that was determined when the sensors were sent back to Sea-Bird for post-cruise calibration. The final maximal estimated uncertainties for temperature and salinity are ±0.002°C and ±0.003, resulting in a ±0.0025 kg m⁻³ uncertainty for the density. Measurements of dissolved oxygen with the CTD unit were also obtained on the cruises of June 2006, October 2006, and May 2007, for which no cross-checking was done via laboratory oxygen determinations while the profile oxygen values varied from cruise to cruise, possibly due to sensor drift. Therefore, the oxygen data in each CTD cast are used to provide only the vertical structure in the oxygen profiles and not the actual oxygen concentrations. This is accomplished by employing

![Diagram](http://www.inp.demokritos.gr/nestor/).
normalized oxygen values (i.e., oxygen content relative to a minimum recorded oxygen defined for each cruise), and we report only on the spatial structure of the relative oxygen distributions.

In addition to the typical temperature, salinity, and dissolved oxygen measurements, the CTD profiles included measurements of water transparency expressed as percent light transmission. This refers to the percent red-light intensity detected at a distance $s$ of 25 cm relative to the intensity emitted from a light source at $s = 0$. The light transmission measurements show the relative spatial changes of the water transparency during a specific cruise. Measurements of absolute values of light transmission at various depths in the same area are reported for several wavelengths in the work by Anassontzis et al. (2010).

Apart from the hydrographic work, long-term (3.5 yr) deployments of tall moorings, equipped with RM8, RCM9, and RCM11 Aanderaa current meters, occurred at stations NESTOR 4.5 and NESTOR 5.2 with bottom depths 4.5 and 5.2 km respectively (Fig. 1b). Site NESTOR 4.5 is located at a relatively flat bottom area to the east of the deepest part of the trough, which is depicted by the 4400-m depth contour (Fig. 1b). The tall mooring deployments started in June 2006 and were continued until May 2009 at NESTOR 5.2 and September 2009 at NESTOR 4.5. The current-meter depths ranged from 700 m down to 200 m off the bottom and were selected in combination with criteria relevant to sediment-flux measurements, since the current meters had to accompany sediment traps.

### 3. Water masses

Prior to the early 1990s, the bottom layers of the east Mediterranean were occupied by water masses of Adriatic origin whereas the Cretan water was outflowing into the eastern Mediterranean at intermediate depths (Malanotte-Rizzoli et al. 1999). In the period from the late 1980s to the mid-1990s, the Cretan water was transformed to become dense enough and it massively sank to the bottom of the east Mediterranean as Cretan Deep Water (CDW) (Roether et al. 1996; Theocharis et al. 1999). By the late 1990s the density and the volume of the CDW decreased so that it could not reach the eastern Mediterranean bottom anymore (Theocharis et al. 2002). Water masses of Adriatic origin reoccupied the bottom layers again after the early 2000s (Manca et al. 2006; Hainbucher et al. 2006).

Figure 2a shows profiles of various hydrographic properties at site NESTOR 5.2 in May 2007. Focusing on the deep signatures, two local maxima in salinity and temperature are observed, one at $\sim$1800 m and the other at $\sim$3000 m. The water masses of these local maxima in salinity and temperature originate most likely in the Cretan Sea. Similar double maxima in CTD profiles have been observed in the late 1990s in the area of the east Cretan Straits, where the east outflow channel with sill depth near $\sim$1000 m provides the deeper salinity core and the west outflow channel with sill near $\sim$800 m provides the upper salinity core (Kontoyiannis et al. 2005; Roether et al. 2007). Additional evidence with respect to the origin of the salinity maxima at $\sim$1800 m and at $\sim$3000 m is also observed during 2008 in Figs. 2b and 2c, where we present a comparison between a CTD cast south of the east Cretan Straits (34.38°N, 26.0°E) in May 2008 and the one at site NESTOR 5.2 in the same month. The CTD profiles south of the east Cretan Straits (Fig. 2b) are again characterized by two local maxima in temperature and salinity. The deep part of the potential temperature/salinity ($\theta/S$) curve south of the east Cretan Straits (curve 2) is very similar in shape to the corresponding curve at NESTOR 5.2 (curve 1). Despite the fact that the CDW undergoes along-isopycnal mixing on its spreading to the west by entraining ambient waters, it preserves a strong Cretan Sea component in its $\theta/S$ characteristics.

In the depth range below the lower limit of the CDW, which is at $\sim$3600 m (Fig. 2a), there is a lower-salinity, lower-transparency water of Adriatic origin that fills the near-bottom layers of the eastern Mediterranean again after the early 2000s. The oxygen minimum at $\sim$800 m corresponds to the core of a water body that is affected the least by dissolved oxygen input. It contains a wide mixture of quantities, which may still include old bottom water of Adriatic origin before the early 1990s.

Figure 3a shows for June 2006, October 2006, and May 2007 the deep structure in salinity, potential density referenced to 3000 dbar $\sigma_3$, and normalized oxygen content on the section indicated by the thick black line in Fig. 1b. The normalized oxygen content is defined as the in situ oxygen content measured by the CTD divided by the average of the oxygen minima of the stations in the section. A lens-like water blob with a strong Cretan component, associated with the salinity maximum near $\sim$3000 m, extends between 2500 and 3500 m. This water blob exhibits variability in salt content and size. From June 2006 to October 2006 there is an increase in its salt content and size, depicted by the dashed salinity contour of 38.76. From October 2006 to May 2007 the size and the salinity values of the blob are decreased. The core is confined to site NESTOR 5.2. The bottom panels of Fig. 3a show the deep salinity profiles of the stations in the cross-transect; a comparison of their values with the salinity values of the contour plots confirms the accuracy of the contouring routine and the reality of the deep salinity blob.
A corresponding variability exists in the density and oxygen distributions. In June 2006 the oxygen maxima are at the depth range of the deep Cretan blob and the oxygen concentrations are decreasing toward the bottom in the layers occupied by the waters of Adriatic origin. The density distribution in June 2006 is indicative of anticyclonic motion. In October 2006 an increase appears in the normalized oxygen values. The oxygen maxima are shifted to the bottom layers indicating an intrusion of water masses with higher oxygen into the study area at these layers. The near-bottom densities increase in October 2006 and their structure is indicative

FIG. 4. (left) Objectively mapped horizontal fields of vertically averaged salinities in the depth range of 2400–3600 m, along with (right) the corresponding objective mapping errors for the cruises of June 2006, October 2006, May 2007, and April 2008. Dots indicate the stations of the salinity input data, crosses indicate the outer limits of the rectangular domain of objective mapping, and the dashed line is the 4000-m isobath (Fig. 1b).
of cyclonic motion. In May 2007 the normalized oxygen maxima shift toward the depth range of the Cretan blob.

The decay of the higher salinity blob is continued toward April 2008 and May 2009 (Fig. 3b). In May 2009 the deep salinity peak is preserved only at NESTOR 5.2 while a homogenized layer in salinity extending between 2.5 and 3.5 km appears at NESTOR 4.5. In April 2008 the horizontal density gradients below 3 km have relaxed. At these depths, however, substantial density gradients reappear in May 2009 indicating anticyclonic motion. The current-meter data will elucidate the deep flow during May 2009.

The deep salinity maxima in the depth range 2400–3600 m with a peak near 3000 m are due to an isolated saline lens that is locked over the bottom topography (i.e., the 4000-m isobaths). This is shown in the objective maps of the averaged salinities over the particular depth range at each station (Fig. 4). Our objective analysis scheme uses the approach presented by Bretherton et al. (1976) and adapted by Watts et al. (2001). We use a correlation function of the form $R = (1 - r^2/a^2) \exp(-0.5r^2/b^2)$, where $a = 20$ km and $b = 40$ km, according to estimates of these quantities that appear in Nittis et al. (1993). The error fields, shown in the right panels of Fig. 4, are expressed as percent of the input signal variance and include the effects of both the salinity measurement uncertainty and the mapping uncertainty. The depth-averaged view of this deep saline lens exhibits variability with qualitative characteristics similar to the ones shown in its sectional view of Figs. 3a and 3b.

Qualitative similar results are derived for the profile-temperature maxima at ~3000 m from the corresponding plots of the depth-averaged temperatures, which are not shown. The salinity and temperature anomalies in the core of the deep lens with respect to the surrounding water are ~0.01 and ~0.025°C, respectively.

4. Currents and flow field

Figures 5 and 6 show the 40-h low-passed current stick time series at sites NESTOR 5.2 and NESTOR 4.5, respectively. Some gross statistics on the original unfiltered currents are also shown within the figures for convenience. The flow speeds at both sites are weak, near 2–3 cm s$^{-1}$ in average, while the maxima never exceeded ~18 cm s$^{-1}$, a value that was observed at the depth of 1200 m at site NESTOR 4.5. Site NESTOR 5.2 is characterized by even weaker speeds at all levels with maxima of 10 cm s$^{-1}$ at 1200 m and 7 cm s$^{-1}$ at 4000 and 4800 m.
The progressive vector diagrams in Figs. 7 and 8 are used to indicate the flow direction during periods with data coverage and therefore they are plotted as continuous lines despite some existing data gaps. They show that for most of the deployment period in 2007, 2008, and 2009 the flow at all levels of site NESTOR 4.5 (i.e., from 700 m down to 4300 m) is to the north-northwest approximately parallel to the 4000-m isobath, whereas at site NESTOR 5.2 the flow is to the south at 1200 m and south-southeast at 2900, 4000, and 4800 m (i.e., approximately along the 5000-m isobath) (Fig. 1b). The persistence of flow to a direction nearly parallel to the bottom contours throughout most of the water column at both sites is indicative of topographic steering; the observed flow directions at the two sites suggest that a tall cyclone locked on the bottom topography is dominant after the beginning of 2007. A differentiation in the cyclonic flow pattern exists in June 2006, when the flow at 4300 and 3200 m at NESTOR 4.5 is to the west, suggesting an anticyclonic pattern over the deep part of the trough. Further relevant information will be added by use of the dynamic height maps.

The currents recorded in the study area exhibit variability at all scales from tidal to near-inertial to mesoscale (synoptic). It is of interest to mention that a preliminary analysis shows that near-inertial flow variability extends at least as deep as ~3 km, which was also observed in the western Ionian Sea near Sicily (Rubino et al. 2012). At deeper levels, the high-frequency motions are dominated by semidiurnal tides relative to near-inertial motions. However, the in-depth analysis and presentation of the information existing in the present current-meter dataset is beyond the objectives of this work.

Figure 9 shows dynamic-height maps at 500 m with levels of no motion at 2500 m during June 2006 and October 2006 and at 2500 m with level of no motion at 3850 m during June 2006, October 2006, April 2008, and May 2009. Dynamic-height maps at 500 m with a reference at 2500 m were not constructed for April 2008 and May 2009 due to the lack of adequate horizontal coverage of the CTD stations, as in June 2006 and October 2006, which is necessary to capture the larger lateral extent of the dynamic structures in the 500–2500-m range in comparison to the deeper structures (2500–3850-m depth range) that are locked over the deep narrow part of the trough. The dynamic-height representations are indicative of the flow at the specific depth relative to an observer moving with the flow speed at the level of no motion. In June 2006 an anticyclonic circulation appears in the depth range 500–2500 m, suggesting that the study area is within the northeast periphery of the Pelops anticyclone (Fig. 9a). The anticyclonic motion in June 2006 extends deeper in the depth range of
2500–3850 m (Fig. 9c). In October 2006 and the depth range 500–2500 m, a local cyclonic structure that does not form a closed loop exists to the east of site NESTOR 5.2 (Fig. 9b). This appears to be linked with the cyclonic eddy that (a) is dominant in the deeper layers (2500–3850 m), (b) is steep in dynamic-height topography (Fig. 9d), and (c) is apparently developed by the intrusion of the higher-density water mass (Fig. 3). In late October 2006 the flow at NESTOR 5.2 at 1200 m is to the south (Figs. 5 and 7), whereas at NESTOR 4.5, at 700, 1200, and 2000 m the flow varies from northeast to southeast (Fig. 6), which is in agreement with the corresponding dynamic-height structure in Fig. 9b.

In April 2008 the dynamic-height map at 2500 m relative to 3850 m (Fig. 9e) still indicates a cyclonic motion but with a less steep dynamic topography in comparison to the corresponding structure of October 2006. In May 2009 the flow at 2500 m relative to the flow at 3850 m indicates an anticyclone (Fig. 9f). In the same period, however, the actual deep and near-bottom flow, as observed in the near-bottom current records, remains cyclonic (Figs. 7 and 8). The apparent anticyclonic motion in the dynamic height map of Fig. 9f is due to the flow intensification that occurs in the near-bottom layers relative to the layer above and this is shown in the current-meter records. The current time series at 4350 m at NESTOR 4.5 show that for the entire period from February 2009 to September 2009 the flow is mostly to the northwest, typical of the actual deep cyclone (Fig. 6), but it is characterized by higher speeds relative to the flow at 2000 m.

5. Considerations on mixing: approximate heat/salt fluxes

a. The deep lens

A first overview of the mixing processes is obtained by examining the thermohaline evolution at NESTOR 5.2 and NESTOR 4.5 on $\theta/S$ diagrams for the period 2006–09 (Fig. 10). The two broad thermohaline inversions on each
\(\theta/S\) curve are associated with the salinity and temperature maxima observed at \(\sim 1800\) and \(\sim 3000\) m, discussed in section 3. Considering the temporal \(\theta/S\) changes at \(\sim 3000\) m with respect to the orientation of the isopycnals, it is evident that a strong contribution of cross-isopycnal mixing exists in the changes from June 2006 to October 2006 (Fig. 10, upper panels), whereas along-isopycnal \(\theta/S\) changes and predominance of lateral mixing occur after October 2006 in the layers of the deep warm-saline lens (Fig. 10, lower panels).

Figure 11 shows the shape (i.e., the relative changes) in the temperature profiles from June 2006 through May 2009 at stations 1, 4, NESTOR 5.2, and NESTOR 4.5 (Fig. 1b). Stations 1 and 4 are at the periphery of the deep warm-saline lens, whereas NESTOR 5.2 and NESTOR 4.5 are close to the lens core, with the exception of NESTOR 4.5, which is away from the core in April 2008 and May 2009, since the lens was diminished (Figs. 3 and 4). With the aid of the temperature data in Fig. 11, we further investigate the evidence of horizontal mixing below 1000 m, which appears in the fine-structure anomalies in the temperature profiles. According to Georgi and Schmitt (1983), this fine structure (i.e., the local temperature/salinity profile peaks
with a vertical scale of a few tens of meters) is indicative of horizontal mixing by lateral intrusive motions in cases such as ours where strong horizontal temperature/salinity gradients exist. The lateral temperature intrusions in our profiles have an approximate maximum magnitude of 0.01°C and weaken from 2006 to 2009. They are minimal in the central core of the deep lens as is shown on the profiles of June and October 2006 at NESTOR 5.2.

In addition to the lateral intrusive peaks, temperature steps appear under the deep lens at NESTOR 5.2 in October 2006 and at NESTOR 4.5 in June and October 2006, suggesting evidence of vertical mixing through salt fingers. The deep $R_d$ ratio $[R_d = (\alpha \Delta T/\alpha z)/(\beta \Delta S/\alpha z)]$, where $\alpha$ and $\beta$ are the thermal expansion and haline contraction coefficients, respectively] attains values near $\sim 1.2$ under the high salinity core in these profiles, indicating conditions favorable for the onset of salt fingers.

**FIG. 9.** Objectively mapped dynamic-height anomaly fields at 500 m with level of reference at 2500 m, during (a) June and (b) October 2006, and at 2500 m with level of reference at 3850 m during (c) June and (d) October 2006, (e) April 2008, and (f) May 2009. Black bullets indicate positions of CTD stations; H and L indicate areas of higher and lower dynamic height values respectively. Dynamic-height contour labels are in dynamic meters, while the contour interval is in the inset label in each panel in dynamic millimeters. Dashed contour is the 4000-m isobath.
The above qualitative observations on the spatial and temporal characteristics of the lateral intrusions are substantiated when we quantify their standard deviation. This is accomplished by fitting on each of the temperature profiles a smoothed curve with a 250-m running mean and then subtracting from the original data. The results are shown in Table 1 for the layers of 1100–2200 m, in which an upper broad temperature and salinity maximum appears, and 2200–3600 m, which is the depth range of the warm saline lens (Figs. 11 and 3). We notice that in both layers the smaller activity of lateral intrusions is observed at NESTOR 5.2 in the center of the lens, whereas the peripheral stations 1 and 2 exhibit the strongest activity in lateral intrusions, usually in periods when sharp lateral thermohaline gradients exist in their vicinity, as in June and October 2006 (Fig. 4).

From the available current-meter data and the temperature/salinity objective analysis maps at the current-meter levels during the CTD surveys we can obtain estimates of horizontal eddy diffusivities for heat and salt for the periods after October 2006 when there is a lateral advection–diffusion balance in the heat/salt equation due to the predominance of lateral mixing at the depths of the saline lens (Fig. 10). These estimates can be attempted for the current-meter depth of 2900 m at NESTOR 5.2 in May 2007 and April 2008 and for the current-meter depth of 3200 m at NESTOR 4.5 in May 2007 (Fig. 12). The

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**FIG. 10.** (top) $\theta$/$S$ diagrams for depths greater than −800 m at sites NESTOR 5.2 and NESTOR 4.5 during June 2006 (black) and October 2006 (red). (bottom) As at (top), but for October 2006 (red), May 2007 (green), April 2008 (cyan), and May 2009 (blue). The isopycnals $\sigma_0 = 29.18$, $\sigma_2 = 37.84$, and $\sigma_3 = 41.99$ are also shown for reference. Temperature and salinity measurement uncertainties are shown in the lower right of each panel.
The horizontal advection–diffusion balance for temperature with local time dependence is expressed as

\[ \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \sim K_{HT} (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}), \]

(1)

where \( u \) and \( v \) are the low-pass filtered east and north velocities respectively, \( T \) is temperature, and \( K_{HT} \) is the horizontal eddy diffusivity (mixing coefficient) for heat. The corresponding expression for salinity and horizontal salinity diffusivity \( K_{HS} \) appears when the temperature \( T \) in (1) is substituted by the salinity \( S \). The objective analysis temperature and salinity fields at the current meter depths are on a 5 km \( \times \) 5 km grid (Fig. 12). This grid is subsampled along the \( x \) and \( y \) axes at the locations of the current meters to get the estimates of the first and second horizontal derivatives by employing spline fits on the subsampled data. The results on the computation of the horizontal eddy diffusivities along with their errors are in Tables 2 and 3. The details of the error analysis, along with tests of sensitivity to the temperature/salinity input values in the objective analysis procedure, are in the

**Table 1.** Standard deviation values of fine-structure temperature anomalies of the profiles shown in Fig. 11. All tabulated values must be multiplied by \( 10^{-3} \) to return the standard deviation in °C. Mean values in parentheses for station 4 indicate probable bias due to lack of data in October 2008 and May 2009.

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appendixes. The average diffusivity error is approximately \( \sim 15 \) times the diffusivity value. The resulting ranges of order of magnitude for the horizontal diffusivities, when the information on their errors is utilized, are \( \sim 10 \) to \( 10^2 \) \( \text{m}^2 \text{s}^{-1} \) at the center of the lens at site NESTOR 5.2, and \( \sim 10^2 \) to \( 10^4 \) \( \text{m}^2 \text{s}^{-1} \) at the periphery of the lens at site NESTOR 4.5.

If we assume that the shape of the deep lens resembles that of a cylinder with radius \( r (r = \sim 25 \text{km}) \) and height \( h (h = \sim 1400 \text{m}) \) that loses heat and salt due to horizontal processes, as in May 2007 and April 2008 (Figs. 3 and 10), then for the total salt \( S \) and the total heat \( H \) of the lens we have \( \frac{\partial S}{\partial t} = 2\pi rhF_S \) and \( \frac{\partial H}{\partial t} = 2\pi rhF_H \), where \( F_S \) and \( F_H \) are, respectively, the horizontal fluxes of salt and heat through the side of the cylinder (i.e., salt or heat per unit time per unit area). An overall (vertical and horizontal) mean of salinity and temperature is produced for the entire volume of the cylinder, which is then multiplied by the water mass/heat capacity of the cylinder to return the total salt/heat content of the cylinder. Figure 13 shows the time evolution of the total salt and heat content in the lens for the period June 2006–April 2008, when the lens has approximately the above dimensions of \( r = \sim 25 \text{km} \) and \( h = \sim 1400 \text{m} \) (Figs. 3 and 4). In the period October 2006–May 2007, when lateral mixing predominates, the horizontal fluxes through the entire side of the cylinder are \( \sim 9.5 \times 10^5 \) \( \text{kg} \text{s}^{-1} \) for salt \( (F_S \sim 4.3 \times 10^{-3} \text{kg} \text{s}^{-1} \text{m}^{-2}) \) and \( \sim 6.8 \times 10^9 \) \( \text{W} \) for heat \( (F_H \sim 31 \text{W} \text{m}^{-2}) \). These fluxes decrease by a factor of \( \sim 3 \) for the salt and \( \sim 2 \) for the heat in the period May 2007–April 2008, that is, to \( \sim 3.3 \times 10^5 \) \( \text{kg} \text{s}^{-1} \) \( (F_S \sim 1.5 \times 10^{-3} \text{kg} \text{s}^{-1} \text{m}^{-2}) \) and \( \sim 3.7 \times 10^9 \) \( \text{W} \) \( (F_H \sim 17 \text{W} \text{m}^{-2}) \).

If in June 2006 the lens-averaged and the background salinities are 38.758 and 38.754, respectively, and in April 2008 they decrease to 38.751 and 38.748 respectively (Fig. 4); that is, the extra salinity drops from 0.004 to 0.003 in \( \sim 23 \) months, a gross estimate of the e-folding scale \( t_e \) for the extra salinity reduction is approximately \( \sim 7 \text{yr} \), according to \( 0.003/0.004 = \exp(-23/t_e) \). A similar calculation for heat results in an e-folding scale of \( \sim 2.5 \text{yr} \).

b. The deepest part of the trough

The volume of water below the 4400-m depth contour, considered to represent the deepest part of the trough (Fig. 1b), is \( \sim 1.2 \times 10^{11} \) \( \text{m}^3 \) while the surface area enclosed by the 4400-m contour is \( \sim 3.5 \times 10^8 \) \( \text{m}^2 \). Both estimates are based on HCMR swath-bathymetry data. Because of the bottom geomorphology, which resembles an oblique conical depression, this particular volume of water is expected to be influenced by vertical fluxes through the horizontal surface enclosed by the 4400-m depth contour. The \( \theta/S \) changes at depths 4800 m and 5100 m are small with respect to the \( \theta/S \) uncertainties (Fig. 13). In the period June–October 2006 they stand...
above the uncertainties, while the combined change on the $\theta/S$ diagram is nearly perpendicular to the $\sigma_3$ isopycnal of 41.99. Apparently it is dominated by vertical mixing. The $\theta/S$ changes due to vertical mixing in the deepest part of the trough weaken substantially in the period from October 2006 to October 2008; this observation is in accord with the weakening of the vertical gradients in salinity and temperature at those depths during the same period (Fig. 11) that determine the vertical exchanges. In the period October 2008–May 2009 the direction of the change is again nearly perpendicular to the $\sigma_3$ isopycnals, but only the temperature change stands above the uncertainty.

We consider the cross-isopycnal $\theta/S$ changes in the deepest part of the trough change during the periods June–October 2006 and October 2008–May 2009 (Fig. 13), which are determined predominantly by vertical processes. If we further assume that in these near-bottom layers the mean vertical velocities are negligible, then the dominant balance in the heat/salt equation is between the local temporal change and the vertical diffusion, that is,

$$\partial T/\partial t \sim \partial / \partial z [K_{ST}(\partial T/\partial z)]$$,

(2)

where $K_{ST}$ is the vertical eddy diffusivity for heat. In the deep trough, if we integrate the above balance horizontally and vertically, from 4400 m to the bottom, we obtain the relation

$$\partial T_v/\partial t \sim (A/V)K_{ST}(\partial T_A/\partial z)_{4400}$$,

(3)

where $T_v$ is the mean temperature over the entire volume $V$ of the deep trough; $T_A$ and $K_{ST}$ are, respectively, the mean temperature and the mean vertical heat diffusivity over the area $A$ enclosed by the 4400-m depth contour; and $(\partial T_A/\partial z)_{4400}$ indicates the respective vertical derivative at 4400 m (Axell 1998; Zervakis et al. 2003). The corresponding relationship for salinity and mean vertical salt diffusivity $K_{SST}$ over the area $A$ emerges when the temperature $T$ in (3) is substituted by the salinity $S$.

The existing relationships can be utilized for the salinity and temperature changes in the periods June–October 2006 and October 2008–May 2009 in order to determine the vertical diffusivities $K_{SST}$ and $K_{ST}$ for salt and heat at 4400 m. The volume-mean temperatures and salinities, $T_V$ and $S_V$, are approximated by the temperature and salinity vertical means from 4400 m to the bottom at station NESTOR 5.2, whereas the horizontal mean $T_A$ and $S_A$ by the temperature and salinity values at 4400 m at NESTOR 5.2. The above relationships can be applied if, in the respective periods, $(\partial \Delta T_v/\partial t)$ or $(\partial \Delta S_v/\partial t)$ are processes, other than vertical diffusive transfer, that alter the salinity/temperature of the water above the deepest part of the trough. Apparently this did not happen in the period June–October 2006 when higher-density ventilated water masses entered the study area. In this case, there was an extra salinity increase in the deepest part of the trough in comparison to the salinity increase driven by the vertical salinity gradient at 4400 m in June 2006 and the resulting vertical diffusivity is an overestimate of equal percentage as the extra salinity increase. For the same reason the time rate of change $(\Delta T_v/\Delta t)$ has an opposite sign from the vertical gradient of temperature $(\partial T_v/\partial z)$ at 4400 m in the aforementioned period. For the

### Table 2: Estimates of horizontal heat diffusivities ($K_{HT}$) at sites NESTOR 5.2 and NESTOR 4.5.

<table>
<thead>
<tr>
<th>$U$ (m s$^{-1}$) ($\times 10^{-2}$)</th>
<th>$V$ (m s$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial T/\partial t$ (°C m$^{-2}$) ($\times 10^{-10}$)</th>
<th>$\partial T/\partial x$ (°C m$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial T/\partial y$ (°C m$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial^2 T/\partial x^2$ (°C m$^{-2}$) ($\times 10^{-11}$)</th>
<th>$\partial^2 T/\partial y^2$ (°C m$^{-2}$) ($\times 10^{-11}$)</th>
<th>$K_{HT}$ (m$^2$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>0.05</td>
<td>-4.7</td>
<td>1.74</td>
<td>-4.2</td>
<td>-9.50</td>
<td>-7.69</td>
<td>9 ± 25</td>
</tr>
<tr>
<td>0.87</td>
<td>-1.9</td>
<td>-7.4</td>
<td>5.5</td>
<td>2.7</td>
<td>-2.60</td>
<td>-7.40</td>
<td>11 ± 93</td>
</tr>
<tr>
<td>0.27</td>
<td>1.2</td>
<td>-4.7</td>
<td>17</td>
<td>-8.7</td>
<td>-1.70</td>
<td>-3.40</td>
<td>883 ± 11480</td>
</tr>
</tbody>
</table>

### Table 3: Estimates of horizontal salt diffusivities ($K_{HS}$) at sites NESTOR 5.2 and NESTOR 4.5.

<table>
<thead>
<tr>
<th>$U$ (m s$^{-1}$) ($\times 10^{-2}$)</th>
<th>$V$ (m s$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial S/\partial t$ (°C s$^{-1}$) ($\times 10^{-10}$)</th>
<th>$\partial S/\partial x$ (°C m$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial S/\partial y$ (°C m$^{-1}$) ($\times 10^{-2}$)</th>
<th>$\partial^2 S/\partial x^2$ (°C m$^{-2}$) ($\times 10^{-11}$)</th>
<th>$\partial^2 S/\partial y^2$ (°C m$^{-2}$) ($\times 10^{-11}$)</th>
<th>$K_{HS}$ (m$^2$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>0.05</td>
<td>-1.5</td>
<td>-0.286</td>
<td>-0.920</td>
<td>-2.50</td>
<td>-1.92</td>
<td>8 ± 62</td>
</tr>
<tr>
<td>0.87</td>
<td>-1.9</td>
<td>-2.1</td>
<td>0.320</td>
<td>0.221</td>
<td>-0.490</td>
<td>-0.751</td>
<td>24 ± 612</td>
</tr>
<tr>
<td>0.27</td>
<td>1.2</td>
<td>-1.5</td>
<td>-6.11</td>
<td>-3.21</td>
<td>-0.360</td>
<td>-1.52</td>
<td>480 ± 8160</td>
</tr>
</tbody>
</table>
period June–October 2006 we will not estimate the heat vertical diffusivity, whereas for the period October 2008–May 2009 we will not estimate the salt vertical diffusivity since the salinity change was less than the salinity uncertainty (Fig. 13). The resulting value (overestimate) of vertical diffusivity for salt in June–October 2006 is on the order of $10^{-2}$ m$^2$ s$^{-1}$, whereas the value for heat diffusivity during the period October 2008–May 2009 is on the order of $10^{-3}$ m$^2$ s$^{-1}$ (Table 4). In our data there is no evidence that in the period October 2008–May 2009 the water mass above the interface at 4400 m is influenced by processes other than vertical diffusion as it was during June–October 2006. Therefore the vertical diffusivity of $10^{-2}$ m$^2$ s$^{-1}$ is considered to be a more accurate estimate, despite the fact that the estimate of $10^{-2}$ m$^2$ s$^{-1}$ is in agreement with results of a previous study in the same area, as presented in the section of summary and discussion.

A volume consideration similar to the one for the deep lens can be applied for the salinity and temperature changes below ~4400 m. Figure 14 shows the evolution of the mean salinity and temperature at depths below 4400 m at NESTOR 5.2. The $\theta/S$ evolution at the deepest part of the trough is even slower compared to the evolution at the deep lens. Assuming that these $\theta/S$ values and particularly their time changes are representative of the entire volume of water below 4400 m, a vertical salt flux for the deepest part of the Calypso Deep in the period June–October 2006 is $\sim 6.4 \times 10^4$ kg s$^{-1}$ ($F_S \sim 1.8 \times 10^{-4}$ kg s$^{-1}$ m$^{-2}$) and the corresponding heat flux is $\sim 4.1 \times 10^4$ W ($F_H \sim 1.2$ W m$^{-2}$). The same calculations for the period October 2008–May 2009 result in a salt flux of $\sim 2.2 \times 10^4$ kg s$^{-1}$ ($F_S \sim 6.3 \times 10^{-5}$ kg s$^{-1}$ m$^{-2}$) and a heat flux of $\sim 1.3 \times 10^4$ W ($F_H \sim 0.4$ W m$^{-2}$). The salt and heat vertical fluxes for the period June–October 2006 are higher than the corresponding fluxes of the period October 2008–May 2009 by a factor of ~3, evidently due to the intrusion of the oxygenated, cold, and saline mass in the bottom layers as shown in Fig. 3. Table 5 summarizes the heat and salt flux calculations for the deep lens and for the deepest part of the Calypso Trough. Horizontal fluxes after October 2006 at the deep lens are higher than the corresponding vertical fluxes in the deepest part of the trough by a factor of ~25–30 on average.

### Table 4. Estimates of vertical diffusivities for salt and heat in the deepest part of the trough at the depth of 4400 m. The volume $V$ and the area $A$, used in the computations, are $\sim 1.2 \times 10^{11}$ m$^3$ and $\sim 3.5 \times 10^8$ m$^2$ respectively.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial S}{\partial t}$ (s$^{-1}$)</td>
<td>$\frac{\partial T}{\partial t}$ (C s$^{-1}$)</td>
<td>$\frac{\partial S}{\partial z}$</td>
</tr>
<tr>
<td>$4.58 \times 10^{-10}$</td>
<td>2.387 $\times 10^{-5}$</td>
<td>$2.553 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K_{ZS} = (1.5 \pm 2.5) \times 10^{-2}$ m$^2$ s$^{-1}$</td>
<td></td>
<td>$K_{ZT} = (3.7 \pm 2.7) \times 10^{-3}$ m$^2$ s$^{-1}$</td>
</tr>
</tbody>
</table>

6. Summary and discussion

A saline and warm water lens with a 50-km diameter is identified between depths of ~2200 and 3600 m. It is locked over the Calypso Trough and contains, predominantly, higher-oxygen ventilated Cretan water. In October 2006, there is a salinity increase and temperature decrease in the Cretan lens and in all the layers below it down to the bottom that are occupied predominantly by water of Adriatic origin. Simultaneously, the oxygen maxima are shifted to the bottom, indicating an episodic deep-bottom oxygen increase by admixtures of higher-oxygen Adriatic water that spread into the Calypso Deep; densities below ~3 km increase and a deep bottom-intensified cyclone appears below ~2500 m. After January 2007, this cyclone is also established in the shallow layers, at least up to 700 m. The changes of the local circulation from anticyclonic in June 2006 to cyclonic after January 2007 appear to be linked with the near-bottom dense water intrusion in October 2006.

The particular phenomenology of October 2006 generates questions with respect to a scenario that could justify these observations. We can present only some evidence for a possible scenario based on the existing...
Table 5. Salt and heat variation rates and fluxes due to horizontal transfer at the deep lens and due to vertical transfer at the deepest part of the trough at depths greater than 4400 m. Positive (negative) values indicate gain (loss).

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Salt (kg s(^{-1}))</td>
<td>(-9.5 \times 10^5)</td>
<td>(-3.3 \times 10^5)</td>
<td>(+6.4 \times 10^5)</td>
<td>(-2.2 \times 10^4)</td>
</tr>
<tr>
<td>Salt (kg s(^{-1}) m(^{-2}))</td>
<td>(-4.3 \times 10^3)</td>
<td>(-1.5 \times 10^3)</td>
<td>(+1.8 \times 10^4)</td>
<td>(-6.3 \times 10^5)</td>
</tr>
<tr>
<td>Heat (W)</td>
<td>(-6.8 \times 10^9)</td>
<td>(-3.7 \times 10^9)</td>
<td>(-4.1 \times 10^8)</td>
<td>(+1.3 \times 10^8)</td>
</tr>
<tr>
<td>Heat (W m(^{-2}))</td>
<td>(-31)</td>
<td>(-17)</td>
<td>(-1.2)</td>
<td>(+0.4)</td>
</tr>
</tbody>
</table>

After October 2006, no deep salt addition occurs and the Cretan lens decays in salt and heat content mostly due to lateral mixing caused, seemingly, by lateral intrusions. The lateral diffusive fluxes at the lens are \(~3 \times 10^{-3}\) kg s\(^{-1}\) m\(^{-2}\) for salt and \(~25\) W m\(^{-2}\) for heat, whereas the vertical diffusive fluxes at the deepest part of the trough are lower by 1 to 2 orders of magnitude (i.e., \(10^{-5}\)–\(10^{-6}\) kg s\(^{-1}\) m\(^{-2}\) for salt and \(1\)–\(0.4\) W m\(^{-2}\) for heat).

Estimates of horizontal eddy diffusivities which include the associated errors indicate ranges between \(~10\) and \(10^2\) m\(^2\) s\(^{-1}\) near the center of the lens, where the activity of lateral intrusions is less, and \(~10^2\) to \(10^4\) m\(^2\) s\(^{-1}\) at the periphery of the lens, where mixing is higher. To our knowledge, there have been no other estimates of horizontal diffusivities in the literature of the eastern Mediterranean, if not the entire Mediterranean, for the time and spatial scales we deal with in this study. Daniaux et al. (1994) have calculated horizontal diffusivities without error estimates by using an advection–diffusion balance in the area of the Mediterranean outflowing vein in the Atlantic, west of the Iberian Peninsula, where there is a prevalence of mesoscale lateral mixing. They report diffusivity values between 69 and 825 m\(^2\) s\(^{-1}\) with one value as high as \(~1500\) m\(^2\) s\(^{-1}\). The results of both studies appear to be in qualitative agreement.

The computed values of the vertical eddy diffusivity at the deepest part of the trough are on the order of \(~10^{-3}\) m\(^2\) s\(^{-1}\) with one overestimate around \(~10^{-2}\) m\(^2\) s\(^{-1}\). These vertical diffusivities are large in comparison to values estimated for the open ocean (Gregg 1998). However, similar estimates of vertical diffusivities in the deep Mediterranean waters appear in the studies by Cuypers et al. (2012) and by van Haren and Gostiaux (2011). The former study reports values as high as \(~10^{-3}\) m\(^2\) s\(^{-1}\), while the latter reports a value near \(~10^{-2}\) for the deep layers.
slightly north from our site NESTOR 4.5. Both studies argue that these high vertical diffusivities are likely to exist very near the bottom and in cases with weak stratification (i.e., in conditions similar to the ones in our study).

The salt–heat aggregation and subsequent decay of the present deep Cretan lens, which is observed in an area close to the main spreading path of the Cretan outflow, have some similarities with the warm-saline lenses that originate from the Mediterranean outflow in the Atlantic (i.e., the Meddies; Armì et al. 1989). However, apart from the differences in salinity and temperature anomalies relative to ambient water that are much higher in the Mediterranean lenses (0.6/2.5°C), the basic difference is that the present Cretan lens is trapped in space and does not transfer its salt and heat away from its source area.

Acknowledgments. This work was partly funded by the EU in the 6th Framework Program under Contract Number 011937 and by the Greek state. We thank the officers and the crew of the R/V Aegaeo. We also thank Mr. P. Renieris and Mr. A. Morfis, technicians of the Hellenic Centre for Marine Research, for supporting the field work with instrument preparation and cruise participation. Mike Spall suggested that we do the error analysis on the diffusivity estimates.

APPENDIX A

Errors on Estimates of Horizontal Eddy Diffusivities

Calculating the horizontal diffusivities (\(K_{HT}, K_{HS}\)) requires first- and second-order differentiation in space and first-order differentiation in time of the temperature and salinity fields. Two types of error are introduced, which are (a) the numerical (\(N\)) or truncation error, since the local spatial and time derivatives are approximated by finite differences, and (b) the statistical error (\(\sigma\)), since the quantities employed in the formula of the eddy diffusivity have their own uncertainties due to mapping and/or measurements that propagate through the mathematical manipulations of the formula. The total error is the square root of the total squared numerical error and the total squared statistical error.

Centered finite differences with increments \(\Delta x = \Delta y = 10\) km are used for the spatial first and second derivatives of the temperature and salinity at the current-meter positions. If \((x_0, y_0)\) is the position of a current meter, the objective temperature/salinity map produced on a 5 km × 5 km grid is subsampled along \(x\) at \(y_0\) and along \(y\) at \(x_0\). A spline fit is performed on each series of subsampled points to produce a series of interpolated points at 1-km spacing. Using finite differences on these interpolated points yields the series of the first spatial derivatives at 1-km spacing. By performing the same procedure on the first derivatives we obtain the second spatial derivatives at 1-km spacing; in the same manner, higher-order derivatives can be obtained.

The numerical error \(N_T\) in the estimate \(T_{i\sim}(\Delta T)/\Delta x\) of the first spatial derivative of temperature at a point \((x_0, y_0)\) is given by \(N_T \sim (\Delta x^2/24)T_{xx}\), where \(T_{xx}\) represents the maximum value of the third-order derivative in the range from \(x_0 - (\Delta x/2)\) to \(x_0 + (\Delta x/2)\) (Ames 1977). Application of the same finite differencing scheme on \(T_x\) would produce the second spatial derivative of temperature \(T_{xx}\) and similarly the numerical error of \(T_{xx}\) would be \(N_{Txx} \sim (\Delta x^2/24)T_{xxxx}\), where \(T_{xxxx}\) is the fourth-order derivative. The same procedure applies for the derivatives in the \(y\) dependence of temperature and their numerical errors but also for both the \(x\) and \(y\) dependence of the salinity field. The numerical error in the time rate of temperature change \(T_t \sim (\Delta T)/\Delta t\), where \(\Delta t\) is up to ~12 months, is computed by fitting an exponential curve on the CTD temperature values at the current meter position and comparing the finite-difference estimate to the analytic one. Similarly we compute the numerical error in the salinity temporal changes.

According to Eq. (1), the formula that provides \(K_{HT}\) in a finite difference approximation is \(K_{HT} \sim A/B\), with \(A = u(\Delta T)/\Delta x + v(\Delta T)/\Delta y + (\Delta T)/\Delta t\) and \(B = \Delta(\Delta T)/\Delta x + \Delta(\Delta T)/\Delta y\).

The uncertainty \(\delta(K_{HT})\) in \(K_{HT}\), due to measurement and mapping errors in the quantities appearing in the formula of \(K_{HT}\), can be computed by the following relationships:

\[
\frac{[\delta(K_{HT})/K_{HT}]^2}{[\delta A/A]^2 + [\delta B/B]^2}, \quad (A1)
\]

\[
(\delta A)^2 = [\frac{(\Delta T)_x}{\Delta x}(\delta u)^2] + [\frac{u(\Delta T)}{\Delta x}(\delta(\Delta T))_x] + [\frac{(\Delta T)}{\Delta x}(\delta(\Delta T)_x)] + [\frac{u(\Delta T)}{\Delta y}(\delta(\Delta T)_y)] + [\frac{(\Delta T)}{\Delta y}(\delta(\Delta T)_y)]^2 + [\delta(\Delta T)/\Delta t]^2, \quad (A2)
\]

\[
(\delta B)^2 = [\frac{2}{(\Delta x)^2}(\delta(\Delta T))^2] + [\frac{2}{(\Delta x)^2}(\delta(\Delta T))] + [\frac{2}{(\Delta y)^2}(\delta(\Delta T))^2] + [\frac{2}{(\Delta y)^2}(\delta(\Delta T))]^2, \quad (A3)
\]
where $\delta(\Delta T) = 2^{1/2}\delta(T)$, $\delta(\Delta x) = 2^{1/2}\delta(x)$, and $\delta(\Delta y) = 2^{1/2}\delta(y)$, with the positioning uncertainty $\delta(x) = \delta(y) = \pm0.5\text{m}$, and the current measurement uncertainty $\delta(u) = \delta(v) = \pm0.5\text{cm s}^{-1}$, while the temperature mapping uncertainty $\delta(T)$ is provided by the objective mapping routine (Watts et al. 2001) and the uncertainty $\delta(T)$ is the temperature measurement uncertainty ($\pm0.002\text{C}$).

In all cases of our horizontal diffusivity estimates, including the sensitivity tests described below, the total error ranges from $\sim10$ to $\sim25$ times the actual value of each estimate whereas, for the given values of $\Delta x$, $\Delta y$, and $\Delta t$, the total numerical error has a contribution to the total error of 2%–3% at most.

**APPENDIX B**

**Tests of $K_{HT}/K_{HS}$ Sensitivity to the Objective Analysis Temperature/Salinity Input**

The values of $K_{HT}$ and $K_{HS}$ at a site depend strongly on the local temperature and salinity horizontal gradients. In the specific tests, we investigate the changes in the horizontal diffusivities and their errors, which result from changes within measurement uncertainty of the temperature and salinity values near sites NESTOR 4.5 and NESTOR 5.2 that are used as input to the objective mapping at the depths and the periods shown in Fig. B1. The results are summarized in Table B1.

**APPENDIX C**

**Errors on Estimates of Vertical Eddies Diffusivities**

According to Eq. (3), the formula that provides $K_{ZTA}$ in a finite difference approximation is $K_{ZTA} \sim CD$, with $C = V(\Delta T_y)/\Delta t$ and $D = A(\Delta T_A/\Delta z)|_{4400}$. As in the case of the horizontal eddy diffusivities, the truncation errors in the vertical eddy diffusivities are much less than the statistical ones. The uncertainty $\delta(K_{ZTA})$ due to the uncertainties in the quantities appearing in the formula of $K_{ZTA}$, can be computed by the following relationships:

$$\left[\frac{\delta(K_{ZTA})}{K_{ZTA}}\right]^2 = \left[\frac{\delta(C)}{C}\right]^2 + \left[\frac{\delta(D)}{D}\right]^2,$$

(C1)

$$\delta(C)^2 = [(\Delta T_y)/\Delta t\delta(V)]^2 + [V/\Delta t\delta(\Delta T_y)]^2,$$

and (C2)

$$\delta(D)^2 = [(\Delta T_A/\Delta z)|_{4400}\delta(A)]^2 + [A/\Delta z\delta(\Delta T_A)]^2,$$

(C3)

where $\delta(\Delta T_y) = 2^{1/2}\delta(T_y)$, $\delta(\Delta T_A) = 2^{1/2}\delta(T_A)$, $\delta(A) \sim 10\% A$, and $\delta(V) \sim 15\% V$. The uncertainties $\delta(T_y)$ and $\delta(T_A)$ are due to both (a) the uncertainty in the measurement of $T$ as it propagates through the volume and the area averaging and (b) the assumption that the volume average $T_V$ and the area average $T_A$ are approximated by employing only the profile at NESTOR 5.2. An estimate of the uncertainties in $T_V$ and $T_A$ due to these approximations may be obtained if we further assume that station NESTOR 4.5 is within the region enclosed by the 4400-m depth contour and compute $T_V$ and $\Delta T_A$, used in the vertical derivative $(\Delta T_A/\Delta z)|_{4400}$, by employing both profiles at NESTOR 5.2 and NESTOR 4.5. The uncertainties due to the volume and area averaging are $\delta(T_V) = \delta(T)/(N_V)^{1/2}$, and $\delta(T_A) = \delta(T)/(N_A)^{1/2}$, with $\delta(T)$ being the measurement uncertainty of temperature and $N_V$ and $N_A$ the number of temperature data points used in the vertical and area averaging respectively. The combined uncertainties are $\delta(T_V) \sim \pm0.0024^\circ\text{C}$, $\delta(S_V) \sim \pm0.0035$, $\delta(T_A) \sim \pm0.0021^\circ\text{C}$, and $\delta(S_A) \sim \pm0.0032$.

**Table B1.** Variation range of $K_{HT}$ and $K_{HS}$ in tests of sensitivity to changes, within measurement uncertainty, of the temperature and salinity values near sites NESTOR 4.5 and NESTOR 5.2.

<table>
<thead>
<tr>
<th>Site/month year/depth (m)</th>
<th>Variation range of $K_{HT}$ ($\text{m}^2\text{s}^{-1}$)</th>
<th>Variation range of $K_{HS}$ ($\text{m}^2\text{s}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NESTOR 4.5/May 2007/2900</td>
<td>$10 \pm 29$ to $13 \pm 27$</td>
<td>$9 \pm 63$ to $14 \pm 40$</td>
</tr>
<tr>
<td>NESTOR 5.2/Apr 2008/2900</td>
<td>$5 \pm 101$ to $19 \pm 124$</td>
<td>$8 \pm 75$ to $35 \pm 140$</td>
</tr>
<tr>
<td>NESTOR 4.5/May 2007/3200</td>
<td>$10 \pm 84$ to $1633 \pm 41000$</td>
<td>$357 \pm 3500$ to $550 \pm 10450$</td>
</tr>
</tbody>
</table>
REFERENCES


