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Variational assimilation of Lagrangian trajectories in the Mediterranean ocean Forecasting System

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Abstract

A novel method for three-dimensional variational assimilation of Lagrangian data with a primitive-equation ocean model is proposed. The assimilation scheme was implemented in the Mediterranean ocean Forecasting System and evaluated for a 4-month period. Four experiments were designed to assess the impact of trajectory assimilation on the model output, i.e. the sea-surface height, velocity, temperature and salinity fields. It was found from the drifter and Argo trajectory assimilation experiment that the forecast skill of surface-drifter trajectories improved by 15 %, that of intermediate-depth float trajectories by 20 %, and moreover, the forecasted sea-surface height fields improved locally by 5 % compared to satellite data, while the quality of the temperature and salinity fields remained at previous levels. In conclusion, the addition of Lagrangian trajectory assimilation proved to reduce the uncertainties in the model fields, thus yielding a higher accuracy of the ocean forecasts.

1 Introduction

A novel method to correct ocean surface-velocity field predictions has been developed by implementing variational data assimilation of Lagrangian surface-drifter trajectories in the Mediterranean ocean Forecasting System (MFS). Assimilation of drifter observations in ocean models has previously been attempted using various numerical methods, e.g. optimal interpolation (Molcard et al., 2003), nudging (Fan et al., 2004), and Kalman filtering (Ozgokmen et al., 2003), all with promising results.

The MFS provides operational forecasts and analyses for the Mediterranean Sea since 1998 (Pinardi et al., 2003), and the output is useful for multi-purpose near-real-time applications, such as search-and-rescue operations and oil-spill predictions (Coppini et al., 2011). In order to guarantee state-of-art ocean analyses, a three-dimensional data assimilation scheme called OceanVar (Dobricic and Pinardi, 2008) is under continuous development, and recently glider observations (Dobricic et al., 2010) and Argo-float trajectories (Nilsson et al., 2011) have been successfully assimilated.

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The scope of the present study is to show some encouraging first results due to the implementation of the new drifter trajectory assimilation scheme. Moreover, additional numerical experiments were undertaken where drifter data were assimilated together with Argo float trajectories at intermediate depth. It will be shown that the three-dimensional data-assimilation scheme (OceanVar) in MFS is capable of simultaneously correcting the surface and sub-surface velocity fields through Lagrangian trajectory increments. In addition, the modified MFS is able to maintain previous quality levels of the daily-mean sea surface height (SSH), temperature, and salinity model fields.

The study is structured as follows: Section 2 provides a brief overview of the MFS and the OceanVar assimilation scheme. The observational data sets and the numerical experiments are detailed in Sect. 3, the results are subsequently presented and discussed in Sect. 4, and finally Sect. 5 comprises some conclusions and an outlook.

2 The Mediterranean ocean Forecasting System

2.1 The ocean general circulation model

The Mediterranean Forecasting System is a daily 10-day forecast system in operational use since 1998 (Pinardi et al., 2003; Pinardi and Coppini, 2010). In the present study we employ the ocean general circulation model (OGCM) described by Tonani et al. (2008) with a horizontal resolution of $1/16^{\circ} \times 1/16^{\circ}$ and 71 un-evenly spaced vertical levels with a 3-m resolution near the surface; the model output is saved as daily-averaged temperature, salinity, sea-level and horizontal velocity fields.

Satellite-observed sea level anomalies (SLAs Le Traon et al., 2003) and sea-surface temperatures (SSTs, Marullo et al., 2007), as well as temperature and salinity profiles from expendable bathytermographs (XBTs, Manzella et al., 2007) and Argo-float profilers (Poulain et al., 2007) are assimilated daily by OceanVar. The heat flux, on the other hand, is corrected by relaxing the modelled surface-layer temperatures towards the satellite-observed SST data (Dobricic et al., 2005).

2.2 The OceanVar assimilation scheme

The model fields produced by the OGCM are corrected daily by the OceanVar data assimilation scheme described by Dobricic and Pinardi (2008). This procedure involves the minimization of a cost function that finds a maximum likelihood model state estimate based on the OGCM forecast of the background model state as well as all available observations. The corrected state vector contains the temperature, salinity, velocity and sea-level.

The non-linear cost function is linearized around the background state, minimized by iterations, and the resulting model increments are used to re-initialize the OGCM. The misfits, viz. the differences between the background fields and the observations, are saved daily, as they are useful for evaluating the quality of the model output. The assimilation of surface-drifter positions requires the implementation of a non-linear trajectory model in the observational operator that maps the model to the observational space, hence facilitating comparisons between the Lagrangian observations and the modelled Eulerian fields. The non-linear particle advection equation was discretized and used for this purpose, and its application proved successful for assimilating Argo-float positions in the Mediterranean Sea; detailed descriptions of the trajectory model implementation and evaluations of the numerical experiments are available in Taillandier et al. (2006a,b); Nilsson et al. (2011).

Here, this trajectory model has been modified to also assimilate surface-drifter trajectories, where drifter-position forecasts were calculated by daily 24-h integrations of the trajectory equation. The analyzed positions are obtained by minimizing the linearized cost function around the background positions, viz. by reducing the distance between the observed and forecasted Lagrangian trajectory end-points. By variationally adding increments to the Eulerian model fields, the uncertainties related to model state variable fields (temperature, salinity, velocity and sea-level) can be expected to diminish.

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3 Design of the model experiments

3.1 Lagrangian observations

In this study, we describe the assimilation of surface-drifter positions as well as sub-surface float positions, a procedure undertaken separately and in concert. The Mediterranean Surface Velocity Programme (MedSVP) has managed surface drifter operations and has archived drifter data since 1986 in the Mediterranean and Black seas, and in the present study drifter data from the Eastern Mediterranean (Gerin et al., 2009) were used. The quantity of drifters operating simultaneously reached about 20 in mid-November 2005, providing a good opportunity for data assimilation in fall 2005. All drifters were SVP designs with a surface buoy and a sub-surface drogue centred at a nominal depth of 15 m (Gerin et al., 2009), hence, these observations are representative of the near-surface circulation. The surface drifter positions were edited, interpolated, low-pass filtered to remove high frequency currents (periods less than 36 h) and sub-sampled at daily intervals. Argo-float data, originating from the Coriolis Operational Oceanography data center, were post-processed and quality checked by Menna and Poulain (2010). These floats are programmed to descend to a parking depth of 350 m followed by a 4.5-day drifting period, whereafter they complete the cycle by re-emerging at the sea surface to transmit data via the Argos satellite system. The Argos positioning uncertainties related to the drifter and Argo float coordinates were approximated to 1000 m (Gerin et al., 2009) and 250–1500 m (Menna and Poulain, 2010), respectively.

An overview of the available surface-drifter and Argo-float positions is provided in Fig. 1. Two sub-regions with large amounts of surface drifter data can be indentified from Fig. 1a: east of the Strait of Sicily and across the central part of the Ionian Sea, as well as the south-western part of the Levantine basin. The Argo-float data (cf. Fig. 1b) were sparsly scattered over the basin, however, present in both the western and eastern parts of the Mediterranean Sea.

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3.2 Numerical experiment set-ups

Four experiments were designed to evaluate the influence of Lagrangian trajectory assimilation on the model fields, subsequently referred to as CTRL, SURF, SURF2, and ARGO (cf. Table 1). All experiments were initialized with the same forcing fields on 1 September 2005, and stopped after 4 months on 31 December 2005. A sensitivity test showed that applying a 5000-m drifter position observational error secured a stable convergence of OceanVar and yielded the best model results in terms of root-mean-square (RMS) misfits. It is noteworthy that the magnitude of this error is significantly larger than the applied observational error for the Argo-float positions in OceanVar (2000 m, Nilsson et al., 2011), however, it is smaller than the model horizontal resolution which is ~ 7 km. Moreover, forecasting accurately the highly variable small- and meso scale dynamics in the upper ocean is a great challenge, and thus, in this context, the observational errors of these Lagrangian data sets could be interpreted as a measure of the uncertainties of the modelled surface and intermediate-depth velocity fields.

The control experiment (CTRL) assimilated daily satellite SLA and SST data as well as temperature and salinity profiles, whereas the SURF experiment also included observations of surface-drifter positions. Moreover, in the SURF2 experiment surface-drifter and Argo-float positions were assimilated, and thus the surface as well as the intermediate-depth trajectories were simultaneously modified. The ARGO experiment assimilated Lagrangian data from Argo floats as well as the observations used in the CTRL experiment; the quality of the output from this model set-up has been assessed over a 3-yr period in Nilsson et al. (2011).

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4 Results and discussion

4.1 Statistical analysis

The impact of Lagrangian data assimilation of surface-drifter data on the model output was evaluated in terms of 4-month basin-average RMS misfits between the observed and forecasted temperature and salinity values, as well as the drifter and float trajectory end-point estimates. The SLA RMS misfits were calculated both as basin averages and in close vicinity of the drifters (1° radius and a 3-day time span); this since applying only basin-mean statistics for SLA could lead to underestimating the local effects of the surface-drifter trajectory assimilation due to the large amount of satellite-observed data in areas without surface drifters. All RMS misfits are provided in Table 2, and in particular, the "near-drifter" SLA RMS misfits are given within the brackets next to corresponding basin-average values.

It was found that the quality of the forecasted surface temperature and salinity fields remained at the previous levels of $\sim 0.7°$ C and ~ 0.2 psu, respectively (Tonani et al., 2009). The quality of the forecasted SLA improved by 5 % in the proximity of the assimilated drifter positions, yielding a decrease of RMS differences from 3.3 cm in CTRL and ARGO to 3.1 cm in the SURF and SURF2 experiments. (The basin average SLA RMS misfits remained around 3.3 cm for all experiments.) Moreover, the accuracy of the 24-h drifter-trajectory forecasts at the sea surface improved by 15 % when drifter assimilation was introduced in OceanVar, here evaluated in terms of RMS distances between the observed and forecasted drifter-trajectory end-points, yielding 17.5 and 15.2 km in the CTRL and SURF experiments, respectively. The quality of the SURF2-forecasted SLA, temperature and salinity fields as well as the surface-drifter trajectories was maintained compared to the accuracy of the SURF fields, while the 5-day float-trajectory forecasts improved by 20 %, with, notably, RMS misfit distances decreasing from 25 km (CTRL and SURF) to 20.5 km (SURF2). The RMS misfits based on the results from the ARGO experiment were in general agreement with those obtained in Nilsson et al. (2011), were it was reported maintained quality of the forecasted SSH,

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temperature and salinity fields, and improved sub-surface trajectory forecasts. (The RMS misfit between the observed and forecasted float-trajectory end points was found to be around 20 km during the autumn of 2005.)

In conclusion, these statistical results indicate that OceanVar is capable of correcting the pressure-gradient field at different vertical levels using two different Lagrangian observational data sets without compromising (and indeed improving slightly) the quality of the other forecast variables.

4.2 Influence of Lagrangian data assimilation on the surface fields

Since the drifter data were located in the Eastern Mediterranean basin during the 4-month test period, the comparisons of the model experiment results have been limited to this area. Next, the influence of surface-drifter-trajectory assimilation on the horizontal surface velocity and the SSH fields will be considered. Figure 2 gives an example of the development of the CTRL and SURF velocity fields at a depth of 15 m during 1–10 November 2005. In this period there were approximately four operating drifters (Gerin et al., 2009), including two units located in the Ionian Sea (57 319 to the east, and 59 733 to the west in the figure). The CTRL model results were compared (and validated) with these observations, and it was found that the circulation in the vicinity of drifter 59 733 was well reproduced in the output on 10 November, whereas the velocity field near drifter 57 319 was less accurate. An a posteriori control of the SURF experiment output showed that these velocity fields were in better agreement with the observed (and assimilated) Lagrangian trajectories, indicating that OceanVar is capable of converging the model fields towards the drifter positions in a satisfactory manner. Another example is provided for mid-December 2005 when ~20 drifters were available per day. The day-to-day differences in the model fields (21–22 December) were calculated and the subsequent differences between the CTRL and SURF residual fields are presented in Fig. 3 for the velocity fields at 15-m depth as well as the SSH fields, along with the drifter observations from 1 September to 21 December. From this figure it is evident that most differences ($\pm 10\,\mathrm{cm\,s^{-1}}$ and ± 3 cm) are located in the immediate proximity of the drifters but not necessarily to the last assimilated positions obtained on 21 December. This suggests that previous corrections of the velocity field are still present in the "model memory", and some differences are located at distance from the surface drifters, indicating a horizontal propagation of the model field corrections. Similar results were found for glider observations in Dobricic et al. (2010) and for Argo-float trajectories in Nilsson et al. (2011). Moreover, the most distinct residuals in both the velocity and SSH fields, in particular in the Cretan Passage and off the North African coast, are likely to be caused by lateral shifts of the meso-scale features (gyres, eddies, coastal current meandering) due to drifter assimilation.

The statistical analysis of the model results indicated a modest improvement of the SSH forecast quality in the vicinity of the assimilated surface drifters. The SSH fields from all four numerical experiments on 22 December 2005 are presented in Fig. 4, with the corresponding velocity vector fields at 15 m depth superimposed. Here the drifter observations during 13–22 December are indicated by dots and the Argo-float positions during 1–22 December by triangles. The main features of the surface dynamics can be recognized in all cases, viz. the near-coastal currents and semi-permanent anti-cyclones (Pinardi and Masetti, 2000; Gerin et al., 2009; Hamad et al., 2005). The location of SSH minima and maxima as well as the intensity and direction of the surface currents, however, varies between the experiments, most notably in the vicinity the drifters and the floats. The modelled surface temperature and salinity fields showed corresponding shifts of the horizontal gradients compared to the SSH fields due to drifter assimilation (not shown).

It can be concluded that the drifter assimilation has an ameliorating impact on the quality of the modelled small- and meso-scale dynamics in the surface layer. In particular, assimilation changed the meandering patterns of the Libyo-Egyptian (LE) current (along the African coast near 26–28° E), and shifted slightly the location and shape of the Iera-Petra (IP, ~26° E, 34° N) and Mersa-Matruh (MM, ~29° E, 33° N) in the SURF and SURF2 velocity fields. It was established from the drifter-position RMS misfits that the SURF and SURF2 surface velocity and SSH output was more accurate than the

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CTRL results, and furthermore, the quality of the SURF2 SSH fields was slightly improved compared to the SURF results. Thus the SSH fields from the drifter assimilation experiments were found to be more realistic than the CTRL fields, since the modelled sea-level gradients are in better agreement with the observed drifter trajectories (as to be expected in areas characterized by geostrophic flow).

It should be noted that the SSH and surface velocity fields in Fig. 4 from the CTRL and ARGO experiments bear large resemblances in the near-drifter areas (same "errors"), while similarities were found in the SURF2 and ARGO flow structures near the observed and assimilated Argo floats (similar corrections of surface fields due to intermediate-depth trajectory assimilation). This example indicates how suble the velocity field corrections have been blended into the model fields from the Lagrangian data assimilation experiments, to be compared with the less accurate CTRL output. Furthermore, these findings confirm that assimilation of sub-surface trajectories can influence and occasionally improve the strength and direction of the modelled surface flow, as suggested in Nilsson et al. (2011).

4.3 Impact on the intermediate velocity fields due to surface trajectory corrections

Here, it is investigated if assimilation of Lagrangian surface drifter data can influence the meso-scale dynamics at intermediate depth. The RMS misfits between the observed and forecasted drifter positions indicated that surface-drifter assimilation could also improve the forecasting capabilities of the Argo trajectories at 350 m depth, cf. 20.5 km (SURF2) and 21 km (ARGO) in Table 2. However, it should be kept in mind that the difference between these estimates is on the order of the Lagrangian observational errors thus the improvements made on the intermediate-depth velocity fields due to drifter assimilationon should not be overinterpreted.

A comparison of the model velocity fields at 365 m on 22 December 2005 is available in Fig. 5, with superimposed drifter and Argo trajectory data. Similar differences in flow patterns compared to those observed in Fig. 4 can be identified for each experiment,

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such as the changes in the small-scale dynamics along the LE current as well as the locations and dimensions of the IP and MM gyres. Furthermore, the model results presented in this figure show that surface drifter assimilation is capable of influencing, and possibly correcting, the Levantine circulation down to at least 350 m depth. The assimilation of the Argo float trajectories have also yielded improvements in the intermediate depth velocity field, and in particular can be pointed out the area near 31° E, 35° N, where the data assimilation appear to have had a decelerating effect of the near-float velocity field.

Finally, a transect along 26° E was made of the zonal flow across the Cretan passage on 22 December 2005 (cf. Fig. 6), in order to illustrate the differences between each experiment's representation of the velocity field in the vertical plane. This transect, on this day, was opportune for detailed analysis as 3 drifters (nr 59 753 at 26°12′ E, 34°37′ N; nr 59 757 at 26°15′ E, 34°42′ N; and, nr 59 755 at 25°39′ E, 32°12′ N) and one float (nr 50 755 at 26°4′ E, 34°25′ N) were located near the 26° E-meridional, which provided favorable circumstances for evaluating effects of combined surface and intermediate depth Lagrangian data assimilation.

The strong east- and westward velocities of the Atlantic waters in the upper 200 m (Hamad et al., 2006) of the transect are caused by the LE current and the IP gyre, showing typical velocities of 10–30 cm s^{-1} (Gerin et al., 2009). The strength of the surface velocities vary between the four experiments on the order of ±5–10 cm s^{-1} (cf. Fig. 3a), and this is mostly related to the laterally shifted baroclinic-instability front of the meandering coastal current (cf. Fig. 4). The IP gyre seem to be clearly influenced by the Lagrangian assimilation of drifter and Argo data, both in terms of current velocities and the vertical extent of the gyre. Some of the velocity variability could be explained by the fact that the gyre is centered differently in each model field, however, also Figs. 4 and 5 reveal changes in the flow field intensity. The two model setups including float trajectory assimilation appear to have a limiting effect on the gyre depth. In the CTRL and SURF velocity output, the intense core of the IP gyre extends down to ~ 600 m, while in SURF2 and ARGO this depth has been reduced by approximately 100 m.

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This modified gyre depth would be in general agreement with the results due to Popov (2004) who estimated observationally the vertical scales of the IP gyre to approximately 500 m. Moreover, the results from the SURF2 and ARGO experiments imply, that float assimilation have tended to reduce the velocities of the intermediate layer waters also in this case.

5 Conclusions

Four numerical experiments have been presented where variational assimilation of Lagrangian observations from Eastern-Mediterranean surface drifters and Argo floats (together and separately) was undertaken for a 4-month period, thus changing the Eulerian SSH, temperature, salinity and velocity fields in an OGCM. The results of these investigations indicate that the quality of the surface and intermediate-depth velocity fields improved when the Lagrangian data sets were assimilated, yielding more accurate surface-drifter and Argo-float position forecasts (~ 15 and ~ 20 %, respectively) in terms of relative differences in RMS misfits. The basin-mean RMS misfits of temperature and salinity remained unchanged, while the local impact close to the drifters could not be evaluated due to lack of observations. Moreover, the SSH gradient fields from the drifter-assimilation experiment proved to be in better agreement with observations (the SSH forecast improved locally by ~ 5 %) compared to the output from the control experiment.

Local studies of the model fields from the four experiments gave an interesting insight on the influence of Lagrangian trajectory corrections on the surface and intermediate velocity fields. It was shown that the best quality of the model output was obtained when all observational data sets were assimilated simultaneously by OceanVar. Improving the accuracy of the predicted surface meso-scale dynamics can be of particular interest for improving oil-spill predictions and the capability of back-tracking objects at sea, both of which are calculated off-line using stored OGCM velocity fields.

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In the present study, the influence of inertial currents on the model analyses have not been taken into account, since these frequencies are outside of the time range dealt with here (36-h low-pass filtered observations and daily-average model fields). However, it would be important to examine these effects in detail within the framework of drifter trajectory assimilation in a future study.

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Table 1. Design of numerical experiments, the assimilated observations are marked with X. SLA (sea level anomalies), TEM (temperature profiles), SAL (salinity profiles), TRD (surface drifter positions), and TRA (Argo float positions).

Exp. name	SLA	TEM	SAL	TRD	TRA
CTRL	X	X	X		
SURF	X	X	X	X	
SURF2	X	X	X	X	X
ARGO	X	X	X		X

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Table 2. 4-month basin-average RMS misfits between model values and observations for sea-level anomalies, sea-surface temperature and salinity, as well as surface-drifter and Argo-float positions. "Near-drifter" SLA RMS misfits are given within the brackets.

Exp. name	SLA (cm)	T (°C)	S (psu)	TRD (km)	TRA (km)
CTRL	3.32 (3.33)	0.77	0.22	17.5	25.2
SURF	3.29 (3.10)	0.79	0.22	15.2	25.0
SURF2	3.28 (3.08)	0.78	0.22	15.3	20.5
ARGO	3.31 (3.36)	0.77	0.22	17.7	21.0

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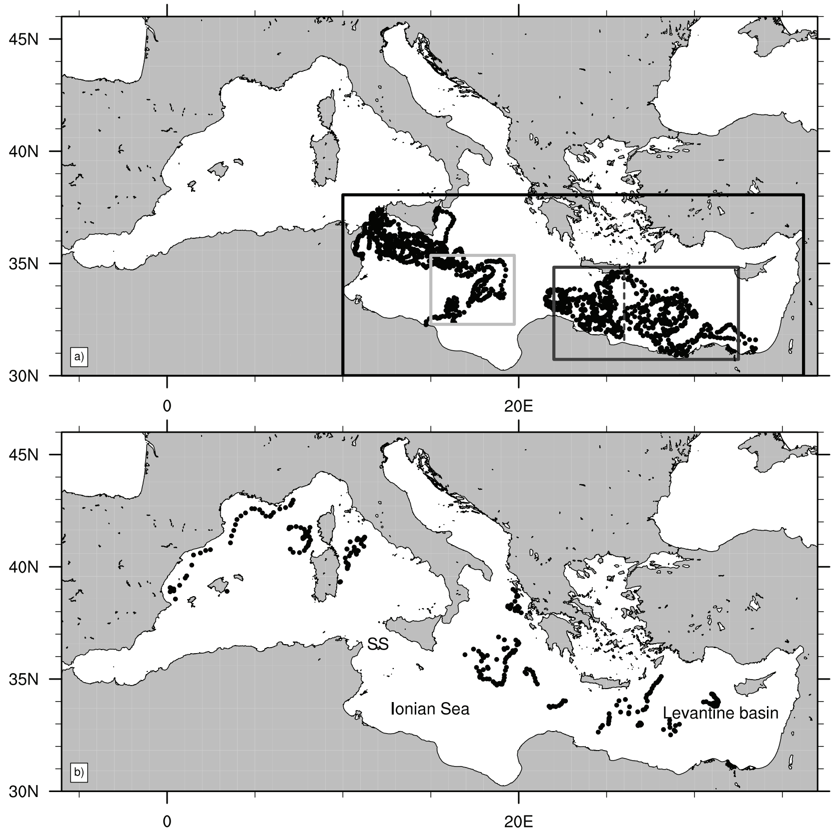

Fig. 1. Distribution of Lagrangian observations during the test period 1 September–31 December 2005: **(a)** Surface drifter positions, and **(b)** Argo float positions. The boxes indicate the location of the forth-coming zoom-in's of the Eastern Mediterranean (black), Ionian (light grey) and Levantine (dark grey) basins, respectively, while the dashed line mark the transect across the Cretan passage. Abbreviation: Strait of Sicily (SS).

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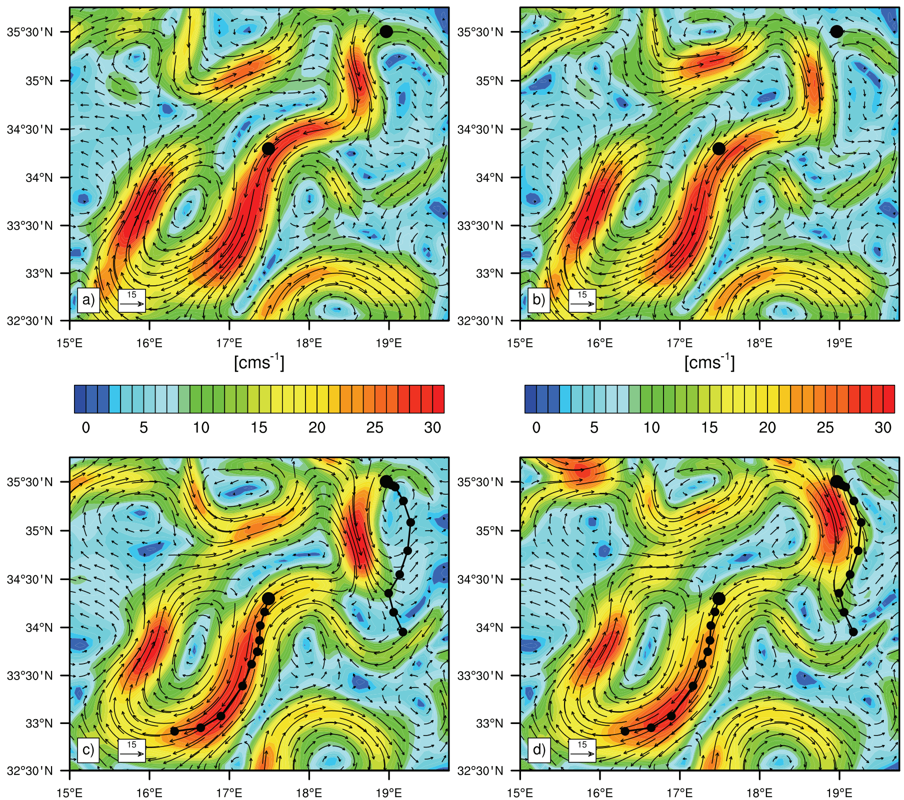

Fig. 2. Upper panels: Velocity fields at 15 m depth on 1 November 2005 from the **(a)** CTRL, and **(b)** SURF experiments, with the observed surface drifter positions from platforms 57 319 and 59 733 on 1 November indicated by large black markers. Lower panels: Velocity fields at 15 m depth on 10 November 2005 from the **(c)** CTRL, and **(d)** SURF experiments, with the observed surface drifter positions on 1–10 November shown by the black markers.

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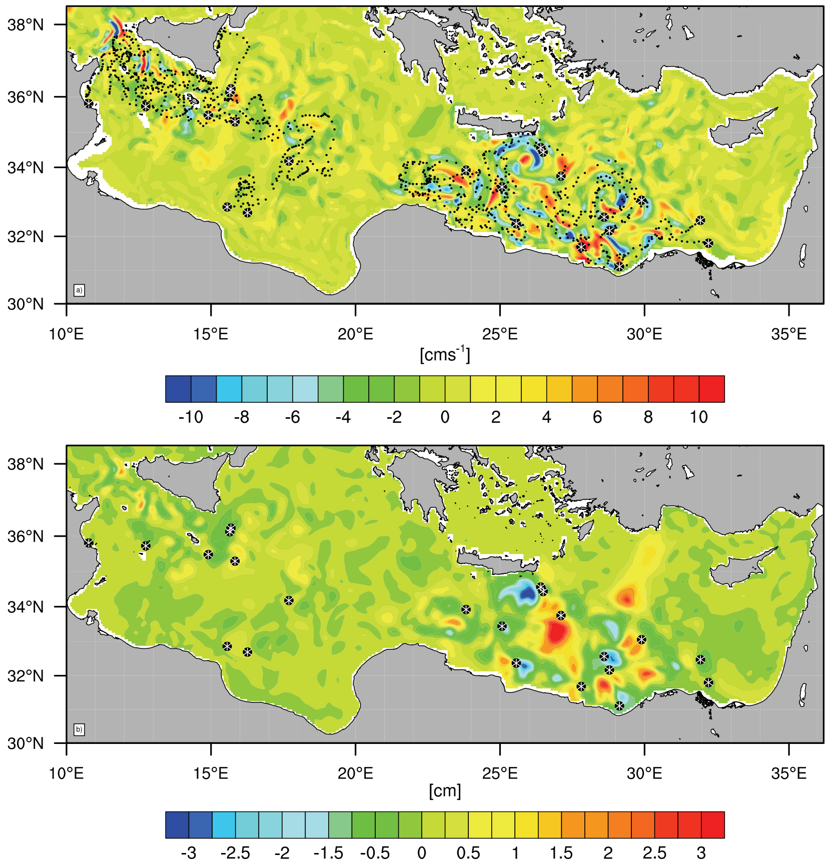

Fig. 3. Differences between the day-to-day residuals from 21 to 22 December 2005 of the CTRL and SURF **(a)** velocity fields at 15 m depth, and **(b)** SSH fields. Previously observed drifter positions (1 September–20 December 2005) are indicated by black dots, while the observations made on 21 December are shown by the larger black-white markers.

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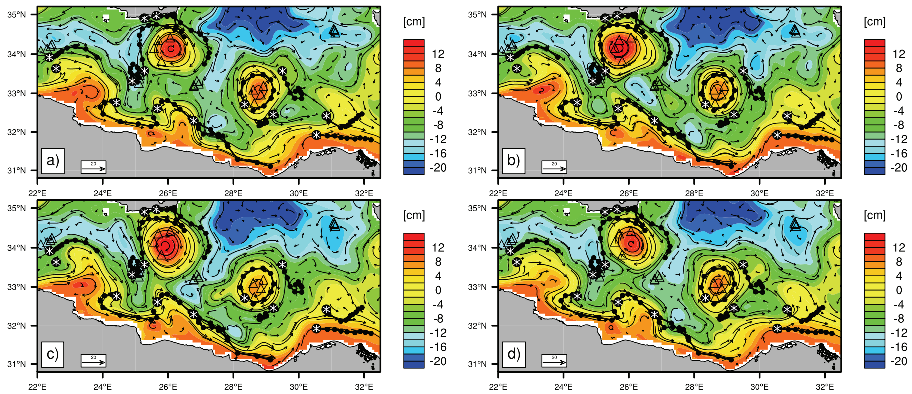

Fig. 4. Sea-surface height fields (cm) on 22 December 2005 with superimposed velocity vector fields at 15 m depth from the **(a)** CTRL, **(b)** SURF, **(c)** SURF2, and **(d)** ARGO experiments. The observed surface drifter positions during 13–22 December are indicated by the black dots (start positions in white), and the observed Argo float positions during 1–22 December are marked with triangles.

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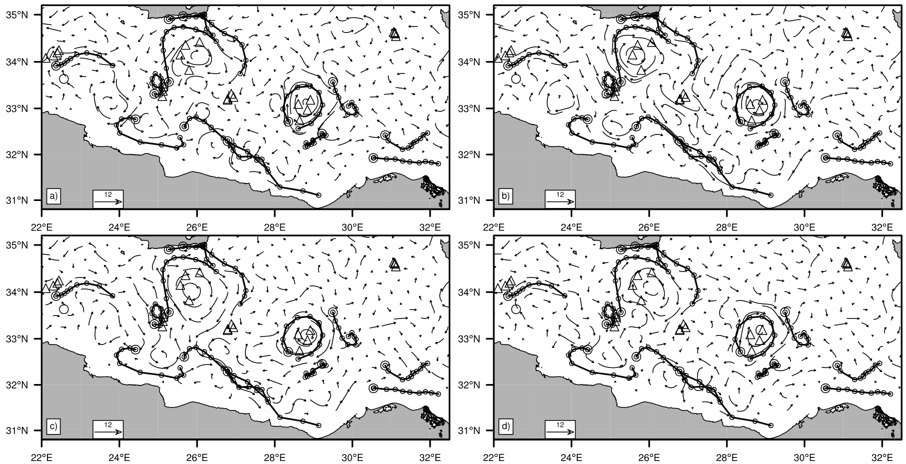

Fig. 5. Velocity vector fields at 365-m depth on 22 December 2005 from the **(a)** CTRL, **(b)** SURF, **(c)** SURF2, and **(d)** ARGO experiments. The surface drifter positions during 13–22 December are indicated by the black circles, and the Argo float positions during 1–22 December are marked with triangles.

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Variational assimilation of Lagrangian trajectories

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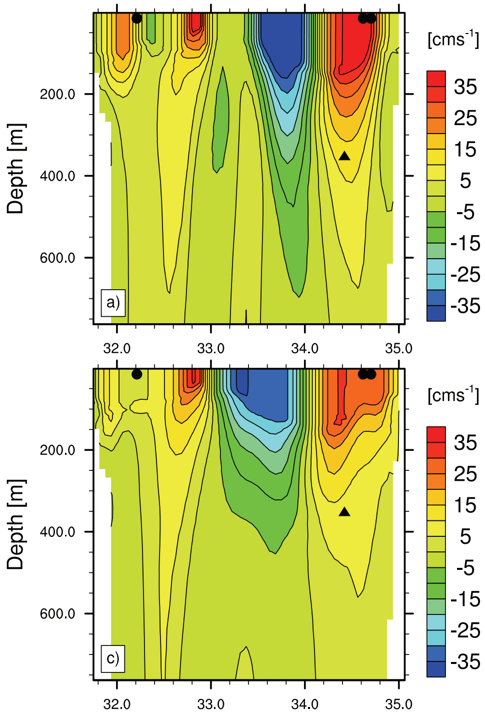

Fig. 6. Zonal velocity transect across the Cretan Passage (26° E) on 22 December 2005: **(a)** CTRL, **(b)** SURF, **(c)** SURF2, and **(d)** ARGO. The surface drifter (Argo float) positions on 21 December are indicated by the black dots (triangle).

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