CIrculation and water properties in the NorthEast Levantine (CINEL)

Mid-term Report

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Introduction

The CINEL project aims at measuring the currents and water mass properties in the northeastern areas of the Levantine Basin (Mediterranean Sea) in order to study the complex circulation features governing the dynamics near the coast and in the open sea. The measurement program in the northeastern Levantine, with main focus on the area between Cyprus, Lebanon and Israel, is separated into a preliminary summer phase, followed by intensive summer and winter phases in order to investigate seasonal variability. In this region, mesoscale and sub-basin scale eddies are predominant, and strongly interact with a persistent coastal current. *In-situ* observations from gliders, floats, and drifters are interpreted in concert with the distribution of tracers (sea surface temperature, chlorophyll), and altimetry data obtained from satellites. Numerical simulations with a high resolution model in which deep profiles of temperature and salinity from floats and gliders are assimilated will be used to fine tune the observational array and to interpret the local dynamics. OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy) coordinates the project, and OC-UCY is primarily responsible to carry out flow simulations, deploy the float and drifters and carry out missions with one of its gliders. OGS will also carry out missions with one if its gliders, as well as handle float and drifter data and related analysis. Satellite comparisons, advanced analysis and publications will be carried out jointly. In this report, the first half of the project is described with a focus on the methodology and a preliminary look at results.

Overview

The CINEL project began in earnest on 31 August 2016 with phase I, when the OC-UCY glider SG150 was launched from the southeast coast of Cyprus and followed a path south and east of Cyprus, measuring sea pressure, temperature, conductivity, dissolved oxygen, optical backscatter (470 nm and 700 nm) as well as chlorophyll-a fluorescence (em: 470 nm/ex: 690 nm). At the same time, two numerical simulations of the northeast Levantine hydrodynamics and thermodynamics were initialized by OC-UCY: both using the same initial, surface, and lateral conditions, but with one run using glider data to correct ocean fields using a data assimilation (or “d/a”) system. The second run is called the “control run.” After a technical problem on 15 October, the OC-UCY glider was replaced by the OGS glider (SG554). On 4 November another glider (SG149) joined to finally allow a 2-glider mission. In this phase II of the project, temperature and salinity profiles from both gliders were assimilated into the d/a run, and the control run continued with the same, daily updated, surface and boundary forcing. These gliders were recovered on 7 December, 2016, while both numerical runs continue to run up to today in free (with no initialization or data assimilation). Seasonal changes in the mixed layer were observed, as well as anticyclonic circulation, particularly intense around a core of warm, salty Levantine Intermediate Water (LIW). In phase III of the project, expected to start 9 February, 2017, SG150 (now repaired) and SG554 will carry out similar, approximately two-month missions while the numerical experiments will continue. One new numerical experiment will be added, in which coarse resolution model fields from the ALERMO system will again be used to initialize the same hydrodynamic model, with the same surface and boundary conditions, and data assimilation. We plan to update the model to assimilate temperature and salinity from profiling floats in the region.

Observations

Drifters and Float

Floats and drifters were received by OC-UCY and prepared for operation, and instructions were given to a young researcher. See Figure 1. Drifters (4) and floats (1) were deployed by OC-UCY during phase II of CINEL. Deployment information is shown in Table 1. For a detailed description of the observations and tracks made, please see the project web site http://nettuno.ogs.trieste.it/sire/cinel/.

Figure 1.Preparation of CINEL drifters and float.

Table 1. Deployment information for phase I of CINEL drifters (d1, d2, d3, d4) and float.

	d1	d2	d3	d4	Float
IMEI	68230	65570	64260	64260	6903201(WMO)
Deployment time	14:26 20/10/2016	17:36 20/10/2016	20:54 20/10/2016	00:18 21/10/2016	00:24 21/10/2016
Coordinates	34°11.91’ N 33°00.04’ E	33°48.06’ N 32°59.99’ E	33°24.00’ N 32°59.96’ E	32°59.99’ N 33°0.164’ E	32°59.98’ N 33°0.028’ E

Glider Missions

Mission Description

The first CINEL glider mission was with SG150, which began on 31 August 2016, until a roll motor error on 15 October 2016 caused a critical failure. It was recovered by the dive vessel *ScubaCat* two days later. On the same day, OGS glider SG554 was deployed for the first time in Cyprus. In order to complete the objective of two simultaneous glider missions, SG149 was launched on 4 November, 2016 and was recovered together with SG554 on 7 December 2016. The OC-UCY gliders followed the trajectories shown in Figure 2.

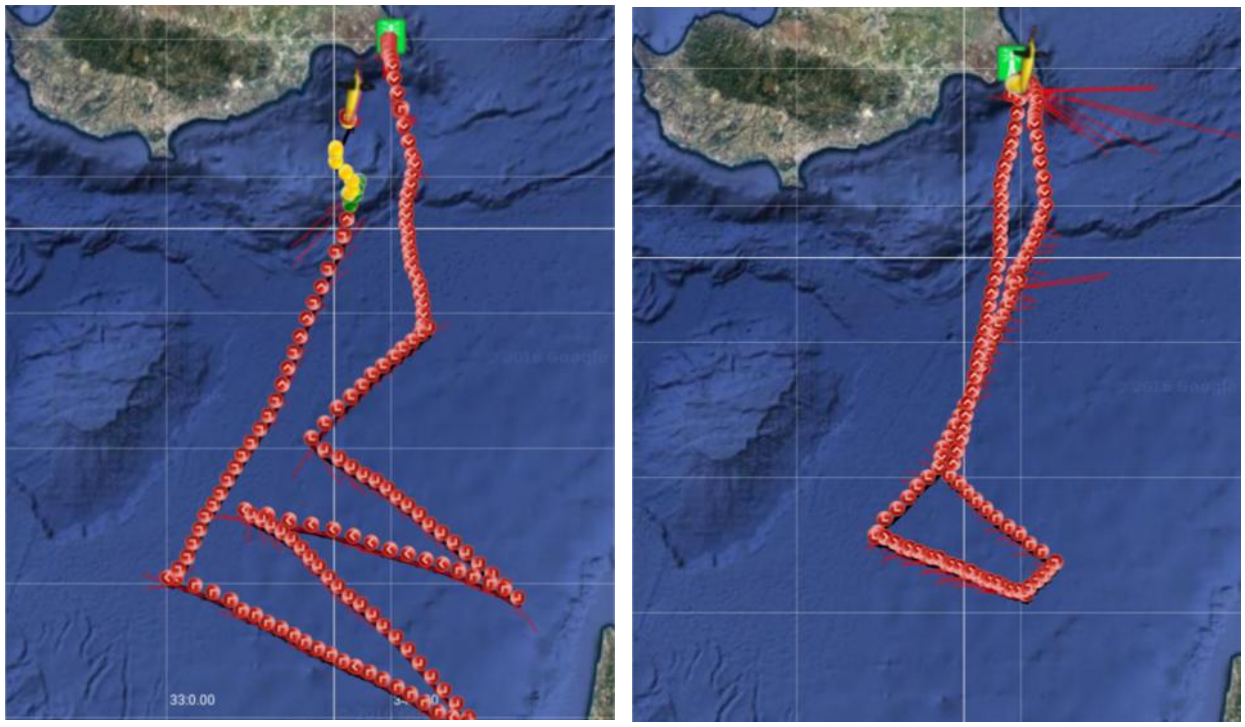

Figure 2. Trajectory of SG150 (left) from 31/8/2016 to 15/10/2016 and of SG149 from 4/11/2016 to 6/12/2016. Deployment location is indicated by the green marker and recovery by the yellow glider. The SG149 mission carried out the box in counter-clockwise fashion.

The gliders were programmed to collect data throughout the dive/climb cycle every 10 seconds for pressure, temperature and conductivity and every 60 seconds for dissolved oxygen and optical parameters (backscatter 470 nm, backscatter 700nm, chlorophyll-a fluorescence 470/690 nm). Dives were programmed for 1000 m maximum depth, with altimeter configured so the glider could avoid the seafloor if less than 1000 m. Optical parameters were only sampled in the upper 300 m, and dissolved oxygen only in the upper 600 m (with exceptions for both at the beginning and end of the missions for deep water reference).Typically, glider dive velocity was programmed at 8.0 cm/s in the vertical, and the desired maximum allowed (negative) buoyancy was set as to maximize horizontal travel at this vertical speed. This resulted in horizontal speeds of approximately 30 cm/s relative to the water. Dive cycles

were nearly always to 1000 m depths and took approximately 7 hours. Surfacings were approximately 8.5 km apart, depending of course on depth averaged currents (also computed).

Mission Observations

Vertical sections of temperature, salinity, and dissolved oxygen as a function of track distance are shown in Figure 3. Optical data will be shown in the final report, since they need further processing. Clear evidence of the water masses is shown:

- Very warm and salty Levantine Surface Water (LSW) is found at depths shallower than about 50 m, which gradually cools and freshens throughout the mission. LSW also shows a slow increase in dissolved oxygen in phase II.
- Atlantic Water (AW) is found at depths just below LSW, revealed as a local minimum in salinity and local maximum in dissolved oxygen, which is slowly destroyed as the summer season comes to an end in December.
- Levantine Intermediate Water (LIW) is found at depths from below the AW down to approximately 300 to 400 m is indicated by a relative maximum in salinity and temperature. Deeper excursions of the lower boundary of this layer are associated with anticyclonic eddies.
- Eastern Mediterranean Deep Water (EMDW) is found at the deepest depths, as seen by a slow transition from LIW to colder, fresher conditions.

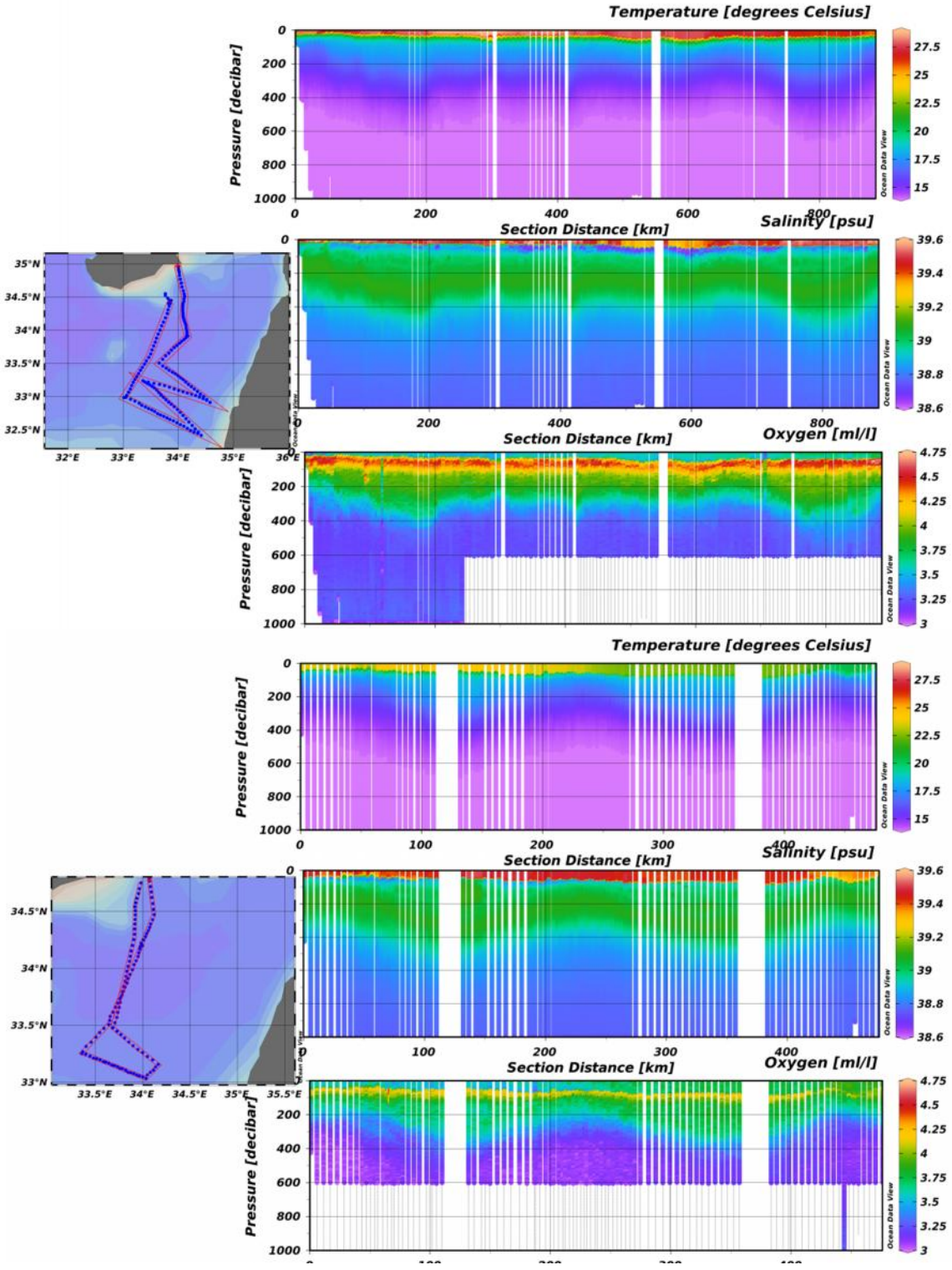

Figure 3. Vertical sections of temperature, salinity and dissolved oxygen as a function of track distance for SG150 from 31/8/2016 (when deployed at SE coast) to 15/10/2016 (when recovered at offshore location). Note the change in sampling of dissolved oxygen after 210 km of travel to occur only in upper 600 m rather than 1000 m. Lower panel shows the same figure, but for SG149 from 4/11/2016 to 7/12/2016.

Numerical Simulations

Hydrodynamic Model

The Oceanography Center at the University of Cyprus has developed an operational flow forecasting system based on the Princeton Ocean Model (POM) known as the Cyprus Coastal Ocean Model (CYCOM). The version of CYCOM discussed here is nested within a regional model of the Eastern Mediterranean (Aegean Levantine Eddy Resolving Model: ALERMO), which is in turn nested within the operational regional model of the Mediterranean (Mediterranean Forecasting System: MFS). Both nesting procedures use one-way, passive downscaling techniques. This version of CYCOM is similar to that of Zodiatis et al. (2008) but with horizontal grid spacing of 1.0 km and with the open southern and western boundaries at 33.0 ^{o}N and 31.0 ^{o}E, respectively. See Figure 4. The resulting longitude-latitude grid has dimension of 489 x 438 grid points. Vertical sigma levels are 24 and are logarithmic near the top and bottom. Bottom bathymetry is a bilinearly-interpolated version of the 1-minute U.S. Navy Digital Bathymetric Database. Minimum depth is set to 5 m and maximum is 2770 m. The bathymetry was smoothed to avoid numerical artifacts. Internal and external time steps were 120 and 2 seconds, respectively. For more model details, please see Zodiatis et al. (2008). The present CYCOM also uses atmospheric forcing from the Skiron forecasting system of the University of Athens (Kallos, 1997, http://forecast.uoa.gr/). Skiron provides hourly fields for 120 hours updated on a daily basis and 5 km resolution.

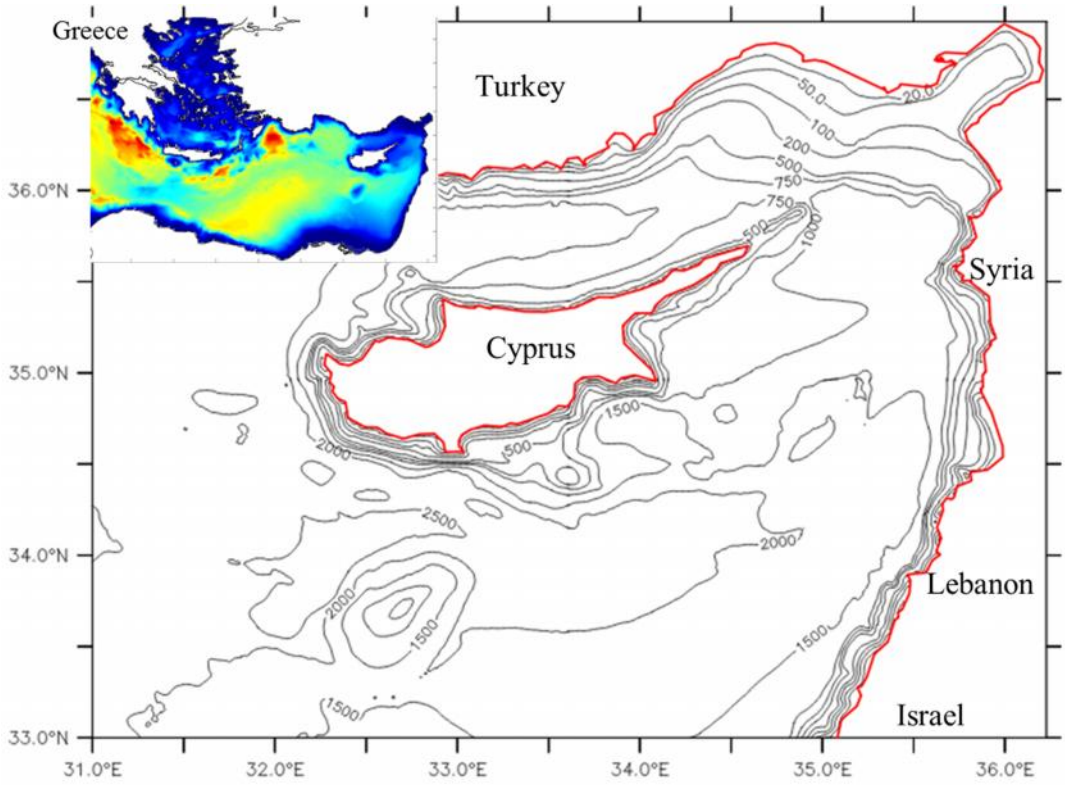

Figure 4. Domain and bathymetry of the CYCOM model and ALERMO model (inset).

The Aegean Levantine Eddy Resolving Model (ALERMO) of the University of Athens was used in this study to initialize CYCOM (http://pelagos.oc.phys.uoa.gr/mfstep/bulletin/). It has a horizontal resolution of 1/30^{o}, and does not include data assimilation of *in situ* data, only Sea Level Anomaly. It is in turn nested within the Mediterranean Forecasting System (MFS) v2, with daily restart and also uses Skiron. It has one open boundary on the west at 20^{o} E. An initialization routine was used in order to reduce numerical oscillations and incorrect transports across density surfaces over steep topography: the horizontally-averaged density profile is computed and subtracted from the density variable before solving the density equation. The basin MFS model is described by Tonani et al. (2008) and Pinardi et al. (2003). During the experiments discussed here, data on SLA, Argo, and XBT were assimilated using the 3DVAR OceanVar package (Dobricic and Pinardi, 2008). This only enters the CYCOM model via the initialization using ALERMO, at the beginning of phase I.

Data Assimilation System

For this study, OceanVar (Dobricic and Pinardi, 2008) has been adapted for use in CYCOM. OceanVar iteratively finds the minimum of the cost function of the analyzed state vector written as the sum of the background error and observation error. The method of minimization of the cost function is described in detail in Dobricic and Pinardi (2008) and used in similar studies in the Mediterranean by Dobricic et al. (2010), and Adani et al. (2011).

This technique requires the computation of the vertical empirical orthogonal functions (EOFs) of the temperature and salinity anomalies from the monthly mean profiles at each model point. Historical CYCOM operational forecast runs were used (24 months of daily average output). From the first five of these EOFs for the month of interest, a set of measured misfit profiles of temperature and salinity can be converted to model innovations, which are 3-D corrections to the model fields, applied at the next model start in forecast mode. OceanVar was configured with a radius of correlation of 10 km. An analysis window of 24 hours was chosen, centered on 1200h. Observational errors were assigned constant values of 0.15 C^{o} and 0.05 for temperature and salinity, respectively.

Glider data were assimilated in the CYCOM only, without influencing the coarser resolution models that provide the initial and boundary conditions, see Figure 5. Every day, the model was run in hindcast mode for 1.5 days, starting 2 days back, during which misfits were computed based on available glider data. At the end of the hindcast, the data assimilation tool OceanVar calculated corrections to the temperature and salinity fields, which were introduced into the initial 20 time steps of a second 1.5 day hindcast run starting one day back. This run also calculated misfits between observations with model (profiles nearest in time and space) and OceanVar again calculated corrections to apply to the forecast of the current day. The forecast run continued for 4.5 days. The daily runs were carried out from 31 August 2016 until present, during which time a single ocean glider carried out pattern described above, except for the period from 4 November to 7 December when two gliders were active. Note that the latest available open boundary conditions from ALERMO and surface forcing from Skiron were used every day.

A control run was executed daily using the same code, with exactly the same initial and boundary conditions, but with no temperature or salinity observations assimilated. Both runs produced daily averaged output, daily instantaneous output, and 6-hourly averaged output.

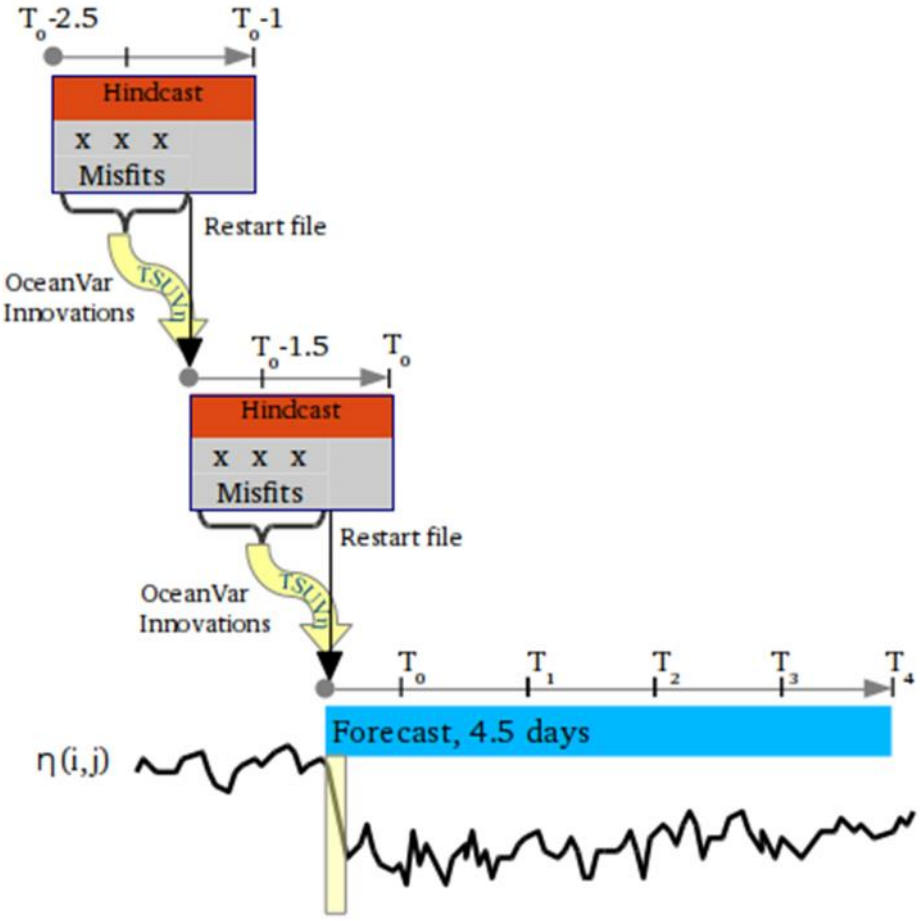

Figure 5. Operational forecast scheme for data assimilation, including hindcasts and forecasts. T_o is 1200h GMT on the day of the operational run. Note that innovations are integrated linearly over the first 20 time steps of the following run.

Numerical Results

Example output at different times is shown from both the control and d/a runs here. First, it is noted that both runs show cyclonic circulation around the NE Levantine, following the Middle Eastern and Turkish coasts (Figure 6). The interior region, south of Cyprus, is characterized by anticyclonic circulation. The warmest and saltiest waters at 30 m are found in the coastal areas, in particular in the Gulf if Iskenderun in the NE corner of the Levantine, but also within the anticyclonic region south of Cyprus. Both control and data assimilation runs show the same basic structure in currents, temperature, and salinity at 30 m throughout the experiment, but the d/a run shows more intense anticyclonic circulation in the region of the glider missions, only starting between mid-September and early October. This region also show higher temperature and salinity in a more intense, and westward-shifted anticyclone, which could be the Cyprus eddy or the Shikmona eddy previously observed south of Cyprus in the 1980s (Brenner, 1989) the 1990s (Zodiatis et al. 2005), and in the 2000s (Hayes et al., 2011).

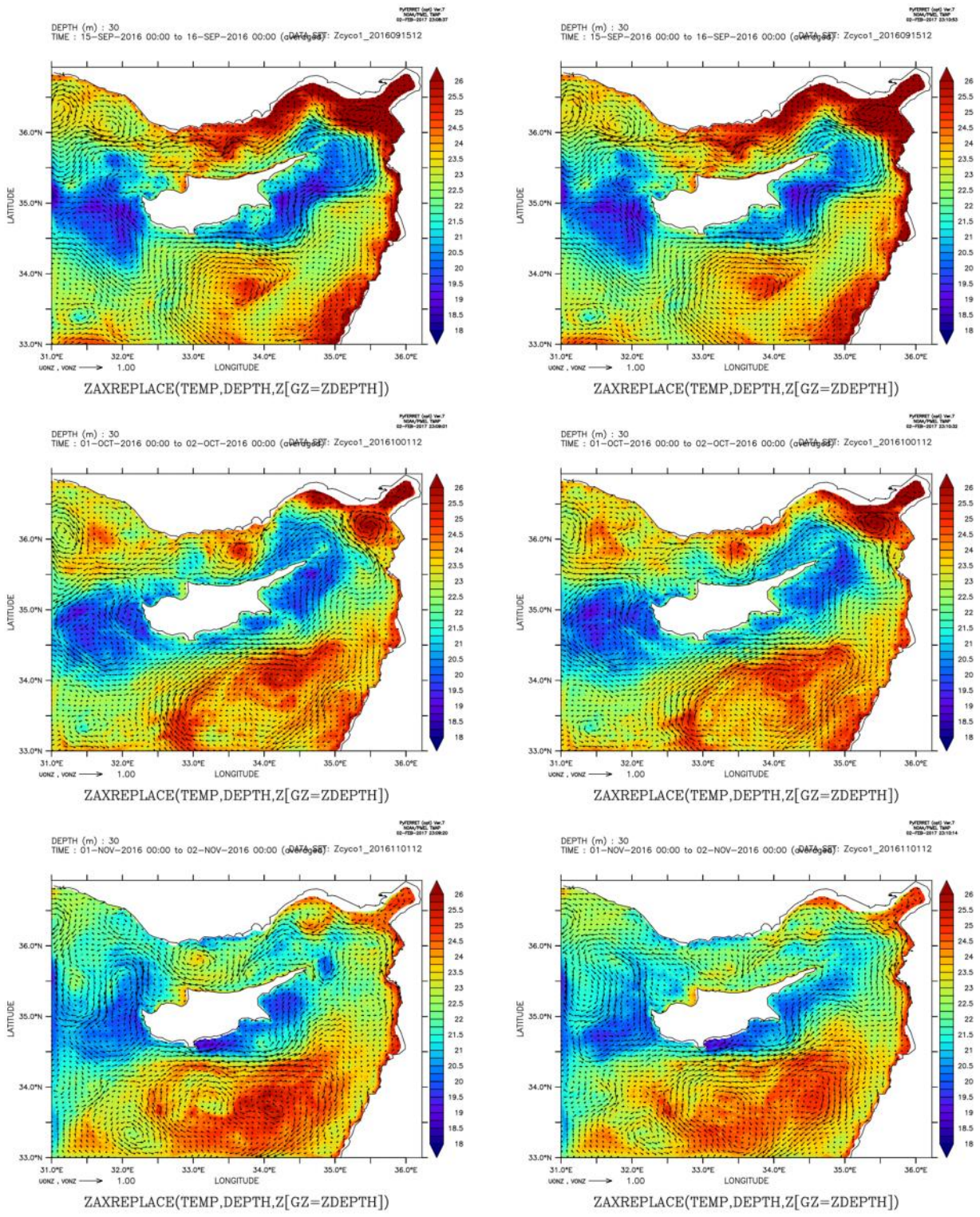

Figure 6. Maps of temperature and currents at 30 m depth from three different dates: 15 Sep, 01 Oct, and 01 Nov 2016 for data assimilation run (left) and control run (right).

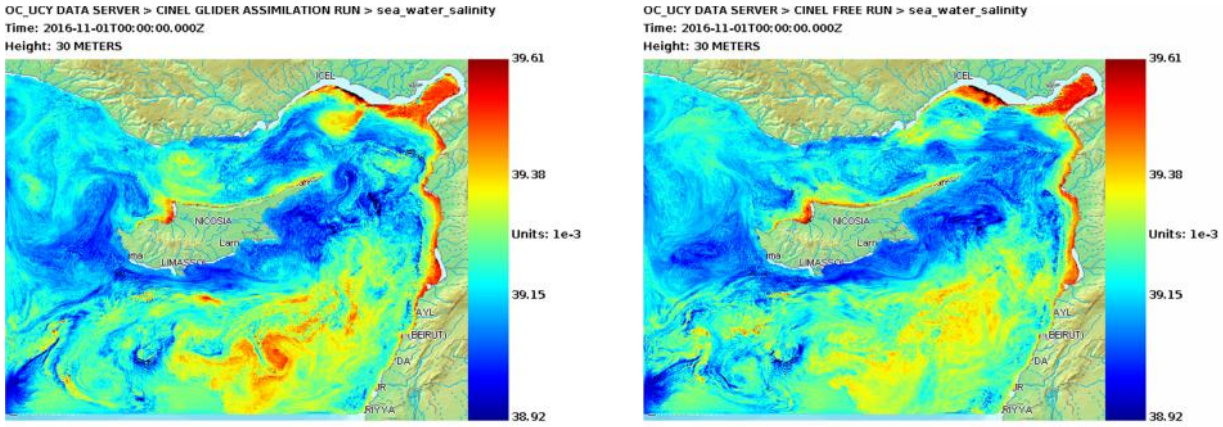

Figure 7. Maps of salinity at 30 m on 1 Nov 2016 for data assimilation run (left) and control run (right).

In order to understand the impact of data assimilation, an example of model-observation misfits, with the calculated innovation, for a particular day is shown in Figure 8. The innovations shown are only for the points of observation, but this is really a small part of the 3-D correction applied on the entire model data field on the next restart. Horizontal slices at 100 m through this 3-D field are shown in Figure 9.

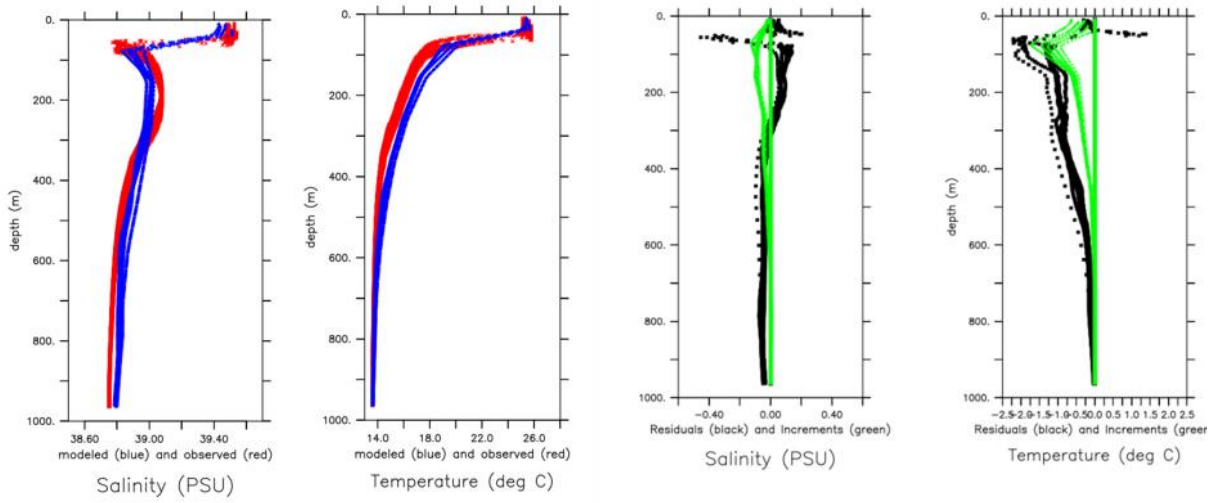

Figure 8. Vertical profiles of salinity and temperature from the data assimilating model (blue) and observations (red) (both on left) and their differences (black) and resulting model correction profiles (green) (both on right). Only profiles from 1 Nov 2016 assimilation window are shown.

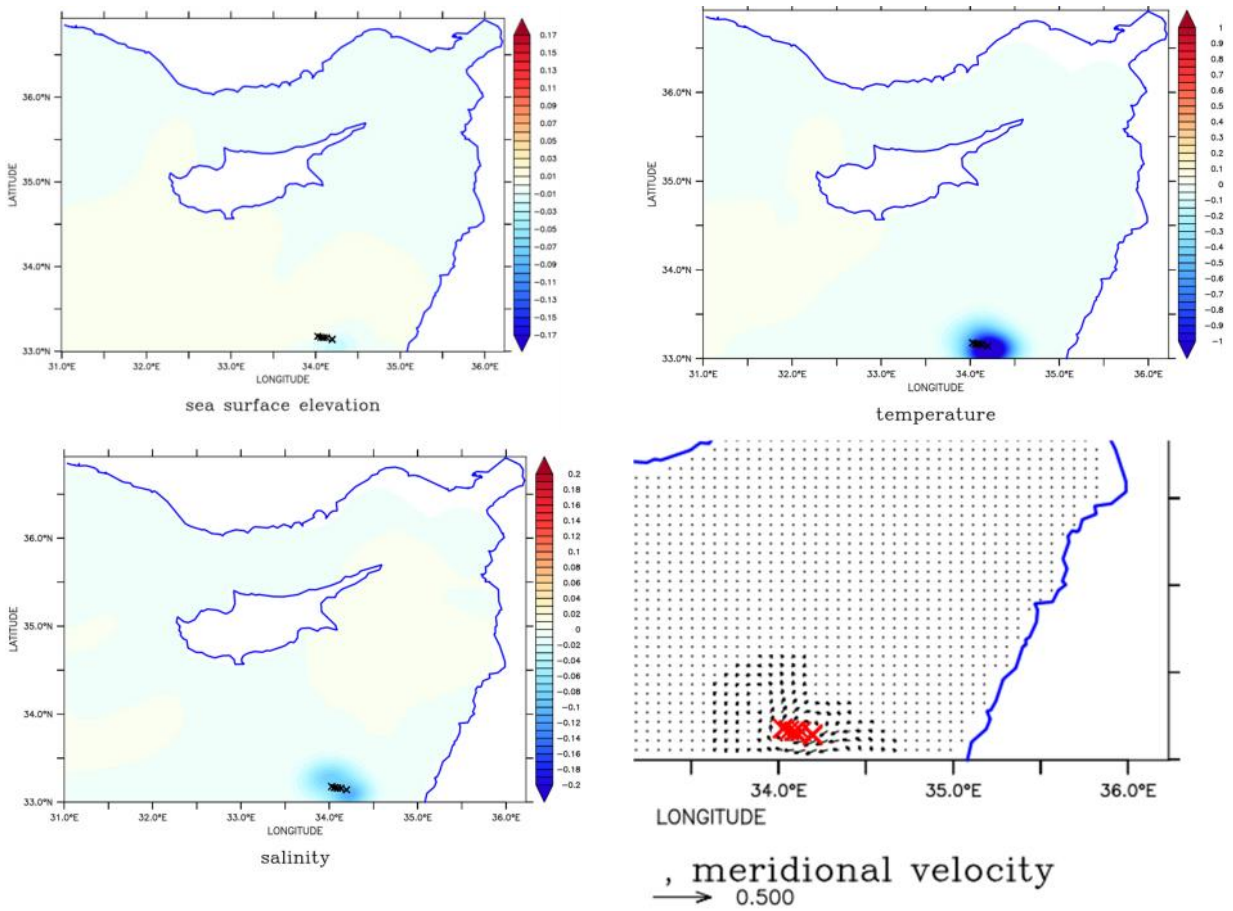

Figure 9. Horizontal slice at 100 m depth for the 3-D correction (innovation) fields computed for 1 Nov 2016. Sea surface elevation (upper left), temperature (upper right), salinity (lower left), and velocity (lower right). Glider position is shown by "x" in each plot.

Summary and Future Plans

As described in the Overview, this report represents the midpoint of CINEL. Data have been collected from all 3 platform types (3 separate gliders, 4 drifters, and 1 float). Numerical simulations have been carried out using data assimilation of glider temperature and salinity (d/a run) and without (control run). These simulations have continued since the gliders have been recovered, and the d/a run will start assimilating glider data in phase III when the OGS and OC-UCY gliders are deployed again during February and March 2017. A new numerical run will be initialized with the latest output of the ALERMO low resolution model, and will also assimilate glider data. We also plan the following:

- Prepare and assimilate profiling float temperature and salinity profiles in near real time
- Investigate ways to fine tune the data assimilation to better capture vertical structure of AW and LIW.
- Analyze further the observations from all CINEL platforms and numerical simulations for the details of the observed anti-cyclone and the factors that affect its evolution, such as interaction with the surface fluxes (wind curl, density and momentum fluxes) and ageostrophic processes.

- Compare the numerical simulations to other data sets from remote sensing (such as sea surface temperature, sea level anomaly) and from other products such as drifter-based current maps or other observations made in the region.
- Investigate the temperature and salinity profiles and property plots over a range of the experiment.

Acknowledgements

Monica Demetriou should be acknowledged for deploying the CINEL drifters and float in phase II, as well as Prof. Georgios Georgiou for his efforts to secure the proper research permits and MOU, to clear the equipment shipped from Italy, and to address many other administrative issues.

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