Elsevier Editorial System(tm) for Dynamics of Atmospheres and Oceans
Manuscript Draft

Manuscript Number: DYNAT-D-09-00020R1

Title: Impact of data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean)

Article Type: Full Length Article

Keywords: Data assimilation, glider, Atlantic Ionian Stream

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Abstract: Glider observations of temperature, salinity and vertically averaged velocity in the Ionian Sea (Eastern Mediterranean Sea), made in the period October 2004 - December 2004, were assimilated into an operational forecasting model together with other in-situ and satellite observations. The study area has a high spatial and temporal variability of near-surface dynamics, characterized by the entrance of the Atlantic Ionian Stream (AIS) into the Northern Ionian Sea. The impact of glider observations on the estimation of the circulation is studied, and it is found that their assimilation locally improves the prediction of temperature, salinity, velocity and surface elevation fields. However, only the assimilation of temperature and salinity together with the vertically averaged velocity improves the estimate of all observed parameters. It is also found that glider observations rapidly impact the analyses even remotely, and the remote impacts on the analyses remain several months after the presence of the glider. The study emphasizes the importance of assimilating as much as possible all available information from gliders, especially in dynamically complex areas.

Dear Andrew,

I am sending the revision of our manuscript. We have made a major revision in which, after the suggestion by both reviewers, we have removed the part describing the circulation and concentrated on the impact of the assimilation of glider observations. The title is changed to "Impact of data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean)". In the revised manuscript we have tried to fully respond to all comments and suggestions by the reviewers. The detailed description of changes is listed in the response to the reviewers.

I would like to thank the two unknown reviewers for very useful and stimulating comments and suggestions.

Sincerely,

Srdjan Dobricic

We would like to thank the reviewer for very useful comments and suggestions. We have tried to reply to all of them in a satisfactory way.

Here are our replies in detail (underlined italic characters):

Reviewer #1: The manuscript "Data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean): a study of the path of the Atlantic Ionian Stream" is studying the impact of the assimilation of glider data, in addition to sea level anomaly data and to other types of in situ data, in the Ionian Sea. It also studies the dynamical mechanisms of the Atlantic Ionian Stream meandering and of the seasonal variability using model analysis. The assimilation of temperature and salinity measurements from the glider, and even of mean velocities derived from drifts of the glider yield interesting improvements. The focus on improvements yielded by the assimilation of estimates of mean velocities is promising. In the second part of the paper, the study on the AIS variability resume previous studies on the Ionian Sea and yield valuable new conclusions. It is interesting to see that ocean analysis based on data assimilation can bring improvements in the understanding of the circulation variability. However, the link between the two parts is not obvious in the present version of the paper, at least because the latter does not show any impact of the assimilation of glider data on the features of the circulation that are studied in section 4. The following general comment gets into more details about this issue. The paper should develop stronger links between section 4 and the glider data assimilation or should be split in two different papers. A major revision is thus needed. Below is a list of comments/questions that the authors need to address in their revision of the manuscript.

General comments:

A) As stated above, the link between the two main parts of the present version of the paper is weak because the latter does not show any impact of the assimilation of glider data on the features of the circulation that are studied in section 4. Section 4 even focuses on a period "after the glider assimilation period" (page 14): the 3 months following the last glider measurements, in order to study a seasonal variability that cannot be represented in the glider observations.

The statement "during its repeated passes in the western Ionian Sea, the glider crossed a meander of the AIS and provided information about the initial development and subsequent detachment of an anticyclonic eddy from the AIS" justifies the association of both studies in the introduction, but (i) this point is not investigated or discussed in the text (ii) section 4 is actually describing the detachment of an anticyclonic eddy from the AIS in February-March, while the glider delivers data only until December (in December only quite far from the anticyclonic gyre).

The authors seem to interpret the lack of impact of assimilation of glider data as a demonstration that the analysis are realistic enough to justify what is said in section 4 ("the differences in the surface circulation due to the assimilation of glider observations in comparison to the control analyses were on small spatial scales, indicating that the control analyses were already depicting the regional-scale surface circulation with a satisfactory accuracy. The quality of the control analyses..." page 19; see also "most of the features of the sea level field in the control experiment were in good general agreement with the observations by the glider" page 14, at the end of section 3). Such a validation could link sections 3 and 4 but:

(i) there is no evidence of this interpretation and then of this validation in the present version of the paper. It seems more natural to explain the lack of impact of glider data assimilation on large scales as a result from the weak coverage of the glider, from the use of small horizontal correlation scales in the data assimilation system, and from the assimilation of many SLA data in both the control experiment and the experiment using glider data (it is not surprising to see similar SLA fields during these two experiments; even in the vicinity of the glider path, it seems there are many SLA observations that are assimilated). Without further description and explanation of the results, we can suppose that there are large scale errors in the region of glider paths that are not corrected even when assimilating the glider.

(ii) If comparisons to glider data are useful to check that the analysis are realistic enough, but the assimilation of glider data does not improve the large scale circulation, why would not the authors consider only direct comparisons between the control analysis and the data from the glider instead of studying details about the assimilation of those data before section 4 ?

The need to show that the assimilation of glider data yields improvements but at the same time that analysis far (in space and time) from the locations of glider observations are realistic enough (especially because there is no glider data in the Sicily strait and during winter) seems to lead to contradictory conclusions: for exemple, biases shown in Figure 4 and 5 that are said to be corrected when assimilating glider data (in section 3 and in conclusion) do not seem local, but it is stated that "the temperature and salinity averaged over the top 200m are very similar" (page 13) with or without assimilation of glider data.

Those quite "contradictory conclusions" let suppose that there are potential impacts of the assimilation of glider data on the meandering of the AIS and that the paper could explore a bit more consequences of the important corrections on temperature and salinity that are seen on Figures 4 and 5. A more precise characterization of the length scales of corrections could be useful.

Following the comments by both reviewers we have removed Section 4 and expanded Section 3. In this way the manuscript is concentrated only on the impact of glider observations. Section 3 is expended by describing in more detail how the glider observations impact the analysis. In particular we have shown how the velocity observations in addition to T/S observations improve the accuracy of the analyses (pages 12-15, Table 1, Figs. 6-7). In order to make this analysis we have performed another experiment in which we assimilated only velocity observations. The title is also changed, because the manuscript concentrates *only on the impact of glider data.*

Now we extend the comparison of the control and glider analyses to the period of three months after the last glider observation and over the whole Eastern Mediterranean (pages 15-16 and Figs 8-10). We were surprised to find differences in the sea level field even remotely and long time after the glider observations. Now we show that it is difficult to improve significantly the rms of SLA misfits, because the already in control analyses it close to the errors of satellite observations (page and Fig. 10). In fact in both control and glider analyses show very similar positions of eddies, but their shapes and intensity differ.

Unfortunately, the SLA is the only observational data set with a high temporal and spatial coverage. In the absence of a large number of independent in situ data we cannot evaluate horizontal biases in temperature and salinity, because SLA depends only on their horizontal gradients. However, now we show that there is a small positive impact of glider observations on the sea level even remotely.

We have omitted the sensitivity to the change of horizontal correlation scales, because we have found earlier in our analyses that although different scales may impact the rms of misfits, they do not change significantly the circulation structures due to the large number of SLA observations. (p 8)

B) Some parts of the text, especially the introduction, the section 2.3 on the data assimilation system, the beginning of section 3 and comments on Table 1, need to be reorganized and clarified. The minor comments illustrate that point.

Minor comments :

sec 1

page 3:

- "efficient monitoring of the basin scale structures" what does that mean, or how does that take into account conclusions given at the end of section 3 ?

Now this phrase is removed. (p 3)

- based on observations that are dynamically consistent in space and time: I'm not sure to understand what is this consistency about

This is changed to "because they produce best estimates of circulation fields based on observations and background states that are dynamically consistent in space and time" (p 3)

- "in particular, glider measurements ... measurement area": the idea is quite identical to "the assimilation of observations from additional types of instruments has the potential to provide an improvement in the quality and accuracy of MFS analyses" in the previous paragraph, gliders could be introduced there. "The analysis offer the opportunity..." could be introduced before "One of the major challenges...". Whatever change is done, things could be better organized.

<u>This part is moved to the previous paragraph and reorganized. (p 3)</u>

page 4 and 5

- From "Pinardi and Navarra" to "completely investigated": things need to be reorganized, they are confusing. Contradictions or complementarity in the conclusions from different studies are quite lost or made questionable by this presentation. Do the "realistic circulation patterns" from Pierini and Rubino 2001 or Molcard 2002 have a fully realistic seasonal and interranual variability ? Don't those different studies just show an estimation of the relative influence of different driving mechanisms for the dynamics and variability in the Ionian Sea (this seems to be said by the authors at the end of the paragraph) ? So why should we think that they provide "somewhat contradictory theoretical explanations" ? Isn't the conservation of potential vorticity acting on studies like those of Pierini and Rubino 2001 or Molcard 2002 that "present an AIS always turning northward after entering the Ionian Sea" ? So should not this point about the potential vorticity be introduced first ?

<u>This is now shorter and we avoid the description of potential vorticity, because Section 4 is removed. We have tried to rewrite this part in a more clear way. (p 3-4)</u>

page 6

sec 2.1

page 6
- Davis et al. 2003 should be moved to the first occurrence of "Gliders" at the beginning of this section 2.1

<u>We have added Davis at al. 2003 at the beginning of the section. (p 5)</u>

sec 2.2

page 8:

- before Castellari et al 1998 a logical link is missing, something as "using the bulk formulations" of Castellari...

<u>This is now reformulated. (p 7)</u>

- where are the objective analyses of the satellite sea surface temperature coming from ?

Now there is a reference for the SST objective analyses. (p 7)

sec 2.3

page 8 - page 9

- "The scheme models .... linear operators" and the following may have to be rewritten (avoiding details such as "successive applications of one-dimensional recursive filters" ?), or you should enter into more details because it is not clear in this form. The "control space transformation" and "the first linear operator transforms weights of vertical EOFs into vertical profiles of T and S" do not really mean anything by themselves (about the EOFs: at that point it seems that the SSH is not included in the vertical EOFs because of "vertical profiles of temperature and salinity").
Another issue is that you start to describe the operators one by one using general informations and then you loop again on each of them with a different order to give other details (or the same ones, cf "isotropic" and further "a function of the distance only"). So again, things need to be reorganized.

This part is rewritten in order to be more clear (p 8).

- "Emprirical" remove the "r"

This is corrected (p 8)

- The analysis are produced... : make a new paragraph at the beginning of this sentence ?

There is a new paragraph now (p 9)

- "the assimilation of SLA "uses" the mean dynamic topography" the "uses" is not clear, maybe say you are comparing SLA+MDT to the surface elevation in the model ?

This is now rewritten for clarity (p 9).

"During ... profiles" should come before "the assimilation of SLA" because you should not explain that you will assimilate SLA just after having explained how you will assimilate SLA. The acronym SLA is used far earlier, you should not develop it here

This corrected on page 9.

page 10

- "Clearly..."
this statement has quite already been made during the introduction, it looks like it is only a repetition, but figure 3 actually increases the pertinence of this remark. Maybe try to add a simple information from figure 3 ("there are no other in situ measurement in this region" for example, which is useful to justify the following statement "and also provide an information about accuracy...").

We have added that there were no other in situ observations in this area. (p 9)

- couldn't we suppose a priori that corrections arisen from assimilation of in situ data in remote regions impact indirectly the region where the AIS enters the Ionian sea ?

It appears to be the case with glider data. Now this is shown in Figs. 8 and 10.

sec 3

- why "adapted" in "adapted assimilation scheme" ?

It had to be "adopted". Now this is removed completely (p 9).

- "Furthermore....": things have to be reorganized. Here a beginning of justification is given for the spatial averaging, and this justification is ended further with "corrections at spatial scales..." with new informations. But in the meanwhile you give the scales for the averaging. "Corrections at spatial scales shorter than two grid points...": it doesn't seem precise or clear enough to make sense.
Note that you average data horizontally inside windows corresponding to the error correlation scale in order to assimilate "independent" observations, but that on the vertical, using a limited selection of vertical EOFs, you are probably assimilating several data that are not "independent".

In fact, we average also in the vertical with one "superobs" per model level. Still the data are not independent, but at least numerically we did not find any problems. This is now explained in the manuscript (p 10).

page 11

- The observational operator inside OceanVar should be better introduced if you really want to give details about it. "are assimilated using observational operator" or "are assimilated by constructing" are shortcuts.
In section 2.3, you explain things about the assimilation of SLA, not about the assimilation of T and S data, while now in section 3, you give those general informations that do not only concern the glider data. The beginning of section 3 could be moved into section 2.3.
"Horizontal velocity observations were also temporaLLy (ll instead of r) averaged": I'm lost, we can't clearly understand that both model outputs and observations are averaged in time, cf "also" vs "velocity observations" in the same sentence, cf also "from the observations and the background". You should rewrite this whole paragraph to improve the clarity.

This part is now rewritten. We have moved the description of observational operators to the top of page 9. Now this paragraph only describes the processing of observations. (p 10)

- "analysis which assimilated": shortcut if as previously said analysis are the product of data assimilation

Now we changed this to "analyses with glider observations" (p 10)

- why is there a gap in Hovmoller diagrams ? sections from figure 2 seem to indicate measurements during the missing period

The observations on those days were near the coast in areas shallower than 150m, and the analyses scheme was set to assimilate observations only in the deep ocean. This is now explained in the figure capture and the top paragraph on page 9.

- I hardly see anything on December 1, is it the actual date ?

In fact this was our mistake. We apologize for it. It is removed now.

- It is hard to see your bias below the thermocline. Maybe describe it better. When you compare control analysis to observations it seems that you say there are only mesoscale discrepencies (you do the same for the salinity: "but they do not capture the small scale structures" and further "it also eliminates the salinity bias...").

This is now corrected. We state that the mean salinity along the path of the glider is lower than observed. (p 12)

page 12

- again it looks like there is a mistake about the date of December 1

We apologize once again. This is removed from the text.

- you should provide "more" details about the agreement on the position of the AIS (depth position only ?), and it is not really obvious that "the control analyses are in general capable to depict the major path of the AIS". "but they do not capture the small scale structure at the depth of ~50m during the period 28 October-10 November" it looks worse than that all the time, quoting this particular point looks strange. More generally, it seems figures 4 and 5 should be analyzed more carefully.

We think that control analyses depict the horizontal position of the AIS. It is mainly characterized by the low salinity, which is clearly present in the control analyses in Fig. 5 whenever the glider crosses the anticyclonic meander. At the same time the glider and control analyses show the signature of the anticyclon in the temperature field (Fig. 4). We have tried to explain this more carefully in the new version of the manuscript and added a paragraph that summarises the analysis of Figs. 4 and 5. (p 12)

- the control analysis become the control experiment because you are not anymore looking at analysis but at short time free simulations from analysis. One could believe this is also what you were doing on figures 4 and 5. So introduce the control experiment and experiments with glider, and then the difference between analysis and simulations initialized with analysis, before presenting results from fig 4,5 and then table 1, or at least do something less confusing than "the rms of misfits represents an independent..."

Now after the definition of control and glider analyses we define the corresponding simulations. (p 11, second paragraph in Section 3).

- you say "T and S from the glider" but not "assimilation of T, S and velocity observations from the glider"

This is corrected now. (p 13)

- "which compares the rms of misfits" is vague: do you compare only to T and S from the glider or also to T and S from other sources of in situ measurements ? what is the period for the mean in RMS ? Even the legend of Table 1 is incomplete. At that point it seems that no T or S data was assimilated in the control experiment.

Now it is stated that only glider observations are used for temperature and salinity misfits. Also the averaging time is the period of glider observations. (p 13)

- Using 1 day assimilation windows and data spaced by 12 km, one could say that you don't really have an "independent estimate" (what does independent mean precisely ?). If you were not expecting correlations between data assimilated and data that will be observed, you would not estimate decrease in the error to the observations non assimilated when using data assimilation. Are you considering misfits to observations within 1 day window ? we don't really know (especially because you are speaking about 5 days window for SLA), and we should not have to guess that you are comparing only to data that will be assimilated during the coming correction.

It can be calculated that with our radius of correlation and data spacing it is sufficient that the intensity of the mean current is about 20cm/s to advect in one day the corrections away from the area where the next observation is made. In fact, different experiments with glider data in Table 1 show that there is an impact of the dynamics even in one day. Five days is the minimum repeat time for SLA observations, but most of them have longer repeat times (Fig. 3).

- "the variation in the distance from 55 km to ..." are you taking SLA observations in the vicinity of the location of the non assimilated or of the previously assimilated glider observations ? in both cases, 55 km surround the region where you had previously assimilated the glider data and then one could suppose the only part of SLA impacted is the SLA that is within the 15km correlation scale of the glider observation. "The variations in the distance from 55km to 220km..." does not bring interesting information about the length scale of the actual area inside of which the assimilation of in situ observation impacts the SLA.

Here again we take into account the possible impacts of the advection and the dynamical adjustment. Although the corrections have a small radius of correlation, the dynamics in the *model rapidly adjust the fields in a larger area. This is now visible in the new figure (Fig. 8). We apologize that in the first version of the manuscript we did not notice this behaviour. Now we try to explain this in the manuscript (p 13-14)*

- "334 SLA observations" doesn't it depend on the glider location that is considered ?

It does depend on the glider location. The number is only mentioned to emphasise that the statistics is sufficiently robust.

page 13

- "The table shows that the ....(by 30-50%)" again what is "short term" ? we should not have to guess it is corresponding to 1 day, or rather 12h (because data assimilated with 15km correlation length scale are a priori far more influencing data that will be observed 12 km away 12h later than 25 km away 1 day later).

In fact we do not know from the rms what is the short term, but we think that this is a general problem of the validation of the analyses which is out of the scope of our study. Like we mentioned in the previous comment the sensitivity of the rms shows that there is an important impact of the dynamics in this area which would make the analysis of this kind very complicated.

- were -> where

This is corrected.

- "The reason for this result": one could also suppose that vertical EOFs are unadapted here and are responsible for the increase in misfit for SLA, or that imperfections in the MDT used to estimate surface elevation from SLA would lead to inconsistencies with in situ data (differences in the misfits for SLA are very small between experiments "Control" and "T,S", so it may be hard to draw such a conclusion from such results).

We think that we can exclude both EOF and MDT errors here. EOFs are not important, because gliders resolve very well the vertical structure, and 20 EOFs are more than sufficient to fit them. The MDT error can be excluded, because the velocity assimilation clearly improves the result.

- "completely independent" would mean that "independent" (cf above p12) is not "completely independent" ?

We removed this.

- "while eventually ..." could be rewritten in order to be less informal. By correcting the SLA, data assimilation can also correct temperature and salinity (you have multivariate vertical EOFs). So the reason why it is "surprising" in one case and not in the other one is not clear.

Now we explain the improvement by the fact that assimilating velocity the horizontal structure of corrections is improved. (p 14)

- "A reason for this result could be ..." maybe but it looks quite surprising that the model is adapting its T and S to local velocity corrections rather than the opposite. Couldn't the explanation be found inside the data assimilation process ?

Temperature, salinity and velocity corrections are balanced by the geostrophic relationship.

- "of the period OF glider observations" ?

This is removed.

- "glider assimilation experiment": with or without assimilation of mean velocities ?

This is changed to "glider analysis".

page 14

end of section 3

- "most of the features of the sea level field..." is it also the case for temperature and salinity at depth ? "similar" and "good general agreement" is quite vague. "most of features of the sea level field... in a good general agreement with the observations by the glider" see the first general comment about this sentence.

This is removed. Now there is an extension of Section 3.

section 4

This section is removed from the manuscript. However, we would like to thank the review for his comments. We will take them into account and try to formulate a new study which will address them.

- figure 7: isn't the arrow rather pointing the western Ionian anticyclonic gyre and then the anticyclonic eddy detached ? on Feb/March the AIS has gone south. Actually I guess that the legend meant that arrows indicate the AIS meander and then the anticyclonic eddy but it has to be clarified.

- "the cyclonic circulation shifts southward": one could think you are speaking about the cyclonic meander of the AIS when it enters the sea ("before" the anticyclonic meander), especially as it is the only one that has been introduced in this paragraph, but on page 15, we understand that we are looking at the western Ionian cyclonic gyre ("after" the anticyclonic gyre).

page 15

- "In synthesis" could be removed

- "In the 1987 circulation" what does that mean ?

page 16

- the whole paragraph about upwelling seems to go round in circles: we read "temperature gradients contribute substantially to the strength of the AIS" and then "temperature gradients are formed in summer, because the local conditions produce upwelling that induces a strengthening of the eastward flowing AIS current" and then "the area with upwelled cold waters defines the position of the surface AIS in the Sicily Strait and the horizontal temperature gradients due to the upwelling enhance the AIS".

page 19

conclusion

- "It removed cold and fresh biases..." to what extent ? what is locally meaning: how can you represent more accurately MAW "locally" ? how "along the Atlantic Ionian Stream path" can be "local" ?

Here locally means that remotely we do not have observations to estimate the impact on the path. However, locally we find an improvement. In the new manuscript we also find a small positive impact on the sea level in remote areas (p 18).

- "significantly increased the acCuracy"

We removed "significantly".

- new paragraph for "The analysis show that" ?

We removed this section from the manuscript.

*Detailed Response to Reviewer 2

We would like to thank the reviewer for very useful comments and suggestions. We have tried to reply to all of them in a satisfactory way.

Here are our replies in detail (underlined italic characters):

Reviewer #2: Review of "Data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean): a study of the path of the Atlantic Ionian Stream" by S. Dobricic et al.

[1] This paper describes the addition of in situ glider observations to the Mediterranean Forecast System and discusses some features of Ionian Sea circulation in the resulting simulated flow fields. The assimilation system developments are described well and the inclusion of glider drift velocity as data is novel and an interesting added feature of the paper. The analysis of the modelled circulations is superficial and it is not clear how these two aspects of the paper are integrated.

Following the comments by both reviewers we have decided to remove the description of the circulation (Section 4). Now the manuscript is concentrated only to the description of the impact of the glider. The title is also changed in order to respect the new objectives of the manuscript.

[2] The procedure by which glider data are processed and included into the data assimilation system is explained very clearly and concisely - this is a strength of the paper. The impact of the *added* data (I did not notice on first reading that the control simulation had assimilation of other data - it might pay to state this more prominently, perhaps by restating it in the figure captions) is assessed in terms of the improvement in forecast skill, which is a valid approach. However, it is not explained (page 12) which forecast was used (i.e. how far into the future) to calculate the skill metrics presented in Table 1. Were these 1-day, 1-week etc. forecast values? The text indicates the metrics were calculated with respect to data not yet assimilated, so it cannot be analysis skill.

Now we state that each rms is calculated for the period of the glider observations (Ocober 1 December 23) (p 13). We also explain that these are short term simulations before the insertion of the data (top paragraph on page 11) and why they can be an approximation for the analysis accuracy (p 13).

[3] The authors have missed an opportunity to consider in detail the duration for which the addition of glider data provides useful skill and how this differs for state variables. . I would expect rather more extended added skill for T/S than for velocity. This would be an interesting extension to the results. When it is considered the skill values discussed are only the 16 values in Table 1 it is a rather thin skill assessment.

Now we expand the description of the impact of glider observations. On page 17 and Figs. 6-7 we evaluate how the assimilation of each T/S or velocity data set impacts the near surface circulation. On pages 18-19 and Figs. 8-10 we evaluate the impact of glider observations over a larger area and a longer time period. We find that the information from glider observations rapidly spreads remotely and remains a long time after the last glider observation.

[4] It is stated (p 13) that temperature and salinity misfits reduce by assimilation velocity, but the velocity only assimilation case is not considered. It could be for completeness.
Now results of an experiment with the assimilation of only velocity are given in Table 1 and Fig. 7. This experiment further clarifies how the velocity data impact the analyses. (p 14, 16).

[5] Is the improvement in mean squared error dominated by reduction in bias, or is there also a significant improvement in mesoscale feature detail as perhaps would be indicated by considered cross-correlation in the control and assimilated simulations with data?

There is a significan improvement in the mesoscale covariance. It is now reported in the manuscript. (p 11,12)

[6] The spatial extent of the information added by the glider data would be more evident if Figure 6 presented anomalies with respect to the control simulation. The anomaly figures could also show the locations of observations so the reader can see how the assimilation scheme propagates the information in the horizontal, and time evolution of the influence of the observations.

In the new manuscript anomalies are presented in Fig. 8 in a larger area and for a longer time period. It also shows how the anomalies propagate in space and time. (p 18)

[7] The analysis presented in section 4 is qualitative, yet with a dynamical model constrained to give a realistic state estimation through data assimilation, I feel strongly we could expect a lot more analysis here. I do not suggest anything is wrong - there is just not much here.

Following the comments by the reviewers we have removed this section.

[8] Presumably, all the features described in pages 14-17 occur in the control model and the glider assimilation model. If so, then it does not follow that the assimilation effort has added anything to the science here. If this is not so, then that is a key result and deserving of further analysis to explain, dynamically, how the influence of the in situ glider data so changes the simulations.

This section is removed. However, we will carefully take into consideration the reviewer's comments when preparing a new study which describes the circulation features.

[9] e.g. p16-17: "On the other hand, Fig. 8 further shows that at the end of winter (March) the temperature-derived dynamic height has smaller gradients and the salinity-derived surface dynamic height gradients prevail in determining the position and intensity of the AIS." A

dynamical or statistical analysis is required to demonstrate that salinity derived dynamic height gradients are determining anything.

Also in this case will take into account this comment when preparing a new study.

[10] Considering typical temperature and salinity differences in the surface waters of the observations I see salinity ranges of 37.9 to 38.6 PSU and 16 to 24 degrees C. These correspond to density differences of 0.5 kg/m3 and 2.2 kg/m3 respectively, which suggests to me that the dynamical influence of salinity is distinctly secondary to temperature.

Again, we will take into account this comment in the new study.

[11] The discussion of wind stress curl is similarly superficial. Is there is indeed a dynamical correlation between curl(tau) and circulation then the authors have model output with which to test this hypothesis with some rigor. There is no dynamical or statistical analysis whatsoever. Their qualitative analysis could well have been achieved looking simply at the data. The model has not bee used to inform the scientific process. This is the greatest weakness of the paper - the data assimilative modeling and physical oceanographic interpretation are not complementary.

The same as in the previous three comments.

[12] In summary, I recommend the authors consider the following two broad approaches to making the paper suitable for publication.

(a) (i) expand the skill assessment to show more extensively how the information added from the glider data propagates through the model (in time and space), (ii) paying attention to the time scale of added skill; delve more deeply into what features of the skill are improved mean squared error (reduction in bias, improves cross-correlation, more realistic variance),

(b) (i) explain how glider assimilation modifies the interpretation of the circulation, (ii) formulate dynamical hypotheses for the changes in the mesoscale circulation that stem from subsurface in situ data assimilation, (iii) undertake an analysis of the model vorticity dynamics to substantiate the curl(tau) conjecture, or undertake a statistical analysis to strengthen the arguments that there are coherent processes at play.

In the new manuscript we have tried to respond to the point (a). Following also the comments of the other reviewer we have removed the description of the circulation and will do it in a separate study (point b).

Impact of data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean)

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Abstract

Glider observations of temperature, salinity and vertically averaged velocity in the Ionian Sea (Eastern Mediterranean Sea), made in the period October 2004 - December 2004, were assimilated into an operational forecasting model together with other in-situ and satellite observations. The study area has a high spatial and temporal variability of near-surface dynamics, characterized by the entrance of the Atlantic Ionian Stream (AIS) into the Northern Ionian Sea. The impact of glider observations on the estimation of the circulation is studied, and it is found that their assimilation locally improves the prediction of temperature, salinity, velocity and surface elevation fields. However, only the assimilation of temperature and salinity together with the vertically averaged velocity improves the estimate of all observed parameters. It is also found that glider observations rapidly impact the analyses even remotely, and the remote impacts on the analyses remain several months after the presence of the glider. The study emphasizes the importance of assimilating as much as possible all available information from gliders, especially in dynamically complex areas.

1. Introduction

The Mediterranean Forecasting System (MFS) (Pinardi et al. 2003) provides daily analyses of the circulation of the Mediterranean Sea. The analyses are based on the production of background fields by a high resolution general circulation model and the assimilation of in-situ and satellite data using a variational assimilation scheme. One of the major challenges of MFS is to assimilate the largest possible number of satellite and in-situ observations in real time. The variational multivariate assimilation scheme currently assimilates at the same time satellite Sea Level Anomalies (SLA) and Sea Surface Temperature (SST) and in-situ observations of temperature and salinity profiles by eXpendable BathyThermographs (XBT) and Argo floats. However, the assimilation of observations from additional types of instruments has the potential to provide an improvement in the quality and accuracy of MFS analyses, and MFS started to investigate the importance of gliders that measure temperature, salinity and velocity in the top 200m of the ocean. The analyses offer the opportunity to study in detail the dynamics of interesting circulation structures, because they produce best estimates of circulation fields based on observations and background states that are dynamically consistent in space and time. In particular, glider measurements, which can be repeated for several months in the same area, could greatly improve estimates of the local circulation. Eventually they may impact analyses even in remote areas.

The glider used here surveyed the central-western Ionian Sea, an area characterized by an intense surface intensified jet stream called the Atlantic Ionian Stream (AIS) (Robinson et al. 1999). The AIS is one of the branches of the Modified Atlantic Water (MAW) stream system that enters the Sicily Strait and occupies the central-northern part of the Strait, near the southern coasts of Sicily (Fig. 1). At the Maltese escarpment, the AIS detaches from the continental shelf and slope region of the Sicily Strait and enters the 3000m deep Ionian basin. Historical in-situ and satellite observations and modeling studies indicate complex circulation patterns of the AIS at the entrance to the Ionian Sea and a high interannual variability (e.g. Malanotte-Rizzoli 1997; Robinson et al. 1999; Lermusiaux and Robinson 2001; Pinardi et al. 2006). The most detailed investigation of the physical structure and properties of the AIS circulation was obtained with detailed “Conductivity-Temperature-Depth” (CTD) surveys between 1994 and 1996 and by the assimilation of observations into a regional oceanographic model (Robinson et al. 1999; Lermusiaux and Robinson 2001). Other modeling and observational studies provide somewhat contradictory theoretical explanations for the factors determining the path and the northern extension of the AIS. While studies by Pinardi and Navara (1993) and Demirov and Pinardi (2002) show that the wind stress curl has an important impact on the seasonal and interannual variability of the circulation in the Northern Ionian Sea, some other studies (e.g. Pierini and Rubino 2001, Molcard et al. 2002, Napolitano et al. 2003, Sorgente et al. 2003) find that the density gradients mainly influence the path of the AIS.

Additional in situ observations may provide a better understanding of the complex processes that govern the dynamics of the AIS in the Ionian Sea. During its repeated passes in the western Ionian Sea, the glider crossed a meander of the AIS and provided information about the development the AIS dynamics. The aim of this study is to show the relative impact of glider data assimilation on the quality of the MFS analyses in this area, and to suggest an improved use of the information from glider observations. Section 2 will describe the methodology. It will give an overview of the glider observations, describe the Mediterranean general circulation model and the data assimilation scheme. Section 3 will compare analyses with and without assimilated glider observations to show the impact of the glider observations on the quality of the MFS analyses in the Ionian Sea and the Levantine. Conclusions will be given in Section 4.

2. Data and methods

2.1 Glider observations

Gliders are autonomous underwater vehicles of a small size that can ‘fly’ underwater along slightly inclined paths by changing their density (Davis et al. 2003). The buoyancy force results in forward velocity (~40cm/s) as well as vertical motion (~15cm/s). So gliders move on a sawtooth pattern, gliding downwards when denser than the surrounding water and upwards when buoyant. The high efficiency of the propulsion system enables them to be operated for several months. They can be steered remotely and the measurements can be downloaded during surfacing by a two-way communication system via satellite. When at surface, gliders also take Global Positioning System (GPS) fixes to correct the dead reckoning positions used for navigation. This gives an estimate of the horizontal currents averaged over the glider trajectory between two contact GPS fixes.

In the period 1 October 2004 - 23 December 2004 a glider from the Webb Research Corporation (Davis et al. 2003) was deployed in the Ionian Sea. The glider made observations of conductivity, temperature, and pressure along a section which spanned ~300km to the south east of the Italian coast (Fig. 2). It was programmed to dive to 200 m depth and collected 4254 downcasts in about 3 months of operations at a rate of approximately 50 profiles per day; the distance between profiles being approximately 500 m. It had contact with land every eight profiles (~4 hours). Classical CTD profiles carried out during the deployment/recovery operations at a few hundred meters from the first/last glider profile allowed the calibration of the conductivity cell in order to match an accuracy of 0.005 PSU in salinity.

2.2 Mediterranean model set-up

The Mediterranean Sea general circulation model set-up (Tonani et al. 2008) is based on the free surface version of the OPA 8.2 code (Roullet and Madec 2000). Its horizontal resolution is $1/16^o$, and the domain spans from 18^0W to 36^0E and 30^0N to 46^0N. The model covers the whole Mediterranean Sea and includes a part of the Atlantic Ocean. At the boundaries in the Atlantic, temperature and salinity fields are relaxed towards the Levitus climatology (Levitus et al. 1998), and the cross-boundary fluxes are set to zero. The model has 72 levels defined in the vertical. The top level is 3 m thick, and the resolution gradually decreases toward the bottom layers. Horizontal diffusion and viscosity are defined by a bi-Laplacian operator with the constant diffusion coefficient $K_H=5x10^9m^4s^1$ and viscosity coefficient $K_M=3x10^9m^4s^{-1}$. The vertical diffusion is parameterized in terms of the mixing scheme developed by Pacanowski and Philander (1981), with the addition of enhanced constant vertical value of the mixing coefficient in case of vertical instabilities. The advection of tracers uses a second order accurate upstream scheme (Webb et al. 1998), whilst the momentum advection uses an energy conservative form of the central differencing scheme. Surface fluxes are calculated interactively every 6 hours (Castellari et al. 1998) by bulk formulations using atmospheric fields of of air temperature, humidity, winds and cloud cover from the operational analyses of the European Centre for Medium-range Weather Forecasts (ECMWF). Surface heat fluxes in the model are corrected by a term proportional to the difference between the temperature at the top model layer and objective analyses (Buongiorno Nardelli et al. 2002) of the satellite SST. The coefficient of relaxation applied in the surface heat fluxes correction is 40 Wm^{-2} K^{-1}. A detailed description of the model set-up is given in Tonani et al. (2008). The model simulation initial condition is set to correspond to January 1, 2002 using the temperature and salinity MEDATLAS climatology (The MEDAR Group 2002).

2.3 Data assimilation scheme

The data assimilation scheme is the three-dimensional variational scheme called OceanVar and developed for oceanographic models (Dobricic and Pinardi 2008). The scheme models the background error covariances through the control space transformation by a successive application of linear operators. The vertical part of temperature and salinity background error covariances is represented by most significant Empirical Orthogonal Functions (EOFs) of their long term variability. The control space contains weights that in the first linear operator multiply each

EOF in order to produce vertical profiles of temperature and salinity corrections. Then the second operator models horizontal covariances, assumed to be isotropic Gaussian functions of horizontal distance, by successive applications of recursive filters and by taking into account the presence of coastlines. Once the three-dimensional corrections are estimated for temperature and salinity fields, the third operator estimates the corresponding sea level corrections. It is a barotropic oceanographic model that finds the steady state sea level distribution corresponding to the constant forcing by the vertically averaged buoyancy force calculated from corrections in temperature and salinity. The last two operators estimate baroclinic velocity components by applying the geostrophic relationship in the presence of the coastlines. A detailed mathematical description of linear operators is given in Dobricic and Pinardi (2008).

The horizontal background error covariances have the radius of 15km. This value is estimated empirically from the evaluation of the horizontal correlation of misfits between background fields and SLA observations in the period 2001-2004. The analyses are not very sensitive to small variations of this parameter. As the Rossby radius of deformation in the Mediterranean is about 10-15 km (e.g. Robinson et al. 1987) the corresponding typical length scale of eddies is 50-100km (Stammer 1997; Eden 2007) and the used correlation scale is smaller than the average eddy size. Multivariate EOFs used to represent the background error correlations in the vertical direction are estimated from sea level, temperature, salinity and barotropic stream function covariances. The Mediterranean Sea is divided into 13 regions with different physical properties, and EOFs are calculated in each region and for each season from the variability around the mean of a model run spanning the time period 1993-2000. All the details of the methodology to estimate vertical EOFs are found in Dobricic et al. (2005) and Dobricic et al. (2007).

In order to calculate misfits, temperature, salinity and sea level background fields are linearly interpolated to the positions of observations. The observations are assimilated only in areas deeper than 150m, because it is assumed that more shallow areas are dominated by coastal processes and there observations are inappropriate for the deep ocean analyses. The SLA estimates by the model are obtained by subtracting the mean dynamic topography from the model sea level field. A new observational operator is constructed in OceanVar in order to assimilate observations of the vertically averaged velocity. First it horizontally interpolates daily averaged background velocities on the daily averaged position of the glider and then vertically averages interpolated values. The background velocity is averaged over the one day in order to remove the inertial oscillations.

The analyses are produced starting from 1 June 2004 with a daily assimilation cycle. It is calculated by combining the estimate by Rio et al. (2007) and unbiased estimates from in-situ observations used in the operational assimilation system (Dobricic 2005). Fig. 3 shows the observational coverage of SLA and in situ temperature and salinity observations in the Ionian Sea and the Sicily Strait. We can see that SLA observations cover the whole area with a high frequency. On the other hand, in situ observations are distributed unevenly and have a limited spatial and temporal coverage. Clearly, the introduction of glider observations in the area where the AIS enters the Ionian Sea could improve locally the quality of ocean state estimates and also provide an information about accuracy of the estimates based only on the assimilation of SLA observations, because during this period there are no other in situ observations in the area.

3. Assimilation of glider observations

Given the assumed horizontal error correlation scale of 15km, glider observations spaced ~500m would not be independent. Therefore the raw observations were averaged within a 12 hours long time window, giving rise to observations spaced approximately 12km. This spacing is represented by approximately two model grid points at 1/16 degrees model resolution. This further justifies the averaging of observations, because any corrections at spatial scales shorter than two grid points cannot be represented by the model finite difference scheme and would be removed as noise during the model integration. The observations are also averaged in the vertical direction by producing a single averaged observation at each model level. It is important to notice that the vertical averaging does not produce completely independent observations, because the vertical dimension in the control space is reduced to 20 EOFs. However, these vertical dependencies did not seem to have any impact the rate of the convergence of the minimizer (not shown).

The observations of the horizontal drift of the glider during the immersion were transformed into observations of the mean horizontal velocity in the top 200m of the water column, and temporally averaged over the one day long period in order to remove the inertial signal. Hereafter we refer to ‘control’ experiment as the experiment with the assimilation run without glider data, but with the assimilation of all satellite SLA and Argo and XBT in situ observations. This section will compare control experiment to experiment which in addition assimilated glider observations, so-called glider experiment. Analyses from the control and glider experiments will be called control and glider analyses respectively. Furthermore, the rms of misfits will be calculated between observations and short term simulations starting from the analyses. Simulations that start from control analyses will be called control simulations, while there will be three sets of glider experiments in which analyses assimilate only temperature and salinity, only velocity, and temperature and salinity together with velocity. Unless it is stated explicitly, it will be assumed that glider experiments assimilate all temperature, salinity and velocity observations by the glider.

Fig. 4 shows a Hovmoller diagram of the daily averaged glider observations for temperature. In autumn 2004, the vertical stratification changed from a shallow thermocline in October (around 30m deep) to a weaker and deeper thermocline in November, and to an almost vertically homogeneous water column in December. The control analyses were capable to reproduce the high vertical stratification in October, the deepening of the mixed layer in November and the enhanced vertical mixing in December, but did not depict some of the mesoscale features that were observed by the glider, and the thermocline was diffuse. For example, the glider observations show a large deepening of isotherms, probably corresponding to anticyclonic motion, on October 10, October 30 and November 8, whereas the control analyses show only a weak signal. Due the differences at mesoscales, the correlation of temperature in the top 100m between observations and control analysis was 0.60. On the other hand, the glider assimilation analyses show that these mesoscale features were introduced by the assimilation of glider observations, and the correlation of temperature between the observations and glider analyses was 0.81.

Daily averaged observations of salinity are shown in Fig. 5. The observed minima of salinity, corresponding to the core of MAW, show the position of the AIS in agreement with previous observations (e.g. Lermusiaux and Robinson 2001). In October the salinity minimum is located at the depth of ~40m. Its position becomes deeper in November, and reaches ~60m on December 1. Furthermore, in November the salinity minimum extends from the ocean surface to the depth of ~50m, indicating enhanced vertical mixing. Fig. 5 shows also that the control analyses are in general capable to depict the major path of the AIS but they do not capture some small scale structures at the depth of ~50m during the periods October 5 to 15 and October 28 to November 10. This inability to depict mesoscale features gives the correlation of salinity in the top 100m between observations and control analyses of 0.39. The assimilation of glider observations corrects the salinity field (Fig. 5) in the proper direction and produces a marked minimum of the salinity at ~50m. The improved representation of mesoscale features increases the correlation of salinity between observations and glider analyses to 0.81. The assimilation also increases the mean salinity along the path of the glider in accordance with the in situ observations.

We may conclude that along the path of the glider the horizontal position of the anticyclonic meander of the AIS, characterized by the low salinity, was generally well depicted by the control analyses in periods October 6-14, November 4-18, and November 21-28. However, the glider observed more variability at smaller scales. It is important to notice that in each of periods October 6-14 and November 4-18 the glider changed the direction at the borders of the AIS and crossed twice its core. On the other hand control analyses show a very smooth area of low salinity, which also has the minimum close to the surface instead at the depth of 50m. We may explain the agreement in the horizontal position of the anticyclonic meander of the AIS by the fact that control analyses assimilated a large number of SLA observations (see Fig.3). They constrained the near surface flow to depict the position of the AIS in a general accordance with in situ observations. However, the absence of in situ observations in control analyses introduced larger uncertainties in the estimates of vertical profiles. The vertical temperature and salinity gradients appeared more diffusive than observed, the mean salinity was lower than observed, and the minimum of the salinity was close to the surface. The insertion of in situ observations by the glider clearly improved the estimate of vertical structures and removed the salinity bias.

The impact of the assimilation of glider observations is further emphasized in Table 1 which compares the rms of misfits between the control experiment, the experiment with the assimilation of only temperature and salinity observations by the glider, the experiment with the assimilation of only velocity observations by the glider and the experiment with the assimilation of temperature and salinity together with velocity observations. A single rms of each parameter is calculated during the period of glider observations (October 1 to December 23). The rms of misfits represents an independent estimate of the quality of the estimates because it computes the difference between simulations starting from the analysis and observations before the observations are assimilated. Therefore it estimates the accuracy of the analyses by comparing short term simulations to independent observations. If we assume that the most of the errors present in short term simulations are due to the errors in the initial conditions, we may assume the rms of misfits provides an independent estimate for the accuracy of the analyses. Temperature and salinity misfits are calculated only with respect to glider observations, because there are now other in situ observations close to the glider. In addition to the rms of temperature and salinity misfits the table shows the results for the rms of misfits for the u and v components and the magnitude of the velocity averaged in the top 200m of the water column with respect to glider observations. Furthermore, it shows the rms of SLA misfits in the vicinity of the glider. It is calculated from satellite SLA observations distant less then 110km from each glider observation and during five days after the glider observation. There were 334 SLA observations satisfying these two criteria. The variations in the distance from 55km to 220km and in the temporal window from 2 to 7 days gave qualitatively similar results (not shown). The area of 110km is significantly larger than 15km of the horizontal covariance radius. Therefore, by choosing 110km we expect that the information from glider observations is rapidly spread in a much larger area than the correction. As it will be shown later in this section the information from the glider observations indeed spreads very rapidly.

The table shows that the assimilation of only temperature and salinity observations clearly improves the short term prediction of temperature and salinity (by 30-50%). However, it also worsens the prediction of velocity and SLA. The reason for this result could be that in the horizontal direction OceanVar uses an isotropic correlation function which may be inappropriate in an area with strong dynamics where both SLA and velocity fields have high temporal and spatial variations. When only the vertically averaged velocity is assimilated the rms of velocity misfits improves. It is interesting that also the rms of SLA misfits improves (by 8%). However the rms of temperature misfits near surface becomes significantly worse then in the control experiment (by 45%) as well as the rms of salinity misfits near the surface (by 23%). We may explain this result by the fact that the errors in the gradient of the surface elevation are efficiently reduced by assimilating in situ observations of velocity. On the other hand, in the absence of in situ temperature and salinity observations the inaccurate vertical structure of mass corrections balancing velocity corrections leads to less accurate temperature and salinity fields. As it could be expected, the assimilation of velocity, together with temperature and salinity profiles, improves the rms of velocity misfits (by 30%). However, just like the assimilation of velocity only it also significantly reduces the rms of SLA field (by 8%). Furthermore, it systematically reduces the rms of temperature and salinity misfits (up to 15%). In fact the experiment which assimilates the velocity in addition to temperature and salinity predicts most accurately all parameters. While eventually it could be expected for SLA misfits, the reduction of temperature and salinity misfits by assimilating also the velocity is somewhat surprising. We can exclude the impact of errors in EOFs, because the glider observations resolve very well the vertical profiles of the errors and 20 EOFs are most probably sufficient to approximate them accurately. Furthermore, the MDT errors can also be excluded, because the in situ velocity observations appeared to be consistent with SLA observations. A reason for improvements due to the assimilation of velocity could be that the corrected velocity field advects in a more realistic way the temperature and salinity fields, thus producing a lower misfit at subsequent times. However, the experiment which assimilates velocity only indicates that this not the case, because it gives significantly worse rms of misfits for both temperature and salinity. It seems that the assimilation of temperature and salinity gives accurate corrections in the vertical structure of the temperature and salinity fields, while due to the mass balance constraints the assimilation of velocity further improves the three-dimensional structure of the temperature and salinity corrections by introducing horizontal gradients. Therefore, the main advantage of assimilating velocity in addition to temperature and salinity is to improve the three-dimensional structure of the corrections. Clearly, this is very important in dynamically complex areas like the AIS.

It is interesting to evaluate how much the improvements obtained by the assimilation of glider observations impact the general structure of the surface flow in the Northern Ionian Sea. Fig. 6 shows the sea level at the end of the period by glider observations in the glider assimilation and control experiments. Its general structure is very similar in both experiments even along the glider path. In both experiments the AIS, marked by the high gradient of the surface elevation, enters the Ionian Sea at 35^0N flowing eastwards. At 16^0E it turns northward, forms an anticyclonic meander up to 38^0N, turns back southwards to 37^0N, and then flows eastwards towards the Levantine. All eddies in two experiments are positioned at the same places. However, they slightly differ in shape and intensity. These differences give a smaller rms of SLA misfits in the experiment which assimilated glider data. When temperature and salinity averaged over the top 200m are compared, both experiments show a similar penetration of warm and fresh MAW into the Northern Ionian Sea forming the Western Ionian anticyclonic Gyre. However, the experiment with glider data shows higher temperatures and lower salinity of the Ionian waters that flow southwards along the Sicilian coast. The high general similarity in the sea level field was observed throughout the period of glider observations (not shown). We may conclude that, although the assimilation of glider observations improved the estimate of the smallest scales, most of the features of the sea level field in the control experiment were in a good general agreement with the observations by the glider.

It is also interesting to see how the assimilation of only temperature and salinity, and only velocity impacted the general structure of the near surface flow at the end of the assimilation of glider data. Fig. 7 shows that in the case of the assimilation of only temperature and salinity the anticyclonic meander extends further to the north until it reaches the coast and cuts in two the area occupied by

Ionian waters. A larger quantity of MAW is advected northwards, and Ionian waters advected southwards along the Sicilian coast have even lower temperature than in the control experiment. Fig. 7 further shows that in the case of the assimilation of only velocity the anticyclonic meander extends similarly like in the control experiment, but the temperature is much higher along the path of the glider. Furthermore, the temperature is increased south of the AIS, and the near surface circulation is modified even in the Sicily Strait. It is clear from the rms of misfits shown in Table 1 that near surface analyses shown in Fig. 7 are less accurate than those given by the experiment assimilating all glider data (Fig. 6).

Fig. 8 shows differences between analyses by the glider experiment and the control experiment during and after the presence of glider observations. Initially, during October and November, the differences are located along the path of the glider. However, at the end of December, three months after the first glider observations, the differences are spread in an area extending about 1000km to the east. They further grow and reach the maximum at the end of February, about two months after the last glider observation. During March the differences are slowly attenuated. The differences spread rapidly, because OceanVar finds the global minimum of the cost function over the whole Mediterranean. This means that changes of the cost function due to the presence of additional observations in a small area may rapidly impact the solution in remote places. In fact, it can be seen in Fig. 8 that there are small remote differences already at the end of November. Furthermore, at the end of December the differences in the Levantine are as large as those close to the glider position. Fig. 9 shows the sea level field in the Levantine in control and glider analyses at the end of February when the remote differences have the largest intensity. It can be seen that at 30^0E the coastal current detaches from the coast in a form of a free jet. In this area it could be expected that remote differences can become large due to the strong dynamics. Even after the presence of the glider the differences may grow by the fast dynamical processes, because different background states give different minima of the cost function. However, the same SLA observations are continuously assimilated in both experiments. Slowly they attenuate the differences between the two sets of analyses, and at the end of March they are reduced in comparison to those at the end of February. Fig. 9 further shows that even at the end of February when the differences were the largest, both analyses show a very similar position of eddies. They mainly differ in the shape and the intensity. The fact that the sea level analyses from the two experiments are very similar is emphasized by the weekly rms of SLA misfits in the area from 14^0E to 30^0E (Fig. 10). Even in February-March the difference between the rms of SLA misfits in two experiments is small, although the experiment assimilating glider observations has a slightly higher accuracy. It is important to notice that the rms of SLA misfits is very close to the estimated error of satellite SLA observations of about 3cm (Menard et al. 2003). Therefore, it is difficult to improve it significantly in remote areas by the assimilation of additional observations.

5. Conclusions

The study has shown that the assimilation of temperature, salinity and velocity observations from a glider monitoring experiment in the Ionian Sea locally improved the Mediterranean Forecasting System (MFS) analyses. It reduced the fresh bias in the salinity field and represented more accurately the Modified Atlantic Water (MAW) subsurface maxima along the Atlantic Ionian Stream (AIS) path. Either the assimilation of only temperature and salinity profiles or of only vertically averaged velocity had a negative effect on the accuracy of some analyzed parameters. On the other hand, the assimilation of temperature and salinity profiles, together with the velocity observations increased the accuracy of all analyzed fields. This result emphasizes the importance of assimilating the information on the vertically averaged velocity estimated by the glider, especially in dynamically complex areas. It should be noticed that the velocity is not the directly observed variable, but it is derived from the observed drift of the glider. Therefore, it would be more advantageous to directly assimilate the drift by forming an observational operator in the form of a Lagrangian trajectory. A similar observational operator is already operative in OceanVar for the assimilation of the drift data from Argo floats (Taillandier et al. 2009), and in the future could be applied to gliders, too.

The study of the differences between the control analyses and the analyses that assimilated glider observations showed that the information from the glider initially is located in the area close to the glider observations. However, the impact of glider observations spreads rapidly to remote areas and differences between glider and control analyses growth even a few months after the last observation by the glider. The remote impact of glider observations in remote areas appears to be slightly positive. The fast spreading of the information by the glider observations to remote areas may be explained by the properties of the OceanVar data assimilation scheme that globally adjusts all fields during the minimization of the cost function. Once the background states are modified remotely the differences from the control analyses may persists for months and even growth. However, on the long term the assimilation of a large number of SLA observations in both glider and control analyses attenuates the differences.

The study shows that the glider observations locally improved the quality of the basin scale analyses. They also had a visible impact on the surface circulation in remote areas that was persistent several months after the last glider observation. Several new deep ocean gliders are being deployed in the Mediterranean. They are capable to measure temperature, salinity and velocity down to 1000 m and we may expect that they will improve the quality of the basin scale analyses.

Acknowledgements

This work was partially funded by EU projects MFSTEP (Mediterranean Forecasting System: Towards Environmental Predictions, Contract number: EVK3-CT-2002-00075) and MERSEA (Marine Environment and Security for the European Area, Contract number: SIP3-CT-2003-502885). Special thanks to Giuseppe Zappalà of the Istituto Talassografico of Messina who helped with the logistics of the glider experiment.

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List of figures:

Fig. 1: Bottom topography of the Sicily Strait and the Ionian Sea (m), and path of major surface currents drawn after Pinardi et al. (2006). The dotted line shows the path of the glider in the period October 2004-December 2004. Nomenclature is: MAW-Modified Atlantic Water, AIS-Atlantic Ionian Stream. Circulation features indexed by numbers are: 1 – Ionian Shelf Break Vortex, 2 – Western Ionian anticyclonic Gyre, 3 - Western Ionian cyclonic Gyre.

Fig. 2: The path of the glider in the period 1 October 2004-23 December 2004. Dots indicate the daily averaged positions of the glider. The bottom topography is also displayed. Isobaths are 250m, 500m, 1000m, 2000m and 3000m.

Figure 3: Other observations assimilated in all experiments during the period of glider observations (01 October 2004 – 23 December 2004). Colored squares show the number of SLA observations in each model grid point. Each satellite measured SLA at least twice in the same grid point. Crosses indicate points where temperature profiles were measured by the XBTs, and circles indicate positions of observations of temperature and salinity profiles by Argo floats.

Fig. 4: Daily averaged vertical temperature profiles (^{0}C) along the path of the glider for the period October-December 2004. Upper panel: glider observations, averaged daily; Middle panel: control daily analyses. Lower panel: glider assimilation analyses. Between October 25 and October 30 the glider was in the

area shallower than 150m, and the observations were automatically discarded by OceanVar as “coastal observations”.

Fig. 5: Same as Fig. 4, but for salinity.

Fig. 6: Comparison daily averaged fields between glider assimilation (left) and control (right) analyses on 23 December 2004. Top panels show surface elevation (cm), middle panels mean temperature (^{0}C) in the top 200m and bottom panels mean salinity (PSU) in top 200m.

Fig. 7: Same as Fig. 6, but for the analysis that assimilated only temperature and salinity profiles (left), and only vertically averaged velocity (right).

Fig. 8: Daily averaged sea level differences between glider and control experiments (cm). The differences are shown at the end of each of six months following the introduction of glider observations.

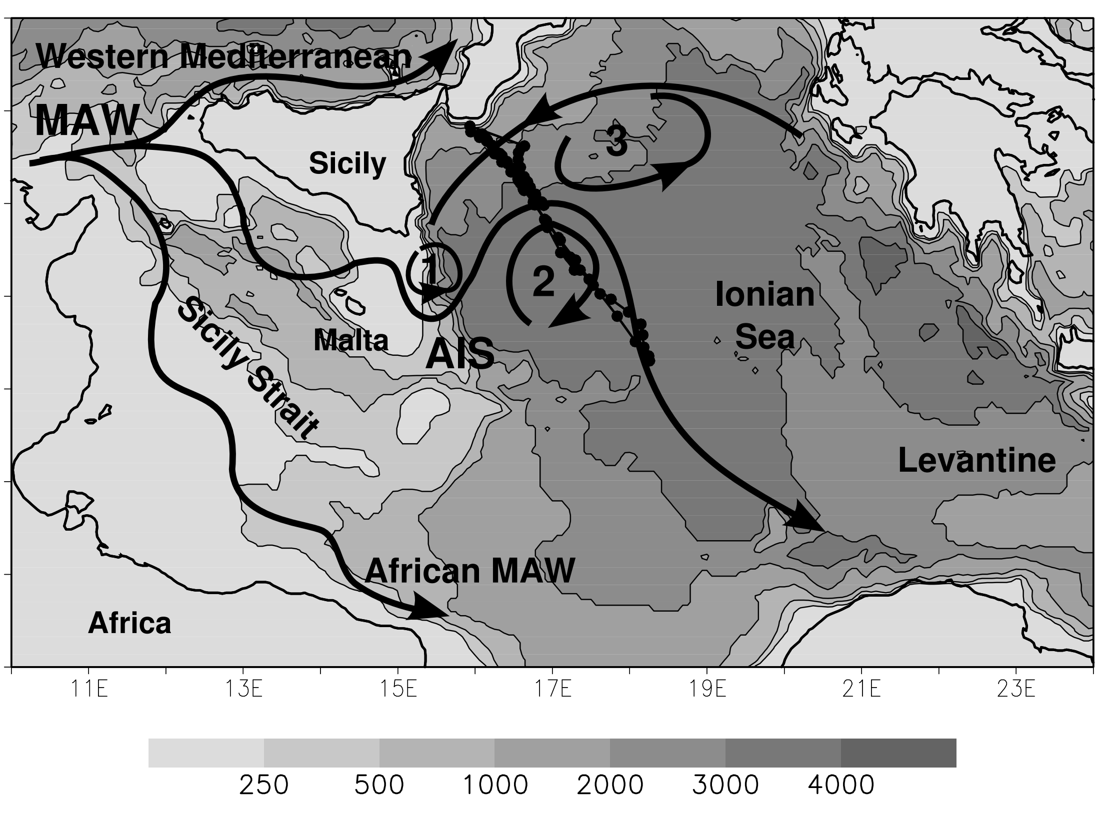
Fig. 9: Daily averaged sea level field (cm) on 28 February 2005 corresponding to the day with the largest differences shown in Fig. 8. The left panel shows the glider analysis, and the right panel shows the control experiment.

Fig. 10: The weekly rms of SLA misfits (cm) calculated over the area from 14^{0}E to 30^{0}E (see Fig. 8). The full line shows the glider experiment, and the dashed line the control experiment.

	Control	T,S	v	T,S,v
$\overline{rms(T)}^{0-50m}$	1.47	0.90	2.14	<u>0.86</u>
$\overline{rms(T)}^{50-200m}$	0.46	<u>0.31</u>	0.51	<u>0.31</u>
$\overline{rms(S)}^{0-50m}$	0.39	0.22	0.48	<u>0.21</u>
$\overline{rms(S)}^{50-200m}$	0.28	0.13	0.30	<u>0.11</u>
$rms(\overline{u}^{0-200m})$	0.101	0.121	<u>0.80</u>	0.091
$rms(\overline{v}^{0-200m})$	0.087	0.089	0.82	<u>0.059</u>
$rms(\lvert\overline{\mathbf{v}}^{0-200m}\rvert)$	0.096	0.118	0.11	<u>0.083</u>
$rms(SLA)$	4.06	4.10	<u>3.79</u>	<u>3.79</u>

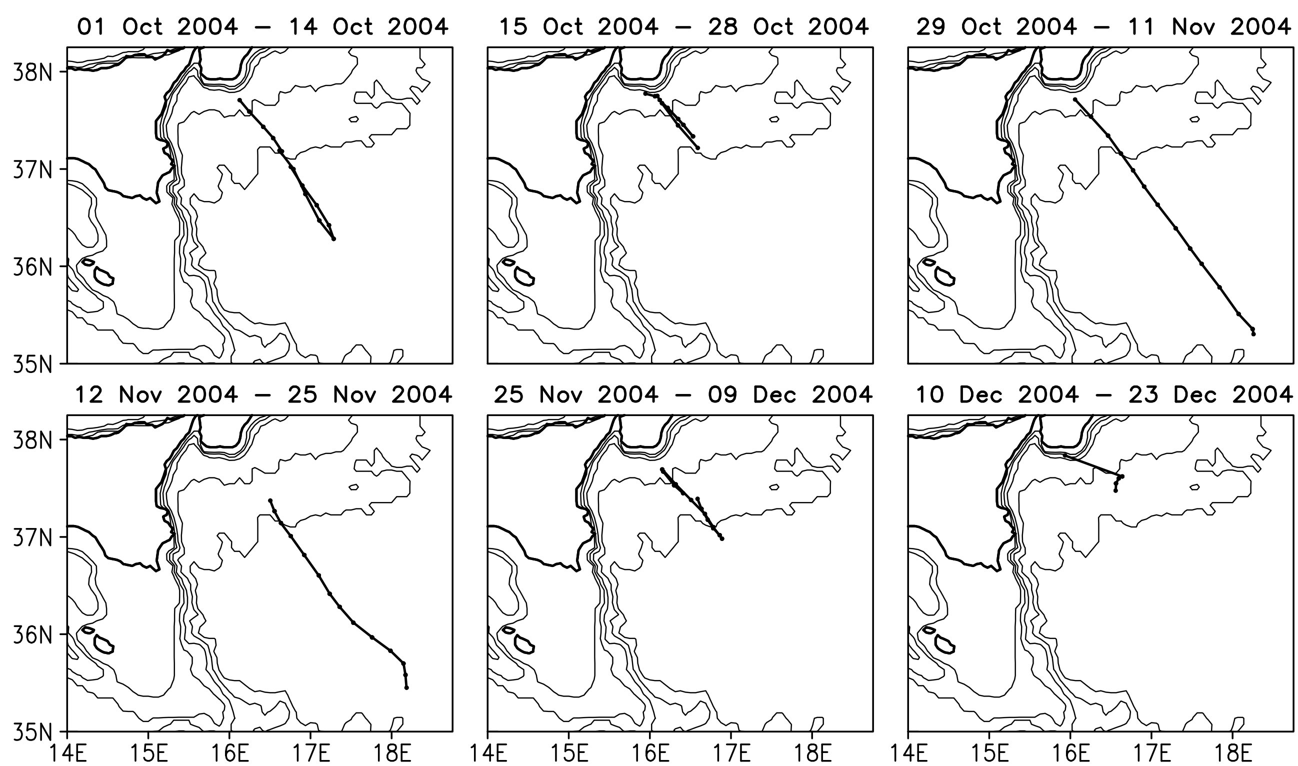
Table 1: The rms of misfits for temperature observations in the top 50m ($\overline{rms(T)}^{0-50m}$) and from 50m to 200m depth ($\overline{rms(T)}^{50-200m}$) in ^{0}C, for salinity observations in the top 50m ($\overline{rms(S)}^{0-50m}$) and from 50m to 200m depth ($\overline{rms(S)}^{50-200m}$), rms for the zonal component ($rms(\overline{u}^{0-200m})$), for the meridional component ($rms(\overline{v}^{0-200m})$),for the magnitude of the vertically averaged velocity ($rms(\lvert\overline{\mathbf{v}}^{0-200m}\rvert)$) in ms^{-1} and rms for SLA in cm. The control experiment is marked by “Control”, the experiment assimilating temperature and salinity profiles only by “T,S”, and the experiment assimilating temperature and salinity profiles and the vertically averaged velocity by “T,S,v”. The lowest rms for all three experiments is underlined for each parameter.

Figure 1



Western Mediterranean
MAW
Sicily
1
2
3
Ionian
Sea
Malta
AIS
Sicily Strait
Levantine
African MAW
Africa
38N
37N
36N
35N
34N
33N
11E
13E
15E
17E
19E
21E
23E
250
500
1000
2000
3000
4000

Figure 2



01 Oct 2004 – 14 Oct 2004
15 Oct 2004 – 28 Oct 2004
29 Oct 2004 – 11 Nov 2004
12 Nov 2004 – 25 Nov 2004
25 Nov 2004 – 09 Dec 2004
10 Dec 2004 – 23 Dec 2004
38N
37N
36N
35N
14E
15E
16E
17E
18E

Figure 3

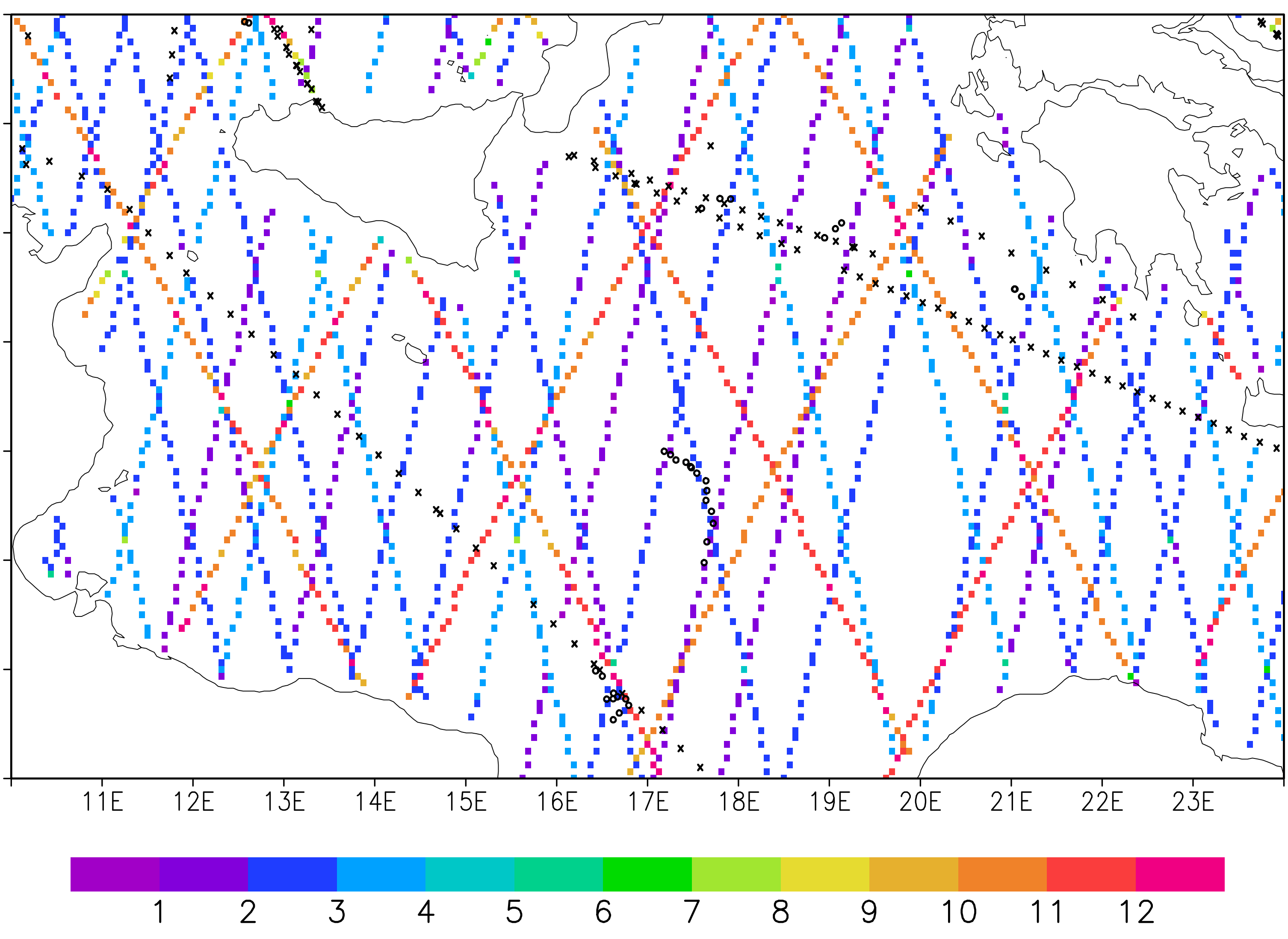
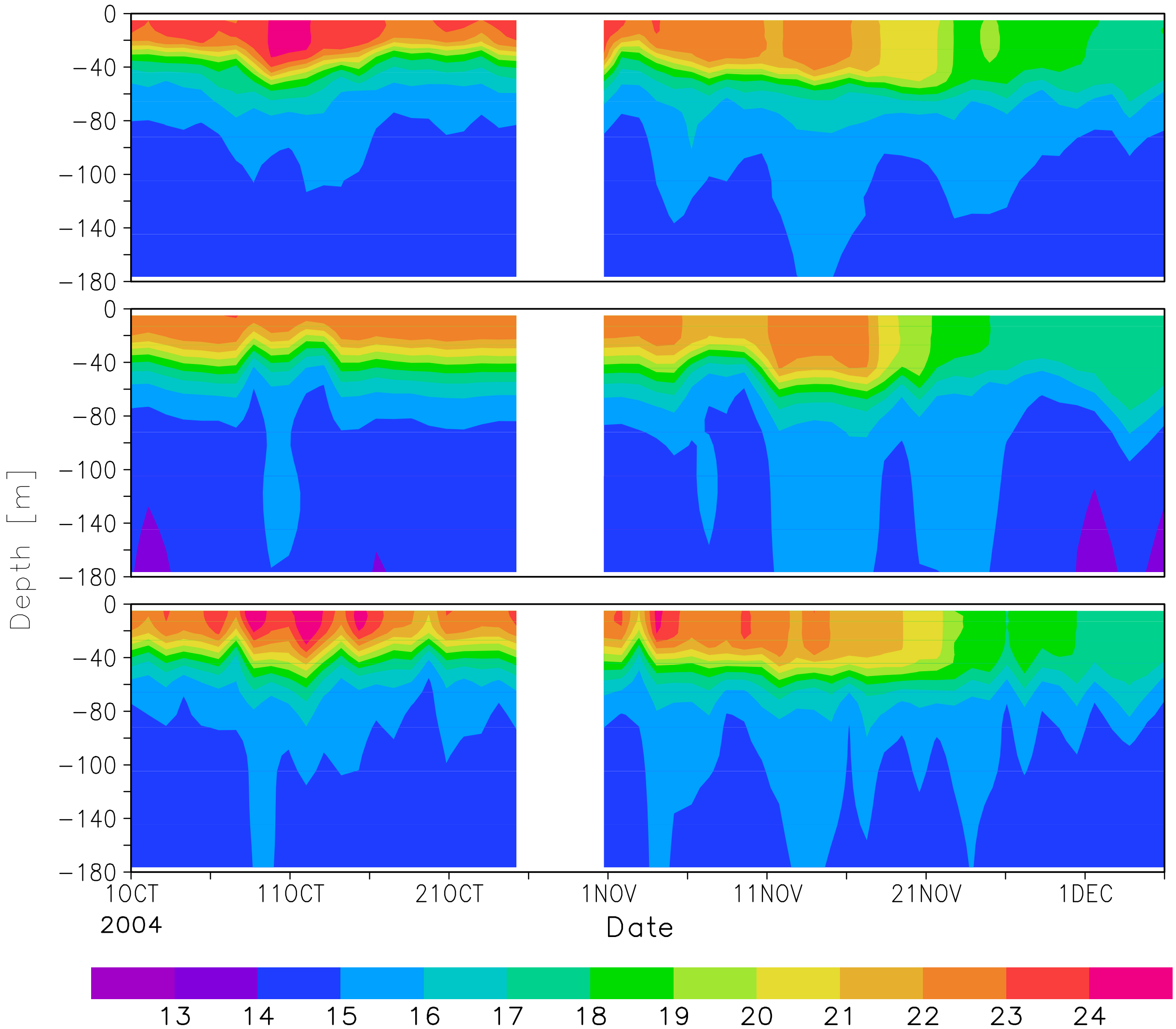
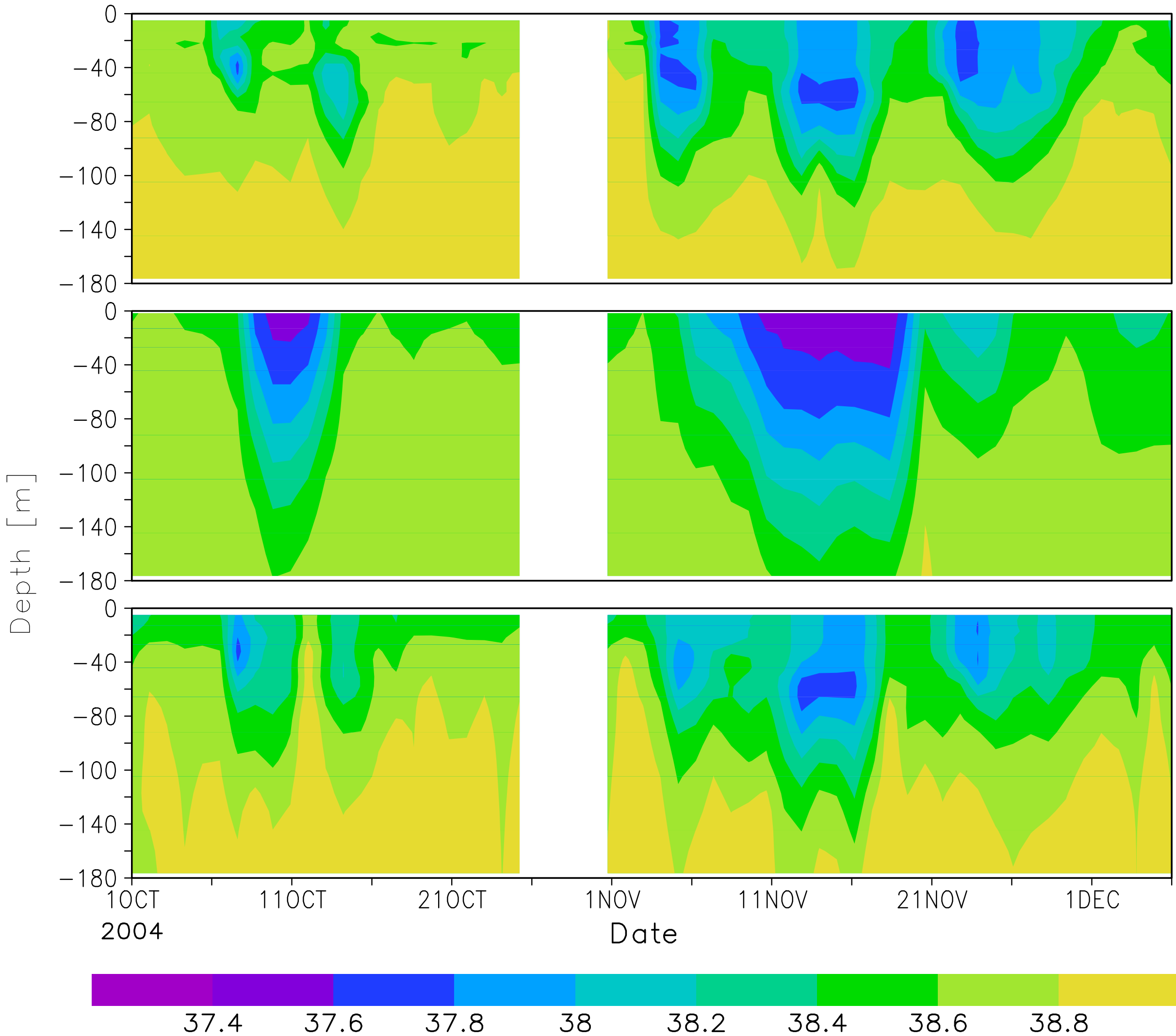

38N
37N
36N
35N
34N
33N
11E
12E
13E
14E
15E
16E
17E
18E
19E
20E
21E
22E
23E
1
2
3
4
5
6
7
8
9
10
11
12

Figure 4



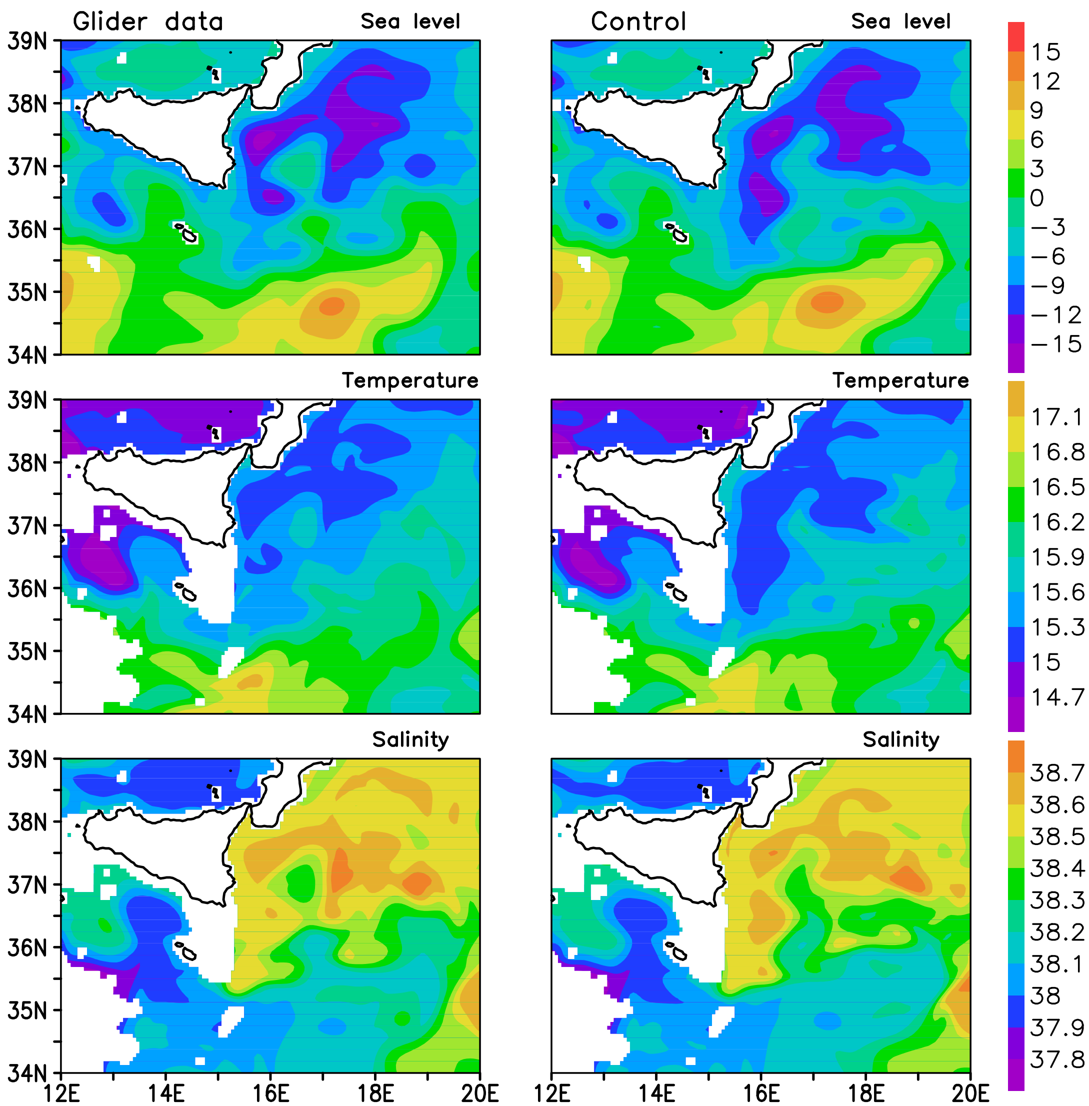
0
-40
-80
-100
-140
-180
Depth [m]
1OCT
2004
11OCT
21OCT
1NOV
11NOV
21NOV
1DEC
Date
13
14
15
16
17
18
19
20
21
22
23
24

Figure 5



0
−40
−80
−100
−140
−180
Depth [m]
1OCT
2004
11OCT
21OCT
1NOV
11NOV
21NOV
1DEC
Date
37.4
37.6
37.8
38
38.2
38.4
38.6
38.8

Figure 6


Glider data
Sea level
Control
Sea level
Temperature
Temperature
Salinity
Salinity
39N
38N
37N
36N
35N
34N
12E
14E
16E
18E
20E
15
12
9
6
3
0
−3
−6
−9
−12
−15
17.1
16.8
16.5
16.2
15.9
15.6
15.3
15
14.7
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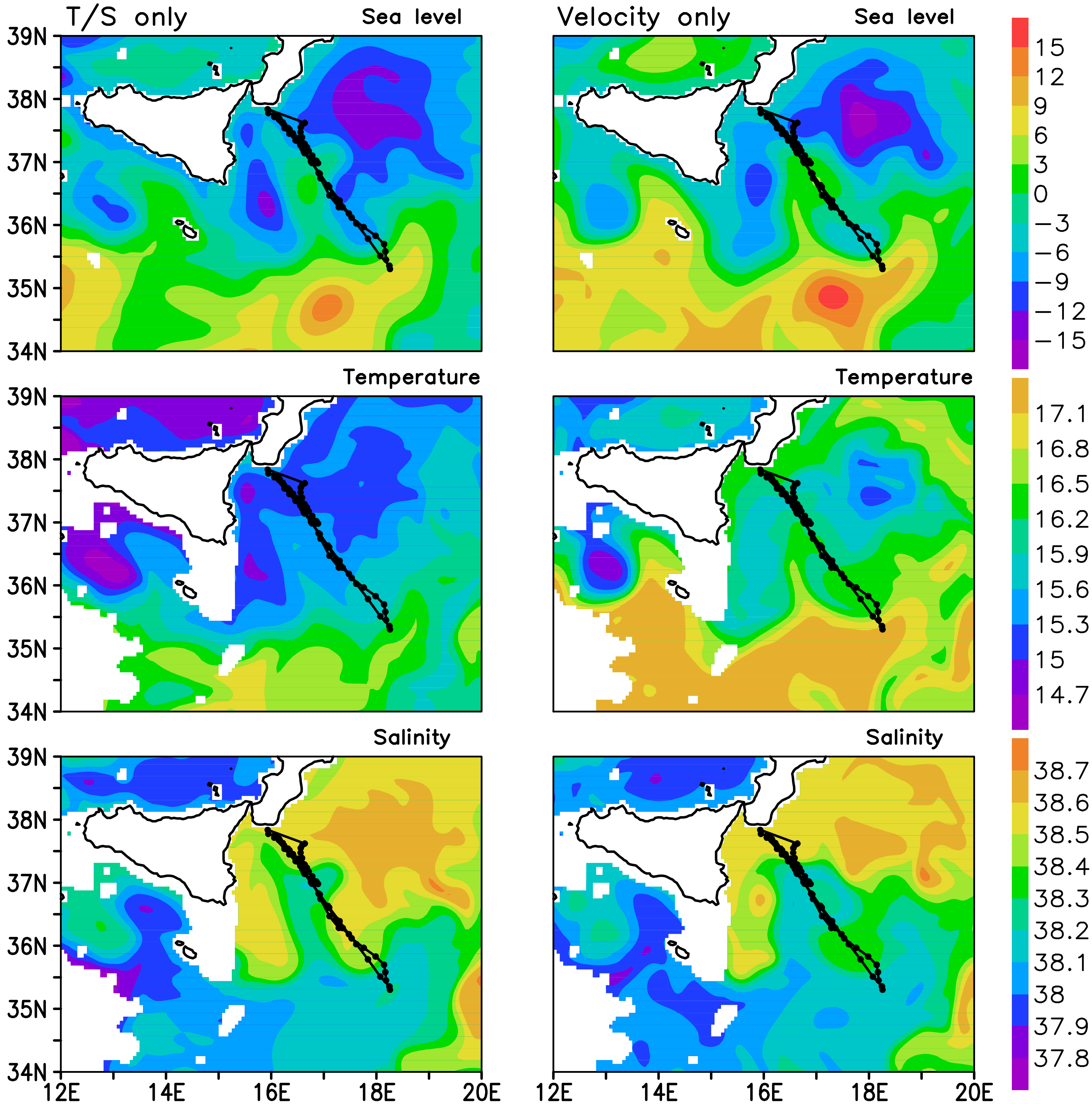
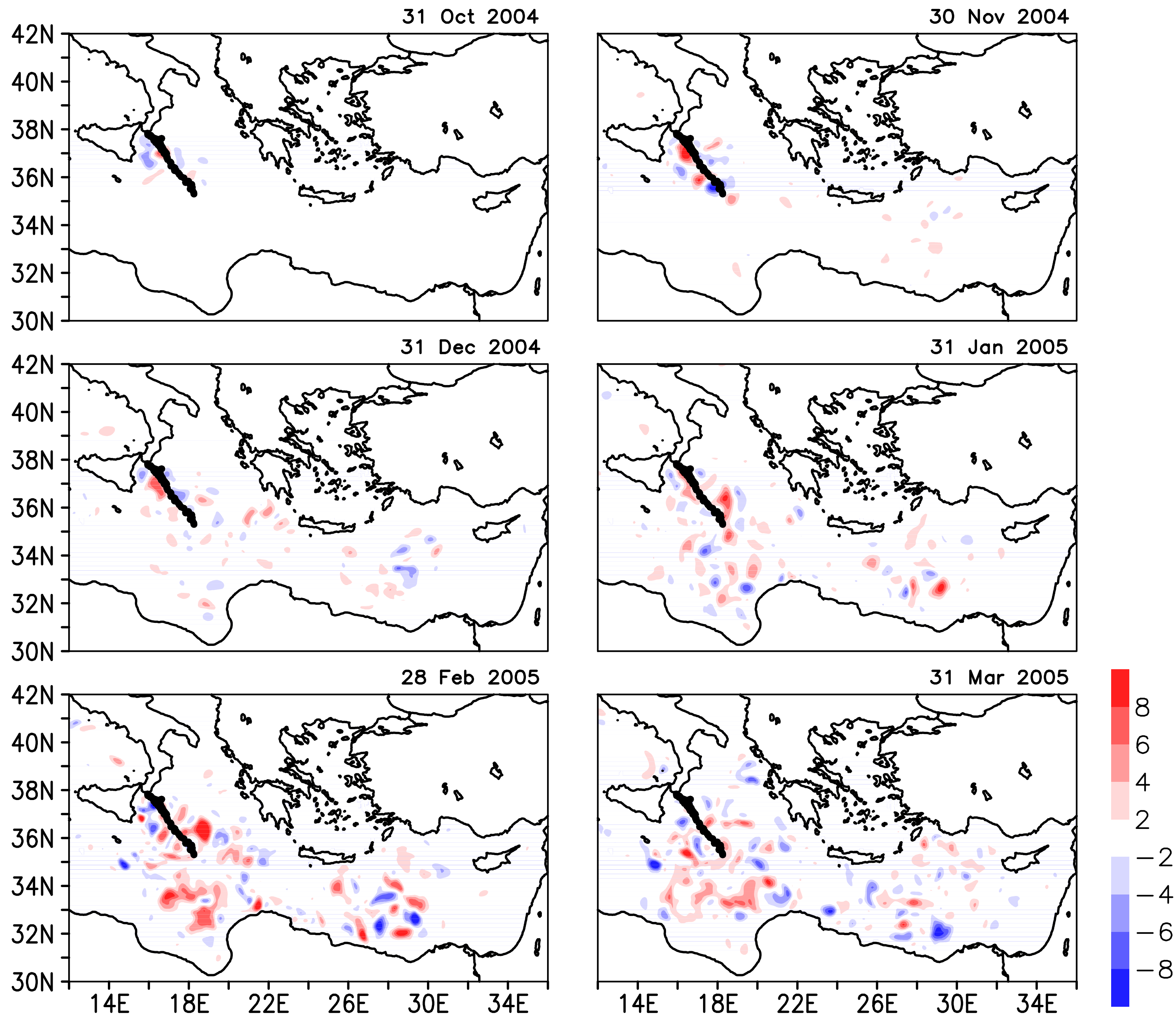
38.6
38.5
38.4
38.3
38.2
38.1
38
37.9
37.8

Figure 7



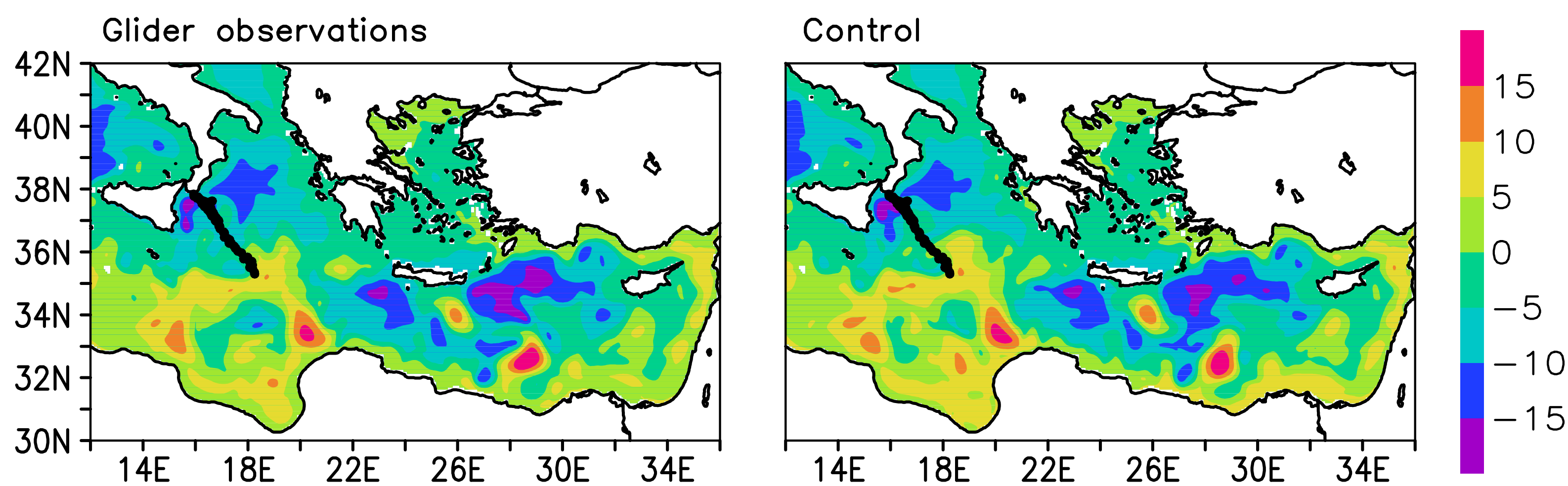
T/S only
Sea level
Velocity only
Sea level
Temperature
Temperature
Salinity
Salinity
39N
38N
37N
36N
35N
34N
12E
14E
16E
18E
20E
15
12
9
6
3
0
−3
−6
−9
−12
−15
17.1
16.8
16.5
16.2
15.9
15.6
15.3
15
14.7
38.7
38.6
38.5
38.4
38.3
38.2
38.1
38
37.9
37.8

Figure 8



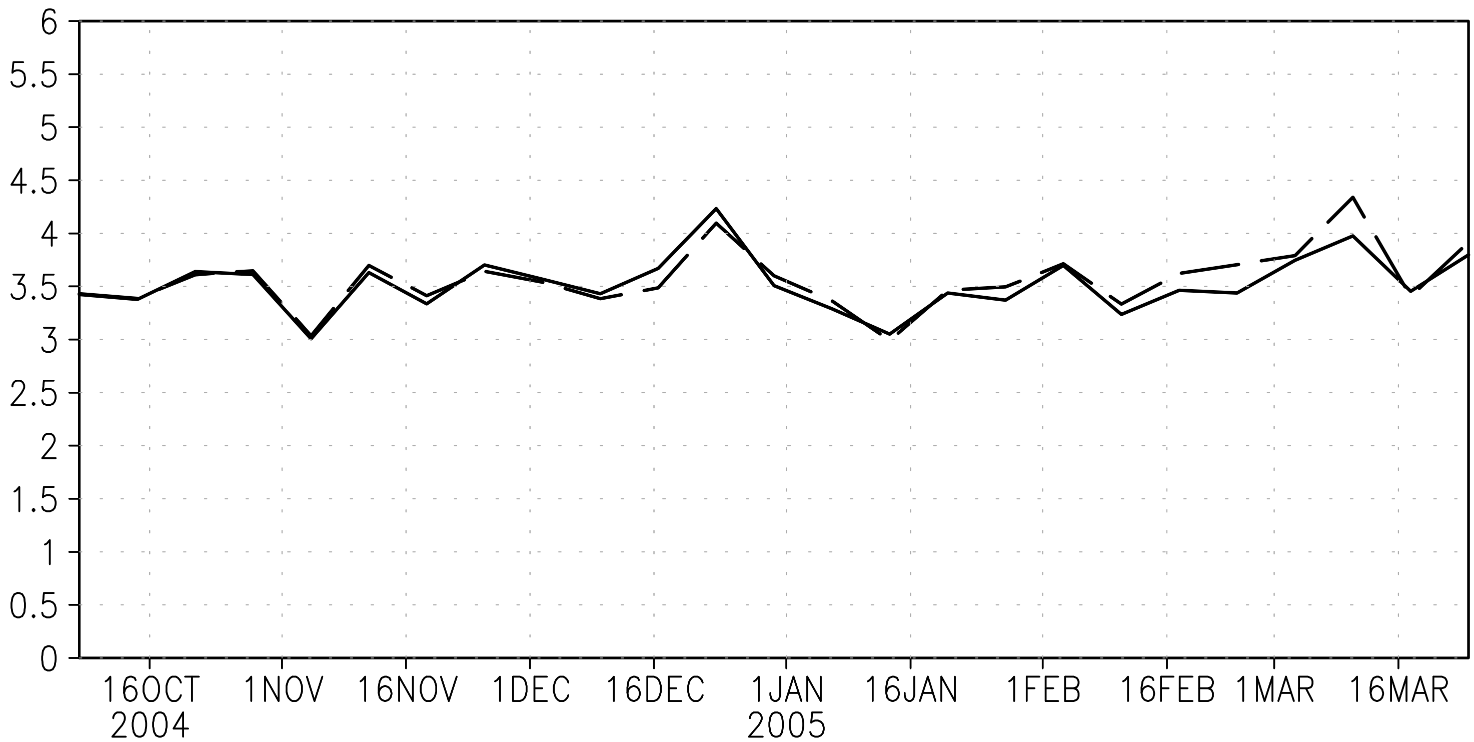
31 Oct 2004
30 Nov 2004
31 Dec 2004
31 Jan 2005
28 Feb 2005
31 Mar 2005
42N
40N
38N
36N
34N
32N
30N
14E
18E
22E
26E
30E
34E
8
6
4
2
−2
−4
−6
−8

Figure 9



Glider observations
Control
42N
40N
38N
36N
34N
32N
30N
14E
18E
22E
26E
30E
34E
15
10
5
0
−5
−10
−15

Figure 10


6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
16OCT
2004
1NOV
16NOV
1DEC
16DEC
1JAN
2005
16JAN
1FEB
16FEB
1MAR
16MAR