Acoustic observations of heat content across the Mediterranean Sea

The THETIS-2 Group:

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Interest in monitoring the heat content of the ocean over long distances has increased in recent years, due to current research emphasis on the ocean's role in climate change, on variability of the ocean state, and on operational ocean observing systems. These new foci in ocean science have led to international programs which are now being initiated like CLIVAR (Climate Variability and Predictability)[1] and GOOS (Global Ocean Observing System)[2]. Large-scale observations of the variability of the surface-to-bottom ocean heat content are useful for studying interactions with the climate system, for observing water mass formation processes, for calibrating surface heat fluxes, and for constraining numerical ocean models. While the upper layer of the ocean can be routinely observed on large scales with methods like satellite remote sensing (altimetry, infrared imagery) and with expendable probes dropped from commercial vessels, the ocean interior and deeper layers are more difficult to monitor. For this, ocean acoustic tomography is a promising approach, being the only technique available today which can provide systematic, instantaneous, repeated measurements (up to several times a day) of the ocean interior, over significant parts of an ocean basin. Here we report on a first application of this technique to measure heat content across an entire (albeit small) ocean basin, where the results can be compared with surface heat fluxes, and merged with satellite altimetry data in a numerical circulation model.

Minimal absorption in the ocean allows low-frequency acoustic transmissions over long horizontal distances. Measuring the traveltime of the sound then yields large-scale integrals of the (inverse) sound speed, which are tightly related to heat content. The most ambitious application of this approach is the ongoing ATOC project (Acoustic Thermometry of Ocean Climate)[3] which aims to observe climate signals in the deep ocean by basin-scale acoustic transmission in the Pacific. A prior demonstration of heat content measurements using tomography on a 1000 km scale was given in ref. 4. There, data collected over a four-month period along a triangle in the open Pacific yielded good measurements of the heat content, but a heat budget combining heat content and surface heat fluxes could not be balanced, because of horizontal advection effects in that open ocean environment.

Here we present preliminary results from a 9-month long tomography experiment involving

7 moorings which was conducted in the western Mediterranean. A combination of aspects make this application unique and particularly relevant to the issues mentioned above. The western Mediterranean is a nearly closed basin, and a large part of it was covered with the distributed network of 7 instruments. This allowed estimation of the various terms of the heat budget during a seasonal cycle. A direct comparison with the surface heat fluxes over the basin, which have been the topic of a variety of recent studies[5–7], is therefore possible. The Mediterranean also is a convenient test laboratory with most of the oceanographic processes of the major oceans, while being more accessible, controlled (nearly closed), and of smaller size. For example, a climate-like deep warming trend has been observed in some part of the basin, but it is not clear how wide-spread this signal is and whether it is caused by changing atmospheric conditions[8,9]. Another advantage is that the scales of the basin are such that it can be covered with a network of standard tomographic instruments. In addition, various numerical models of the region exist already for assimilation studies.

The experiment, called THETIS-2, was conducted in order to demonstrate the capabilities of tomography for basin-scale measurements and heat flux calibrations, to provide a data set for assimilation studies, and to prove the concept for long-term acoustic monitoring in climate studies or operational systems. Figure 1 shows the sampling of the western Mediterranean by the mooring array of tomography instruments that was deployed for the THETIS-2 experiment from January until October 1994 (covering the extrema of the annual heat content cycle). The measurement principle is the standard acoustic tomography approach[10], where the discrete acoustic arrivals result from different depth penetration of the corresponding ray paths and thus provide a vertical sampling of the ocean (figure 1 bottom). For initialization and verification, also a substantial number of hydrographic profiles (temperature, salinity) were collected in the basin covered by the experiment, and an XBT (expendable temperature probe) line was occupied every two weeks using a commercial ship. The transmission path from H to $W3$ was specifically aligned exactly with this XBT track, in order to allow detailed comparisons.

After standard tomographic signal processing[3], Doppler phase drift compensation, and clock and mooring motion correction, the acoustic travel times represent a high-quality measure for the temperature integrated along the ray paths across the basin. We present preliminary analyses for total heat content along three of the sections and for a 3-D average of the basin heat content. For this, at present only single deep-turning ray paths were used (see figure 1), since they sample most of the water column. Numerical simulations with historical seasonal vertical profiles, vertical EOFs (empirical orthogonal functions) and typical oceanographic perturbations for each tomography section were used to establish a (non-linear) relation between the travel times and the total heat content of the section, including error estimates. Figure 2 gives the results of this relation to yield the heat content of the section H–$W3$ from the traveltimes of a deep-turning ray, compared to estimates of the same quantity from the CTD and XBT surveys. The figure shows a high degree of agreement between the two types of data, and the deviations are in the range of the calculated error bars.

The main signal seen is, as expected, the seasonal cycle of heating and cooling, but there are significant deviations from the historical mean annual cycle, which is also plotted in figure 2. The departures of the acoustic measurements for 1994 from the mean cycle are about 10% in terms of overall amplitude for this particular section - on other sections the difference is larger or has the opposite sign. In addition to the annual cycle there are distinct features and events of limited duration. These are also more pronounced on other sections analyzed, see figure 3, and some of them are undoubtedly related to the significant mesocale variability revealed by the XBT sections. We have processed two more sections the same way (H–$W1$ and H–$W5$), and combined them to give an optimal linear estimate of the horizontally averaged (3-D) heat content of much of the basin (1°E to 9°E), using horizontal covariance scales computed from historical data and from a numerical model. The resulting curve for the 1-9°E basin-mean heat content is shown in figure 3 (top), along with the three individual time series that were used to construct it. Rather large regional differences are visible with pronounced local events, as well as their signature in the optimally weighted average. The 3-D average is only preliminary, since the acoustic estimate will improve as more sections are included. However, this is the first time-series of instantaneous three-dimensional heat content estimates for the Mediterranean, and a comparison with surface heat fluxes is already possible.

Surface heat fluxes represent a major forcing for the ocean, yet they still have insufficient accuracy for many oceanographic applications. For example, observations of the heat transport through the Strait of Gibraltar dictate that the average surface heat loss in the

Mediterranean should be about –5 W m^{-2} [11], but direct calculations for the heat flux from ship measurements have ranged from 0 to +29 W m^{-2} [5–7]. Gilman and Garrett[7] suggested various corrections to achieve agreement with the Gibraltar measurements in the mean, but calibrations or corrections for the time-varying parts are even harder to perform. With our heat storage observations this can be attempted, since for a nearly closed basin, the time variations in the total heat content must equal the time integral of the surface heat fluxes plus that of the heat transport through the openings (straits).

We have obtained ECMWF (European Center for Medium Range Forecasting) surface heat fluxes for the Mediterranean for the entire year 1994, and integrated them in time and over the western basin between the Straits of Gibraltar and Sicily , as well as the above 1-9° E subregion. After correction for heat transport through the straits, the result can be compared to the observed heat storage time series (figure 3 bottom). We see that in spite of the approximations used, there is an agreement to within about 3%, which corresponds to a mean heat flux of approximately 4 W m^{-2}. Some of this agreement may be fortuitous, since the error in the tomography estimates is approximately $0.015°C$ in this preliminary analysis. Combined with the uncertainty in the strait transports, the actual error bar is about four times higher than the current mismatch. In addition to the mean seasonal heating amplitude, there is also some agreement visible for single events, especially the strong cooling in late September. Note that the climatology shows a seasonal amplitude about 20% higher than the ECMWF flux integral. More detailed estimates, after complete processing of the tomography data available and with improved strait transport measurements currently underway, can provide a severe test for surface heat flux formulae.

Another unique aspect of this data set is the fact that it provides good unaliased spatial integral coverage and long time series for an ocean basin for which a number of realistic numerical models with ongoing assimilation studies exist. Numerical models can benefit from assimilating real data about the state of the ocean, either to determine and correct model deficiencies or to initialize operational forecasting simulations, and assimilations will soon be routinely performed with e.g. satellite altimetry data. The expectation is that large-scale internal temperature observations as obtained here will complement the satellite surface data and will efficiently constrain models and/or forcing fields[12]. Even if the absolute heat content of a model is not dynamically relevant, its time evolution and the large regional differences seen in figure 3 (top) are essential observables that a model should reproduce - not necessarily at single points but in an area-mean. The first joint assimilation of real tomography and altimetry data has been performed with the present data in a simple application and is presented in a companion paper[13]. In that study, a time-evolving circulation state for the basin was found that is consistent with the model dynamics, the altimetry and the tomography integrals.

The results presented here have only analyzed a subset of the available data. Measurements are available along all the sections shown in figure 1, and taken altogether the accuracy of the area-mean or the spatial resolution will significantly increase. Also, here we have not exploited the depth-resolution contained in the sampling by ray paths penetrating to various depths (figure 1). This work is in progress, and has been successfully performed already for the H-W3 section. It is clear that separate heat content timeseries can be obtained for the depth ranges corresponding to the different water masses (surface layer, Levantine Intermediate Water, and deep water). Future publications will report on these.

Most of the moorings in THETIS-2 were located just off steep topography near a coast, where the same measurements could be performed with land-cabled instruments. Thus the THETIS-2 project has also demonstrated that the large-scale fluctuations and evolution of a basin like the Mediterranean could be sampled and monitored with existing means by acoustic transmissions between shore-based stations.

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Figure captions

Figure 1: Horizontal and vertical sampling of the western Mediterranean in the THETIS-2 experiment.

Top: Network of tomography sections in the basin. The 'heart' of the experiment was a 250 Hz HLF-5 sound source at location H, insonifying the entire basin under investigation. The remaining instruments ($W1$–$W5$ and S) were 400 Hz transceivers (combined transmitters and receivers). All systems except S had dual-channel receivers to record both the 250 Hz and 400 Hz signals. The seven instruments were operational for the time period deployed, and each transmission path shown had a large number of well-resolved stable acoustic arrivals (corresponding to the ray paths in the bottom panel) in at least one direction. The heavy line along H–$W3$ marks the XBT section occupied every 2 weeks, and LB denotes a land-based receiving/monitoring hydrophone.

Bottom: Vertical distribution of some discrete ray paths which the sound energy can take from mooring H to $W3$, superimposed here on the salinity field to indicate the typical scales of oceanic variability. Each ray path samples a different depth range along the section, and can be identified in the data since it has a unique discrete traveltime. This allows a vertical sampling of the section.

Figure 2:

The heavy black line shows the acoustic average of potential temperature (relative to 13.111°C) over the 0–2000 m layer and over the 600 km long section from H to $W3$, using the traveltime measurements for a deep-turning ray path. Dots and crosses are estimates of the same quantity from CTD and XBT surveys along the same line. The error interval (shaded) indicates the uncertainty of the acoustic estimates based on scatter in the travel time-heat content relation and on uncertainty in the travel time measurements. The error of the CTD and XBT averages is smaller than this, but it should be kept in mind that the XBTs only sample to 800 m depth.

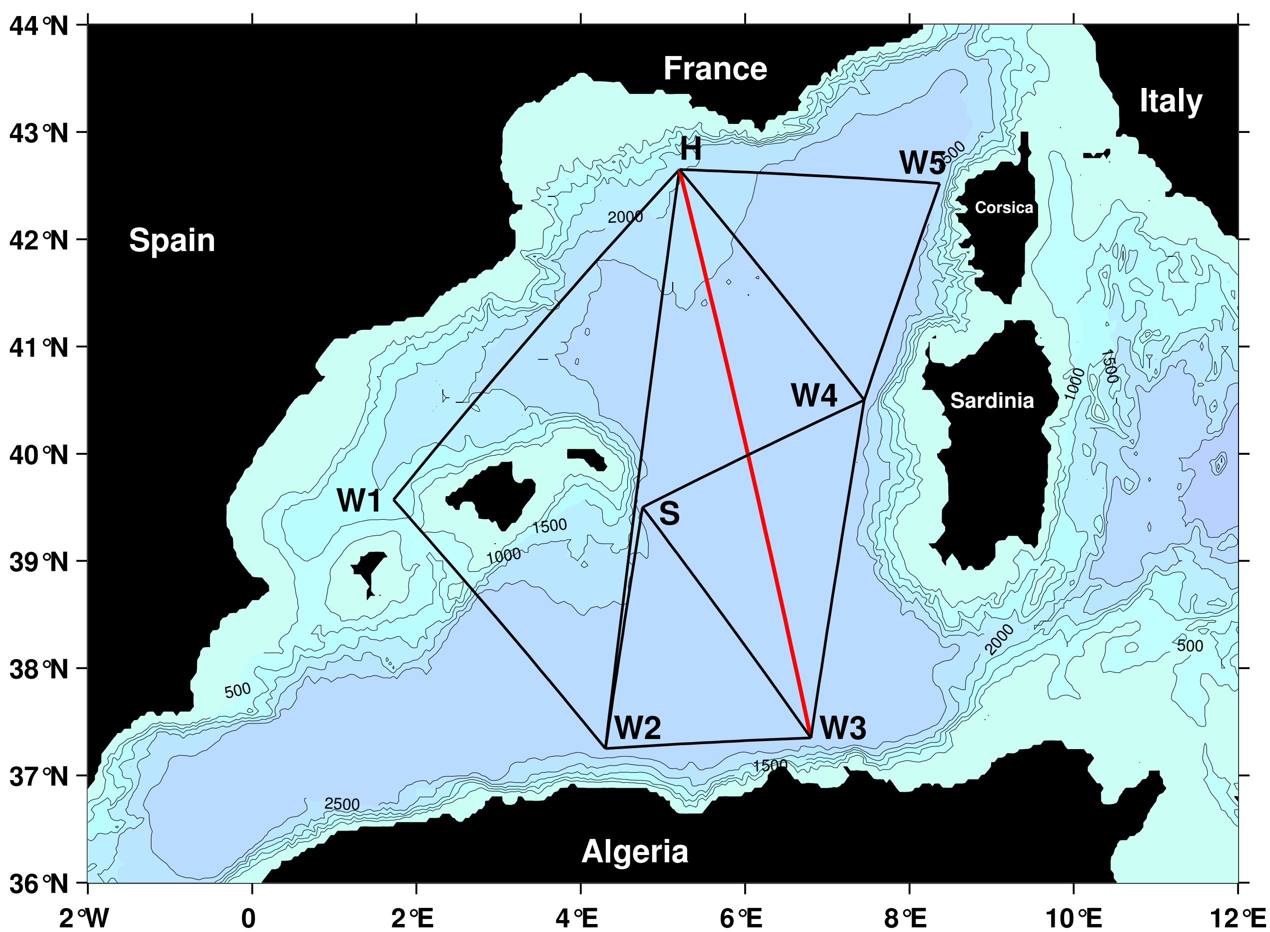
Also shown is the annual mean curve for the 0-2000 m average temperature along the section from the climatology (thin black). This mean seasonal cycle was constructed from a comprehensive climatology, based on 85000 MBT/XBT/CTD (mechanical and expendable bathythermographs, lowered conductivity-temperature-depth sensors) and bottle sample profiles. Averaged over the whole basin, the heat content amplitude of the climatology is in very good agreement with mean surface heat fluxes calculated from the COADS (comprehensive ocean atmopshere data set) [14] data for the years 1946–1992 after Gilman and Garrett[3].

Figure 3:

Top: Individual estimates of 0–2000 m mean temperature anomaly along the acoustic sections H–$W1$, H–$W3$, and H–$W5$, processed like the data in figure 2 (thin lines). The optimal linear estimate from these for the 3-D average over the 1-9° E part of the basin is shown by the heavy curve (error approximately 0.015°C).

Bottom: The 3-D average heat content for 1994 from the top panel (heavy) together with the climatological curve (dashed) and the time-integral of the ECMWF surface heat fluxes for the 1-9° E subbasin (dotted). Strictly, the surface fluxes cannot be integrated over a subregion of the basin, since the ocean may transport the heat out of this area. We tested the relation by comparing the 1-9° E subregion with the full basin in climatological heat content data and in ECMWF heat flux integrals. The entire basin had an amplitude larger by 6% and 9% respectively. Therefore we have adjusted both the full-basin ECMWF integral and climatological seasonal amplitudes by a mean factor of 7.5% to represent data for the 1-9° E subregion. At a later stage, we expect to perform this "extrapolation" dynamically via assimilation into numerical models.

For comparison with the heat content observations, the heat transport through the openings of the basin should also be added to the surface heat flux. Using the historical data and results from refs. 11, 15 and 16, the estimates for the Strait of Gibraltar and Strait of Sicily are 3.3 ± 0.8°C Sv and 2.1 ± 1.3°C Sv, respectively (1 Sv= 10^6 m^3 s^{-1}), yielding a net heat transport into the western Mediterranean of 1.2 ± 1.5°C Sv which is equivalent to an area-mean surface heat flux of 5.7 ± 7 W m^{-2}. Between the extrema of the seasonal cycle (March-September) this gives an extra heating of 0.011 ± 0.013°C averaged over the upper 2000 m of the water column, that should be added to the temperature changes predicted from the ECMWF heat flux integral. The thus corrected curve is shown as a thin solid line.



44°N
43°N
42°N
41°N
40°N
39°N
38°N
37°N
36°N
2°W
0
2°E
4°E
6°E
8°E
10°E
12°E
France
Italy
Spain
Corsica
Sardinia
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2000
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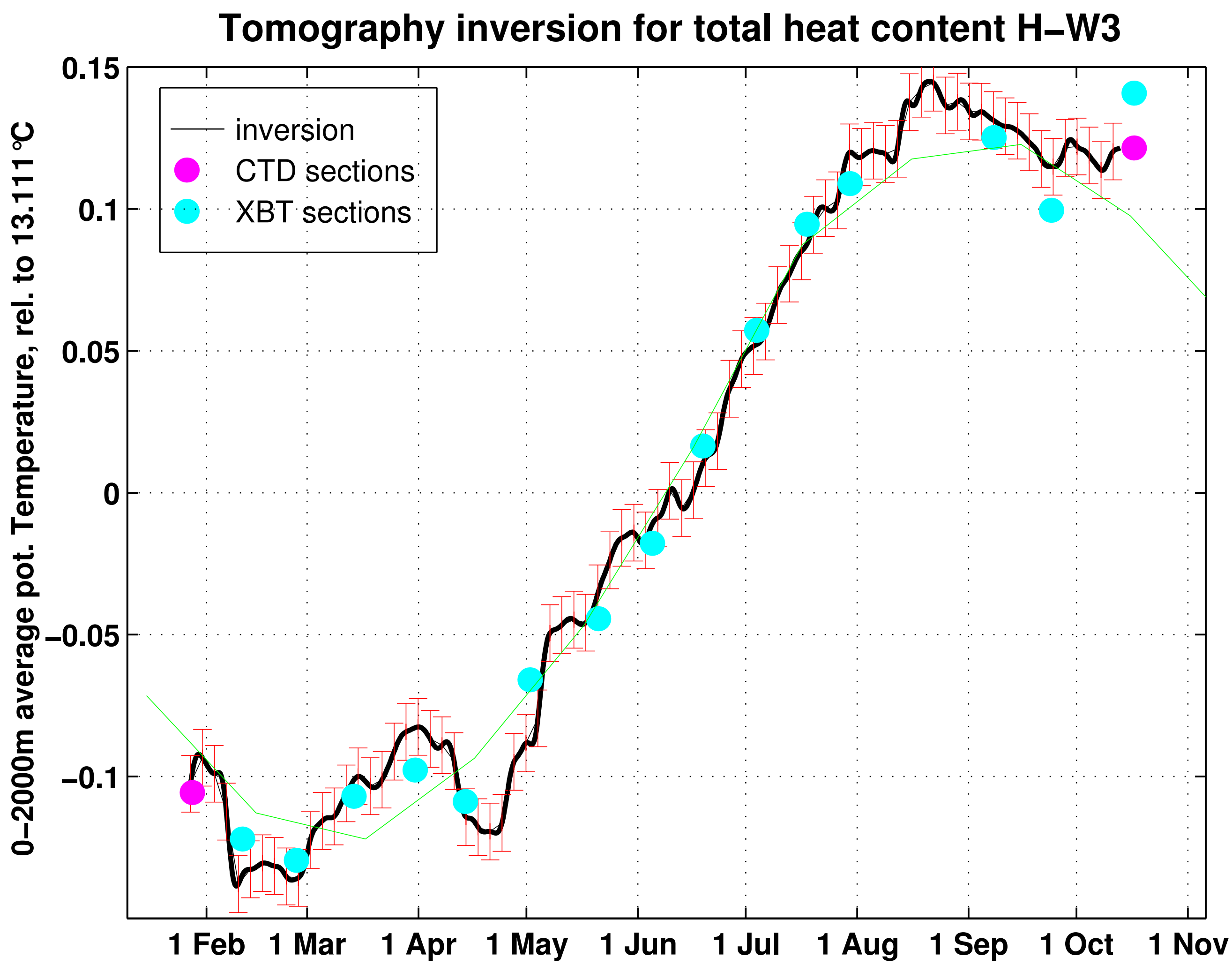
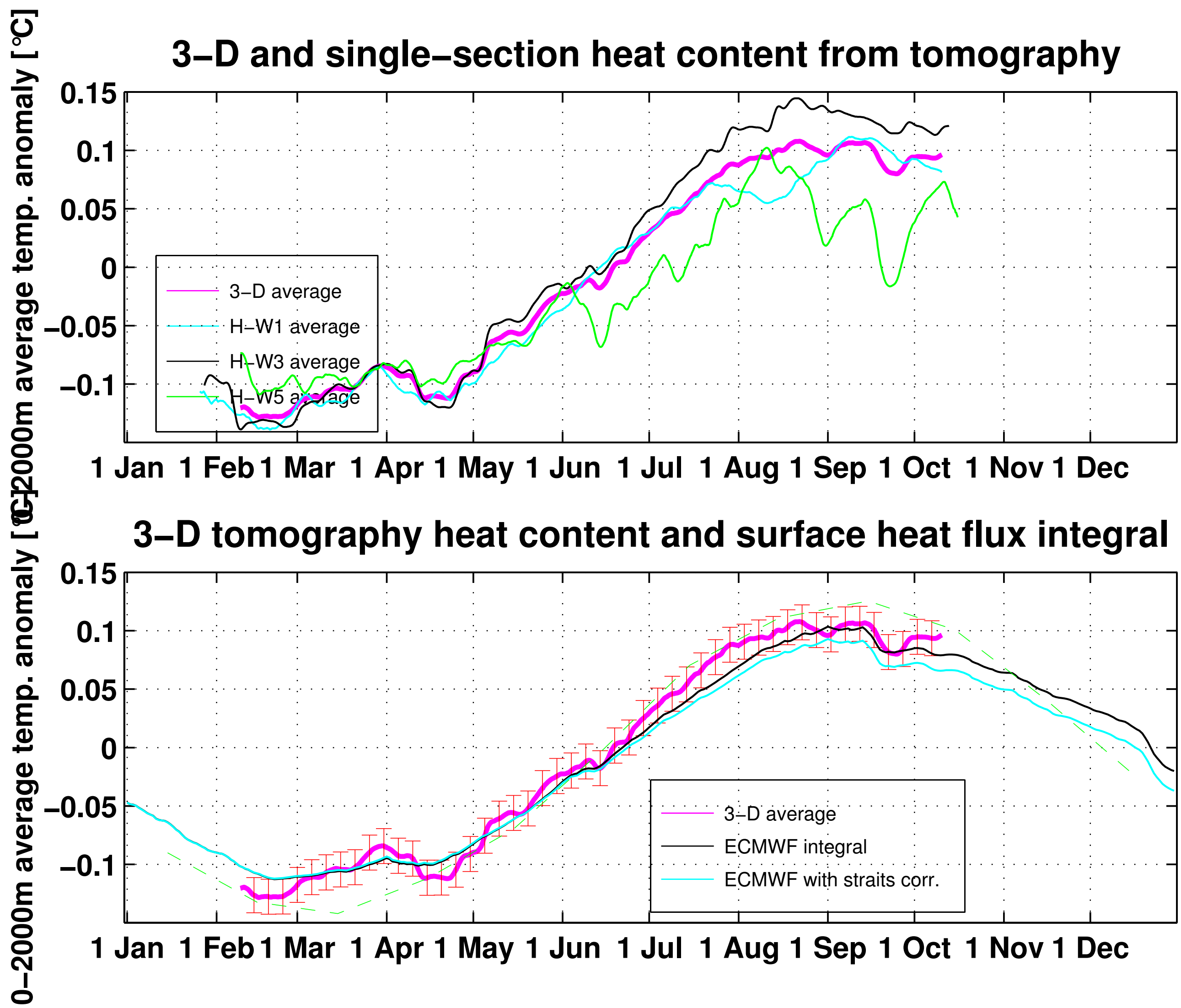

Tomography inversion for total heat content H−W3
0–2000m average pot. Temperature, rel. to 13.111 °C
0.15
0.1
0.05
0
−0.05
−0.1
inversion
CTD sections
XBT sections
1 Feb
1 Mar
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov



3−D and single−section heat content from tomography
0−2000m average temp. anomaly [°C]
3−D average
H−W1 average
H−W3 average
H−W5 average
1 Jan 1 Feb 1 Mar 1 Apr 1 May 1 Jun 1 Jul 1 Aug 1 Sep 1 Oct 1 Nov 1 Dec
0.15
0.1
0.05
0
−0.05
−0.1
3−D tomography heat content and surface heat flux integral
0−2000m average temp. anomaly [°C]
3−D average
ECMWF integral
ECMWF with straits corr.