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Analysis of in-situ observations in the Strait of Gibraltar

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Abstract. During the EU-project CANIGO intensive ship-board observations were carried out in April 1996 and October 1997 in order to observe the spatial and temporal variability of the flow, of the internal bore and of the water mass structure in the Strait of Gibraltar. An inverse model for the current and interface-fluctuations was developed to remove tidal currents from the measurement and to calculate the volume transport for the in and outflow seperately. In addition traveltime measurements across the strait have been analysed to test the suitability of acoustical instruments for a longterm monitoring of the exchange through the strait.

Introduction

The Strait of Gibraltar is the choke point for the water mass exchange between the Atlantic Ocean and the Mediterreanean Sea. Accurate observations of the mass, salt, and heat transports in the strait provide important integral information about the processes in the interior of the Mediterranean basin. Also the outflow of Mediterranean Water has significant influence on the water mass properties and the circulation of the North Atlantic.

The Strait of Gibraltar is a complicated environment with strong tidal currents, large horizontal and vertical shears, internal bores, and hydraulically controlled flow which contribute to the difficulty in studying this area.

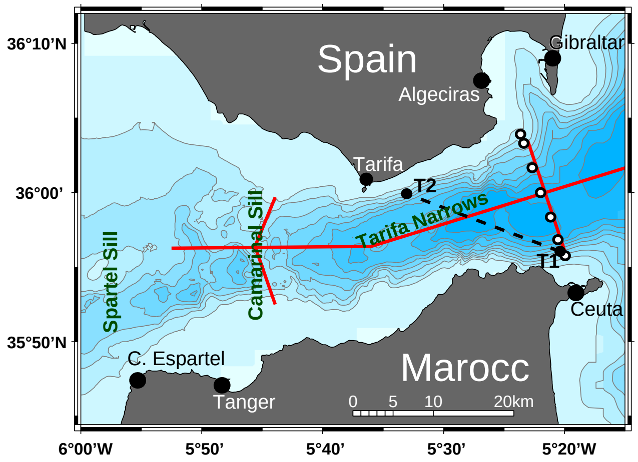

Figure 1. Topography of the Strait of Gibraltar, showing the position of the acoustical instruments T1, T2 and the raypath between them (dashed line). ADCP sections are shown as solid lines and CTD stations at the eastern entrance as dots.

The mean flow can be approximately described with a system of three layers. The upper one is formed by the inflowing fresh Atlantic Water and the lower one by the outflowing salty Mediterranean Water. In between is a region of high shear in flow, temperature, and salinity. However, it is quite common to describe the flow through the Strait of Gibraltar with a two-layer model, where the strong shear zone (intermediate layer) is neglected.

Measurements

During CANIGO, intensive oceanographic measurements were carried out focusing on the monitoring of the currents and the depth of the interface between Atlantic and Mediterranean water. The scientific goal of these measurements was to determine the volume transport through the Strait of Gibraltar (*Baschek et al.*, 2001), to obtain a better understanding of the dynamics and temporal changes of the exchange processes between the Atlantic and Mediterranean Sea, and to design future observing systems (*Send and Baschek*, 2001).

The eastern entrance of the strait (Algeciras-Ceuta section) was intensively observed during two cruises in April 1996 and September 1997. Here, the interface fluctuations are much smaller than at the Camarinal Sill, therefore contributing significantly less to the volume transport.

Figure 2 shows a mean of the quasi-synoptic ADCP sections at the eastern entrnce, over the depth range covered by the vmADCP. The typical currents here ($+20\,\mathrm{cm\,s^{-1}}$ to $+100\,\mathrm{cm\,s^{-1}}$, and $-80\,\mathrm{cm\,s^{-1}}$ to $+40\,\mathrm{cm\,s^{-1}}$ for upper/lower layers) are not as extreme as at the sill, but the resolved shears are comparable (up to $0.034\,\mathrm{s^{-1}}$ in the vertical and $9.3\,10^{-4}\,\mathrm{s^{-1}}$ in the horizontal). One sequence of vmADCP sections over a tidal cycle is available from spring and one from fall. Although there are some differences be-

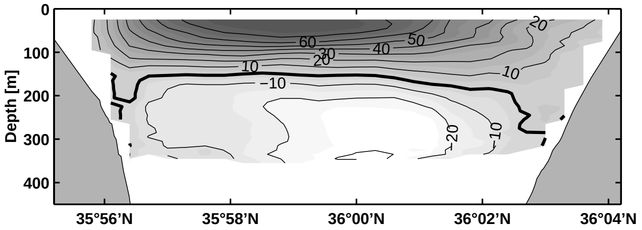

Figure 2. Approximate tidal-mean along-strait current $[\mathrm{cm\,s^{-1}}]$ through the eastern entrance of the Strait of Gibraltar from vmADCP sections.

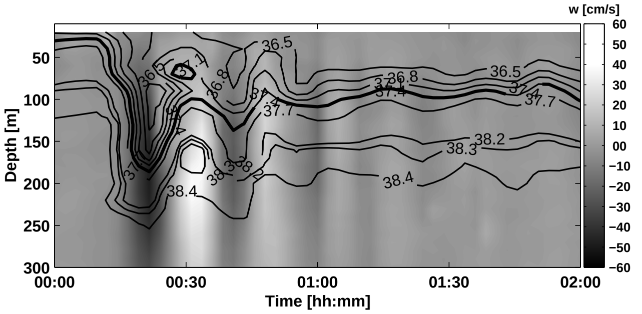

Figure 3. Obsevation of an internal bore (April 1996) near Camarinal Sill. The given time is relative to high water in Tarifa. *Shaded*: Vertical currrent $[\mathrm{cm\,s^{-1}}]$ (vmADCP). *Lines*: Isohalines (CTD). Bold line is the 37.4-isohaline.

tween these two tidal averages, we only show the total average from both seasons.

Another set of intensive observations was dedicated to the internal bore, which is released at the Camarinal Sill when the outflowing tide weakens and the water is pushed from the Atlantic back into the Strait of Gibraltar. The measurements of the internal bore at various locations in the strait with rapid CTD yoyos and vmADCP data allowed us to observe the evolution of the bore while it propagates towards the east into the Mediterranean Sea. It is a dominant but very short-lived feature, and it is not clear whether it is of importance for processes of larger scale. Figure 3 shows an observation of the bore at the Camarinal Sill. Before the bore reaches the location of measurement, the current has nearly no vertical shear. Vertical velocities are neglegible and the 37.4-isohaline, which roughly represents the location of the interface between Atlantic and Mediterranean water at the sill, lies in about 30 m depth. The arrival of the bore is indicated by a sudden lowering of the interface by about 150 m. This is accompanied by a strong increase of the vertical shear (values up to $0.035\,\mathrm{s^{-1}}$ were observed) with currents in the upper layer of up to $150\,\mathrm{cm\,s^{-1}}$ and in the lower layer of up to $-80\,\mathrm{cm\,s^{-1}}$. All this happens within minutes and is associated with extreme vertical currents reaching values of $\pm 50\,\mathrm{cm\,s^{-1}}$.

It is still not clear whether the flow through the Strait of Gibraltar is hydraulically controlled or not, or if it may flip from one state to the other (*C. Garrett et al.*, 1990). In the theory these two possible states are related to maximal and submaximal exchange (*L. Armi and D. Farmer*, 1986, *D. Farmer and L. Armi*, 1986). Timeseries of the composite Froude number were estimated from simultaneous vmADCP and CTD measurements at the eastern entrance of the Strait in spring (spring and neap tides) and in fall.

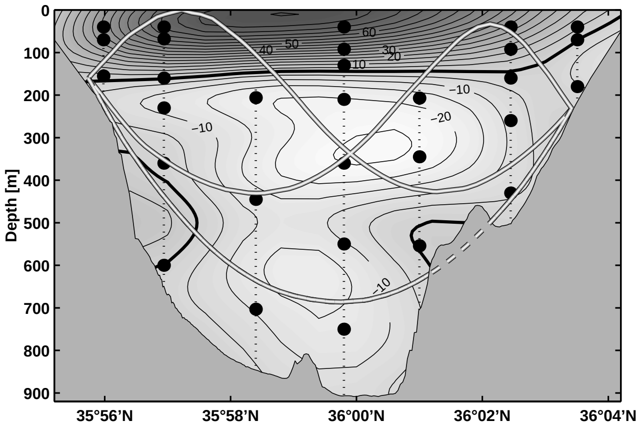

Figure 4. Measured mean along-strait current $[\mathrm{cm\,s^{-1}}]$ at the eastern section. Tides were removed by the inverse model. The dots represent moored rotor-current-meters and some ray paths of the acoustic transmission are shown.

These estimates, as well as the observed qualitative tilt of the interface in along-strait direction, are consistent with hydraulically controlled flow and maximal exchange in April 1996. Corresponding conditions were not observed in October 1997, the interface being lower and with typical surface flows of smaller amplitudes.

Inverse model

Inverse modeling provides a tool to combine long timeseries from moorings with ship-board observations providing high spatial resolution, which allows it to extract the temporal as well as the spatial information from the measurements. This means that also the locations with an insufficient temporal sampling (where averages would normally be aliased by tides) can be taken into account and complemented with information from adjacent locations.

All data, which were measured at the eastern entrance of the Strait, were sorted into a grid of 16 horizontal and 29 vertical boxes. The distance between the boxes is approximately 1 km in the horizontal and 20-50 m in the vertical. To reduce the amount of data, 2-hour mean values were taken before they were sorted into the boxes, yielding a total of approximately 135,000 data.

To calculate the mean flow (Figure 4), the model was used to remove the tidal currents from the measurements. The mean currents of the residuals was calculated for every model box. The spatial gaps due to empty boxes were filled by using an objective analysis.

A similar model has been used for the movement of the

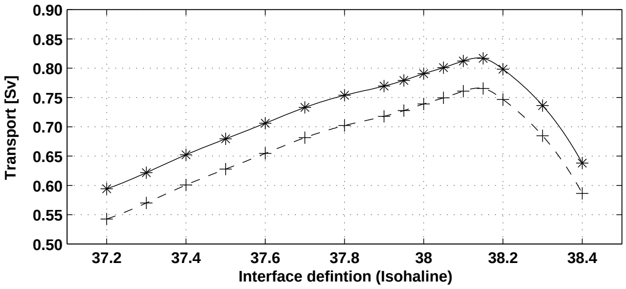

Figure 5. Relation between the interface definition (isohaline) and the calculated volume transport of the upper layer (solid) and lower layer (dashed).

interface at the eastern entrance. , which was used in combination with the inverse model for the current speed to calculate the volume transports in both layers. The estimate of the upper and lower layer volume transports depends on the choice of the separating isohaline. When for example the chosen isohaline lies somewhere in the upper layer, the area of the cross section used for the upper-layer calculations is smaller than it should be and hence also the estimated upper-layer transport is too small. The relationship between the separating isohaline and the volume transport for both layers is shown in Figure 5. The isohaline for which the transport is maximal ($S = 38.1$) is taken as interface definition yielding a volume transport of $0.81 \pm 0.07 Sv$ for the upper layer and $-0.76 \pm 0.07 Sv$ for the lower layer.

Acoustic measurement

In the Strait of Gibraltar tomographic transceivers were deployed at locations T1, T2 (Figure 1) measuring the two-way traveltime of sound for the acoustic path in between the instruments.

The difference in traveltime ($t_{T1T2} - t_{T2T1}$) is a direct measure of the flow along and parallel to the raypath while the traveltime sum ($t_{T1T2} + t_{T2T1}$) is a measure for the soundspeed, which mostly depends on temperature.

Assuming that the current across the strait is negligable, lower layer current can be calculated using the traveltime differences of the deepest ray (Figure 4), which is sampling only the layer of Mediterranean Water. The lower layer current is shown in Figure 6 together with the model current integrated along the raypath. Since the inverse model cannot describe longterm variability, it has been calculated from the current meter moorings and added to the model current. It was found, that 98% of the lower layer tidal transport variance was resolved by the acoustic measurement (*Send et al.*, 2001).

The small differences between the measured and the modelled currents are mainly of tidal effects, which can be a consequence of different phases and amplitudes between the T1-T2 section and the eastern entrance (*Candela et al.*, 1990) where the model was calculated.

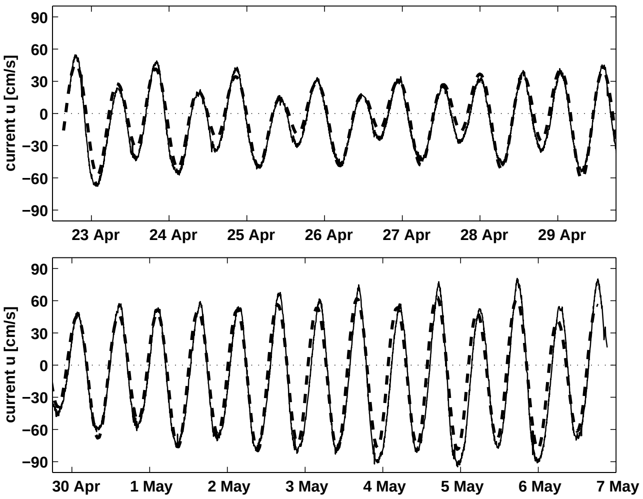

Figure 6. Longstrait current measured with the T1-T2 transceivers (solid line) compared with the sum of the model current and the longterm fluctuations from mooring data (dashed line).

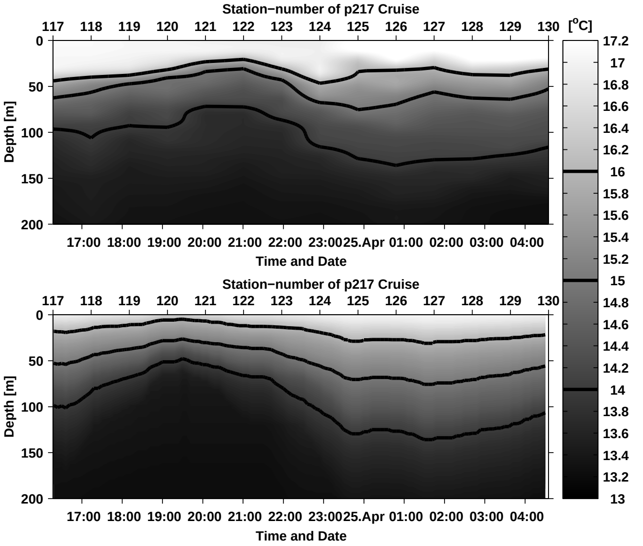

Figure 7. Temperature at the center of the eastern entrance. Upper panel: CTD masurement. Lower panel: Calculation from the traveltime sum.

From the traveltime sums temperature and salinity sections were estimated. Nonlinear effects on the raypath of the ± 2 rays (Figure 4) had to be taken into account to obtain meaningful results. An comparison with 14 repeated CTD casts at the center of the eastern entrance is shown in Figure 7. For this also the slope of the interface along the strait (which was calculated from the acoustic data) and the different amplitudes of the M2 tide between the eastern entrance and the T1-T2 section had to be considered.

Figure 8 shows the 38.1-isohaline depth at the center of the T1-T2 section for the whole period of the acoustic measurements. It shows variations of $\pm 50\ m$ at a semidiurnal period and remarkably strong longterm variations of about

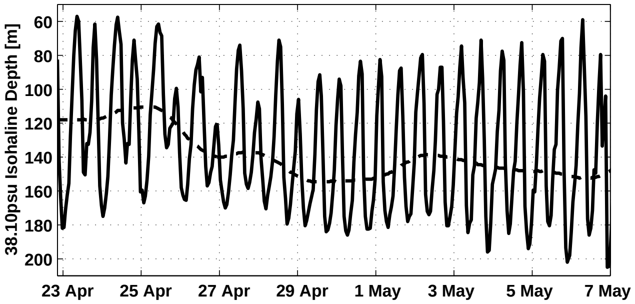

Figure 8. Depth of the interface at the center of the T1-T2 section (solid line). The dashed line shows the 2 day lowpass filtered data.

$\pm 20\ m$. With this method the interface depth can be determined within 10 to 20% (depending on the interface definition). Most of the error is due to small scale variations seen in the CTD profiles, whereas the tomography is an integral technique measuring integrated properities of the water. Therefor the error in the longterm variability is expected to be less than 20%.

The work on the acoustic data was motivated to test the feasibility of installing a quasi-permanent, real-time, shore-based observing system. The results show that tomography is a suitable tool for observing fluctuations in the Strait of Gibraltar.

Summary

Intensive ship-board observations from two cruises in the Strait of Gibraltar were carried out and were complemented with moorings in that region, yielding to new views of the joint spatio-temporal structures of the flow and stratification fields. All these data were combined with an inverse model to describe the flow and the depth of the interface as a function of space and time. Additionally a test with acoustical transceiver was carried out to determine their suitability of monitoring the Strait of Gibraltar, showing the important results of measuring the lower layer flow and interface depth.

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References

Armi L., and D.M. Farmer, Maximal two-layer exchange through a contraction with barotropic net flow, *J. Fluid Mech., 164*, 27–51, 1986.

Baschek, B., U. Send, J.G. Lafuente, and J. Candela, Transport estimates in the Strait of Gibraltar with a tidal inverse model, *J. Geophys. Res., 106 (C12)*, 31,033–31,044, 2001.

Candela, J., C. Winant, and A. Ruiz, Tides in the Strait of Gibraltar, *J. Geophys. Res., 95 (C5)*, 7,313–7,335, 1990.

Farmer D. M., and L. Armi, Maximal two-layer exchange over a sill and through a combination of a sill and a contraction with barotropic flow, *J. Fluid Mech. 164*, 53–76, 1986.

Garrett, C., M. Bormans, and K. Thompson, Is the exchange through the Strait of Gibraltar maximal or submaximal?, in *The physical oceanography of sea straits*, edited by L.J. Pratt, pp. 271-294, Kluwer Academic Publishers. Dordrecht, 1990.

Send, U., B. Baschek, Intensive ship-board observations of the flow through the Strait of Gibraltar, *J. Geophys. Res., 106 (C12)*, 31,017–31,032, 2001.

Send, U., P. Worcester, B. D. Cornuelle, C. O. Tiemann and B. Baschek, Integral measurements of mass transport and heat content in the strait of Gibraltar from acoustic transmission, submitted to *Deep-Sea Research*, 2001.

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