The source of the Canary current in fall 2009

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Abstract: The source of the Canary Current has been inferred from an inverse box model applied to the hydrographic data of a survey carried out in 2009 in the northeast subtropical gyre (29–37ºN, 9–24ºW). The Portugal Current is observed between 13.5 and 14.8ºW at 37ºN carrying 1.8± 0.4 Sv southward. This current presumably merges with the eastward transport of the Azores Current System and partly contributes to the Mediterranean inflow and partly to the northward recirculation of the Azores Current through the Gulf of Cadiz. The Azores Current System is located in the meridional range 33.50–36.25ºN at 24.50ºW. This System transports eastward 7.2± 0.5 Sv in the thermocline layers and 1.1± 0.8 Sv at intermediate layers. The Azores Current intermediate water mass has the highest portion of Sub-Arctic intermediate water (SAIW) in the region, while the Azores Countercurrent intermediate waters mass is mainly Mediterranean water. The Canary Current extends from 22.25º to 18.50ºW at 29ºN, the westernmost position ever observed. This current transports southward -6.2± 0.6 Sv in the thermocline layers and -2.0± 0.8 Sv in the intermediate layers. This intermediate flow shows a relative maximum of oxygen and a relative minimum in nutrient concentration, indicating the presence of SAIW. The study concludes that, at least in fall 2009, the Canary Current extends to the intermediate waters (approximately <1600 dbar) and that Azores Current feeds the Canary Current at surface and intermediate layers..

Introduction: The Canary Current is the eastern boundary of the North Atlantic Subtropical Gyre that flows through the Canary Islands Archipelago. This surface current carries an average of -3.0±1.0 Sv to the south [Machín et al., 2006]. The Canary Current that presents a seasonal change in space and transport: it flows near the African coast in spring (2.8±0.8 Sv), through the whole archipelago in summer (2.9±0.8 Sv), only through the western islands in autumn (2.7±0.4 Sv) and practically absent in winter [Machín et al., 2006].

The ocean circulation maps before 1980's showed a Canary Current fed by the Portugal Current. This current is a southward flow close to the Portugal coast that is fed by a branch of the North Atlantic Current. This view changed after the studies of Krauss and Wuebber [1982]; Stramma [1984]; Stramma and Siedler [1988]. These studies pointed out that the origin of the Canary Current is an eastward branch of the Azores Current that was first described by Klein and Siedler [1989]. However several authors still suggest that the Portugal Current also feds the Canary Current [Paillet and Mercier , 1997; Tomczak and Godfrey, 2003].

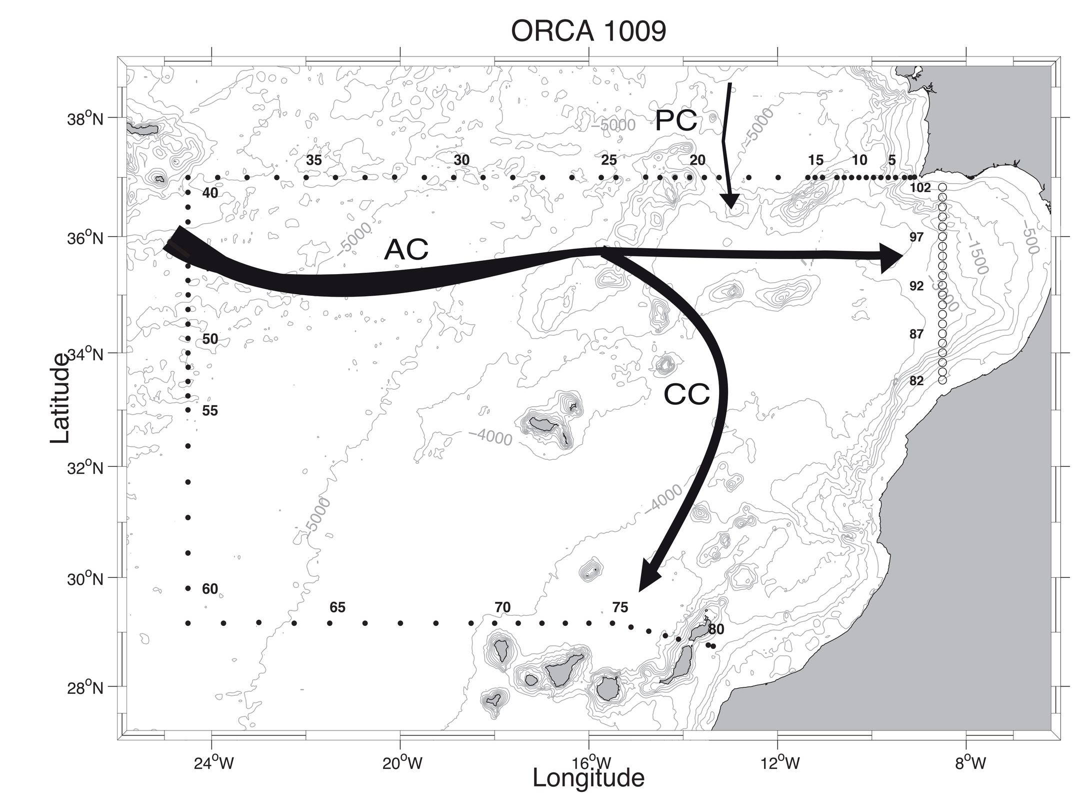

Figure 1. Geographical location of the stations. Black stations correspond to the ORCA 2009 cruise and white stations are those of AR06 1992.

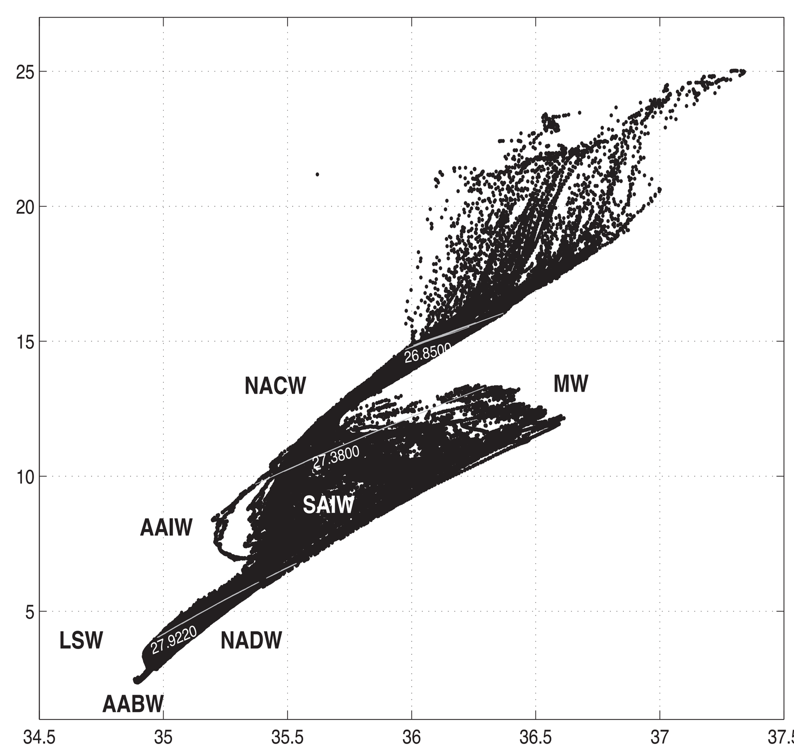

Figure 2. Potential temperature/salinity diagram for all stations. Plotted isopycnals roughly divides the water column into central, intermediate and bottom waters [Hernández-Guerra et al., 2005].

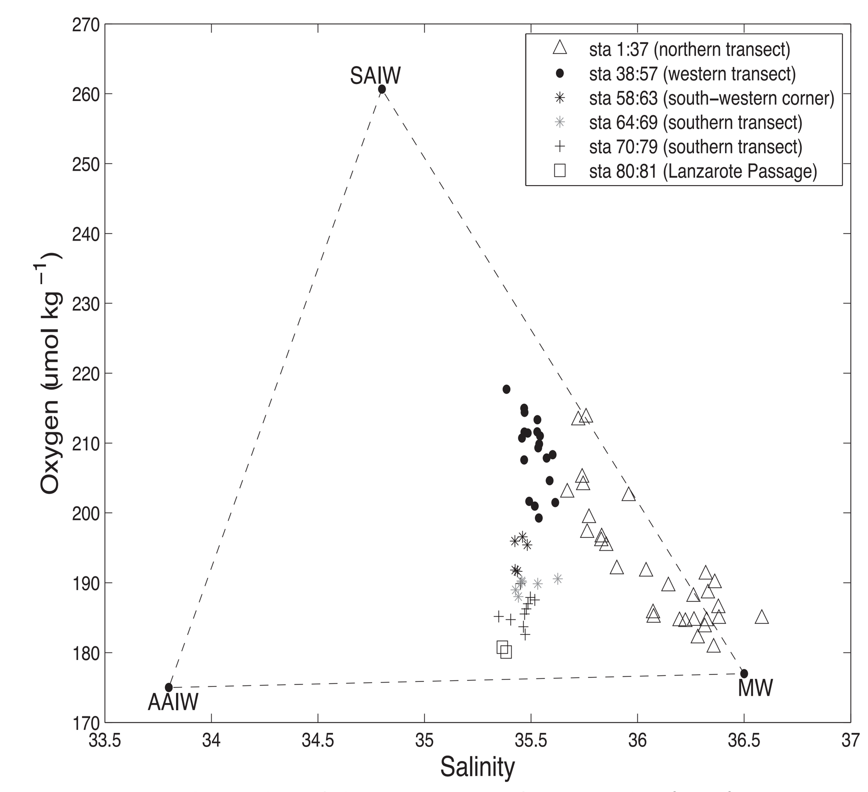

Figure 3. Oxygen (µmol kg) versus salinity at the isopycnal surface of γn approximately equal to 27.8000 kg m -3.

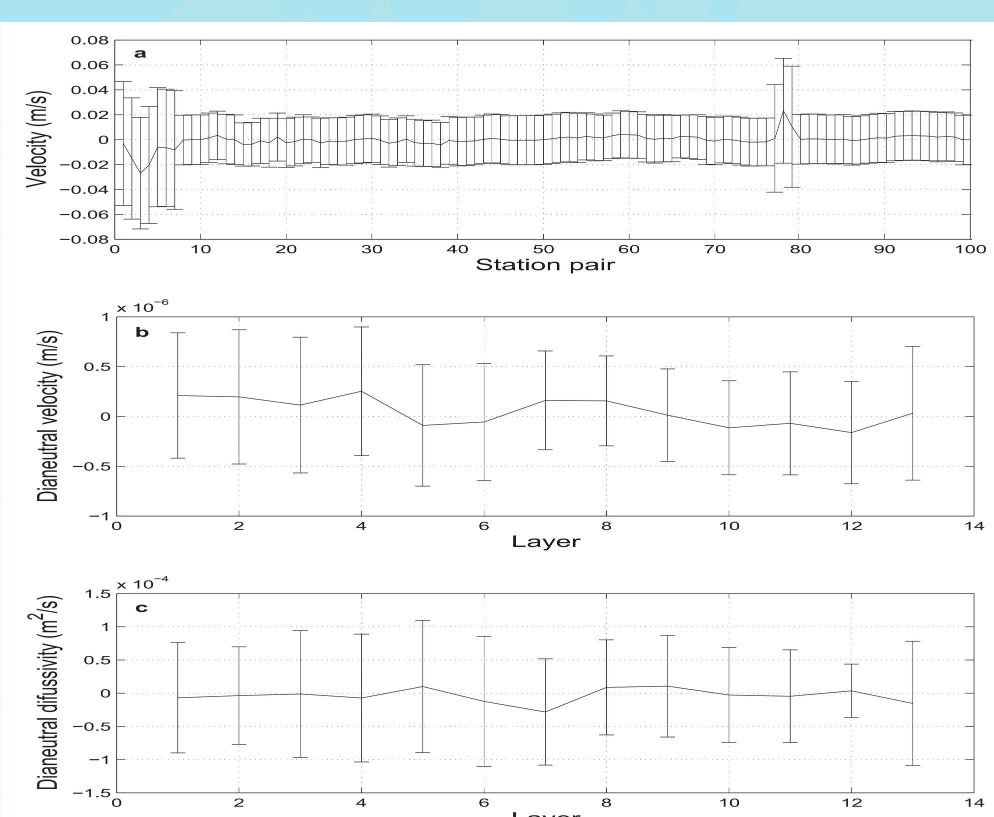

Figure 4. a) Velocities at the reference level for each station pair, b) dianeutral velocities and c) dianeutral diffusivities between layers determined by inverse calculations with their error bars.

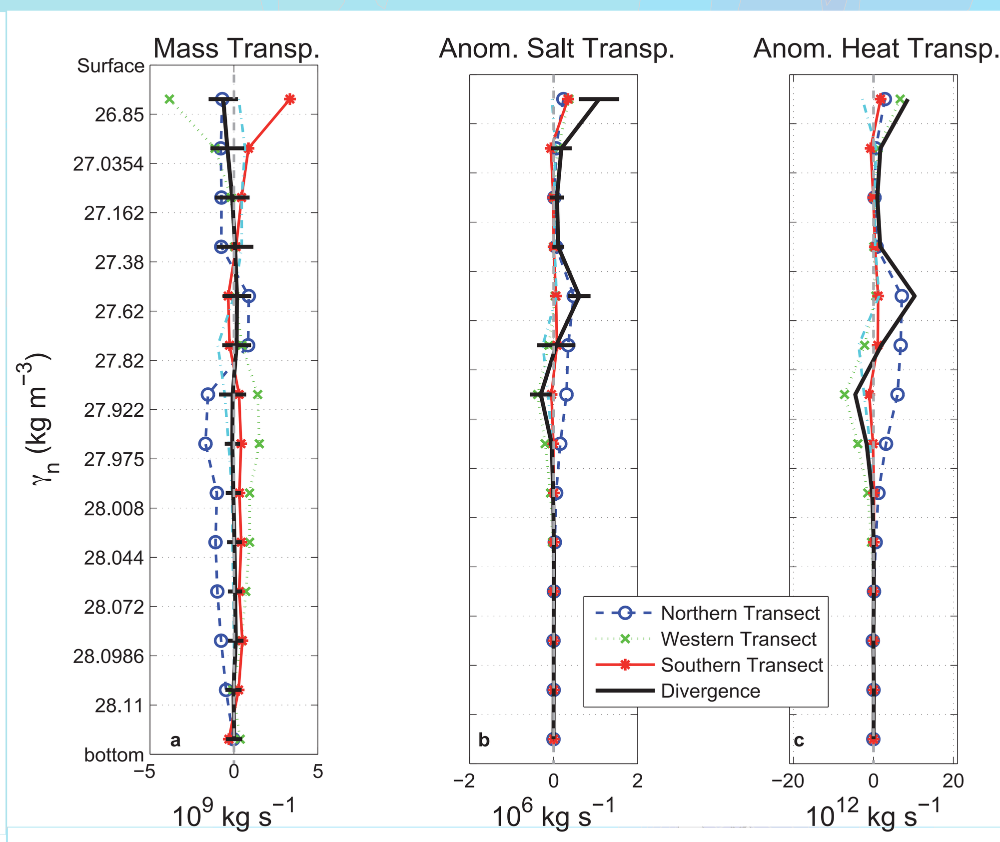

Figure 5. Integrated mass (a), salt anomaly (b) heat anomaly (c) transports using the results of the inverse model together with their error. The sign is taken positive/negative for divergence/convergence flow out/in the box. Each line corresponds to the northern (circles above a dashed line), western (crosses above a dotted line), south (asterisk above a thin solid line)and eastern transects (dashdot line). The divergence of mass, salinity and heat anomalies are shown as a thick solid line (thick solid line). Different x labels are used.

Variables	Preliminary variances
Shallow stations	$(0.05\,ms^{-1})^2$
Stations in the open ocean	$(0.02\,ms^{-1})^2$
Vertical velocity	$(10^{-6}\,ms^{-2})^2$
Vertical diffusivity	$(10^{-4}\,ms^{-1})^2$
Ekman transport northern transect	10% of the initial value
Ekman transport western transect	30% of the initial value
Ekman transport southern transect	10% of the initial value
Ekman transport eastern transect	50% of the initial value
Freshwater flux	50% of the initial value

Table1: Apriori estimates of the unknowns.

Inverse box Model: The inverse box model proposed by Wunsch [1996] is applied to the box of hydrographic data from ORCA and AR06 1992 cruises. This model provides with an efficient method to obtain geostrophic flow using the thermal wind equation once it calculates the reference level velocities and their uncertainties. These velocities are calculated assuming geostrophy and mass and properties conservation. Following Candela [2001] a constant flow is considered in the Gibraltar Strait.

In this study , we have extended the inverse model described in Joyce et al. [2001] to include the approximate conservation of mass and anomalies of salinity and heat, and to allow the transfer between layers. This model also considers adjustment of fresh water flux and Ekman transports in each section. Mass and property equations for a closed volume are respectively:

$$\int\int \rho b dxdz + A_z \times (w^* \bar{\rho}) = -\int\int \rho v_{rel}\, dxdz + Q$$

$$\int\int \rho(C - \bar{C}) b dxdz + A_z \times \left(w^* \rho(C_i - C) - k_z^* \frac{\partial(\rho C)}{\partial z}\right) = -\int\int \rho(C - \bar{C}) v_{rel}\, dxdz + \bar{C} \times Q$$

To solve the inverse problem, we have used the Gauss-Markov method. Gauss-Markov method produces a minimum error variance solution from initial estimates of the unknowns. The preliminary variances assigned are shown in table 1. The preliminary variances assigned to the unknowns of the reference velocities of station pairs,are higher in stations pairs near the coasts than the unknowns of stations pairs on the open ocean. The preliminary variance imposed for the dianeutral advection and diffusivity have been previously used in Hernández-Guerra et al. [2005]. Ekman transports were estimated using winds from the National Centers for Environmental Prediction (NCEP) and Quikscat data (QS). Ekman transport preliminary variances come from the percentage of difference between estimations for each transect. Freshwater flux a priori variance comes from SMD94.

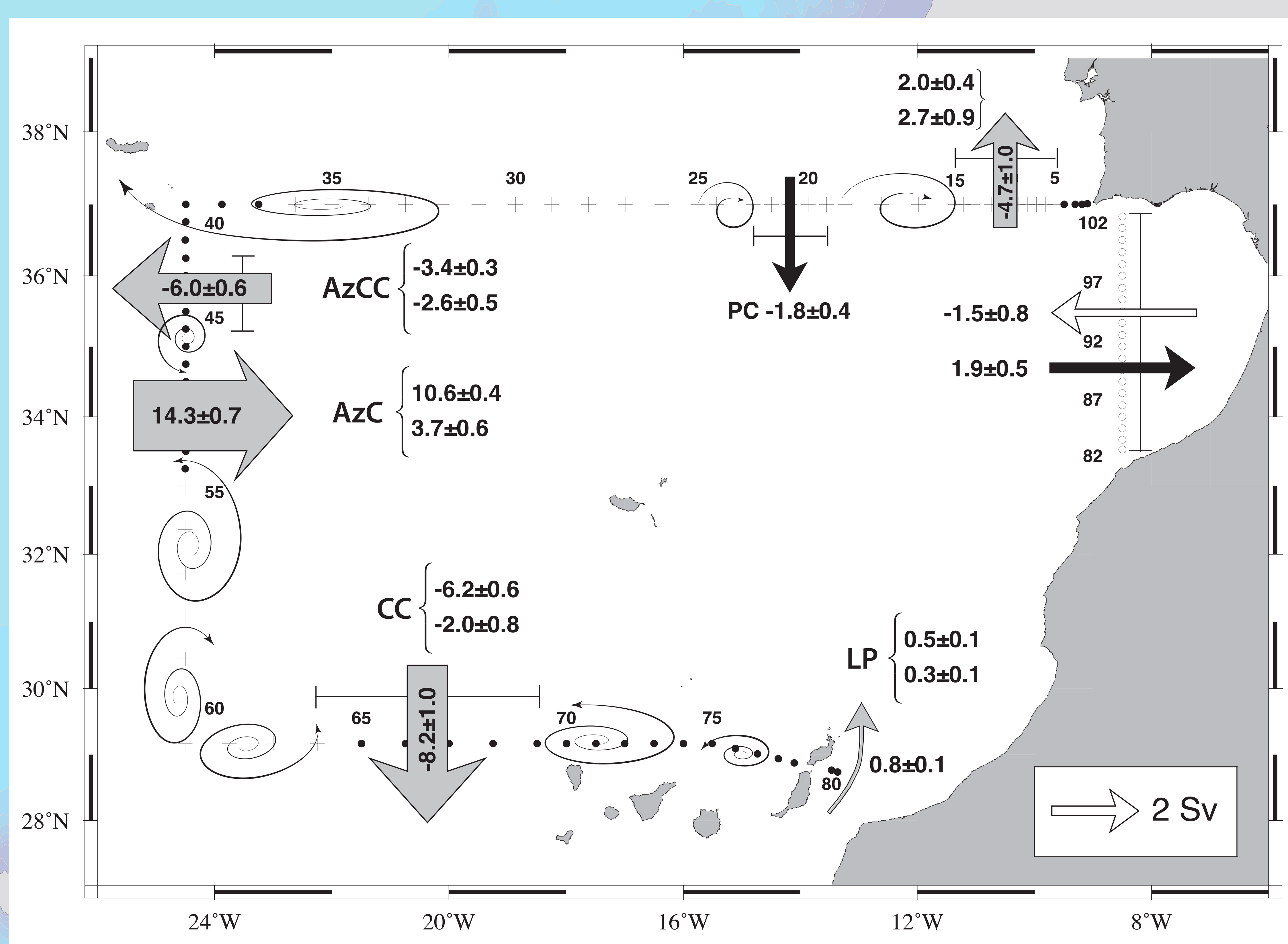

Figure 6. Main currents with their corresponding integrated mass transport (in Sv). PC, AzCC, AzC, CC, and LP stand for Portugal Current, Azores Countercurrent, Azores Current, Canary Current, and Lanzarote Passage, respectively. Curly brackets indicate (top) the surface and (bottom) intermediate mass transport for each current. Gray arrows and the enclosed number, correspond to the integrated sur- face and intermediate transport. The exchange between the Mediterranean Sea and the Atlantic Ocean is shown with black arrows (surface layers) and white arrows (intermediate layers). The width of the arrow shaft is proportional to the mass transport values. Spiral arrows indicate the presence of an anticyclonic/ cyclonic eddy. The stations where deep circulation was found are shown with black crosses instead of black dots (ORCA stations) or white dots (WOCE AR06 stations).

Conclusions: The model results and all the above discussion, suggest the following circulation in the thermocline (Figure 15). Most of the Azores Current feeds the Canary Current in the surface layers. A slide of the Azores Current flows eastward and suffers the rectification of the mesoscale turbulent eddies that generates a westward surface flow north of it [Alves and Colin de Verdie`re, 1999]. This westward surface flow is the surface Azores Countercurrent that carries -3.4± 0.3 Sv. As various studies indicate, a weak fraction of the Azores Current (1.0± 0.8 Sv) continues eastward and reaches the Strait of Gibraltar [Mauritzen et al., 2001 ; Peliz et al., 2005, 2007 ; Kida et al., 2008 ; Mason et al., 2011 ; Laiz et al., 2012]. Between 13.5º W and 14.8ºW, the southward Portugal Current merges with the weak eastward flow, augmenting the transport to 2.8± 0.9 Sv. This transport is very similar to the eastward contribution observed in the vicinity of the Gulf of Cadiz in Peliz et al. [2007] (3.2 Sv) and in Laiz et al. [2012] (observations 2.5± 0.6 Sv and model 3.9 Sv). When this merged flow reaches the Strait of Gibraltar part of it will enter in the Mediterranean Sea [Stramma and Siedler, 1988; Schmitz, 1996; Paillet and Mercier, 1997] and part will recirculate northward through the Gulf of Cadiz to Cape San Vicente [Mauritzen et al., 2001; Peliz et al., 2005, 2007; Kida et al., 2008; Mason et al., 2011; Laiz et al., 2012].

The circulation scheme at intermediate layers is harder to infer from Figure 6. The intermediate waters of the Azores Current are mainly composed of SAIW, and those of the Canary Current present a contribution of SAIW. Both currents present a similar mass transport. Altogether this indicates that most of the Azores Current feeds the Canary Current at intermediate layers, although, part of it continues to flow eastward (1.7±1.0 Sv). Following Comas-Rodríguez et al. [2011], the characteristics of our Azores Current System better agrees with the beta-plume for- mation hypothesis. Thus, the Mediterranean outflow on its way to the Atlantic Ocean generates an eastward flow that forms the Azores Countercurrent intermediate transport. This eastward flow augments its transport by entrainment and with the recirculation of the weak eastward Azores Current intermediate mass transport [Kida et al., 2008; Volkov and Fu, 2010]. The Mediterranean outflow spreads and flows northward in the vicinity of Cape San Vicente [Mauritzen et al., 2001; Peliz et al., 2005, 2007].

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