THE CANARY DEEP
POLEWARD UNDERCURRENT

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-The Canary deep Poleward Undercurrent

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Abstract

Poleward undercurrents are well known features in Eastern Boundary systems. In the California Current Eastern Boundary upwelling System (CalCEBS) the California poleward Undercurrent (CalUC) has been widely reported, and it has been demonstrated that it transports nutrients from the Pacific Equatorial Water (PEW) to the northern limit of the subtropical gyre. However, in the Canary Current Eastern Boundary upwelling System (CanCEBS), the Canary deep Poleward Undercurrent (CdPU) has not been properly characterized. In this study, we use trajectories of Argo floats and model simulations to properly characterize the CdPU, including its seasonal and interannual variability, and the driving mechanism. The Argo observations show that the CdPU flows from 26ºN, near cape Bojador, to approximately 44ºN, near cape Finisterre in the northwest Spanish’s coast. The CdPU flows deeper than the CalUC, although its mean changes slightly with latitude, from 400 m at 23ºN to 800m at 43ºN. The CdPU shows a marked seasonal variability, with its maximum strength in fall, and the minimum in spring.

Introduction

The goal of this study is to contribute to the understanding of the driving mechanisms and variability of the CdPU. The CdPU is interesting from several points of view as physics, the forcing mechanism. And to compare it with other Eastern Boundary upwelling Systems (EBSS) like CalCEBS (Collins et al., 2004), or as biochemist (nutrients and biomass alongshore transport) and water masses exchange from the south to the north of CanCEBS that contributes to the upwelled waters.

The CdPU is not as well understood as the CalUC on the Californian coast. There are current-meters records, but these are remote and in short-term. Therefore they are not enough to detail or describe the CdPU. In general, into the CanCEBS there are not so many directs measurements.

It is already known that the CdPU is an undercurrent with maximum flow in fall, like the CalUC (Connolly et al., 2014; Thomson et al., 2010). However, it is not known the main characteristics of this undercurrent, as the depth of the flow and the actual path of the flow. Although it is known by mooring data that the CdPU appears at 19ºN, being able to reach until 44ºN (Barton, 1989), still without sufficient time and space data records, to affirm it.

It is not known: the main depth and path, the annual and interannual variability, and the physical mechanism that forces the CdPU.
It would be a great advance to detail the CdPU to the knowledge of the undercurrents into the EBSS. In the same way, in the water exchanges from low to high latitudes, being able to influence (modifying the initial features) in any oceanic process close to it (MOW outflow, upwelling, fisheries).

This study pretend to detail the depth, the continuity, the annual and interannual variability and the associated features of the CdPU in the CanCEBS (20°-45°N y 25°-5°W). To achieve that objective, we will use a mooring and Argo floats as direct measurements, and a numerical model (OFES). We will also propose some different physics mechanisms that would be able to generate this phenomenon.

**Material and Methods**

To make this study we have used different data. From direct measures that demonstrate the CdPU existence, to numerical simulations that complement the direct measures and will permit us to be able to understand better the CdPU features.

(a). Direct Measures

We have used Argo floats inside the CanCEBS and the CalCEBS. We have used the YoMaHa database (Lebedev *et al.*, 2007) that contains velocity and trajectories observations from Argo floats in the period 1 January 2008 – 31 December 2015. From this data set, we have selected only the floats at 1000dbar in both regions. Besides this, we took only the poleward trajectories that lasted more than 20 days and then for each trajectory it was selected the actual poleward component section. In the CanCEBS only 20 of a total of 157 floats in the entire region described a poleward flow from more than 20 days (Fig. 1.a). However, in the CalCEBS any float was found with a poleward trajectory that lasted more than 20 days, from a total of 123 floats (Fig. 1.b).

The data obtained in the 20 selected floats by the YoMaHa database were compared with the ANDRO database (Ollitrault *et al.*, 2010) to corroborate it. The method to obtain velocities and trajectories in the ANDRO database is more precise than YoMaHa method, however the ANDRO database only extends to the year 2012. The results were very similar.

Velocity data are used from Lanzarote Passage The EBC4 mooring (Fig. 3), where data have been collected from 1997 to 2006, is located on the 1200-m isobath at 28°45’N, 13°30’W (Hernández-Guerra *et al.*, 2003). Velocity components were rotated 51.2° clockwise, parallel to the local isobath orientation.

(b). Numeric Simulations
To complement the direct observations from the Argo network, model simulations from the Ocean General Circulation Model for the Earth Simulator (OFES) were used. The simulations were done by JAMSTET, based on MOM3, in a global domain with a horizontal resolution of 0.1 degree and 54 vertical levels. Two different wind forcings were used, QuikSCAT (QS) and NCEP winds (Masumoto et al., 2004) like it shows in table 1.

We have used monthly data in the period January 1999 to December 2006 in both regions. And three days data in the period July 1999 to December 2006. Both limited by the available temporal data from QS.

**Results**

_(a). Direct Observations_

In the CanCEBS there were 20 floats that described a poleward trajectory for more than 20 days (Fig. 1.a). In contrast with the CalCEBS, which hasn’t got any floats that describe a continuous poleward trajectory as long as in the CanCEBS at 1000dbar (Fig. 1.b).

In the CanCEBS there are not any Argo float below 25ºN (Fig. 1.a) at 1000dbar. It is due to in this region there are a strong westward superficial current to displace the floats of their original trajectory when they rise up to surface to send us the data. However, upper than this latitude it is possible to see a continuous flow until 44ºN.

The values of salinity or temperature vary alongshore at 1000dbar (Fig. 2). It demonstrates that the CdPU is advecting different water masses, and the properties can be modified along the way. The salinity values rise with latitude due to the contribution of MOW to the CdPU approximately at 36ºN. Before that, like the 690772 float shows the water mass is colder and lower in salinity due to the AAIW influence.

The average velocity component of the CdPU is near to 4cm/s, but with values up to 10 cm/s (Vélez-Belchí et al., 2012).

_(b). Model Validation_

The mean velocity at 800m from the model simulations (Fig. 3) is remarkably similar to the observations from the Argo floats (Fig. 1.a; Fig. 2). Indicating a continuous flow from 25ºN to 44ºN.

The velocity data of the EBC4 mooring were compared with the data obtained by OFES in the same place and depth (EBC4~870m; OFES~790m) (Fig. 4.a). As the data of
EBC4, the numerical simulations data were rotated 51.2° clockwise too. The results of this comparison show us that the magnitude of the velocity values from the OFES model is very similar with the observational mooring values (Fig. 4.b). Moreover the average variability is almost equal that the actual observations in the region. Therefore we can conclude that the OFES model is reliable to use in CanCEBS.

(c). Numeric Simulations

Once we have demonstrated that the OFES simulations are an appropriate representation of the circulation in the CanCEBS, we will use the model simulations to describe the CdPU.

(i). Mean circulation

In the CanCEBS the model simulations show that the CdPU flows continually from near 21°N to 44°N, and it has a biannual variability, (Fig. 5), with the CdPU begging in January and June at 20°N and at a depth of 800-1000m.

The CdPU flows at both sides of the islands of Fuerteventura and Lanzarote (Fig. 3) because inside the Lanzarote Passage the flow stems due to the local orography. This fact makes us to know that the isobath of the CdPU flow is less than the bathymetry of this place. Considering that and the Fig. 3, it can be affirmed that the undercurrent follows the ~1100m isobath. Which agrees with the obtained results. Usually the CdPU has a width of more than 100km, but sometimes it is able to reach more than 200km of width in some places (e.g. in the North of the CanCEBS in fall).

Between each one of the poleward flows set up in January and June, as described before, there was an intense equatorward current at the same depth with the maximum equatorward flow in December (Fig. 5). This current advected water masses from the North of CanCEBS (e.g. the Biscay bay). This current flows until the South of this region. Moreover, in the last middle of summer (July-Aug) and the first weeks of fall (Sept-Oct) there is an input from the CdPU to the deep water of the Biscay bay (Fig. 3). The water mass of the CdPU mixes and transfers its properties to the water of the bay. Based on that, it is possible to say that there are exchanges between different water masses due to the CdPU and the equatorward current around 800m of depth.

(ii). Seasonal and Interannual Variability

As mentioned in the previous sections, the CdPU appears twice a year in the CanCEBS, first in January to March, and then in July to October. During January to March the CdPU is continues until the North of the region, but it is weaker than the CdPU that appears during July to October.
The maximum strength of the CdPU occurs in October, developing instabilities near 32°N and forming mesoscale structures like the CalUC in California (Huyer et al., 1998; Garfield et al., 1999).

The intensity of the CdPU varies by year, with a significant interannual variability (Fig. 6). During years 2000 and 2006, there was a significant contrast between winter and fall, than decreased with time. Overall, as time increased the intensity was lower, however we would need more record data to affirm it.

(d). Forcing Mechanisms for the CdPU

Inside the CanCEBS there are not enough measurement equipment to define the physical phenomenon to produce the CdPU. Therefore we need to use the numerical simulations model to help us to discover the possible reasons for this undercurrent. This can be done because the model is similar with the real observations.

(i). Comparative between QS and NCEP

The difference between QS and NCEP wind forcings are not significant at 800m of depth (Fig. 4.b), indicating that the role of the wind forcing in the CdPU is weak.

(ii). The APF as Principal Forcing

Probably the pressure gradients are the responsible to occur the CdPU. The APF is one of them, which can force to create this undercurrent. These pressure gradients (Fig. 7) are created by a density gradient offshore, which in a geostrophic fluid generates a flow to coast. This flow comes to coast and due to the potential vorticity conservation law creates a poleward flow. This phenomenon has a seasonal variability in the APF, and coincides with the velocities (Fig. 5). Neither it depends of the wind stress (Fig. 4.b). Part of the CalUC is also generates by the APF (Connolly et al., 2014).

Discussion

There were 20 floats in the CanCEBS that drifted poleward for more than 20 days, from a total of 157, indicating that the CdPU is continuous in the entire region. It shows that is coherent with the model average circulation at 800m of depth (Fig. 3) and reinforces the isolated mooring data of Barton (1989).

In the CalCEBS it is different, there are not any poleward trajectory onshore at 800m as long as in the CanCEBS due to the CalUC is upper than the CdPU. The CalUC is found at 400m of depth approximately (Thomson et al., 2010; Connolly et al., 2014).
Looking the four TS diagrams (Fig. 2) it can see that the CdPU is formed by different kinds of water masses. As occur with the CalUC, which transports PEW to the North of CalCEBS and is losing PEW concentration with increasing latitude (Thomson et al., 2010). In CanCEBS it was not known, it was though the CdPU carried the same water on all the way.

The CdPU borders the Lanzarote Passage (Fig. 3) because inside the flow is broken due to the bathymetry of the canal. Which has a maximum depth of 1200m approximately. Therefore the isobath used by the CdPU to displace it along the CanCEBS is more than the 1200m isobath. But in the Fig. 3 it was used the ideal isobath (near ~1800m isobath).

How it is shown in the OFES model, inside the CanCEBS it is been able to affirm that the CdPU is continuous. Beginning from 20°N in January and June at 800m of depth, and it becomes shallower as latitude increases in both cases.

Therefore we can affirm that the CdPU and the CalUC are not equals. Given that the core of the CalUC does not vary a lot (Connolly et al., 2014; Thomson et al., 2010), while the CdPU is created two times per year and both rise up to near the surface.

There are to have in account the exchanges of water masses both South to North and opposite. Associated to the CdPU and the other equatorward current at 800-1000m of depth. Which carry the properties of the different water masses coming from each zone (MOW, AAIW, NACW, etc.). And exchanges properties with the other water masses close to it as occur in CalCEBS (Thomson et al., 2010). These properties are very interesting from the biochemical point of view. As it is shown in several studies about the deep poleward copepods transport alongshore in the CanCEBS (John et al., 1997; Stöhr et al., 1997). In these studies the copepods can be used like tracers of the CdPU.

As happens with the CalUC, the CdPU also can generate some mesoscale structures, which can transfer the properties of this undercurrent into the North Atlantic Ocean (Huyer et al., 1998; Garfield et al., 1999).

It had never studied the possible physical phenomenon as well as we have done in this study despite there are not enough direct observations. With the results obtained using the realistic oceanic model, it appears that the main responsible of this undercurrent is the APF driven by the large scale meridional gradient (Fig. 7). Moreover, the wind stress is not one of the principal factors that force the CdPU, as it is the case for the CalCEBS, because is shallower. We attribute the depth difference between the CdPU and the California Undercurrent to the contrast in waters masses that happens in the CanCEBS but not in the CalCEBS, due to the AAIW and the MOW.
It appears that the CalUC and the CdPU despite are similar, are not equal and have not the same forcing mechanisms.

**Conclusions**

The CdPU appears twice a year at 20°N onshore between 800-1000m of depth. As time passes the CdPU reaches twice the North (44°N) at the same depth. Therefore it is been demonstrated that the CdPU is a continuous undercurrent in the entire CanCEBS’s region at 800-1000m of depth, and is biannual. Totally different with the observations of the CalUC.

The physical mechanism driving the CdPU is the APF forced by the large scale meridional gradient, and playing the wind forcing a minor role. The seasonal cycle of the large scale meridional gradient due to the solar heating causes the seasonal variability of the CdPU. The wind stress has not influence in this phenomenon like it can see in the Fig. 4.b. Similar with the CalUC (Connolly et al., 2014), however the CalUC has influence by the wind stress because is more superficial than the CdPU.
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Table 1. Main features of the numerical simulations employed. Using the same ocean model with different wind forcings: QS and NCEP (Masumoto et al., 2004).

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<th>Wind forcing</th>
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<td>NCEP</td>
<td>Monthly Jan1950-Dec2013</td>
<td>Low resolution (2.5º), smooth winds</td>
</tr>
<tr>
<td>QS</td>
<td>Monthly</td>
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Figure 1. (a) Selected Argo floats trajectories. The parking depth of the floats was 1000dbar. For reference, the 1000m isobaths is presented as a black line. The different colored arrows represent individual selected trajectories, while grey arrows represent the trajectories of all Argo floats in the CanCEBS. (b) The same before, but for the trajectories in the CalCEBS.

Figure 2. Four trajectories of the 23 available are shown in this figure. And are shown their TS diagrams, each one has a color arrow which represents whose trajectory in the map. It’s shown the typical water masses in the region in grey squares. The black dots represent the value at 1000dbar. The grey dots represent the climatology in the region. The numbers in brackets represent the number of the profiles selected in the original trajectory.

Figure 3. Represents the average velocities between August and September in the CanCEBS at 800m of depth. The light (dark) blue arrows represent velocities between 1-2 cm/s (>2cm/s). The grey (red) line represents the 1000m isobath (ideal CdPU way). Red triangle indicates mooring location.

Figure 4. (a) Shows the vertical distribution of current-meters (that actually used is colored in red). (b) Represents the annual average velocities (cm/s) given by OFES (QS and NCEP) with the real observations by the mooring in the LP, all of them at 800m of depth.

Figure 5. Represents the average velocities (cm/s) alongshore on the red trajectory shown in the Fig. 3 from the OFES-QS data at 800 m.

Figure 6. Interannual variability of the average velocity (cm/s) calculated for the CdPU inside of the LP at 800-1000m of depth, from the OFES-QS data.

Figure 7. Pressure (equivalent to m) anomaly alongshore on the red trajectory shown in the Fig. 3 from the OFES-QS data at 800 m.
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Appendix

AAIW: Antarctic Intermediate Water.

APF: Alongshore Pressure gradient Force.

CalCEBS: California Current Eastern Boundary upwelling System.

CalUC: California poleward undercurrent.

CanCEBS: Canary Current Eastern Boundary upwelling System.

CdPU: Canary deep poleward undercurrent.

EBC4: Mooring located in the Lanzarote Passage.

EBSS: Eastern Boundary upwelling Systems.

IEO: Instituto Español de Oceanografía, Spanish Institute of Oceanography.

IOCAG: Instituto de Oceanografía y Cambio Global, Oceanography and Global Change Institute.

LP: Lanzarote Passage.

MOW: Mediterranean Overflow Water.

NACW: North Atlantic Central Water.

NCEP: National Center for Environmental Prediction.

OFES: Ocean General Circulation Model for the Earth Simulator.

PEW: Pacific Equatorial Water.

QS: QuikSCAT (Quik Scatterometer).

ULPGC: University of Las Palmas de Gran Canaria.
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