

LABORATORY MODELING OF GAP-LEAPING AND INTRUDING WESTERN BOUNDARY CURRENTS UNDER DIFFERENT CLIMATE CHANGE SCENARIOS

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Western boundary currents (WBCs), such as, for example, the Kuroshio and the Gulf Stream, are very intense currents flowing along the western boundaries of the oceans. WBCs -and their respective extensions- have an important effect on climate because of their huge heat transports, the corresponding air-sea interactions and the role they play in sustaining the global conveyor belt. It is therefore very relevant to analyze WBC dynamics not only through observations and numerical modelling, but also by means of laboratory experiments; to this respect several rotating tank experiments have been performed in recent years. In this paper we describe the new laboratory experiments proposed for the Hydralab+ 19GAPWEBS project, which are aimed at analyzing the interactions of a WBC with gaps located along the western coast. Examples of such processes include the Gulf Stream leaping from the Yucatan to Florida and the Kuroshio leaping, and partly penetrating, through the South and East China Seas and through the wider gap separating Taiwan to Japan. In the experiments (that will be carried out with the 13-m diameter Coriolis rotating tank at LEGI-CNRS in Grenoble in June-July 2019) a WBC is produced by a horizontally unsheared current flowing over a topographic beta slope; along the western lateral boundary a sequence of gaps of different widths simulate the openings present in the above mentioned locations.

1. INTRODUCTION AND MOTIVATION

WBCs are very intense currents flowing along the western boundaries of the oceans and owe their peculiar structure to the sphericity of the earth, which generates the so-called planetary beta effect (e.g., Pedlosky, 1987). The Kuroshio and Gulf Stream (GS) are notable examples of WBCs belonging to the subtropical gyres of the North Pacific and Atlantic Oceans, respectively. The very important effect that WBCs -and their respective extensions- have on climate is known to be due to their huge heat transports, to the corresponding air-sea interactions and to the role they play in sustaining the global conveyor belt (e.g., Qiu, 2000, 2003; Ganopolski & Rahmstorf, 2002; Kelly et al., 2010). Some of the proposers have developed several numerical model studies with different degrees of complexity to investigate basic aspects of WBC dynamics (e.g., Dijkstra & Katsman, 1997; Schmeits & Dijkstra, 2000, 2001; Pierini, 2006, 2010, 2011, 2014, 2015; Pierini & Dijkstra, 2009; Pierini et al., 2009, 2014; Kramer et al., 2012; Quattrocchi et al., 2012).

One of the most interesting and intriguing WBC phenomena of climate relevance is the interaction of the jet with a gap located along the western coast. Examples include the GS leaping from the Yucatan to Florida, and the Kuroshio leaping, and partly penetrating through the South and East China Seas (SCS and ECS, Fig. 1a). The Kuroshio carrying the northwestern Pacific water intrudes partially into the SCS through the Luzon Strait (Fig. 1c), significantly affecting the hydrology, circulation and mixing in the SCS (e.g., Nan et al., 2015). A similar phenomenon occurs through the wider gap separating Taiwan to Japan (Fig. 1b, e.g., Liu et al., 2014).

Inferred from the satellite and in situ hydrographic data from the 1990s and 2000s, Nan et al. (2013) found that the Kuroshio intrusion into the SCS had a weakening trend over the past two decades, so that the Kuroshio loop and eddy activity southwest of Taiwan became weaker. The same authors noticed that the Kuroshio transport east of Luzon Island also had a negative trend, and suggested that this might have caused the weakening of the Kuroshio intrusion because of the

decreased inertia of the jet. A similar hypothesis was put forward also by Liu et al. (2014) to explain the observed relation between the changes of the Kuroshio intrusion across the ECS and those of the Kuroshio volume transport. To support their hypothesis, these authors invoked the rotating tank experiments of Pierini et al. (2011), in which the different but related process of WBC separation due to inertial overshooting, and its critical behavior, was investigated for varying jet intensity.

The gap-leaping and intruding WBC phenomena are manifestations of an oceanographically generic problem, i.e., that of the interaction of a boundary current with a gap along the coast. This was investigated in several observational (e.g., Centurioni & Niiler, 2004; Liu et al., 2014; Lu & Liu, 2013; Nan et al., 2013, 2015) and numerical model studies (e.g., Sheremet, 2001; Xue et al., 2004; Sheu et al., 2010).

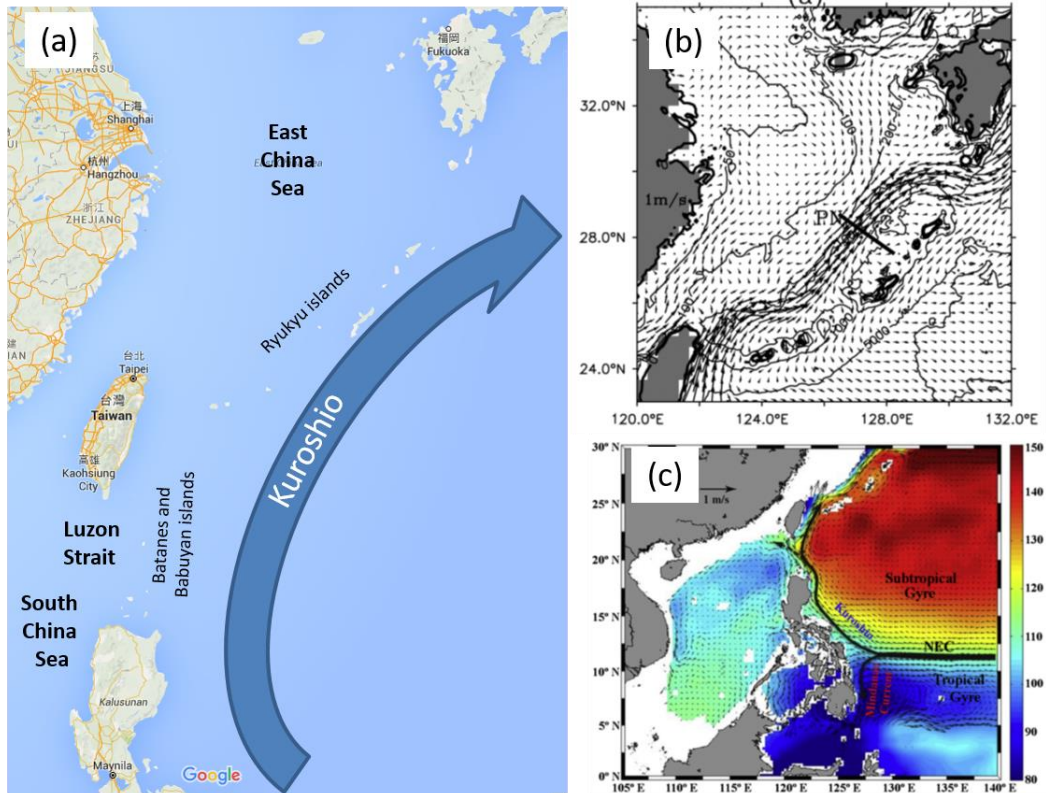


Fig. 1. (a) Schema of the Kuroshio flowing along the gaps connecting the Pacific with the South and East China Seas. Maps of the Kuroshio intrusion into the East [(b), from Liu et al., 2014] and South [(c), from Nan et al., 2015] China Seas.

Laboratory experiments were also performed in a cylindrical tank on a one-meter rotating table by Sheremet & Kuehl (2007) and Kuehl & Sheremet (2009). The great relevance of the problem calls for further laboratory experiments accounting for variations in WBC intensity related to climate change scenarios, but this requires larger scale simulations and, in turn, a larger rotating tank facility.

This motivates the present project, which is based on a substantial extension of three previous laboratory experiments performed by one of the proposers with the 13-m diameter Coriolis rotating tank of CNRS in Grenoble (Pierini et al., 1999; 2002) and with the 5-m diameter Coriolis rotating tank of SINTEF in Trondheim (Pierini et al., 2008; 2010; 2011). The proposed experiments are described in sect. 2; in sects. 3 and 4 the dynamic similarity with the full-scale phenomenon and the synergy effect with mathematical models are respectively discussed.

2. EXPERIMENTAL SETUP AND PROPOSED EXPERIMENTS

The setup proposed to study the problem described in Sect. 1 is reported in Fig. 2. A pumping system located in channel C produces a current of speed u_p that, following the lateral boundaries, generates a virtually unsheared flow at the entrance of the slope Σ_1 , which in turn provides the topographic beta-effect β^* necessary for the intensification (this imposes the use of homogeneous water).

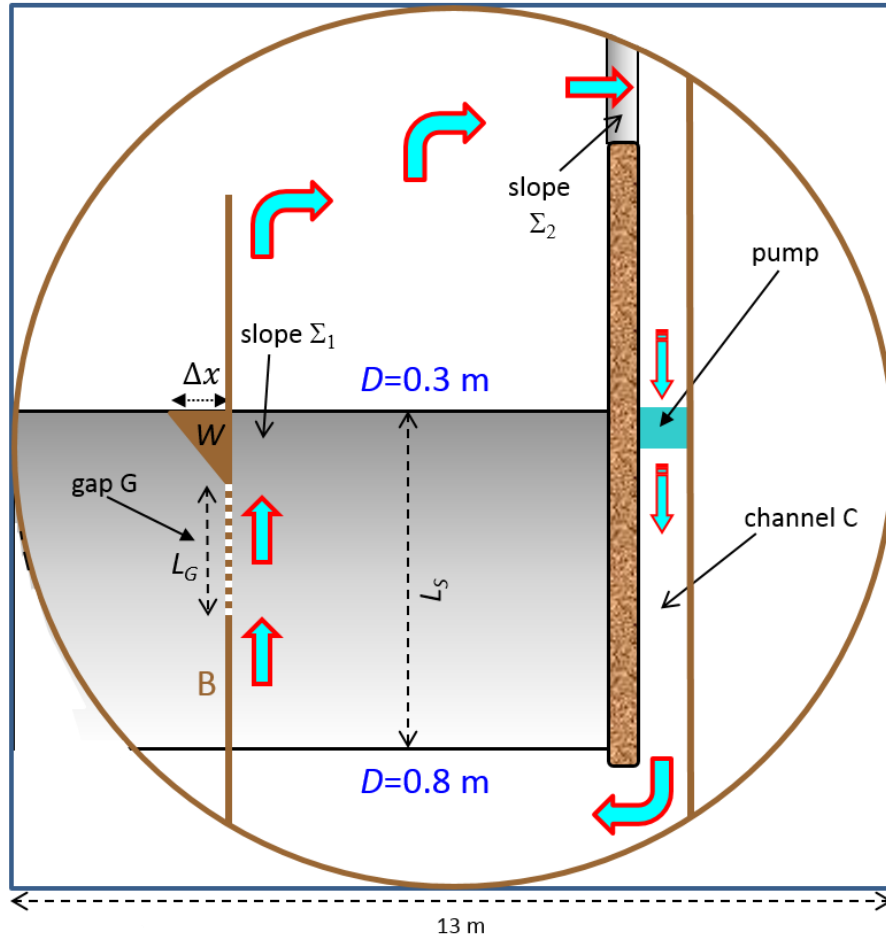


Fig. 2. The proposed setup.

This part of the setup is basically the same as the one adopted by Pierini (2008; 2011): this insures the feasibility of the project. Three substantial improvements are now present:

(i) The motion will be introduced in the channel C by a pumping system rather than through a moving piston. This will allow for experiments with, in principle, unlimited duration (and corresponding very long time series) also for strong WBCs, for which a large u_p is required (see Pierini et al., 2008, 2011, for a discussion on the limited duration of the experiments when a moving paddle is used). The large length of channel C is required to reduce the turbulence at its lower end.

(ii) The length L_S of the slope Σ_1 is $L_S = 2L_{S_old}$ (L_{S_old} is the corresponding length in the setup used by Pierini et al., 2008; 2011) while the inclination of the slope is the same (this requires the water depth to be doubled, which has also the positive consequence of reducing the effect of the free surface deformation): thus, $\beta^* = \beta_{old}^*/2$. The inertial WBC length scale $\delta_I \approx \sqrt{u_p / \beta^*}$ (see sect. 3) is therefore greater by a factor $\sqrt{2}$, so a better WBC resolution is achieved. Moreover, the parameter $\sigma = L_S / \delta_I$ measuring the effective length of the WBC is $\sigma = \sqrt{2} \sigma_{old}$: thus, a longer effective WBC is achieved as well. This will therefore allow us to obtain WBCs whose spatial resolution is the highest ever attained in rotating tank experiments. On the other hand, such high resolution is needed to study the intrusion of WBCs through the gaps: this justifies the use a large scale facility such as the 13-m diameter Coriolis rotating tank of CNRS in Grenoble.

(iii) The completely new part of the setup, specifically designed to analyze the phenomenon under investigation, includes the introduction of the gap G along the “western” boundary B . G will also include smaller gaps to represent islands (e.g., see Fig. 1a). A wedge-shaped obstacle W of width Δx simulating an island (e.g., Taiwan, see Fig. 1c) is also introduced.

Experiments will be carried out by varying: (a) the rotation period T ; (b) u_p (and so the intensity of the WBCs) by taking into account both the various dynamical ranges (see Sect. 3 of Pierini et al. 2011) and the climate change scenarios described by Nan et al. (2013); (c) the length L_G of the gap; (d) the number and width of the islands inside G ; (e) the width Δx of the obstacle W .

The measuring technique will be provided by the Particle Imaging Velocimetry (PIV) covering the area of the slope Σ_1 . The results will be published in an outstanding scientific journal, the dissemination will be provided by means of an ad hoc web site and through presentations to major international conferences and, finally, the data will be stored in a server of the principal investigator's department and will be made available through the internet to the researchers outside the research team according to the HDRALAB+ rules.

3. DYNAMIC SIMILARITY AND DIMENSIONLESS PARAMETERS

To study the dynamic similarity between the proposed experiments and the full-scale phenomenon one can rely on the evolution equation of potential vorticity in the quasigeostrophic approximation (valid for our experiments because the Rossby number ε_R for a typical simulated WBC is $\varepsilon_R \approx 0.05 \ll 1$) in its steady and dimensionless form. For this specific problem one has (Pierini et al., 2008):

$$\varepsilon(uv_{xx} - vu_{xx}) + v = Ev_{xxx} - Bv_x \quad (1)$$

Here, (x, y) and (u, v) are the dimensionless zonal and meridional coordinates and velocity components, respectively, and the dimensionless parameters

$$\varepsilon = \frac{U}{\beta \ell^2} = \left(\frac{\delta_I}{\ell}\right)^2; \quad E = \frac{A_H}{\beta \ell^3} = \left(\frac{\delta_M}{\ell}\right)^3; \quad B = \frac{r}{\beta \ell} = \frac{\delta_s}{\ell} \quad (2)$$

measure the importance of nonlinearities and lateral and bottom friction, respectively (the Reynolds number is $Re = \varepsilon/E$). U and ℓ are typical zonal velocity and length scales, β is the meridional gradient of the Coriolis parameter f (in our experiments it is given by β^*), A_H is either a constant lateral eddy viscosity coefficient in a full-scale schematization of WBCs or the molecular viscosity of water in our experiments, r is the inverse of the spin-down time due to bottom friction, and δ_I , δ_M , and δ_s represent the boundary layer length scales for purely inertial and purely viscous Munk and Stommel flows, respectively. In the derivation of (1), a boundary layer approximation has been made: x is scaled through the width ℓ of the western boundary layer and y through the meridional width L of the low-latitude region where the current flows toward the western boundary, respectively, with $\ell \ll L$ (again, see Pierini et al., 2008, for a detailed explanation; in particular see Sect. 3b, Fig. 7 and Table 2 therein, but see also Sect. 3 and Fig. 5 in Pierini et al., 2011).

The WBC scaling adopted in Pierini et al. (2008; 2011) applies to the proposed experiments as well, but with one difference: as discussed above, now $\beta^* = \beta_{old}^*/2$. From (2) one can see that the relative weights of ε , E and B do not change, nor does Re . On the other hand, the inertial length scale δ_I (the relevant one for simulated WBCs that are dynamically similar to the real ones) increases by a factor $\sqrt{2}$, with the positive consequences pointed out in Sect. 2. Typical values that will be used in the experiments are: $T = 30 \div 60$ s, $u_p = 1 \div 6$ cm s⁻¹. The width L_G of the gap G will be modified according to the WBC width ℓ .

4. SYNERGY EFFECTS WITH MATHEMATICAL MODELS

The interplay between experimental research and mathematical/numerical modeling is quite a subtle issue. As noted by Van Os (1999) in his contribution to the HYDRALAB workshop held in Hannover in 1999, in the '70s and '80s, experimental and numerical hydraulic researches were often seen as competitors; in the '90s experimental research was rather seen as supporting process research for the improvement of mathematical models, but the latter could in turn assist the experimental facility. In a more challenging approach, the integrated use of physical models, numerical models, theoretical analysis and field experiments can provide the best advancements in our understanding of the hydraulic processes under investigation. Thus, according to Van Os (1999), the real challenge is to achieve a two-way cooperation between experimental research and mathematical modeling so as "to migrate from competition to synergy".

According to this view, numerical modeling (based on the same shallow water model used by Pierini and collaborators in their studies on the Kuroshio Extension, see sect. 1) was carried out in synergy with the laboratory experiments performed to analyze Rossby normal modes (Pierini et al., 1999; 2002) and western boundary currents (Pierini et al., 2008).

Following the same approach, in the present project we will implement the Princeton Ocean Model (POM) to a domain that closely represents the experimental setup. It is worth stressing that

one of the proposers is an expert in the application of POM to coastal circulation modeling (e.g., de Ruggiero et al., 2016, 2018). In addition, numerical bifurcation studies on a discretized shallow water model will also be performed (as in Schmeits & Dijkstra, 2001) to study the possible flow patterns (versus parameters) and their variability in the laboratory configuration.

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