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Nonlinear effects on western boundary current structure and separation: a laboratory study

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The role played by nonlinear effects in shaping the structure of barotropic western boundary currents (WBCs) and in determining WBC separation from the coast has been investigated through laboratory simulations by means of the 5-m-diameter Coriolis rotating basin at SINTEF (Trondheim, Norway) in the framework of the HYDRALAB-III project of the European Commission. The laboratory setup is an extension of the one used for a previous study of highly nonlinear WBCs along a straight coast (Pierini et al. 2008) which, in turn, is a generalization of another laboratory study (Pierini et al. 2002). The setup consists of two parallel rectangular channels separated by an island and linked by two curved connections: in the first channel, a piston is forced at a constant speed u_p ranging from 0.5 to 30 mm/s over a distance of 2.5 m, producing a virtually unsheared current at the entrance of the second channel. In the latter, a linear reduction of the water depth provides the topographic beta-effect that produces the westward intensification. Nearly steady currents are obtained and measured photogrammetrically over a region of about 1 m^2. Thanks to the large size of the rotating basin, cross-stream widths of the simulated WBCs as large as 60 cm could be obtained.

The broad range of piston speeds permitted by the new mechanical apparatus has allowed us to achieve an unprecedented coverage of the range of nonlinearity for WBCs in terms of experimental data, so that the cross-stream WBC profile could be analyzed from a weakly nonlinear Munk-type case (e.g., for u_p=0.5 mm/s and T=30 s, where T is the rotation period of the basin) up to the more realistic highly nonlinear limit (particularly significant is the case u_p=10 mm/s and T=30 s, denoted as Exp. 1 below, which is close to be dynamically similar to the Gulf Stream). WBCs over shelf topography have also been modeled by adding a sloping bottom along the western boundary (those results are not shown here). Moreover, in order to analyze the process of WBC separation, coastal variations have been introduced along the western boundary in the form of wedge-shaped continents with different coastline orientations, whose northern limit corresponds to an idealized Cape Hatteras. While weak WBCs follow the coast also past the cape, for sufficiently strong nonlinear effects the current detaches from the coast as a consequence of flow deceleration induced by the interaction with the inclined western boundary. It is interesting to notice that the transition between these two behaviors is marked by Exp. 1 that, as we have already mentioned, is close to be dynamically similar to an idealized barotropic Gulf Stream.

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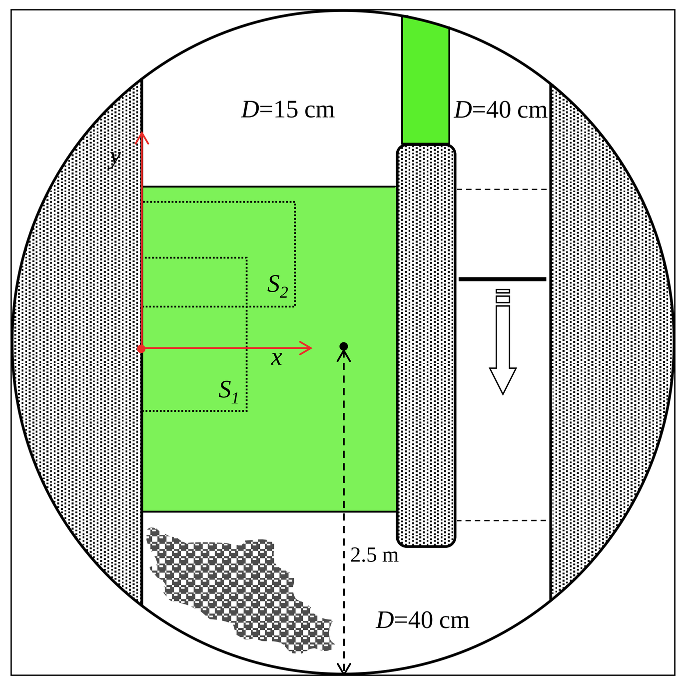
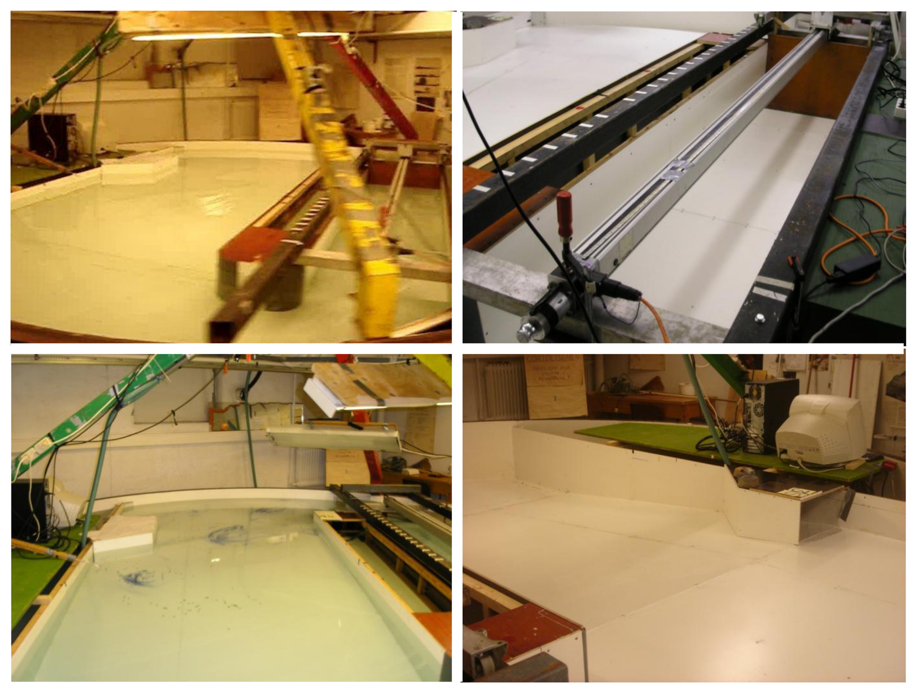




In the panel above (left) the experimental setup is shown. In the green areas bottom slopes are present. A large number of small buoys (needed for the photogrammetry measuring system) were seeded in the irregular gray area before the paddle motion started. The regions denoted S_1 and S_2 are those covered by the photogrammetry: the first one was used for the simulation of WBCs along a straight coast (with and without coastal slope), while the second was used when coastal capes were inserted. In the panel above (right) photos of the apparatus are shown.

In order to analyze the dynamic similarity between the obtained flows and real WBCs, the nonlinear evolution equation for the potential vorticity of a homogeneous layer of fluid in the quasi-geostrophic approximation can be considered. With obvious definitions of the parameters and variables it reads:

$$u\nabla^2 v - v\nabla^2 u + \beta v \cong (A_H\nabla^2 - r)(v_x - u_y)$$

and in dimensionless form:

$$\varepsilon(u' v'_{x'x'} - v' u'_{x'x'}) + v' \cong E v'_{x'x'x'} - B v'_{x'}$$

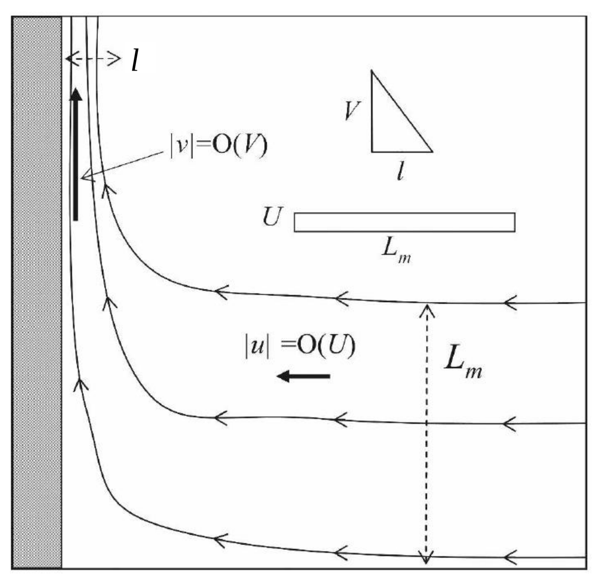
where the variables are scaled as (see the figure to the right):

$$x = lx'; \quad y = Ly'; \quad u = Uu'; \quad v = Vv'; \quad L_m \cong L/2; \quad \frac{V}{U} = \frac{L}{l}$$

and the dimensionless numbers are:

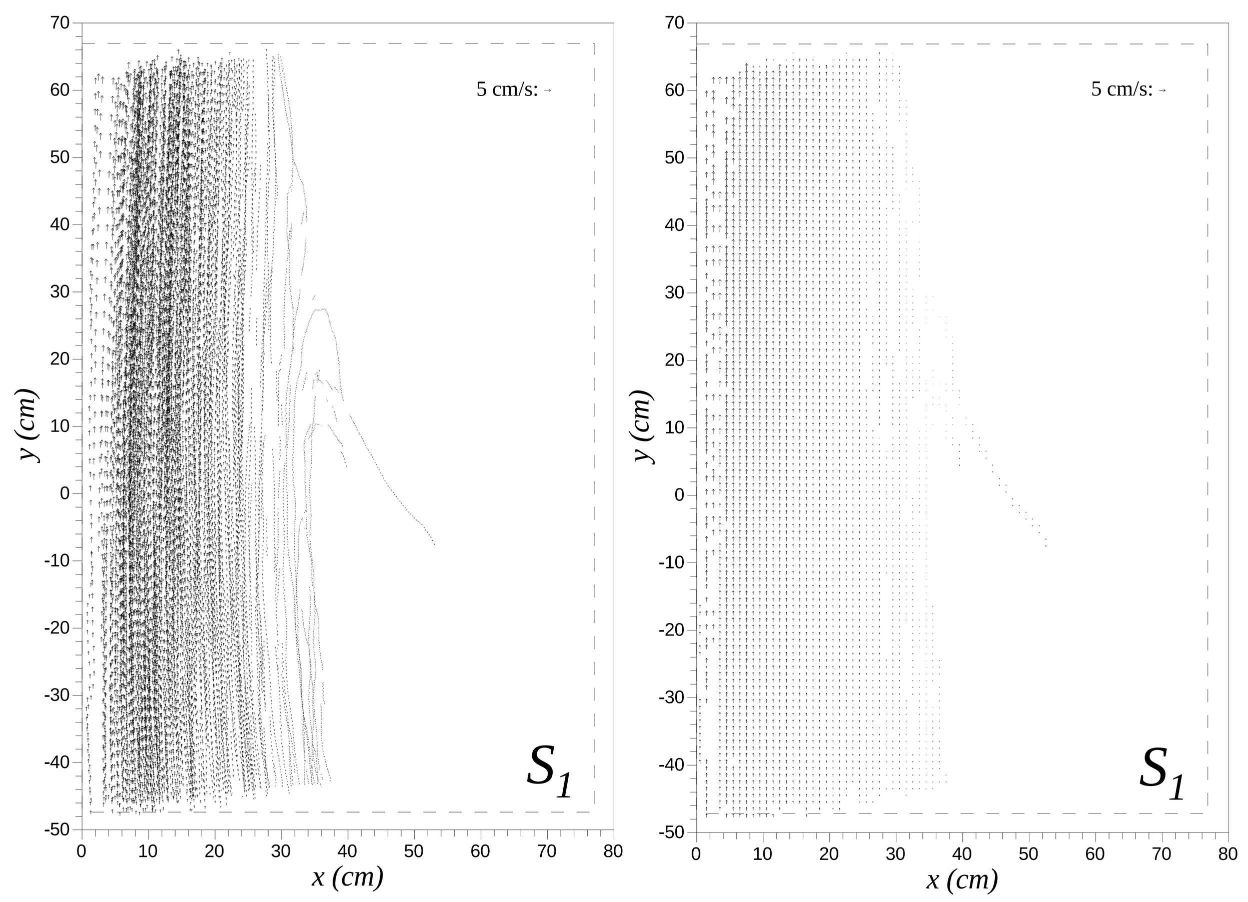
$$\varepsilon = \frac{U}{\beta l^2} = \left(\frac{\delta_I}{l}\right)^2; \quad E = \frac{A_H}{\beta l^3} = \left(\frac{\delta_M}{l}\right)^3; \quad B = \frac{r}{\beta l} = \frac{\delta_S}{l}; \quad \delta_S = \frac{\delta_E f_0}{2D\beta}; \quad \delta_E = \left(\frac{2A_v}{f_0}\right)^{1/2}$$

$$\delta_I = \left(\frac{U}{\beta}\right)^{1/2}; \quad \delta_M = \left(\frac{A_H}{\beta}\right)^{1/3}$$



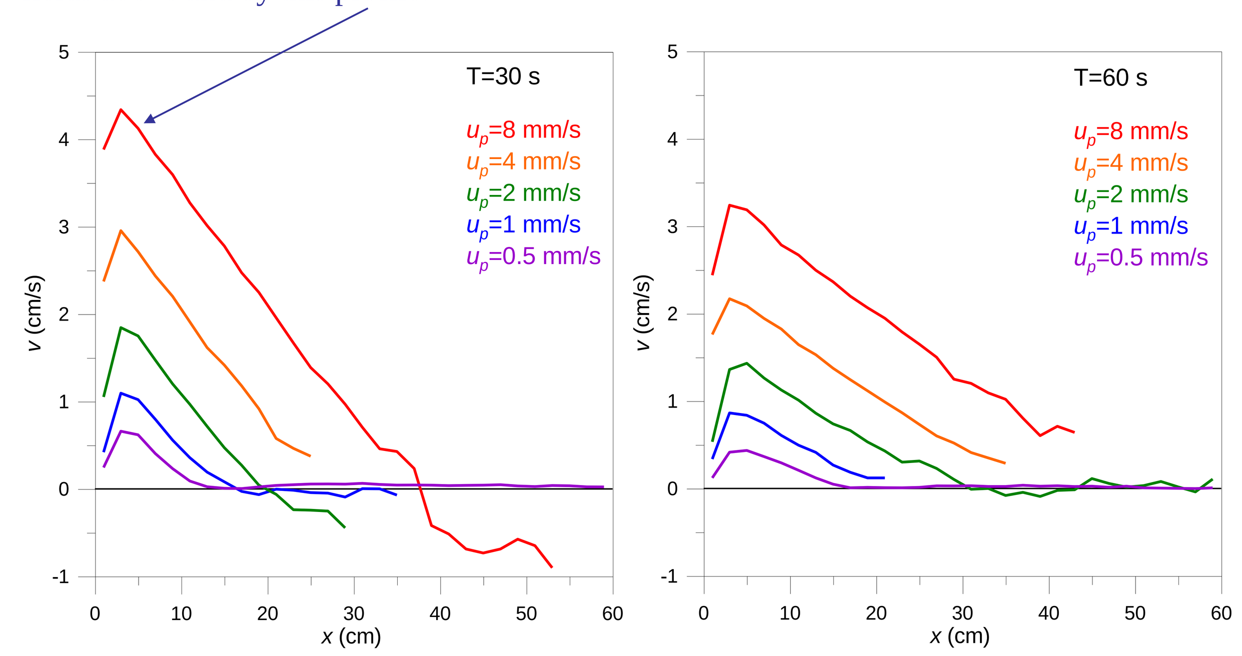
The table to the right shows 3 cases. GS stands for "*Gulf Stream*", while Exp. 1 is a highly nonlinear inertial WBC produced in the laboratory which is dynamically similar to GS (except for the frictional sublayer near the wall). In other terms Exp. 1 is a correct laboratory reference of full-scale WBCs. DSGS stands for "*dynamically similar Gulf Stream*": this flow is fully dynamically similar to the Gulf Stream, and was simulated numerically by Pierini et al. (2008).

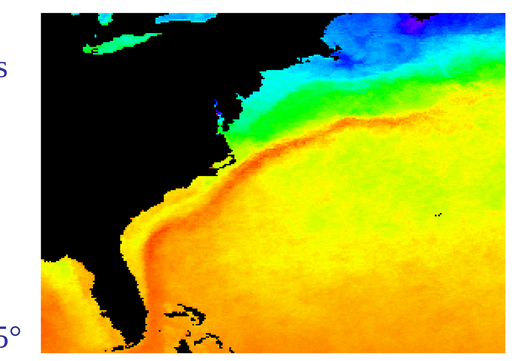
Parameters	GS	**Exp. 1**	DSGS
		Basic parameters	
l	100 km	0.5 m	0.5 m
L_m	1000 km	0.7 m	0.7 m
V	1 m s^{-1}	2.8 cm s^{-1}	2.8 cm s^{-1}
U	5 cm s^{-1}	1 cm s^{-1}	1 cm s^{-1}
A_H	100 m^2 s^{-1}	10^{-6} m^2 s^{-1}	10^{-4} m^2 s^{-1}
β	2 × 10^{-11} rad m^{-1} s^{-1}	0.14 rad m^{-1} s^{-1}	0.14 rad m^{-1} s^{-1}
		Derived length scales	
δ_I	50 km	27.00 cm	27.00 cm
δ_M	17 km	1.90 cm	8.90 cm
δ_S	—	1.10 cm	—
δ_E	—	0.22 cm	—
		Derived dimensionless parameters	
ε	2.5 × 10^{-1}	2.8 × 10^{-1}	2.8 × 10^{-1}
E	5.0 × 10^{-3}	5.7 × 10^{-5}	5.7 × 10^{-3}
Re	50	5000	49
B	—	2.3 × 10^{-2}	—



In the panels above an example (T = 30 s, u_p= 8 mm/s) of velocity data obtained in the area S_1 by the photogrammetry system during a whole experiment with a straight vertical wall are shown. In the left panel the vectors are irregularly distributed, since they correspond to instantaneous locations of particles. In the right panel the data are interpolated on a regular grid of mesh size dx=1 cm.

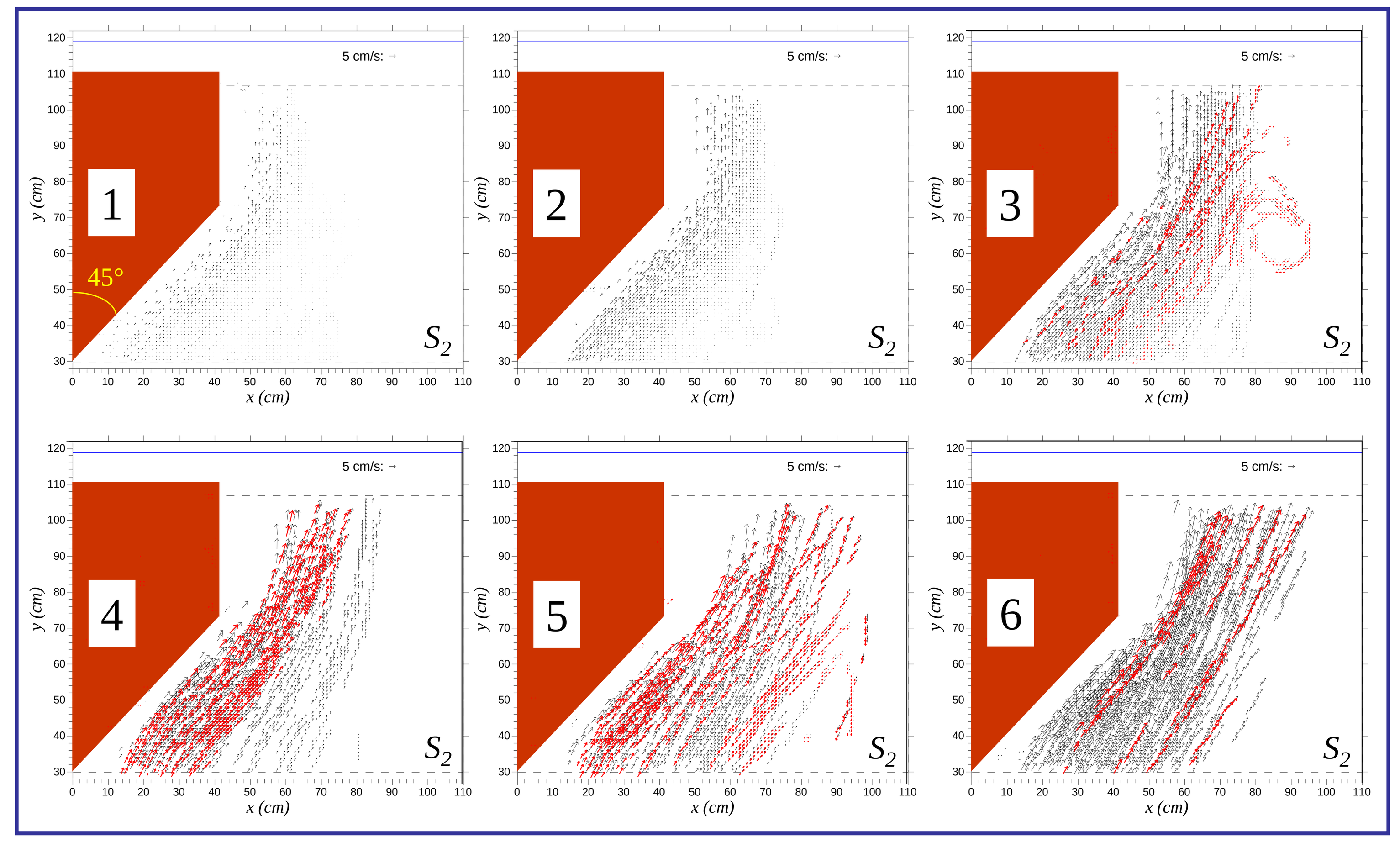
In the panels below, the zonal profiles of the meridional velocity averaged along y are shown for two rotation periods (T=30 s, left, and T=60 s, right) and for five different intensities of paddle speed (u_p = 8, 4, 2, 1, 0.5 mm/s). The strongest flows are highly nonlinear inertial WBCs while the weakest flows (u_p = 1, 0.5 mm/s) are weakly nonlinear Munk-type WBCs. In the previous experiment (Pierini et al. 2008) only the strongest flows could be modeled. In these new experiment an improved mechanical apparatus has allowed us to reach the weakly nonlinear limit as well. As discussed in the panel on the left, a correct laboratory reference of a full-scale idealized barotropic Gulf Stream is represented by the case shown in the velocity fields above and by this profile:



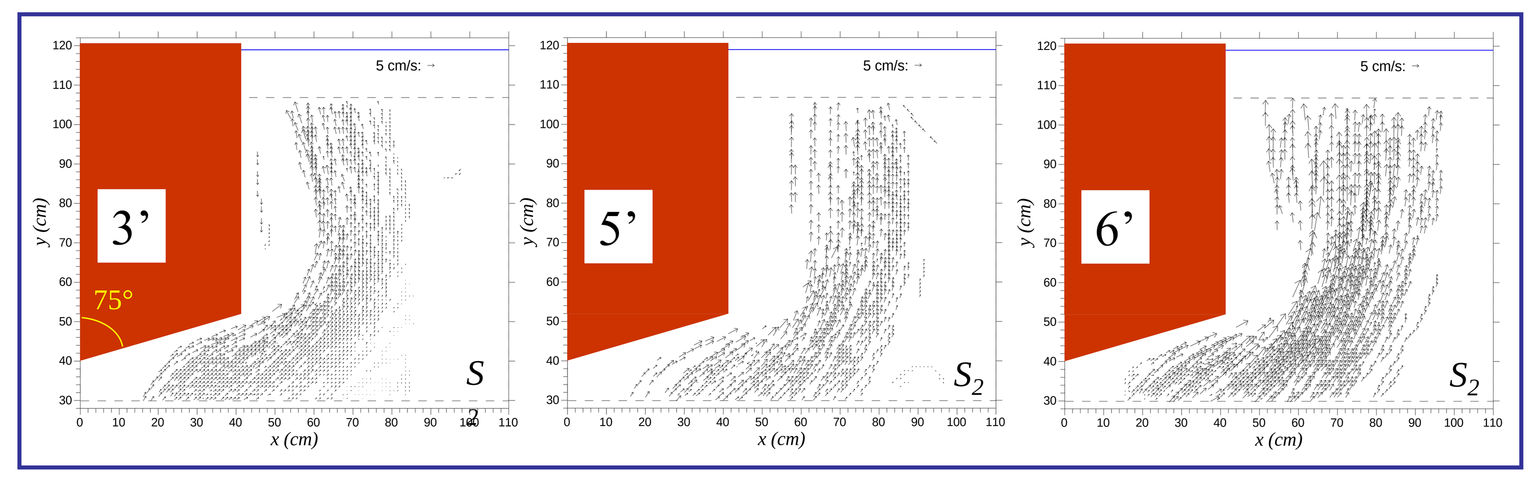


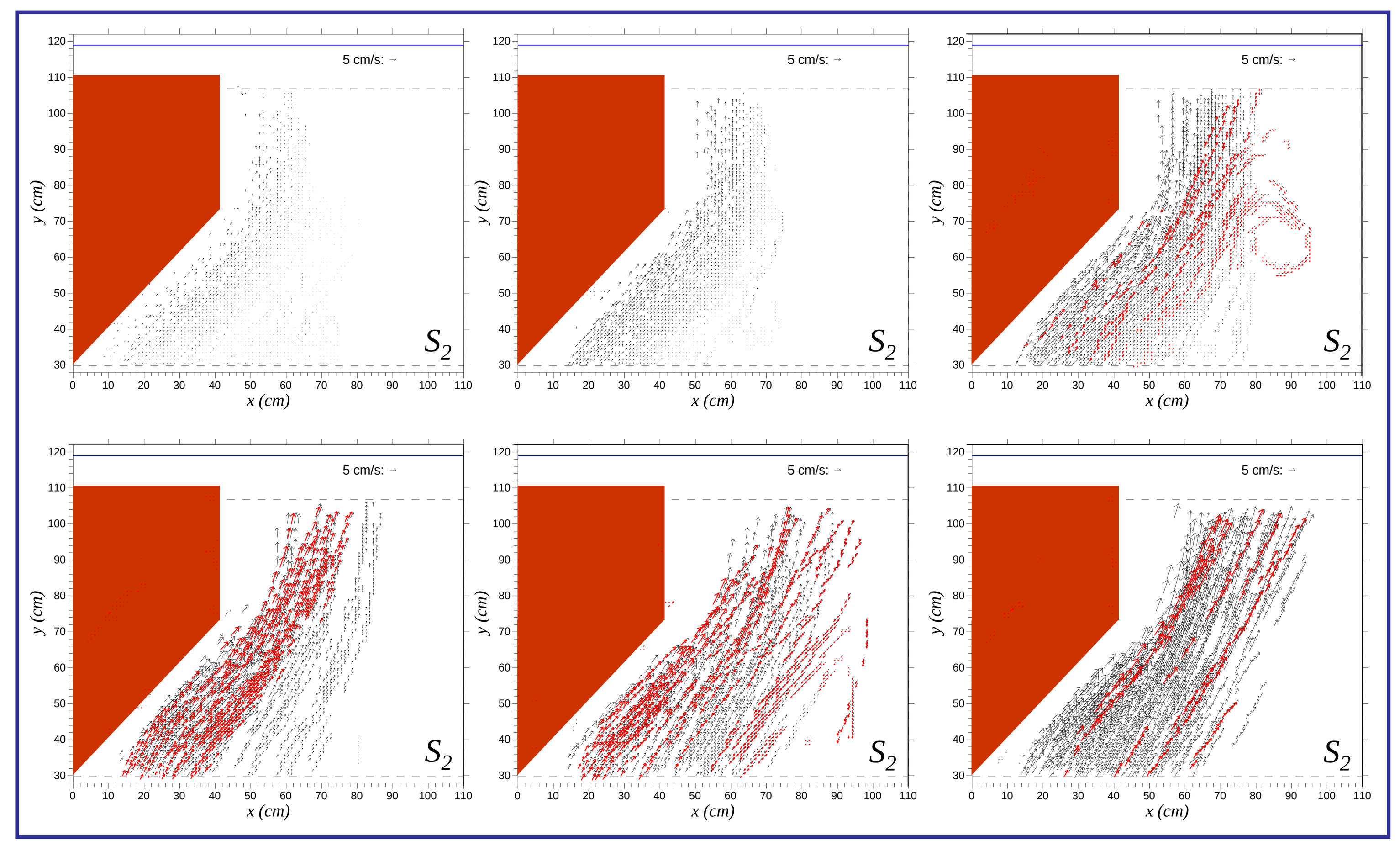
The experiments with wedge-shaped continents have been performed in order to investigate the separation of WBCs from a cape. The interest in this problem was raised by recent numerical model studies on the low-frequency variability of the Kuroshio Extension (Pierini 2006; 2008). In particular, Pierini (2008) analyzed the crucial role played by the shape of the Japanese coastline in producing a KE jet in substantial agreement with observations. Here we focus on the analogous process occurring for the Gulf Steam past Cape Hatteras.

In the 6 panels below the flows along an inclined wall that forms an angle φ = 45° with the western boundary are shown. Cases 1 through 6 refer to u_p = 2.5, 5, 10, 15, 20, 30 mm/s, respectively (T = 30 s); the blue line indicates the limit of the topographic beta effect. The red arrows are the velocities measured during the final part of the experiment, when the steady state is fully achieved. It is interesting to notice that the separation occurs from case 3, which corresponds to a dynamically similar Gulf Stream.

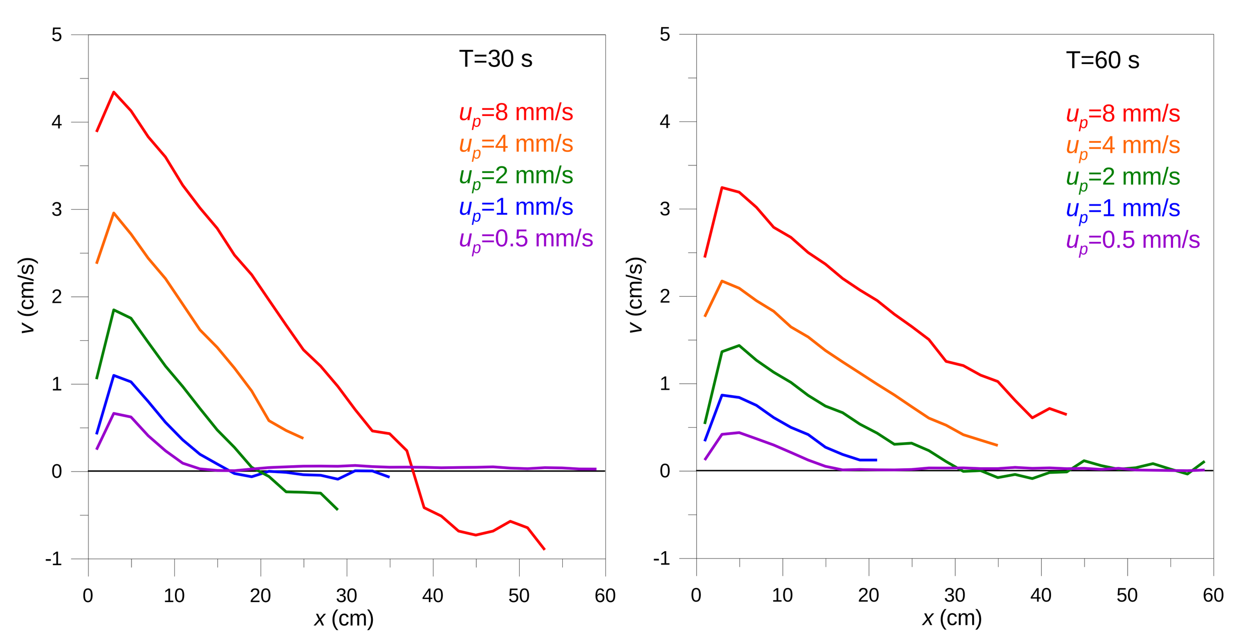


In the 3 panels below, experiments 3, 5 and 6 are replicated with a different continent (now φ = 75°). The increased angle prevents separation. An analysis of these results, and of many others not shown here, is being carried out on the basis of theoretical considerations (e.g., Marshall and Tansley 2001; Munday and Marshall 2005) with the aim of getting a deeper understanding of the processes that determine WBC separation from an inclined western boundary.

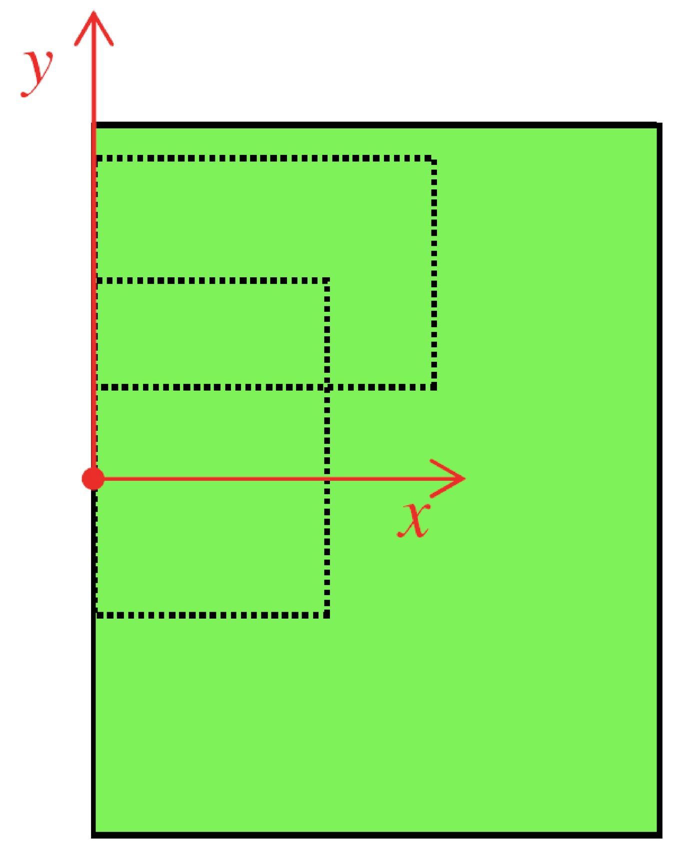


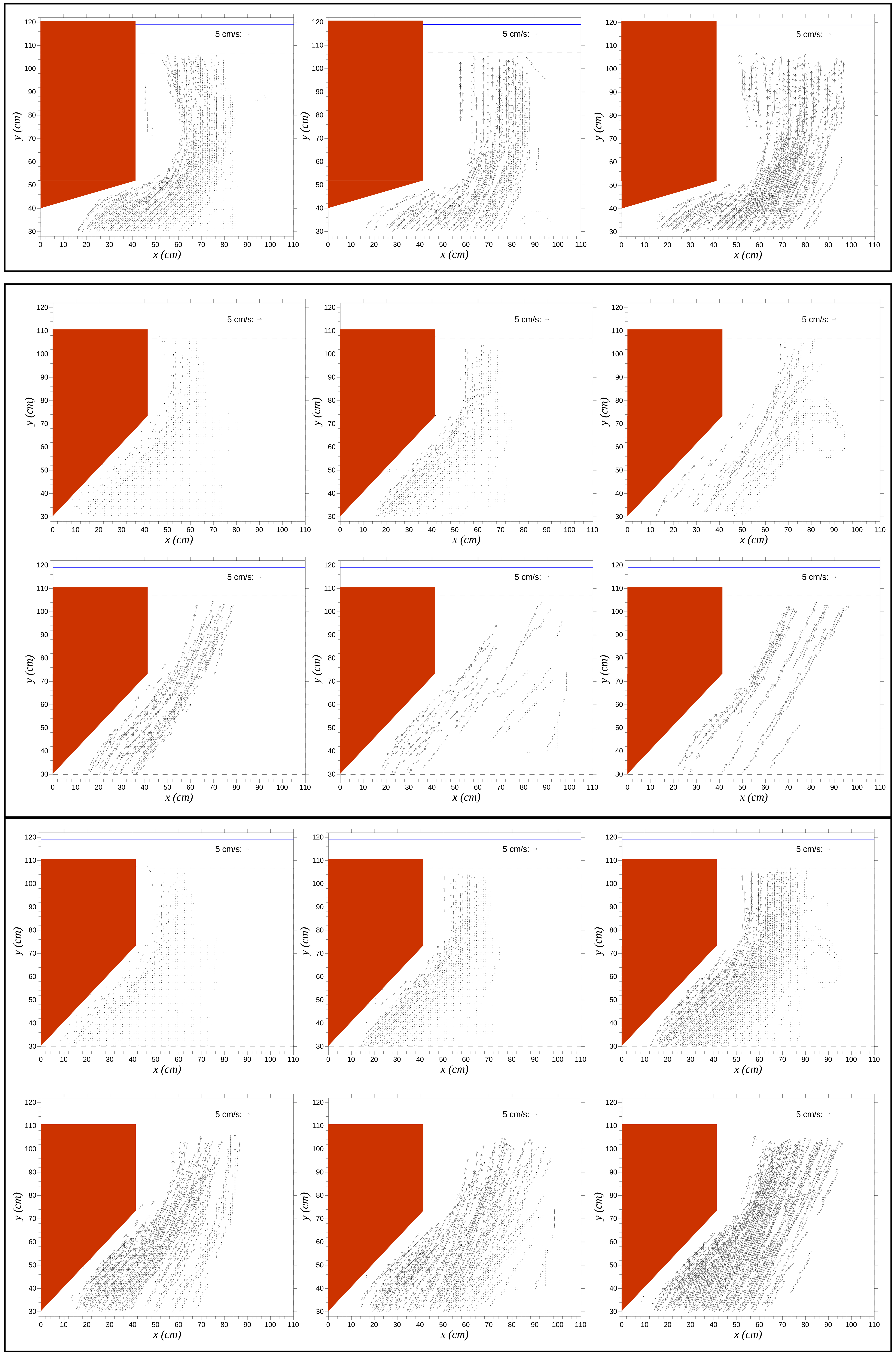


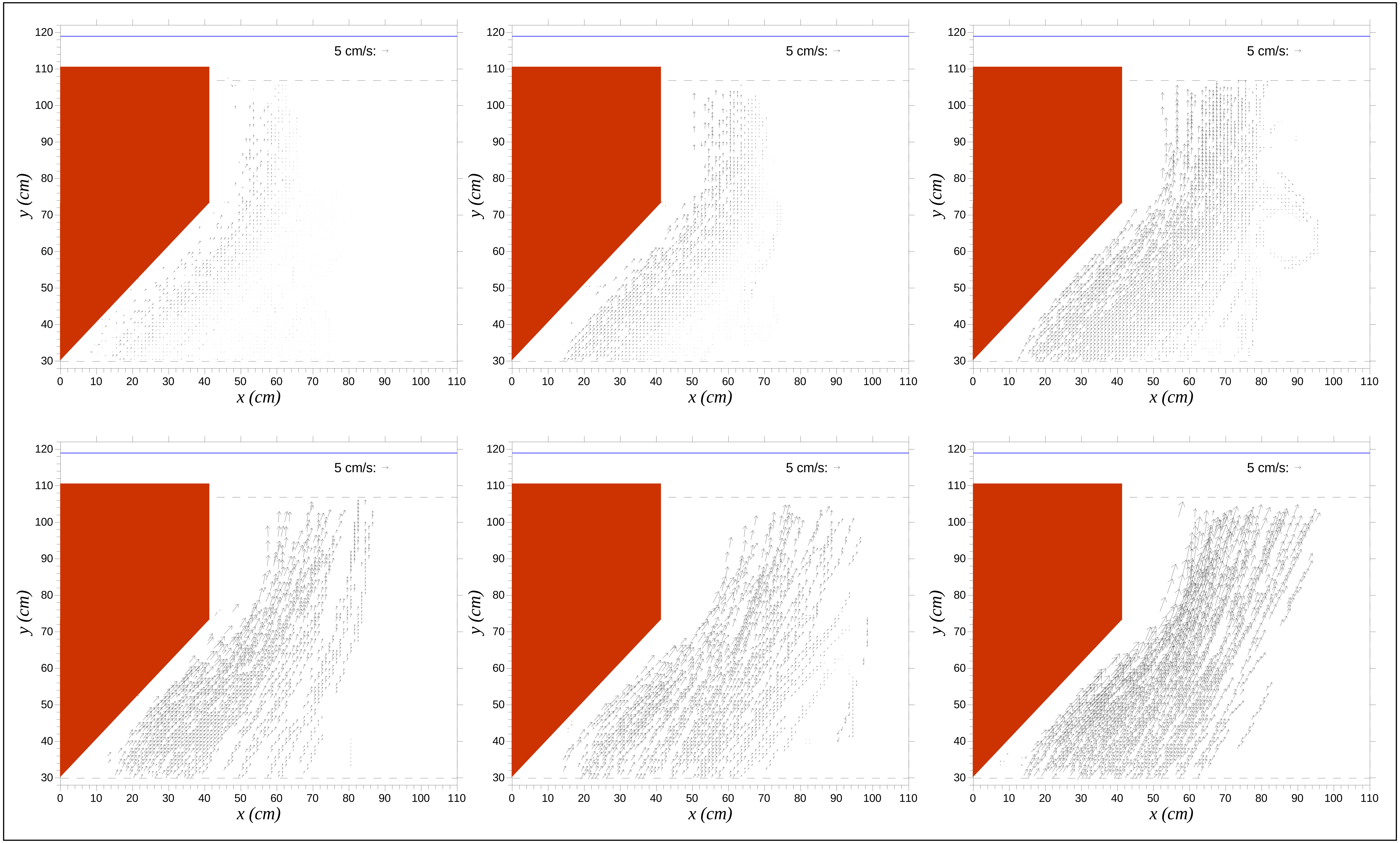
5 cm/s:
y (cm)
x (cm)
S_2



T=30 s
u_p=8 mm/s
u_p=4 mm/s
u_p=2 mm/s
u_p=1 mm/s
u_p=0.5 mm/s
v (cm/s)
x (cm)
T=60 s
u_p=8 mm/s
u_p=4 mm/s
u_p=2 mm/s
u_p=1 mm/s
u_p=0.5 mm/s
v (cm/s)
x (cm)


y
x


5 cm/s:
x (cm)
y (cm)



5 cm/s:
y (cm)
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