The Role of Fine-Scale Winds in Upwelling and Coastal Circulation in the Southern Benguela Upwelling System

Raquel Flügel[1], Giles Fearon[2], Steven Herbette[1], Anne Marie Treguier[1], Jennifer Veitch[2]

1 University of Brest, LOPS, IUEM, Plouzane, France, 2 South African Environmental Observation Network, Egagasini Node, Cape Town, South Africa

Abstract

and vote!

What?

We use a regional numerical model to assess the impact of fine-scale wind on upwelling and the local circulation. This is done in an embayment in the Southern Benguela Upwelling System, where the wind shadow and wind stress curl have a high impact on local upwelling dynamics and oceanic currents. Results show that the decrease in coastal upwelling associated to wind drop-off is not compensated by the increase of vertical Ekman pumping associated to the wind-stress curl. This likely plays a role in the establishment of an intermittent poleward current.

Why?

St. Helena Bay, the most productive embayment of the Benguela upwelling system, is regularly subject to harmful algae blooms and anoxic conditions. These are hypothesised to be generated by the retention and restratification of upwelled water in the bay which follows a relaxation of upwelling favorable winds. Improving the representation of upwelling and hence predictability of bloom generation requires a high-resolution ocean model, capable of reproducing ocean currents and fine scale processes associated to vertical mixing (Flügel et al., 2025). As fine-scale wind variability is often thought to have a strong impact in shallow-waters, one may wonder about the gains of using high-resolution atmospheric models when forcing a regional ocean model. This study wishes to understand how the wind drop off and the resulting cyclonic wind-stress curl affect the dynamics of St. Helena Bay.

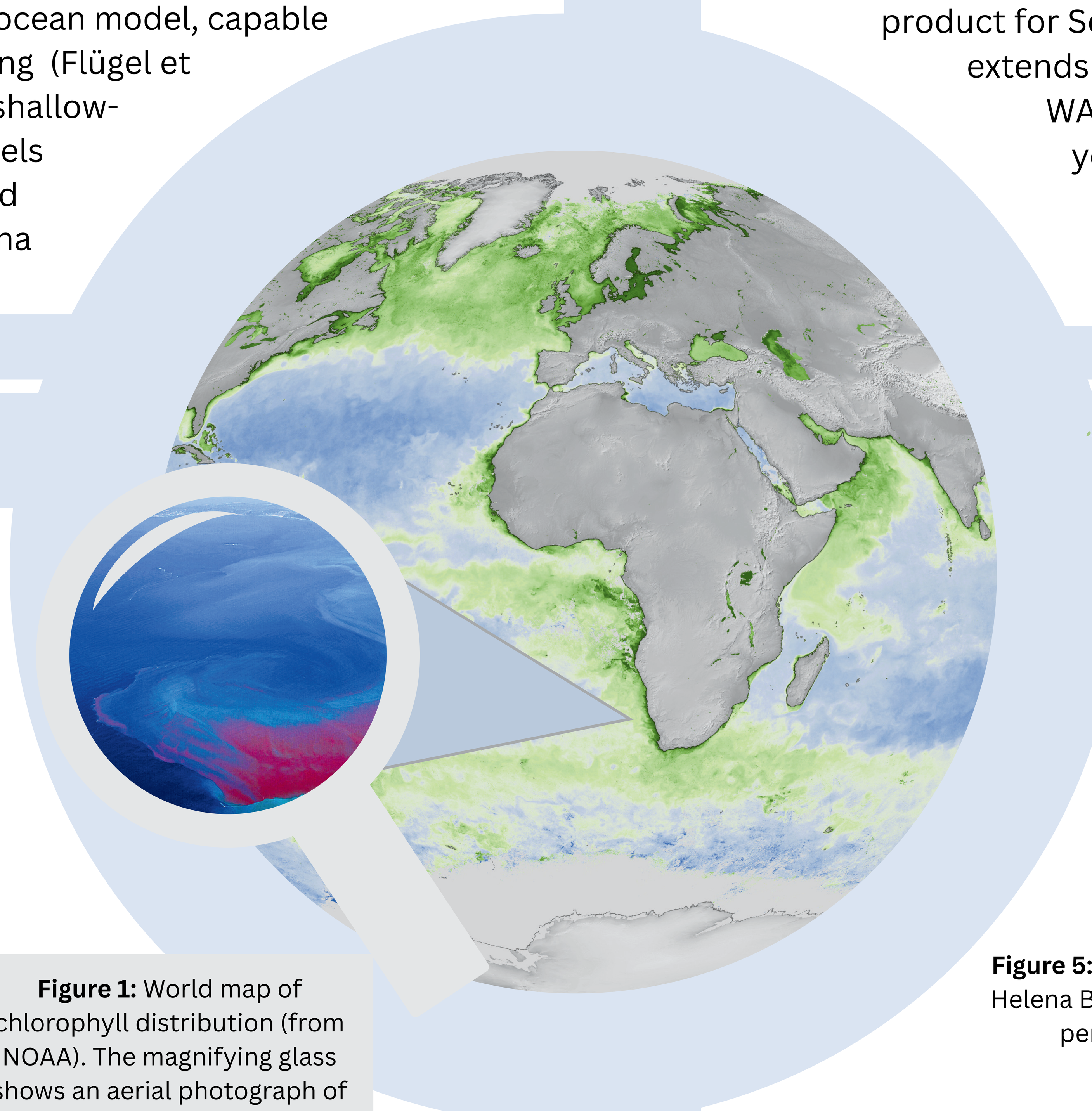

Figure 1: World map of chlorophyll distribution (from NOAA). The magnifying glass shows an aerial photograph of a harmful algae bloom in the Southern Benguela Upwelling System (Pitcher et al., 2008).

How?

We created a high-resolution curvilinear grid embedding the St. Helena bay region of the Southern Benguela Upwelling System (Figure 2) and ran two simulations using the CROCO regional ocean model. The two simulations only differ from their wind forcing:

- one is forced by ERA5 winds with a **30 km** resolution
- one is forced by WASA3 winds with a **3 km** resolution

The latter comes from a refined WRF model which has been forced with ERA5 in order to create a high-resolution wind product for South Africa. The ERA5-forced simulation extends over 27 years (1993-2020), whereas the WASA-forced simulation only covers a five year period (2009-2014). The 2009-2014 period common to both models is used for the subsequent analyses.

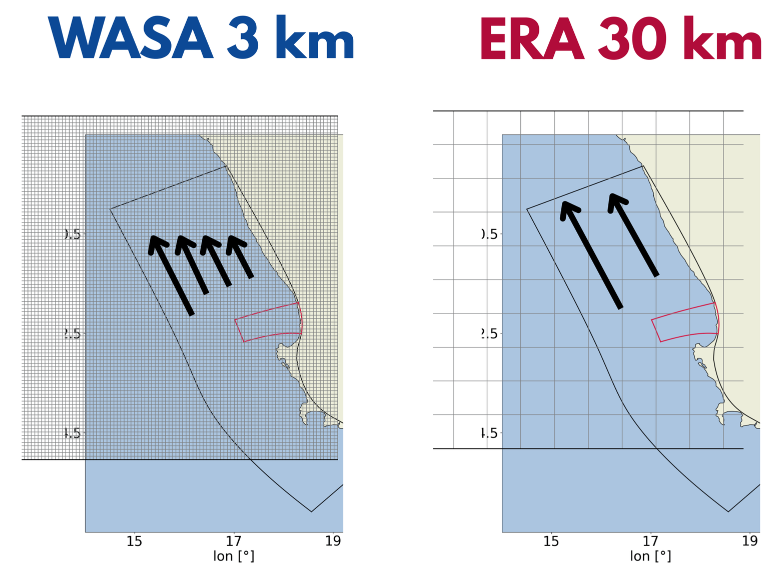

Figure 2: Schematic view of the cross-shore structure of the upwelling favorable winds (black arrows) in the St Helena Bay region in a high (left)/low (right) resolution atmospheric model (WASA/ERA). Extension of the oceanic model is superimposed (black solid), as well as the sub-region used for estimating the upwelling (red solid).

Wind drop-off and upwelling

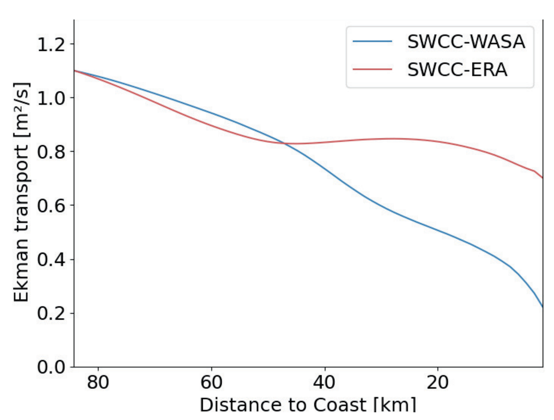

Figure 3: Seasonal mean summer Ekman transport along a cross-shore transect in St. Helena Bay (red solid contours in Figure 2).

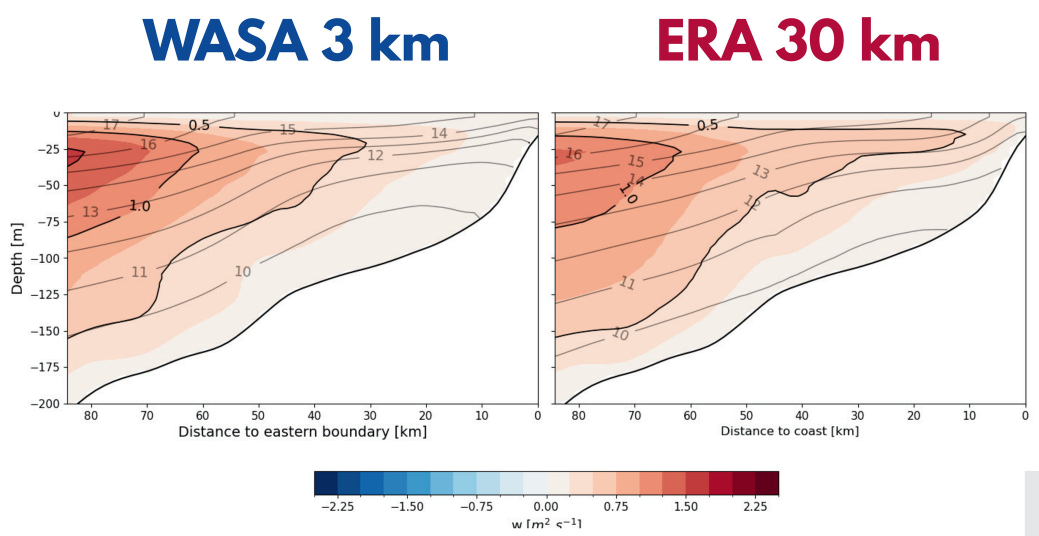

Figure 4: Integrated vertical transport from the coast over the upwelling region, averaged over the St. Helena Bay region (red region in Figure 2). Grey contours show the isotherms.

Both models simulate a similar linear drop-off of the along-shore upwelling favorable winds, which leads to a 33% decrease of the Ekman transport between 100 km and 50 km offshore (Figure 3). Then, within the 50 km width coastal-band, the high-resolution atmospheric model (WASA) simulates a much more pronounced drop-off than ERA. While in WASA there is a 75% decrease of the wind-intensity, the intensity of the upwelling alongshore wind stress remains almost constant in ERA. As expected, weaker upwelling favorable winds in the coastal zone result in the presence of more stratified waters in the WASA than in the ERA forced simulation. Stronger values of offshore Ekman transport in the latter lead to increased upwelling on the inshore side of the bay, in turn leading to cooler temperatures. This is illustrated by the structure of the coastal upwelling cell here represented in Figure 4. However, a less intuitive phenomenon is also observed, consisting in the offshore intensification of the upwelling cell in the WASA run. Previous studies (Albert et al., 2010) have attributed the offshore intensification of vertical transport to enhanced cyclonic wind stress curl associated to the drop-off. However, the cross-shore upwelling profile in the two simulations is very similar.

Wind drop-off and coastal currents

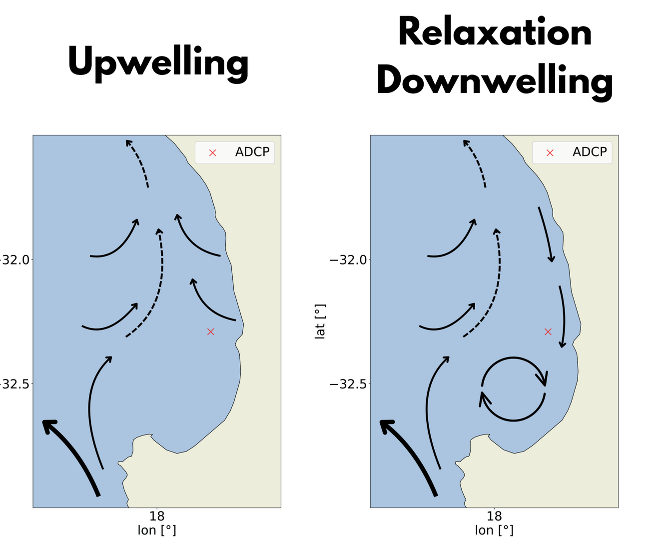

Figure 5: Schematic representation of the circulation in St. Helena Bay during upwelling favorable and wind relaxation periods, concept from Pitcher & Jacinto, 2019.

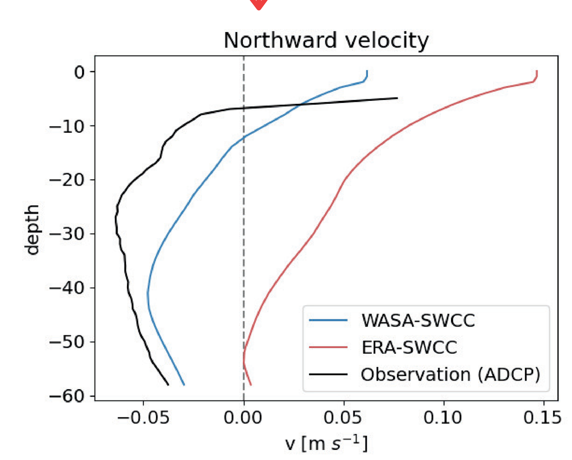

Figure 6: 2-month average (16/02/2011 - 13/04/2011) northward component of the current velocity in St. Helena Bay from in situ ADCP measurements (solid black) and the 2 two simulations described above.

Upwelling favorable conditions are expected to lead to a large-scale equatorward transport by the Benguela jet on the west of the bay, and a smaller but consistent equatorward current along the coast. The relaxation of upwelling favorable winds is hypothesized to lead to a cyclonic recirculation and the development of a poleward current close to the coast - a phenomenon also observed in the California upwelling system during periods of wind relaxation. There, this current is induced by a meridional pressure gradient that slowly builds up during upwelling favorable conditions. When the equatorward wind relaxes, this pressure gradient is no longer in geostrophic balance with the onshore geostrophic flow, resulting in a poleward current. However, in situ current measurements from an ADCP, moored in the coastal region of St. Helena Bay at the end of the upwelling season, show a quasi-permanent poleward flow beneath the surface that episodically outcrops at the surface (Figure 6). This may suggest that, in St. Helena Bay, the upwelling favorable winds could actually act as the drivers of a surface equatorward current that superimposes over the underlying poleward current.

What next?

Mapping the mean state of circulation in St. Helena Bay is a first step in understanding and hence improving the predictability of retention and recirculation in the bay. In order to link the physical dynamics to bloom retention we need a further comprehension of the:

- Spatial structure of the poleward flow
- Its seasonal and intra-seasonal variability
- Synoptic events that lead to a surface poleward flow

References

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