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Shelf-edge jet currents in the southern Benguela: A modelling approach

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ABSTRACT

The dynamics and seasonal variability of jet currents on the southern Benguela shelf-edge are investigated using a climatologically forced Regional Ocean Modelling System (ROMS) model. The jet is primarily forced by the intense horizontal gradients that exist across the southern Benguela shelf. These gradients are set up by nearshore cooling via the strongly seasonal upwelling regime and variable offshore warming by the advection of Agulhas waters. While the nearshore cooling is prevalent only during the spring and summer upwelling season, the offshore warming exists throughout the year. As a result intensified geostrophically adjusted currents exist throughout the year, particularly off the Cape Peninsula and Cape Columbine. However, the distinct shelf-edge jet features are most intense during upwelling seasons and extend, more or less continuously, from Cape Agulhas, the southern-tip of the continent, to Cape Columbine. The spring and summer jet off the Cape Peninsula reaches speeds of at least 0.7 m.s $^{-1}$, bifurcates as it moves northward. The branch that continues northward over the shelf goes on to feed the offshore branch of the Cape Columbine jet (over the 500 m isobath) and to a less extent the nearshore branch (over the 200 m isobath) that is locally enhanced by upwelling processes. During winter, the Cape Peninsula jet is more confined to the shelf region and goes on to feed the whole outer-shelf (200–500 m) region off and beyond Cape Columbine. An ageostrophic component associated with offshore non-linearities related to Agulhas influx causes the mean manifestation of the Cape Peninsula jet to broaden slightly (60 km) compared to its 40 km-wide geostrophic core which is situated over the 350 m isobath. The ageostrophic component is related to the generation of eddies that cause the isopycnals to flatten out.

1. Introduction

The intense jet currents over the shelf between the Cape Peninsula and Cape Columbine, variously known as the Goodhope jet or the Benguela jet, have been extensively studied over the years due to their role in transporting sardine and anchovy eggs and larvae from their spawning ground on the Agulhas Bank to their nursery area in St. Helena Bay ((Shelton and Hutchings, 1982), (Fowler and Boyd, 1998)). More recently, Stenevik et al. (2008) concluded that two different hake species also use the jet current for the transport of fish eggs and larvae. After the spawning of eggs, they need to be entrained into the jet current where they hatch on the way to their nursery ground (Mullon et al., 2003). Therefore, to ensure successful recruitment there needs to be a coupling between the hatching of eggs and the jet current. The shelf-edge jet currents are thus crucial to the successful fishing industry off the South African west coast.

Given the intense horizontal gradients in the region the jet was anticipated and later discovered by Bang and Andrews (1974) and has been described by Shannon and Nelson (1996) as a convergent NW-oriented current system on the western Agulhas Bank that funnels into the west coast and bifurcates at Cape Columbine into an offshore and alongshore component. It is 20–30 km wide, has characteristic speeds of 0.5 m.s $^{-1}$ and is located over the steep shelf in the region. While Nelson and Hutchings (1983) observed that the jet is permanently present, irrespective of wind conditions, Boyd and Nelson (1998) found that the highly seasonal coastal upwelling regime (intense upwelling in austral summer) plays a key role in its location and intensity, which can reach speeds of 0.5 –0.75 m.s $^{-1}$ (Boyd and Oberholzer, 1992) during the peak upwelling season. Huggett et al. (1998) confirmed that the speed of the jet is dependent on the strength of upwelling favourable

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winds and van der Lingen and Hugget (2003) noted that it exists between the 200–500 m isobaths and frequently varies between them. From satellite altimetry, Strub et al. (1998) similarly noted a seasonal strengthening of the jet, which they associated with the injection of water of high steric heights, via Agulhas influx on the offshore side of the jet and upwelled water on the inshore side of the jet and that it is strongest and closest to the coast during the upwelling season. The enhancement of the jet by the Agulhas influx was corroborated in a model experiment by Veitch and Penven (2017) who compared the model-derived jets in a simulation with and without the influence of the Agulhas. Due to the relevance of the jet in the recruitment of sardine, anchovy and hake the SARP (sardine and anchovy recruitment program) monitoring line was established in 1995, extending 55 km southwestward off the Cape Peninsula, taking measurements once a month if possible. While the data provides useful insight into the general characteristics of the jet, a seasonal cycle is difficult to establish given that data was not collected for all months (at least 2 months per year are missing and not always the same months) and that each transect represents a pseudo- 'snapshot'. Despite this, the *in situ* data shows that the jet is deep, situated at the shelf-edge and has typical speeds of about 0.75 $m.s^{-1}$ during summer and is broader and shallower with speeds of about 0.5 $m.s^{-1}$ during winter (Butler, 2012). Fig. 1 shows the meridional and zonal currents along the SARP line for 30 November 2015 and, a day later on 1 December 2015. An intense, 40 km wide, northwestward current is clearly evident in the vicinity of the shelf-edge, the core of which is centered over the 350 m isobath. It almost reaches the bottom, but narrows and weakens with depth. Inshore of the jet is a barotropic alongshore poleward current that was also observed by Nelson (1985). A day later, the shelf-edge jet feature has diminished significantly and the nearshore barotropic poleward flow has taken on a more westward component. While the *in situ* data gives us an idea of the intensity and location of the jet as well as the fact that it can significantly diminish within a day, it fails to provide a spatial or temporal context. In this paper we make use of a climatological model experiment in order to investigate the dynamics and seasonal variability of the shelf-edge jets between the Cape Peninsula and Cape Columbine. The role of Agulhas influx on the jet currents is addressed by making use of a model experiment in which the impact of the Agulhas has been effectively removed from the Benguela system (refer to Veitch and Penven (2017) and Chang (2009)), an analysis of the cross-shelf heat budget for both simulations (with and without the Agulhas) allows for a better understanding of the development of the intense cross-shelf thermal gradient associated with the jet currents and the Ichthyop Lagrangian transport tool (Lett et al., 2008) is used to better visualize jet bifurcation and the connectivity between the jets off the Cape Peninsula and Cape Columbine.

2. Data and methods

2.1. Hydrodynamic model configuration

The Regional Ocean Modelling System (ROMS) is a split-explicit, free-surface, topography-following vertical coordinate model that is well suited for regional applications (Shchepetkin and McWilliams, 2005, 2008; Haidvogel and Beckmann, 1999). It solves the incompressible primitive equations based on the Boussinesq and hydrostatic approximations and is coupled to advection-diffusion schemes for potential temperature and salinity as well as a non-linear equation of state for density. The advection scheme is third-order upstream biased, which reduces dispersion errors, essentially enhancing precision for a given grid resolution (Shchepetkin and McWilliams, 1998). However, the implementation of the third-order advection-diffusion scheme has lead to the development of spurious diapycnal mixing in sigma-coordinate models. A solution to this problem was addressed by Marchesiello et al. (2008) and involves the split of advection and diffusion, the latter of which appears as a biharmonic operator. This solution was implemented in our configuration in order to preserve the low diffusion and dispersion benefits of the original scheme while maintaining water mass characteristics. Explicitly prescribed lateral viscosity is zero everywhere except in sponge layers at open boundaries, where it increases smoothly toward the edge of the domain. Open boundary conditions of the parent domain are a combination of outward radiation and nudging toward prescribed external boundary conditions and are described by Marchesiello et al. (2001). Subgrid-scale vertical mixing is introduced by the nonlocal K-profile parameterization (KPP) scheme (Large et al., 1994). The bottom boundary layer is generated by a KPP bottom drag. The bottom friction coefficient is calculated through the use of a logarithmic boundary layer formulation with a bottom roughness of 10 cm.

In order to maximize computing efficiency, the Adaptive Grid Refinement in Fortran (AGRIF) two-way nesting capability (Debreu et al., 2008) of ROMS was employed in which the boundaries of a higher resolution child domain are provided by a lower resolution parent domain within which the child is embedded. The two-way

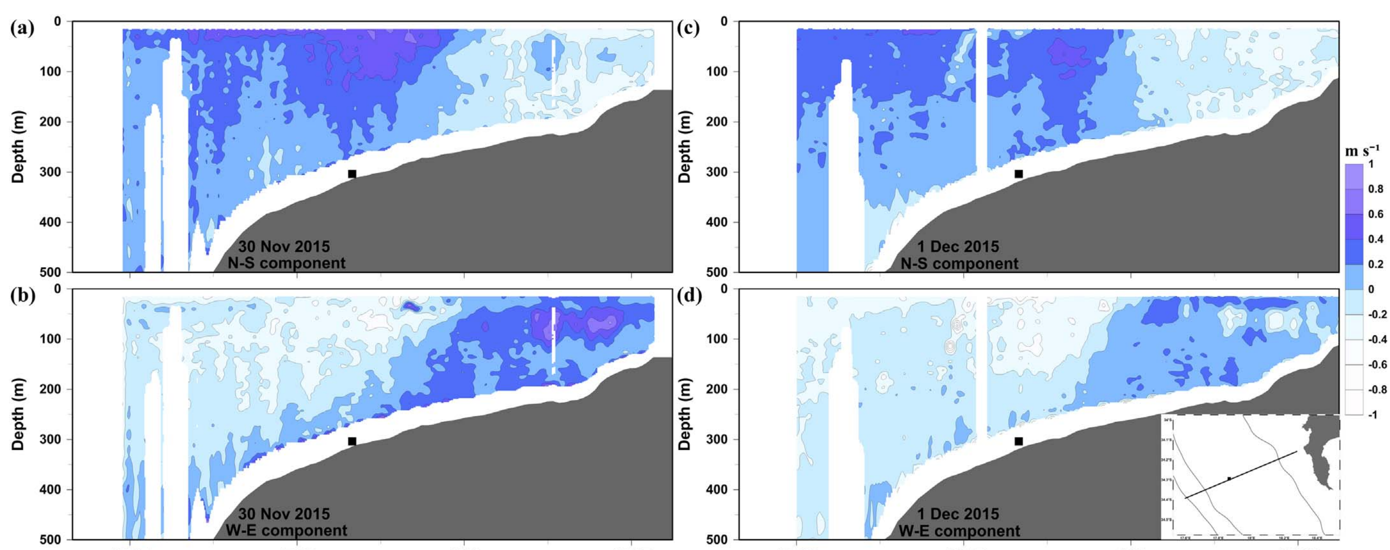

Fig. 1. Meridional (top) and zonal (bottom) velocity components of a transect off Cape Point for the 30 November 2015 and 1 December 2015 (left and right respectively). Positive (negative) values are northward and eastward (southward and westward). The black square indicates the position of the ADCP. Units are in $m.s^{-1}$.