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Coastal upwelling at Cape Frio: Its structure and weakening

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ABSTRACT

Cape Frio at the Angola-Namibia border, is the northern-most coastal upwelling cell of the Benguela Current (~17S, 11E) and is sensitive to climate variability. This study provides new insights using daily high resolution satellite and ocean-atmosphere reanalysis datasets in the period 1985–2015. The annual cycle of SST follows two months behind the net heat balance and wind stress curl, reaching a minimum in July–September. Ranking the daily SST record, two intense multi-day upwelling events stand out. The more recent case of 26–29 August 2005 is studied, given the greater density and sophistication of satellite data. A coastal wind jet $> 10 \text{ m s}^{-1}$ develops next to Cape Frio, with sharp edges imposed by a thermal inversion and the mountainous cape. The cold plume $<$ 14C west of Cape Frio is co-located with cyclonic wind stress curl and downward heat fluxes. Leeward of Cape Frio, a wind shadow and poleward currents contribute to phytoplankton blooms. Daily time series 1985–2015 reveal warming SST +.035C/yr and diminishing winds -0.025 m s^{-1}/yr. The trend toward cyclonic winds over Angola and the northern Benguela Current reflects a poleward and offshore shift of the main axis of southeasterly winds.

1. Introduction

The Benguela Current along the southwestern coast of Africa has a northern zone with austral winter upwelling of cool, fresh, nutrient-rich water (Boyd et al., 1985, Shannon and Nelson, 1996; Gammelsrod et al., 1998; Shillington, 1998), in contrast with a southern zone of austral summer upwelling (Lutjeharms and Meeuwis, 1987; Jury, 1988; Hutchings et al., 1998). The upwelling is driven by equatorward winds that follow the coast causing offshore Ekman transport in a shallow mixed layer (Nicholson, 2010; Skogen, 2013). The northern-most upwelling cell at Cape Frio 16-18.5S sweeps offshore into the South Atlantic. Along the coast of Angola there is a warm poleward current that is part of a cyclonic gyre (Tsuchiya, 1986; Boyd et al., 1987; Shannon et al., 1987; Peterson and Stramma, 1991; Yamagata and Iizuka, 1995; Doi et al., 2007). When trade winds weaken over the tropical Atlantic warm water pushes south of Cape Frio (Shannon et al., 1986; Zebiak, 1993; Carton and Huang, 1994; Lass et al., 2000; Florenchie et al., 2003; Mohrholz et al., 2001) with impacts on the fisheries and climate of Namibia (Hirst and Hastenrath, 1983; Binet et al., 2001; Rouault et al., 2003).

While considerable research has covered the warm intrusions of summer, coastal upwelling at Cape Frio is strongest in late winter (July–September) when pelagic fish spawn over the shelf (Hardman-Mountford et al., 2004). Meteorological processes controlling their food supply involve wind-driven cross-shore transport and vertical motion from wind shear in the lee of capes (Cury and Roy, 1989). Here the objectives emerge from the following scientific questions: what is the structure of coastal upwelling at Cape Frio and how can it be described with satellite-model data? what drives the annual cycle of SST and how much is attributable to local winds and heat fluxes? what processes control daily wind-SST variability at Cape Frio during austral winter? what are the key features of an intense coastal upwelling event? what are the linear trends in upwelling? and what are the regional climatic drivers during austral winter?

2. Data and methods

The coastal upwelling at Cape Frio is analyzed in four ways: mean Jul–Sep maps, annual cycle and its forcing, daily wind-SST variability and statistics, and linear trends. SST fields are derived from 25 km NOAA satellite OIv2 SST (Reynolds et al., 2007) that utilize a.blend of infrared and fog-penetrating passive microwave radiances starting in 1985. The mean annual cycle of SST defines the upwelling season: July to September, while the standard deviation of SST determines the area of interest off Cape Frio: 13-19S, 9-13E (cf. Fig. 1b); similar to that used by Doi et al. (2007).

In-situ observations are limited so coastal upwelling is quantified by reanalysis model assimilation of remotely sensed data. Upper ocean

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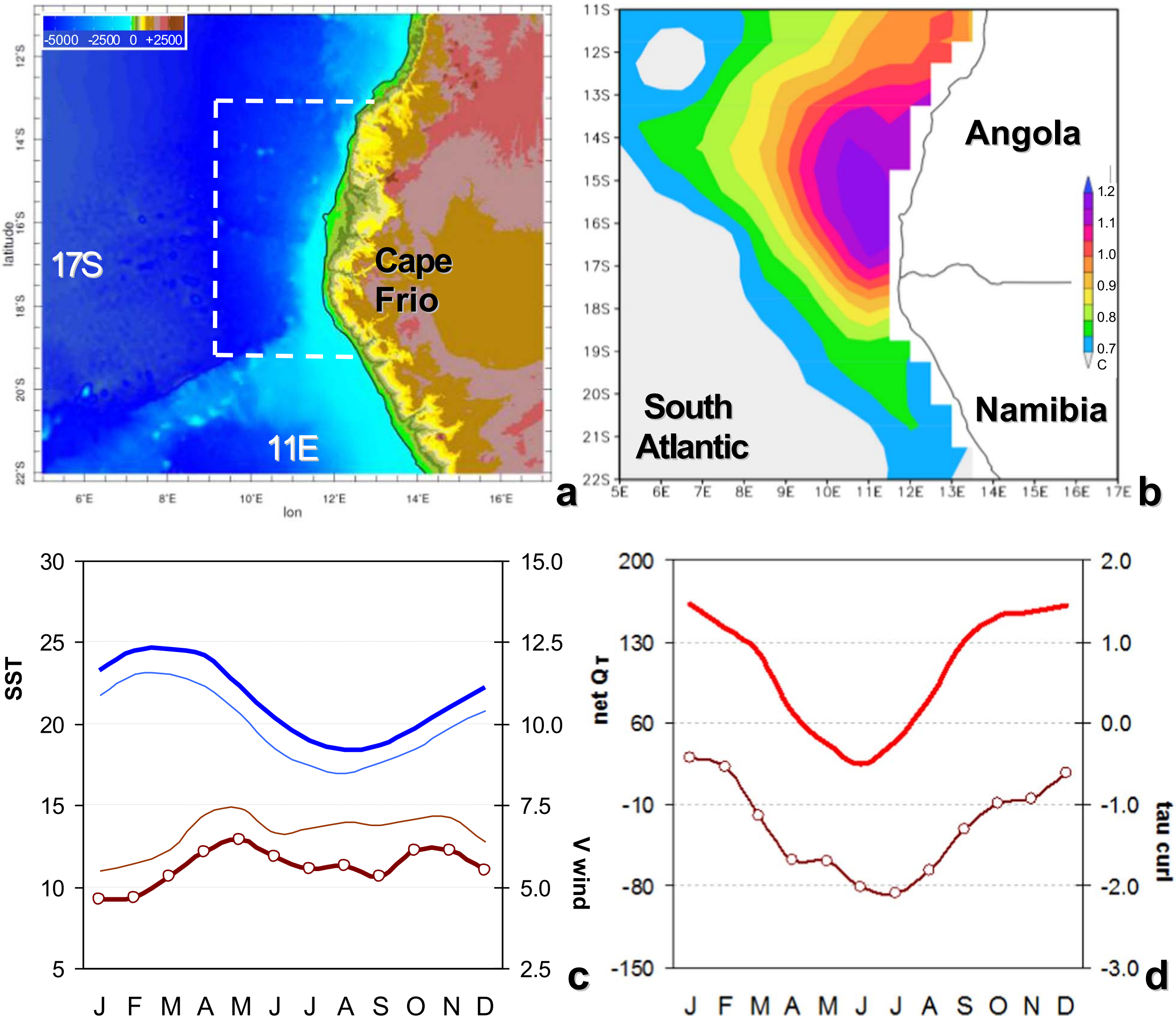

Fig. 1. (a) Location map with elevations and index area. (b) Standard deviation of Jul–Sep SST. Mean annual cycle 1985–2015 of Cape Frio: (c) SST and − quintile, V wind and + quintile, and (d) downward net heat + radiation flux and wind stress curl (cyclonic negative). Indices averaged over the dashed box in (a), exclude the inland plateau.

conditions are characterized at monthly time step by 50 km SODA2 reanalysis (Carton and Giese, 2008). Low level atmospheric winds, sea level pressure (SLP), surface air temperature, and specific humidity are studied using daily 60 km MERRA reanalysis (Reinecker et al., 2011). Sensible heat flux (SHF) and latent heat flux (LHF, evaporation) are calculated in the 25 km WHOI reanalysis (Yu and Weller, 2007). Wind and wind stress are derived from 25 km CCMP reanalysis (Atlas et al., 2011) using passive and active microwave scatterometer data (eg. SSMI, ASCAT) assimilated by the ECMWF model (Dee et al., 2011). Given the local N-S coastal orientation, the northward wind is extracted to represent offshore Ekman transport. Ocean color (chlorophyll) averaged over the Jul–Sep season is available from the 4 km NASA MODIS radiometer. In addition to maps, vertical atmospheric structure is studied along a section on 17S using MERRA reanalysis V wind and air temperature. Dataset acronyms are given in the Appendix.

Statistical insights are gained by correlation of SST, V wind, wind vorticity (curl), surface heat and radiation fluxes, and lapse rate ($\partial T/\partial z$); all averaged in the Cape Frio area (13-19S, 9-13E) in the 31 yr period: 1985–2015. Correlations are evaluated over the annual cycle (N=12) with SST lagged 1–2 months, and at the daily weather scale (N=11320) with SST lagged up to 6 days. Wavelet spectral energy is calculated to identify significant fluctuations in SST and V wind. The daily records have over 30 degrees of freedom, hence $r > |0.3|$ is significant at 90% confidence. The annual cycle has ~3 degrees of freedom, and $r > |0.8|$ is significant at 90% confidence.

Ranking the daily SST record (1985–2005), two intense multi-day upwelling events stand out: 26–29 Aug 2005 and 24–26 Aug 1992. The more recent case is studied, given the increasing density and sophistication of satellite data and model assimilation (HYCOM: Chassignet et al., 2009). Other upwelling cases exhibit similar features, albeit of reduced intensity due to environmental conditions and data limitations. The regional weather scenario is studied using NCEP2 reanalysis (Kanamitsu et al., 2002) sea level air pressure over the South Atlantic and an atmospheric section of zonal wind anomalies on 11E averaged 26–29 Aug 2005. A hovmoller plot of HYCOM sea surface height on 11.6E is analyzed over the Jul–Sep 2005 season, and mean maps of wind curl and divergence are calculated from satellite data.

To quantify the weakening of wind-driven upwelling off Cape Frio, linear trends are calculated in daily SST and V wind time series 1985–2015. Trends are also mapped around Cape Frio in NOAA SST, SODA2 ocean currents, SODA2-ECMWF wind stress and MERRA meridional winds in vertical section on 17S. Trends over the South Atlantic are mapped in the observed NCEP2 surface wind streamfunction and in the CMIP5 25-model ensemble SST field over the Benguela region using the rcp6 scenario (Taylor et al., 2012) projected from 1985 to 2045. Wind streamfunction represents the large-scale rotational circulation, distinct from wind vorticity or curl that reflects local shear.