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Linking wind and interannual upwelling variability in a regional model of the southern Benguela

Bruno Blanke[a], Claude Roy[a*], Pierrick Penven[b], Sabrina Speich[c], James McWilliams[d], Greville Nelson[e]

[a]IRD, Paris, France, and Oceanography Department, University of Cape Town, South Africa
[b]Institute of Geophysics and Planetary Physics, University of California Los Angeles, CA, USA, and IRD, Paris, France
[c]Oceanography Department, University of Cape Town, South Africa
[d]Institute of Geophysics and Planetary Physics, University of California Los Angeles, California, USA
[e]Marine and Coastal Management, Cape Town, South Africa

*: Corresponding author : Claude.Roy@ifremer.fr

Abstract: We quantify the wind contribution to the development of interannual sea surface temperature (SST) anomalies along the shelf of southern Africa. We compare numerical simulations that differ only in the amount of variability kept in the ERS1/2-derived surface wind forcing. Surprisingly, most of the cold and warm episodes over the Agulhas Bank are strictly related to local fluctuations of the forcing, whereas the shelf of the west coast extending 400 km north of Cape Columbine is equally sensitive to open-sea wind fluctuations. We diagnose the respective role of mesoscale eddy activity and of low frequency and intra-monthly wind fluctuations in generating interannual SST variability. The fair degree of correlation obtained at a few locations between the model and concomitant observations confirms the interest of a regional numerical tool to study anomalous events in the Benguela system.

Keywords: Upwelling, Sea surface temperature,Wind fluctuation,Numerical simulation

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Bruno Blanke[1,2], Claude Roy

IRD, Paris, France, and Oceanography Department, University of Cape Town, South Africa

Pierrick Penven[2]

Institute of Geophysics and Planetary Physics, University of California Los Angeles, CA, USA, and IRD, Paris, France

Sabrina Speich[1,2]

Oceanography Department, University of Cape Town, South Africa

James McWilliams

Institute of Geophysics and Planetary Physics, University of California Los Angeles, CA, USA

Greville Nelson

Marine and Coastal Management, Cape Town, South Africa

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1. Introduction

The Benguela Current is one of the four major coastal upwelling systems at the eastern subtropical boundaries of the global ocean. It is most unusual in its low latitude poleward boundary at the southern tip of Africa (34º50'), allowing the Indian-originating, western-boundary Agulhas Current to interact with the Benguela system [*Shillington*, 1998]. Interannual variability in the physical system is usually portrayed as occurrences of cold and warm events [*Shannon and Nelson*, 1996]. Propagating interannual sea level and sea surface temperature (SST) anomalies have also been observed [*Brundrit et al.*, 1987], in a manner somewhat equivalent to (but not in phase with) Pacific El Niños [*Shannon et al.*, 1986].

The knowledge gained during the Benguela Ecology Program [*Payne et al.*, 1992; *Pillar et al.*, 1998] highlighted the importance of coastal environmental processes in modulating the abundance of fish stocks and in driving successive collapses, recoveries and switches in species dominance [*Shannon et al.*, 1992]. In a high-resolution model of the Southern Benguela circulation, local oceanic instabilities were shown to produce significant year-to-year variations in the mesoscale dynamics in the open ocean and over the shelf, in the absence of any synoptic or interannual atmospheric variability [*Penven*, 2000; *Penven et al.*, 2001b], analogous to similar behavior shown for the California Current System [*Marchesiello et al.*, 2002]. Our study is aimed at quantifying the sensitivity of the coastal areas (as depicted by SST anomalies) to intra-monthly and interannual fluctuations of the coastal or open-sea surface wind, focusing on a surprisingly contrasted response between the Agulhas Bank and the west coast upwelling region.

2. Modeling Approach

The hydrodynamic code is the Regional Ocean Modeling System (ROMS) [*Haidvogel et al.*, 2000; *Marchesiello et al.*, 2001]. The curvilinear grid follows the southwestern corner of Africa from 40ºS to 28ºS and from 10ºE to 24ºE. The resolution ranges from 9 km at the coast up to 16 km offshore, and 20 vertical levels preserve a high resolution near the surface. Realistic topographic features are slightly smoothed to ensure stable and accurate simulations [*Haidvogel et al.*, 2000]. As the first-baroclinic Rossby radius of deformation amounts to roughly 20-30 km in the area, the model resolves the dominant scale of the most unstable waves, and baroclinic instabilities are described fairly [*Penven*, 2000]. The model is forced with heat and salinity fluxes from the Coads ocean surface monthly climatology [*Da Silva et al.*, 1994]. At the three lateral boundaries facing the open ocean, an implicit active radiative boundary scheme [*Marchesiello et al.*, 2001], forced by seasonal time-averaged outputs of the Agulhas As Primitive Equations (AGAPE) basin-scale ocean model [*Biastoch and Krauß*, 1999], connects all the variables to the surroundings. In addition, a one-way radiative nesting scheme [*Flather*, 1976] is adopted for the barotropic contribution. All subsequent analyses are developed from the two-day archives of the simulations, sampling the modeled variability to a sufficient degree. For each run, interannual SST anomalies are calculated with respect to a mean seasonal cycle derived from a monthly running mean of the temperature field. Lastly, the legibility of the figures is enhanced with a 10-point-wide boxcar smoothing.

With a coverage extending for almost 10 years and a weekly 1º×1º resolution, the ERS1/2 wind stress is one of the few relevant products to force a regional model in the southern hemisphere. Gridded time series for the August 1991 - January 2001 period and a monthly climatology were made available by the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) [*Bentamy et al.*, 1996]. The availability of high quality meteorological data at Cape Columbine (32º50'S) let us compare the weekly wind vector derived from ERS1/2 with direct anemometer measurements. Hourly in situ values of the meridional component, which drives the coastal upwelling, are averaged over seven successive days and compared with the satellite time series at its nearest offshore location (17.5ºE, 32.5ºS). For the available overlapping period (September 30th 1996 - January 14th 2001), the linear correlation coefficient of both time series amounts to 0.8. On average, the ERS1/2 meridional wind speed is one third larger than the local measurement, likely because of frictional orographic effects accounted by the anemometer, and the variance of both signals is somewhat equivalent (6.7 and 5.4 $m^2 s^{-2}$ respectively). Insofar as the variability of the wind has also a significant impact on the underlying ocean upwelling [*Nelson*, 1992], we calculated the power spectrum of both time series with a maximum entropy method, after filtering the annual cycle and applying a singular spectrum analysis [*Dettinger et al.*, 1995] to retain only the dominant modes of variability. Both spectra show peaks at about 150, 25-45 and 15 days. Meteorological data also indicate significant activity at 10 and 7-day periods (not sampled by ERS1/2) whereas the peak at 18 days present in the satellite wind does not show at Cape Columbine.

3. Interannual Variability

The model gives a realistic picture of the rich coastal mesoscale activity, as the upwelling plume at Cape Columbine, filaments and eddies off the western coast, and Agulhas Current filaments [*Penven et al.*, 2001a; 2001b]. Under climatological forcing conditions (Run A; Table 1), it is worth noting that these processes produce interannual variability. Eddies and filaments indeed develop in different times and places, year after year, mostly in the southern portion of the domain where the Agulhas Current retroflects and generates eddies (mostly cyclonic) throughout the year [*Duncombe Rae et al.*, 1996].

3.1. Interannual Wind Forcing

Substituting the monthly ERS1/2 climatology by genuine ERS1/2 weekly fields, the model is run under several wind configurations (Table 1) from August 1991 to December 2000. Run B is obtained by keeping only the periods in the wind longer than one month, whereas Run C uses the full weekly resolution of the ERS fields. Run D uses the same forcing as Run C but starts from a distinct initial state (the last July time step of year 8 of Run A, instead of year 7). Finally, Run E uses the same interannual wind stress as Run B over regions where the ocean bottom is shallower than 500 m, and the same climatology as Run A elsewhere.

The projection of mesoscale activity onto interannual variability is illustrated by a sensitivity analysis of the SST time series to a change in the initial state of the model. The difference between the variance of interannual SST anomalies of Runs C and D (noted respectively σ_C and σ_D hereafter) seldom exceeds 0.1 $^{\circ}C^2$ (not shown), a sign that the mean level of interannual SST activity in the model domain is not affected by a simple change of the initial oceanic conditions. The spatial structure of the linear correlation coefficient between SST anomalies of Runs C and D (Figure 1) shows a poor correlation in the offshore domain because the wind-driven circulation is masked by the random presence of eddies. On the southeastern shelf, the SST is much less sensitive to the spatial patterns of the initial mesoscale field and is mainly driven by the wind forcing (correlation greater than 0.8). Off the western coast, north of Cape Columbine, the correlation is maximum along the shoreline but seldom exceeds 0.5.

In summary, our analysis shows that the Agulhas Bank and the west-coast upwelling region have contrasted behaviors in their interannual SST variability. The former is mostly driven by the wind, while both the wind and the mesoscale activity are important contributors for the latter with as a result a significantly lower level of predictability of SST.

3.2. Wind-Related Sources of Interannual SST Variability

Assuming that intra-monthly and interannual fluctuations of the wind as well as mesoscale activity define independent added to the SST time series by switching from the monthly climatological stress to the weekly-varying product. The difference between σ_C and σ_A (not shown) is maximum over the Agulhas Bank but also extends all along the continental shelf near the coast, consistent with Figure 1. Up to 90% of the interannual SST variability over the Agulhas Bank and between 30 and 70% over the western continental shelf can be attributed to the wind stress (Figure 2a). Nevertheless, a large portion of the west coast (from 33ºS to 28ºS) appears to be affected significantly by surface mesoscale currents, no matter the existence of obvious upwelling or downwelling signals in the surface wind. In a somewhat more expected way, the retroflection of the Agulhas Current and the pathway along which detached eddies propagate exhibit less sensitivity to the interannual wind stress variability.

The comparison of Run B with Runs A and C provides insight on the percentage of variance added to the SST signal by the low frequency and intra-monthly variability of the wind field, respectively. The former one appears as the main contributor to the interannual SST variability as intra-monthly wind fluctuations explain only a maximum of 20% of the total wind effect (Figure 2b). However, it is worth noting that they have a maximum effect at the shoreline, where short-time atmospheric events can translate immediately into nearshore oceanic variability. Our study cannot address the impact of high frequency atmospheric forcing onto the development of anomalous events since the ERS1/2-derived wind stress does not incorporate sub-weekly frequencies.

The last step of our analysis focuses on the contribution of the local wind to the generation of SST anomalies. Run E allows us to evaluate the fraction of the variance added to SST anomalies over the shelf that is attributable to the purely local forcing (Figure 2c). The full extent of the Agulhas Bank is dominated by local wind fluctuations. The situation is somewhat equivalent north of 29ºS along the western shelf, and, to a lesser extent within and downstream from St Helena Bay. On the contrary, a large area from 35ºS to 30ºS is poorly sensitive to the local wind. A preliminary Lagrangian analysis in the spirit of *Blanke et al.* [2001] suggests that the variability in this area is affected by the advection of structures originating from the southern part of the domain. Wind fluctuations over the open-sea area are likely to modify the characteristics of the structures that reach the western upwelling region. This might account for the relatively low importance of the local wind forcing in that region. Conversely, the northernmost area of the western shelf is partially fed from the north and does not depend as much on the Agulhas retroflection.

The comparison of observed [*Reynolds and Smith*, 1994] and simulated (combination of Runs B and C) coastal SST time series for an equivalent overlapping period (1993-2000) assesses the ability of the interannual wind signal to force a realistic SST field in the Benguela system. The correlation between the observed and modeled interannual SST anomalies is maximum all along the continental shelf, including the Agulhas Bank (not shown). The model shows some obvious skill to reproduce observed warm or cold event in the northernmost part of the domain (Figure 3), with a linear correlation coefficient greater than 0.55, in an area where we have showed that the local wind is a dominant contributor to the interannual variability. Among others, the extreme episode of the austral summer 1999-2000 [*Roy et al.*, 2001] is captured remarkably. Knowing the significant fraction of the variability that is likely attributable to mesoscale processes, much less skill appears near Cape

Columbine, whereas the comparison near Cape Peninsula shows more encouraging results.

These results have some seasonal modulation (not shown here). The relative effect of the wind in driving interannual SST anomalies is maximal in summer for areas close to Cape Columbine and Cape Peninsula, or throughout the year where the upwelling is always fully developed such as 27.5°S.

4. Conclusion

We deliberately restricted our modeling experiment to the contribution of a variable wind stress on interannual SST fluctuations. Variable surface heat fluxes as well as lateral boundary conditions could also be important contributors (and will be investigated soon), but we believe that a step-by-step modeling approach is required to discriminate and quantify the effect of each factor. As intrusions of abnormally warm Agulhas water into the Benguela have already been documented [*Lutjeharms*, 1996], we suggest that this process is more likely to be responsible for driving, at least partially, the offshore SST. Finally, the contrast between the coastal and open ocean SST response to fluctuations in the wind forcing is worth a thought when exploring the impact of the global climate dynamics at the scale of a coastal ecosystem. Our study suggests that one needs to be extremely careful when trying to downscale the result from low-resolution models, analyses or predictions to smaller spatial scales, as there is a high risk of seeing a coastal response diluted within the adjacent open-sea environment.

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B. Blanke, C. Roy, and S. Speich, Idyle-BEP-V group, Oceanography Department, University of Cape Town, 7701 Rondebosch, South Africa.

P. Penven, and J. McWilliams, Institute of Geophysics and Planetary Physics, University of California Los Angeles - Box 951567, Los Angeles, CA 90095-1565, USA.

G. Nelson, Idyle-BEP-V group, Marine and Coastal Management, 5th Floor, Private Bag X2, Rogge Bay, 8012 Cape Town, South Africa.

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[1]Also at LPO, UMR 6523 CNRS/IFREMER/UBO, Brest, France

[2]Now at Laboratoire de Physique des Océans, UFR Sciences, 6 avenue Le Gorgeu - BP 809, 29285 Brest CEDEX, France. (e-mail: blanke, penven or speich@univ-brest.fr).

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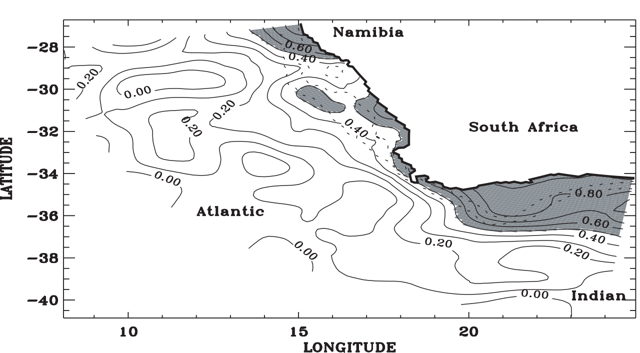
Figure 1. Correlation map of interannual SST anomalies of Runs C and D. Regions were the linear correlation coefficient is larger than 0.5 are shaded. Isobaths 200 m and 500 m are dotted.

Figure 2. (a) Percentage of interannual SST variability attributable to the variable wind stress. (b) Fraction (in %) of the total wind effect attributable to intra-monthly wind fluctuations. (c) Fraction (in %) of the total wind effect attributable to variability above the shelf. Regions with values larger than 50% are shaded. Figures 2b and 2c are contoured only for values in Figure 2a greater than 20%.

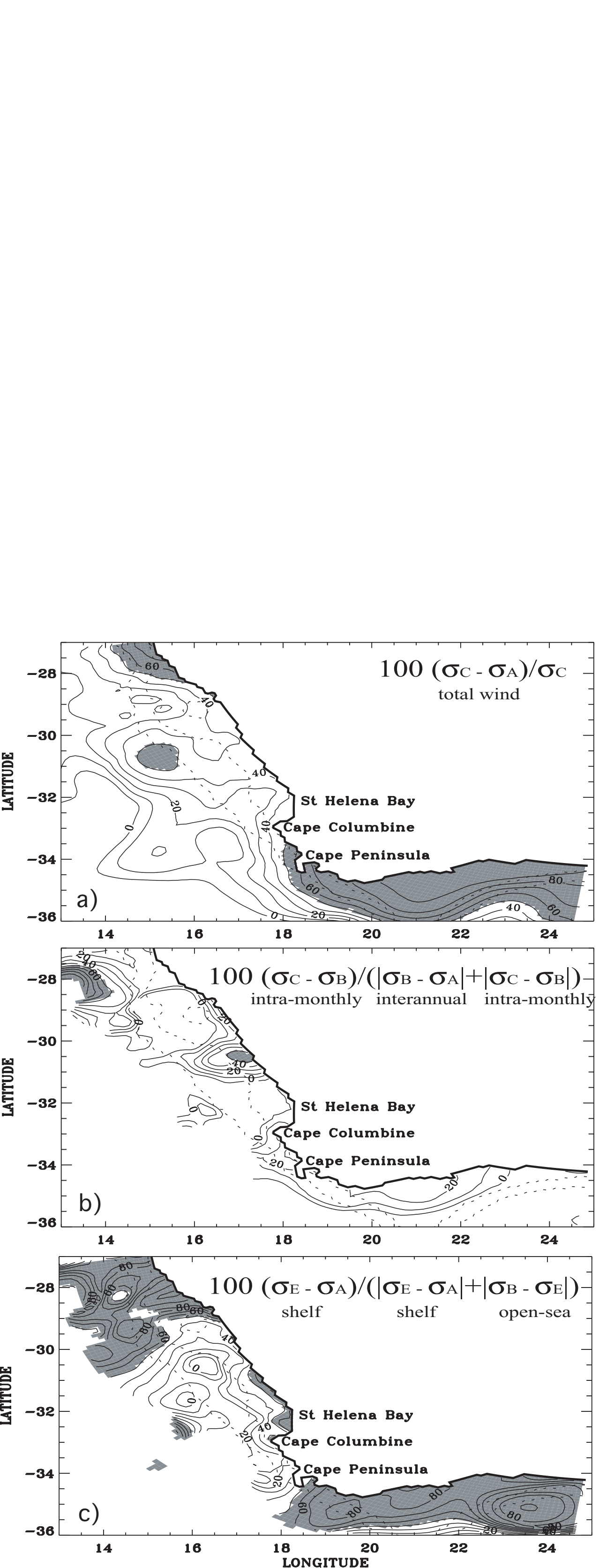
Figure 3. Monthly time series of SST anomalies at three selected locations along the continental shelf, for the model (average of Run B and C; dashed line) and for a global analysis of observations (Reynolds and Smith, 1994; solid line). The value of the linear correlation coefficient between both time series is also given.

Table 1. Characteristics of all model runs

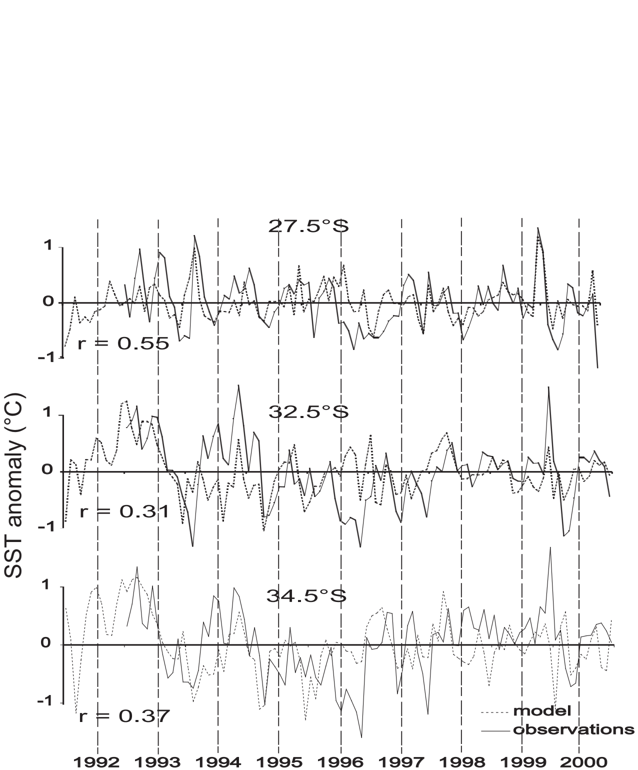
Run	Initial state	Length	Surface wind (ERS1/2 stress)
A	Penven (2001) Jan. 1st, year 9	8 years	monthly climatology
B	Run A Jul. 1st, year 7	Jul. 1991 to Dec. 2000	monthly-averaged weekly values
C	as Run B	as Run B	weekly values
D	Run A Jul. 1st, year 8	as Run B	as Run C
E	as Run B	as Run B	as Run B over the shelf, as Run A elsewhere



Namibia
South Africa
Atlantic
Indian
0.80
0.60
0.40
0.20
0.00
LATITUDE
LONGITUDE
-28
-30
-32
-34
-36
-38
-40
10
15
20



100 (σC - σA)/σC
total wind
St Helena Bay
Cape Columbine
Cape Peninsula
a)
100 (σC - σB)/(|σB - σA|+|σC - σB|)
intra-monthly
interannual
intra-monthly
b)
100 (σE - σA)/(|σE - σA|+|σB - σE|)
shelf
shelf
open-sea
c)
LATITUDE
LONGITUDE


27.5°S
32.5°S
34.5°S
r = 0.55
r = 0.31
r = 0.37
SST anomaly (°C)
1
0
-1
model
observations
1992
1993
1994
1995
1996
1997
1998
1999
2000