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Short communication

On the warm nearshore bias in Pathfinder monthly SST products over Eastern Boundary Upwelling Systems

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ABSTRACT

Using in situ sea surface temperature (SST) data and MODIS/TERRA SST, the monthly AVHRR Pathfinder (version 5.0 and 5.2) SST product was evaluated within the four main Eastern Boundary Upwelling Systems. A warm bias in the monthly Pathfinder data (previous to version 5.2) was systematically found during summer months in nearshore regions where high SST gradients exist. Based on a climatological average spanning 2000–2009, this summertime bias reached up to 3–5 °C in the California, Humboldt, Canary, and Benguela Upwelling Systems. This warm bias could at least partly explain the cold bias often found in numerical models of coastal upwelling. The last release of Pathfinder (version 5.2, September 2011) clearly improved the bias found on the previous Pathfinder version.

1. Introduction

Sea surface temperature (SST) fields from the AVHRR Pathfinder dataset (Kilpatrick et al., 2001) have been extensively used worldwide for various studies. It has notably been used to evaluate high resolution model results at a regional scale (e.g. Shaji et al., 2005; Djurdjevic and Rajkovic, 2008; Polovina et al., 2008) and also at a global scale (e.g. Kara et al., 2006). Modelling studies performed over the main Eastern Boundary Upwelling Systems (EBUS), i.e. California, Humboldt, Canary, and Benguela, often compare their results to the Pathfinder SST fields (Penven et al., 2001, 2003, 2005; Marchesiello et al., 2004; Blanke et al., 2005; Gruber et al., 2006; Machu et al., 2009; Veitch et al., 2009, 2010; Albert et al., 2010; Giraud and Paul, 2010; Colas et al., 2011; Echevin et al., 2011). A number of these studies highlighted the presence of a strong cold bias in the nearshore model SST field at several locations when comparing to monthly or climatological Pathfinder SSTs (Penven et al., 2001, 2003, 2005; Veitch et al., 2009, 2010; Colas et al., 2011). Using 3-daily averaged OSTIA SSTs (Stark et al., 2007), Mason et al. (2011) also found a cold nearshore bias in their model. In some other hydrodynamic modelling studies over EBUS, a cold coastal bias is also found (but not highlighted, Machu et al., 2009; Giraud and Paul, 2010; Echevin et al., 2011) when comparing model SST results to Pathfinder SST at various coastal locations.

As an example, we present in Fig. 1a the SST bias found by Veitch et al. (2010) between their ROMS model (Regional Ocean Model System) and the Pathfinder (version 5.0) dataset for the climatological value obtained during summer months (from January to March) in the Benguela system. The cold nearshore bias in this example reaches between 3 and 6 °C everywhere along the coast. While authors usually assume that the cold bias is due to the uncertainties in the nearshore model wind structure (Penven et al., 2005; Colas et al., 2011; Mason et al., 2011), we demonstrate in this study that the cold nearshore bias generally found in the EBUS models, compared with monthly or climatological values of satellite-derived Pathfinder SST, could be due at least partly to a warm bias in the SST dataset.

The paper is structured as follows: the data used in this study are presented and a first comparison of the data is performed over the Benguela region, followed by a presentation of the warm bias observed in Pathfinder monthly SSTs within the four main EBUS, before a final discussion concludes the paper.

2. Data

In this study, we used two satellite-derived SST products: (i) the Ocean Pathfinder SST project consists of a reprocessing of all

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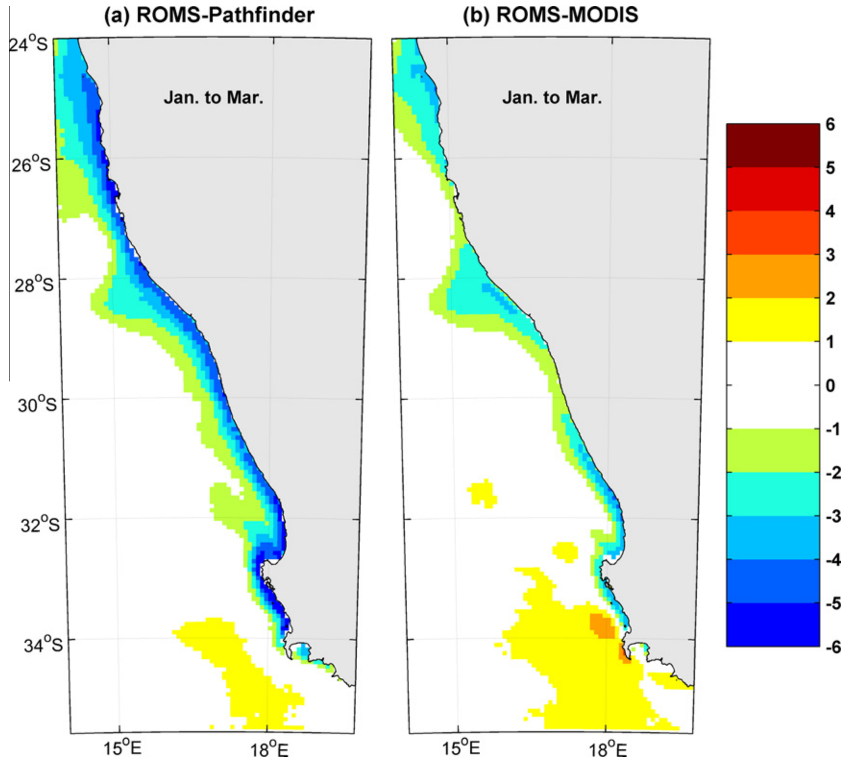

Fig. 1. (a) Difference between ROMS (Veitch et al., 2010) and Pathfinder v5.0 climatological SST (°C) averaged from January to March. (b) Difference between ROMS and MODIS climatological SST (°C) averaged from January to March.

Advanced Very High Resolution Radiometer (AVHRR) instrument data on board NOAA (National Oceanic and Atmospheric Administration) satellites from 1981 to present with the same algorithm (Kilpatrick et al., 2001; Casey et al., 2010). Daytime SSTs of Pathfinder version 5.0 and 5.2 (hereafter called Pathfinder v5.0 and v5.2) at a 4 km resolution were downloaded from the National Oceanographic Data Centre (NODC) website (http://www.nodc.noaa.gov). For Pathfinder v5.0, monthly data are directly extracted, whereas for Pathfinder v5.2, daily data are downloaded and averaged to obtain monthly data. A quality flag of 4, considered as the lowest quality level for acceptable data (Kilpatrick et al., 2001), was imposed for our application. (ii) The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA Terra satellite has been collecting data since 2000. Level-2 MODIS data were downloaded from the Ocean Color website (http://oceancolor.gsfc.nasa.gov) and processed at a 4 km resolution using the SeaWiFS Data Analysis System (SeaDAS – http://seadas.gsfc.nasa.gov). Only the daytime passes were processed, allowing us to use the cloud flag (CLDICE). We also used several other SeaDAS flags (ATMFAIL, LAND, HILT, HISOLZEN, LOWLW, MAXAERITER, ATMWARN, NAVFAIL, FILTER) but not the SST quality flags (SSTWARN, SSTFAIL). The daily data were then averaged to obtain monthly data. This product is hereafter called reprocessed MODIS.

Whereas MODIS and Pathfinder v5.2 SST refer to a "skin" temperature, Pathfinder v5.0 represents a "bulk" temperature. Therefore, in order to homogenise the different data sets, Pathfinder v5.0 is modified to be comparable to a skin temperature. The skin temperature being usually colder by about 0.17 °C than the bulk temperature (Donlon et al., 2002), we subtracted this offset from the Pathfinder v5.0 data.

We also used in situ SST data in this study in order to perform a comparison with the satellite-derived SST. The temperature time series was acquired from 2008 at 35 cm below the sea surface off Cape Town (South Africa) at the position of the operational Slangkop Datawell Waverider buoy (34°12′14″S; 18°17′12″E, http://wavenet.csir.co.za/OnlineData/CapeTown/CapeTownwaveD.htm). Daily daytime (from 6 am to 6 pm) data were first computed and then averaged to give monthly in situ data.

3. Results

3.1. Data evaluation over the Benguela system

We used the reprocessed MODIS summer (January–March) climatology for comparison with the climatology shown by Veitch et al. (2010). In this case, the nearshore cold bias is largely attenuated (Fig. 1b) south of 24°S. In some places off Cape Town, the cold bias is even transformed now into a warm bias.

The hypothesis is that the Pathfinder climatology used by Veitch et al. (2010) presents a warm bias in most of the nearshore Benguela system during austral summer. To support this assumption, Pathfinder v5.0 monthly data were compared with the reprocessed MODIS monthly SST and in situ data off Cape Town. On Fig. 2, the MODIS monthly SSTs (bold black line) is highly correlated (92%) with the in situ time series (dashed bold grey line). A Root Mean Square Error (RMSE) of 0.5 °C and a bias of −0.04 °C is found when comparing MODIS to the in situ monthly SSTs. Daily Pathfinder SST (grey circles on Fig. 2) is in relative agreement with the in situ monthly data only during winter. Thus, during winter months (from June to September) the monthly Pathfinder data are well correlated (96%) with monthly in situ data (over only two common years), whereas there is no correlation if considering all seasons (3%). The RMSE of 0.38 °C and the bias of 0.3 °C also confirm the good match found during winter. During summer, only a few warm Pathfinder daily data values are used to compile the monthly data. This spurious behaviour is a result of the threshold tests implemented when selecting a quality level of four for the final Pathfinder data product that results in the flagging of most of the accurate nearshore data values. This particular flagging

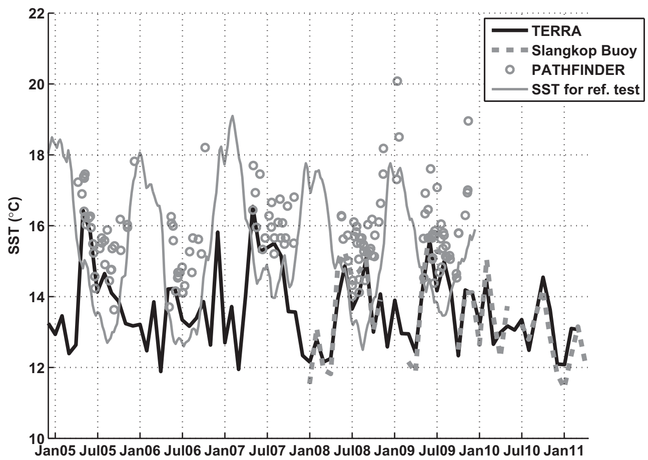

Fig. 2. Comparison between monthly reprocessed MODIS SST (bold black line), monthly in situ SST data (bold dashed grey line) and the daily Pathfinder v5.0 SST (grey circles) at position 34°12′14.40″S; 18°17′12.01″E. The grey line corresponds to the threshold of acceptable values for Pathfinder SSTs with a quality level of 4.

procedure on Pathfinder versions anterior to 5.2 is based on the "Reference Test": if the absolute difference between daily SST and a 3 week mean based on the 1-degree resolution Reynolds Optimally Interpolated SST (OISST, Reynolds et al., 2002) is lower than or equal to 2 °C, then the SST quality is considered to be low and a quality flag lower than or equal to 3 (suspect value) is set (Kilpatrick et al., 2001). Quoting Kilpatrick et al. (2001), this test is known to "occasionally bias quality flags in coastal areas [...] and regions having large SST gradients in time or space". In the southern Benguela region, large SST gradients over short spatial scales are often encountered during the upwelling-favourable austral summer period. This ultimately induces a systematic flagging of the strongest and coldest upwelling events as bad quality data. The minimum value used for the reference test of the SST (grey line in Fig. 2) is calculated from a lower resolution dataset (OISST), which does not resolve the high gradient seasonally encountered in our domain. Thus, only the warm events are kept (i.e. no or low upwelling associated with weak SST gradients) inducing an artificial warm bias in the monthly data in summer.

A similar reference test, based on the difference between MODIS SST and the 1-degree resolution Reynolds OISST reference value (although a higher absolute threshold of 3 °C is used during the test), can be optionally used to process MODIS SST with SEADAS (http://oceancolor.gsfc.nasa.gov/DOCS/modis_sst). Using this flag (SSTFAIL) leads to the same result (not shown here): for satellite-derived monthly data, flagging using a reference test based on 1-degree resolution OISST value is excessive in areas with strong SST gradients, which could lead to a warm bias.

3.2. Warm bias in Pathfinder v5.0 data over EBUS

In order to assess the bias present in the Pathfinder monthly data at a larger scale and for the four main EBUS, we calculated the monthly climatological value for both Pathfinder and MODIS SST products over their common period: 2000–2009.

The two daytime products have been systematically compared in the four systems for each month. Firstly, it appeared that no significant biases were observed between the two products during winter time within the four main EBUS. However, during summer, warm nearshore biases up to 5 °C are present on the Pathfinder SST climatology over the four EBUS (Fig. 3). The extent of the geographic regions on Fig. 3 was determined by the area where a

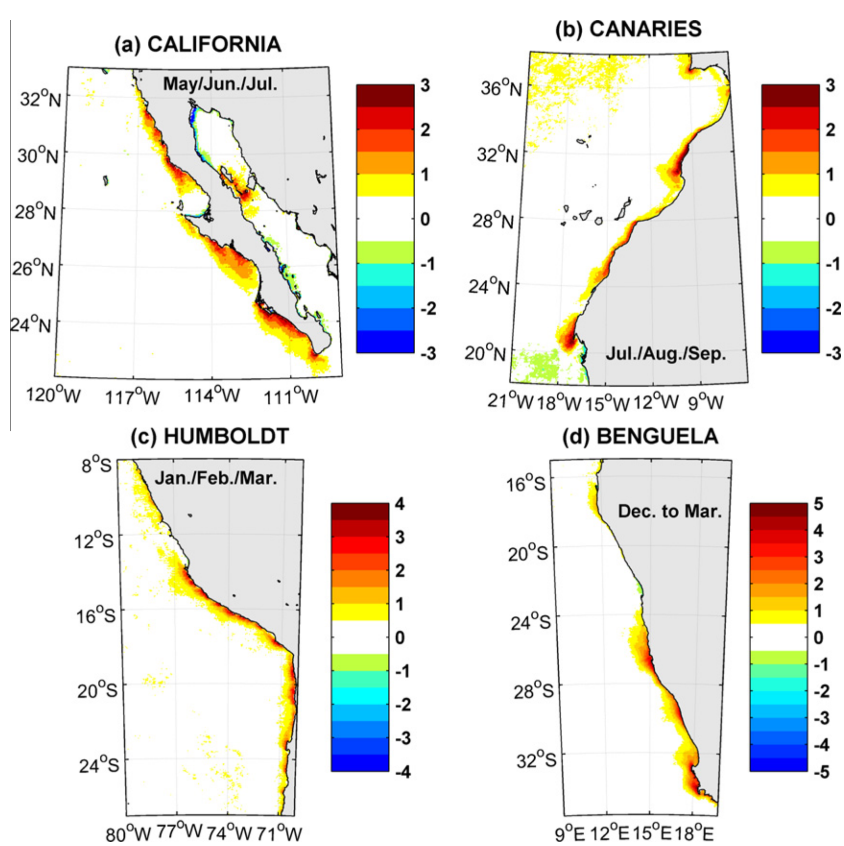

Fig. 3. SST difference (°C) between Pathfinder v5.0 and the reprocessed MODIS from 2000 to 2009 in the four main EBUS: (a) California during May/Jun./Jul., (b) Canary during Jul./Aug./Sep., (d) Humboldt during Jan./Feb./Mar. and (d) Benguela during Dec./Jan./Feb./Mar.

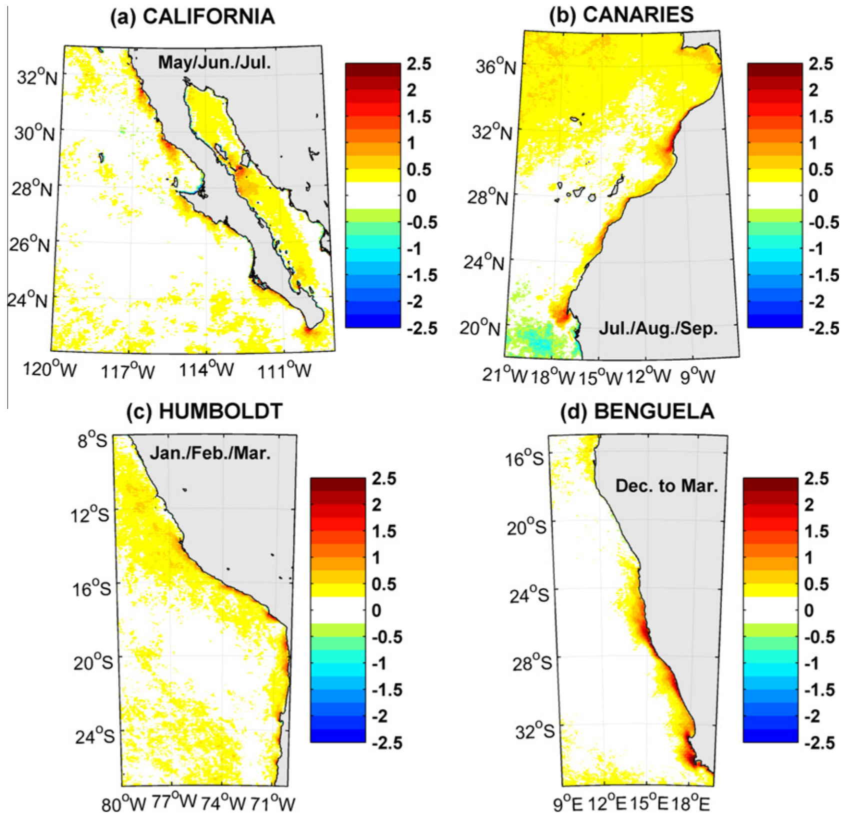

Fig. 4. SST difference (°C) between Pathfinder v5.2 and the reprocessed MODIS from 2000 to 2010 in the four main EBUS: (a) California during May/Jun./Jul., (b) Canary during Jul./Aug./Sep., (d) Humboldt during Jan./Feb./Mar. and (d) Benguela during Dec./Jan./Feb./Mar. NB: the colour scale has been changed to match the lower warm bias. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

warm bias was found (i.e. no significant bias was found outside the limits of the four maps). In more detail, the California system has a warm bias of up to 3 °C in Pathfinder SSTs mainly from May to July and only between 22 and 32°N (Fig. 3a). North of this region, the spatial SST gradients are weaker even during the summer, and no important biases are induced by spurious flagging. Within the Canary system, a warm SST bias of up to 3 °C is found in Pathfinder climatological SST from July to September (Fig. 3b). During June, October and November, a weaker warm bias is found further south between 18 and 22°N (not shown). In the Humboldt system, a warm bias of up to 4 °C in the Pathfinder climatology is found nearshore from January to March all along the coasts of Chile and southern Peru. Off central Peru the bias is rather weak. In the Benguela system, a warm bias of up to 5 °C is found in the Pathfinder climatology from December to March, mostly south of 24°S. In the northern Benguela no important bias is found.

For these four EBUS, the warm bias is not found exactly at the same period. The warm monthly bias is found when high horizontal SST gradient exists. This gradient is maximum during summer time, when surrounding waters are warmed up by solar fluxes while cold upwelled waters are present at the coast. The strength of the gradient within the EBUS is also strongly dependent on the peak of upwelling season, which varies for each specific region.

3.3. Evaluation of the newly released Pathfinder v5.2

Using the same method, the new Pathfinder v5.2 has been compared with our MODIS/TERRA SST for the period spanning 2000–2010 (Fig. 4). Firstly, it appears that the warm bias found over the EBUS is globally largely reduced with Pathfinder v5.2. The bias previously observed is even almost completely removed on both the Humboldt and the California Upwelling System. In the Canary system the bias is reduced to about 1.5 °C maximum during the summer time. The higher warm bias is found within the southern Benguela system although it does not exceed 2.5 °C during summer. Thus, the new Pathfinder product offers a real improvement in comparison with the former releases. However, small warm biases are still encountered locally. For the reference test, Pathfinder v5.2 uses the daily 0.25-degree resolution Reynolds Optimally Interpolated SST which is better positioned to resolve SST gradients than the coarser resolution product (http://www.nodc.noaa.gov/SatelliteData/pathfinder4km). Thereby the flagging process allows a better retrieval of the monthly SSTs in comparison with the former Pathfinder version.

4. Discussion/conclusion

An evaluation of Pathfinder SST has been performed in regards to a reprocessed MODIS/TERRA product. This reprocessing used a cloud flag computed from a visible wavelength, and therefore only a daytime comparison is possible. However, while the Terra satellite is crossing the equator around 10:30 am (Savtchenko et al., 2004), Pathfinder uses several satellites crossing the equator during the afternoon, except for the period 2003–2005 with the use of the ''morning'' satellite NOAA-17 (http://www.nodc.noaa.gov). Therefore, while comparing the two products, a small bias is expected due to solar heating between morning and afternoon. This bias is dependent on both the solar influx (and therefore the geographic location) and the wind strength (Gentemann et al., 2003). Pathfinder would here be expected to be slightly warmer than MODIS everywhere especially during summer (this probably explains a small offshore bias observed on Fig. 4). When comparing night-time

Pathfinder versus daytime MODIS SST (not shown here), the warm bias presented in Figs. 3 and 4 is still present with the same geographic patterns and a slightly lower amplitude. This gives us confidence to interpret the warm coastal bias found in Pathfinder as induced by the processing techniques.

While SST flagging techniques in the Pathfinder v5.0 dataset are supposed to "occasionally" flag good values (Kilpatrick et al., 2001), we found that the flagging may locally be too vigorous and too systematic in EBUS. Although daily Pathfinder v5.0 data are accurate when not flagged, monthly SST values in some regions are not representative during specific periods (i.e. summer and peak upwelling season). The flagging method based on an OISST reference test induces a warm coastal bias in monthly Pathfinder data during summer. This can be explained by strong coastal SST gradients in these regions which cannot be satisfactorily represented by the large scale OISST product. The reference test in those regions is not efficient and induces a systematic warm bias in monthly SST data, and therefore in SST climatology. However, by using a higher resolution OISST product, the new Pathfinder release (v5.2) succeeds in reducing the warm bias observed in the former Pathfinder version. The warm bias does not present the same extent and intensity in the four upwelling systems and the decrease of this bias with Pathfinder v5.2 is also different for each system. This might be due to the characteristics of the SST gradient in each EBUS. As an example, at the climatological scale, the southern Benguela, which exhibits the strongest warm bias, presents the strongest zonal SST gradients (not shown). On the contrary, in the California system, which presents the weakest climatological zonal SST gradients, the bias is almost completely removed in the new Pathfinder version. It is however not so straightforward to explain why the bias is highly reduced with the Pathfinder v5.2 in the Humboldt system while not in the Canary system. We suggest that the characteristics of the SST gradient at daily scale (position, stability, intensity of the front, etc.) in response to the physical forcings of each system could explain this behaviour.

We also suggest that any high resolution satellite-derived monthly SST product using a reference test based on a smooth SST product (e.g. MSG/SEVIRI (Le Borgne et al., 2006) or MODIS L3 (http://oceancolor.gsfc.nasa.gov)) or using optimal interpolation (i.e. using data in a radius of several tenths of kilometres to fill the gaps during cloudy conditions; e.g. OSTIA (Stark et al., 2007)) should be regarded with extreme care in the nearshore regions of the EBUS (especially during peak upwelling season).

Within the main EBUS, many studies have dealt with monthly and climatological Pathfinder data (e.g. Kahru and Mitchell, 2001; Carr, 2002; Carr and Kearns, 2003; Fernandes et al., 2005; Sobarzo et al., 2007; Demarcq, 2009; Relvas et al., 2009; Marcello et al., 2011) and results should also be interpreted with care when analysing nearshore conditions during peak upwelling periods.

For modelling studies, Pathfinder is not only used for model evaluations but could also be part of the forcing functions. As an example, in several ROMS model configurations used over EBUS, the surface heat flux climatology is corrected with a restoring term based on the difference between the model SST and the Pathfinder SST climatology (e.g. Veitch et al., 2009, 2010; Colas et al., 2011). The impact of the nearshore bias in this forcing has been assessed in the Benguela system by comparing the Veitch et al. (2010) ROMS simulation using a flux correction based on the Pathfinder climatology ($ROMS_{pathfinder}$) with another simulation using the MODIS climatology ($ROMS_{modis}$). In the southern Benguela, when comparing $ROMS_{modis}$ with $ROMS_{pathfinder}$ during the summer time, there is a slight cooling (of the $ROMS_{modis}$ configuration) on the shelf of about 0.5 to 1 °C which diminishes toward the core of the upwelling (not shown). Although coastal wind is the dominant forcing in coastal upwellings, the heat flux correction term can have an influence on the shelf.

Finally, regional model studies using Pathfinder SST in upwelling systems should be revisited keeping in mind the existence of the warm bias nearshore in Pathfinder SSTs. As an example, results from Veitch et al. (2010) suggested a nearshore anomaly in their wind field everywhere along the coast to explain the cold bias found in their model. The wind anomaly might finally be slightly weaker than expected, at least south of 24°S. Indeed, the use of Pathfinder is responsible for a significant fraction of the cold bias simulated in the model (about 30% very nearshore; not shown).

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