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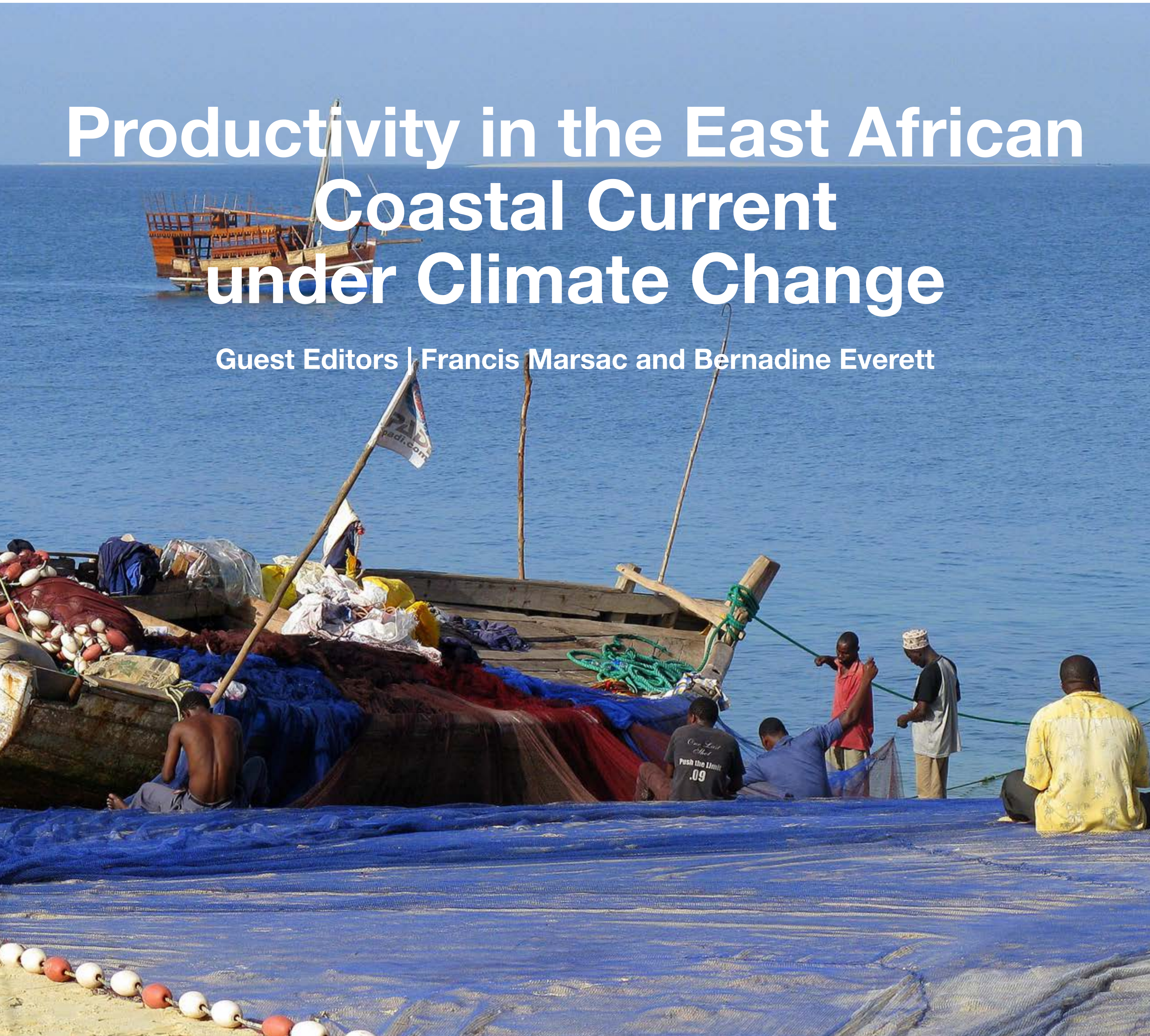
Productivity in the East African Coastal Current under Climate Change

Guest Editors | Francis Marsac and Bernadine Everett



Present and future trends in winds and SST off central East Africa

Marisol García-Reyes[1]*, Shigalla B. Mahongo[2,3]

[1] Farallon Institute, Petaluma, California, USA

[2] Tanzania Fisheries Research Institute, Dar es Salaam, Tanzania

[3] Lake Victoria Fisheries Organization, P.O. Box 1625, Jinja, Uganda

* Corresponding author: marisolgr@gmail.com

Abstract

The coast of central East Africa (CEA) is a dynamic region in terms of climate, in which fisheries and marine-related services impact a large portion of the population. The main driver of regional dynamics is the seasonal alternation of the Northeast (NE) and Southeast (SE) monsoons. Winds associated with these monsoons modulate the prevalent, remotely-forced East African Coastal Current (EACC). Here, present and future trends in winds and sea surface temperature (SST) of the CEA and adjacent regions are investigated using reanalysis and reconstructed data, and an ensemble of General Circulation Models. It was found that the winds and SST show unidirectional trends, with magnitude and spatial differences between the NE and SE monsoons. Winds show weakening trends during the NE monsoon, in the past and future, of the Somali region; with no significant trends during the SE monsoon. SST shows increasing trends in the entire region in the past and future, with stronger warming during the NE monsoon off Somalia; SST trends are smaller in the CEA. These trends could impact the CEA through increased water-column stability and decreased upwelling due to shifting of the EACC separation from the continent. However, given the coarse resolution of data analyzed, regional modeling is still necessary to understand the impacts on local dynamics and productivity in the CEA.

Keywords: Wind trends, SST trends, Eastern African coastal current, East African monsoon, Climate change, Somali current

Introduction

The region encompassing the coasts of Kenya and Tanzania and their islands, referred to here as Central East Africa (CEA), is a highly dynamic, remotely forced coastal region. The CEA is embedded in the northward East African Coastal Current (EACC), which is the northward extension of the South Equatorial Current (SEC) that passes the northern tip of Madagascar before reaching the African continent (Schott and McCreary, 2001; Manyilizu *et al*., 2016); the strength of the EACC and the CEA regional climate depend on the seasonal shift in the Inter-Tropical Convergence Zone that drives the Northeast (NE) and Southeast (SE) monsoons (McClanahan, 1988). During the NE monsoon, from December to February, the EACC is slower and warmer, reaching its highest temperatures in March-April; during the SE monsoon, from April to October, the EACC is faster, cooler and saltier, with a minimum temperature around September (McClanahan, 1988; Mahongo and Shaghude, 2014; Manyilizu *et al*., 2016). In both seasons, low nutrient water from the SEC (Jury *et al*., 2010) flows northward along the coast where it is enriched and mixed by local dynamics: island's wake upwelling (Roberts *et al*., 2008), wind-driven downwelling (McClanahan, 1988), Ekman divergence and convergence (Manyilizu *et al*., 2016), rainfall and runoff (McClanahan, 1988), upwelling due to the separation of the EACC from the continent off northern Kenya where it meets the southward Somali Current during the NE monsoon (Manyilizu *et al*., 2016), and tidal dynamics in between the mainland and the islands (Zavala-Garay *et al*., 2015).

The CEA region is also densely populated where fisheries (commercial, artisanal and recreational), and marine-related tourism services impact a large portion of the population (van der Elst *et al*., 2005; FAO, 2018). Changes in environmental conditions due to climate change is likely to increase pressure on the local marine ecosystems, already stressed by growing

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populations and extensive fisheries (van der Elst *et al.*, 2005). Understanding how environmental conditions are and will be impacted by a changing climate is a first and necessary step in developing, managing and adaptation strategies for this region. Unfortunately, local studies of environmental change are limited due to sparse availability of data, both oceanographic and atmospheric, and while local modeling efforts that accurately represent seasonal variability in the CEA exist (Mahongo and Shaghude, 2014; Zavala-Garay, 2015), projections of the future conditions are still not available at such scales. There is evidence however, that coastal winds off the coast of Tanzania have increased in the past three decades (Mahongo *et al.*, 2012); although off north Kenya NE monsoon winds appear to be decreasing (Varela *et al.*, 2015). Given the remotely forced nature of the EACC and the monsoons, it is possible to investigate past and future changes in regional wind circulation with climate change using an ensemble of General Circulation Models (GCM), and gain insight into coastal conditions. Additionally, changes in regional sea surface temperature (SST), an indicator highly linked to the monsoon dynamic and the EACC at the coast, provides regional context for oceanographic change with climate. In this study, it is hypothesized that changes in winds and SST in the region show unidirectional trends consistent with global warming, but that trends differ between the monsoons leading to changes in the regional seasonal cycle in the EACC.

Data and methods

The area of study was delimited by 15°S to 5°N and 35°E to 55°E, which covers the EACC, the western end north fork of the SEC, passing north of Madagascar, and the southern part of the Somali Current. Monthly wind vectors at 10 m and monthly SST data were analyzed for past and future linear trends. To investigate

Table 1. General Circulation Model List.

Model Name	Source
ACCESS1-0	Australian Weather and Climate Research
ACCESS1.3	"
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration
BCC-CSM1-1m	"
CanESM2	Canadian Centre for Climate Modelling and Analysis
CESM1-BGC	National Center for Atmospheric Research, USA
CMCC-CESM	Centro Euro-Mediterraneo sui Cambianenti Climatici, Italy
CMCC-CS	"
CMCC-CMS	"
CNRM-CM5	Centre National de Recherches Meteorologiques, France
CSIRO-Mk3-6	Australian Commonwealth Scientific and Industrial Research Organisation
GFDL-CM3	Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2M	
HadGEM2-AO	Met Office Hadley Centre, UK
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France
IPSL-CM5A-MR	"
IPSL-CM5B-LR	"
MIROC5	Atmosphere and Ocean Research Institute, University of Tokyo, Japan
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
MPI-ESM-MR	"
MRI-CGCM3	Meteorological Research Institute, Japan
MRI-ESM1	"

past trends, wind vectors from 20th Century Reanalysis V3 (20CR) was obtained from the National Ocean and Atmospheric Administration (NOAA/CIRES/DOE/ESRL PSD, Boulder, Colorado, USA) available at https://www.esrl.noaa.gov/psd, and SST data from the HadISST1 (HadSST) reconstruction dataset provided by the Meteorological Office Hadley Centre in the UK, available at https://www.metoffice.gov.uk/hadobs/hadisst/. 20CR provides 1 degree resolution wind data through a single assimilated model that runs for the entire available time period (Compo *et al*., 2011); 20CR assimilates SST data from the HadSST dataset, which provides reconstructed data with a resolution of 1 degree (Rayner *et al*., 2003). Data were obtained for the period 1950 to 2015. In addition, wind vectors and SST data from an ensemble of GCM, part of the Intercomparison model project (CMIP5, Taylor *et al.* 2012) used in the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5) and available at https://cmip.llnl.gov/cmip5/, were obtained for the historical period (1950 to 2005) and compared to 20CR and HadSST data. Data was also obtained from future projections to estimate future trends under climate change for the period 2006 to 2100, with a simulation that uses the representative concentration path (RCP) 8.5, which represents a "business as usual" scenario in terms of green-house gas emissions and concentrations (IPCC, 2013). From the CMIP5 models, 22 were selected (Table 1) that accurately (qualitatively) represent the seasonality of SST and wind stress compared to HadSST and 20CR. To be able to compare GCM data among them and with HadSST and 20CR, they are scaled to a uniform 1-degree grid, since they all have different resolution and grids.

Based on the seasonality exhibited by the 20CR data, and compared with the description in Mahongo *et al.* (2012), the monsoons were selected as: Northeast monsoon from December to February and Southeast monsoon from April to October; however, DJF averages for the NE monsoon and MJJA averages for the SE monsoon were used to represent seasonal contrast. Analysis trends were performed over NE or SE monsoon annual averages calculated for each grid point, from 1950 to 2015 for the observations, from 1950 to 2005 for the GCMs historical simulations, and from 2006 to 2100 for future projections. Trends for zonal and meridional components of winds were calculated

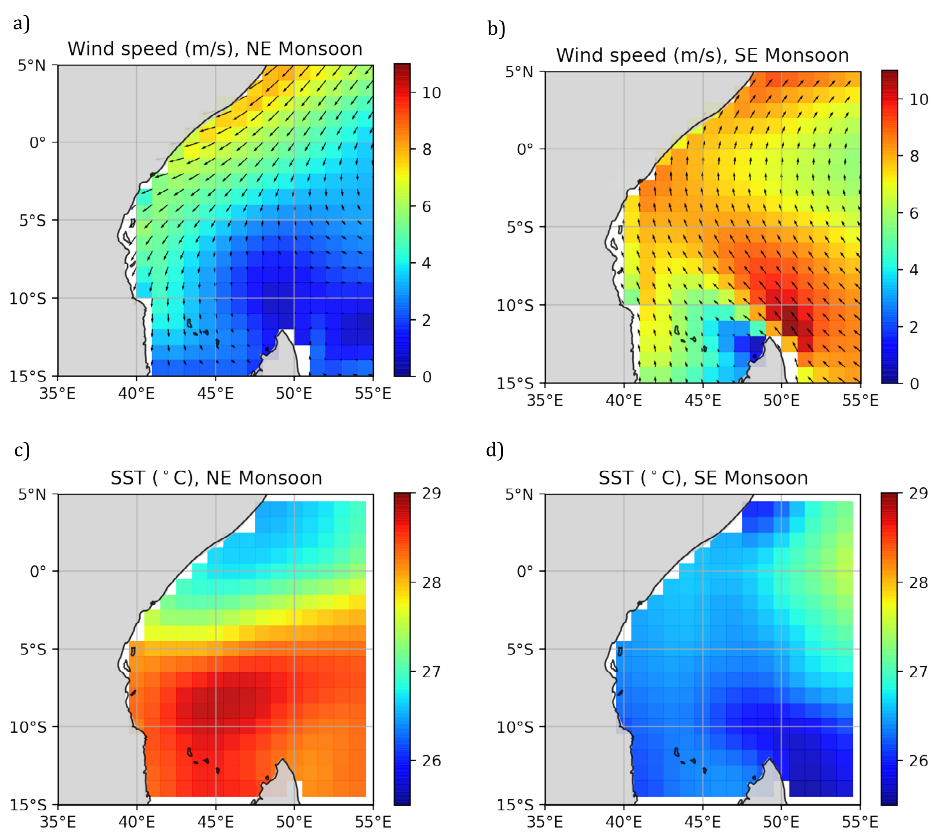

Figure 1. Climatology of SST (HadISST1 Reconstruction, bottom) and wind speed vectors (20th Century Reanalysis, top) for Northeast (NE, left) and Southeast (SE, right) monsoons from 1950-2015.

separately. To estimate trends, a linear regression was fitted to each time series of each grid point. Linear trends were chosen because they represent an estimate of rate and sign of change that is easier to interpret and represent in spatially-explicit analysis. Significant trends are considered for p-values < 0.05. For GCM, a significant trend was considered for a given location if the ensemble had 10 or more models showing a significant trend ($p<0.05$) for a given grid point, after which the significant trends from individual models were averaged. To further evaluate the significance of trends in the GCMs, signal to noise ratios (SNR) were calculated and locations with SNR values < 1 were considered non-significant. SNR were calculated by dividing the mean trend value of all models exhibiting significant trends (only where 10 or more are significant) by the standard deviation of those trends (noise). All analyses were performed in Python 3.

Results

The climatology (Fig. 1) of wind shows that the NE monsoon winds are limited to the coast, and strongest off the Somalia coast, consistent with cooler temperatures, decreasing in the CEA, and weak or zero in the north and east of Madagascar. SST shows warmer temperatures below 4°S. During the SE monsoon, winds are prevailing from the south in the entire region, but weaker in the CEA, east of Madagascar and the northeast area. SST is more uniform during the SE monsoon, only warm toward the northeast of the region where winds are weak and with a colder signature of the SEC and the upwelling area off Somalia.

Historical trends in 20CR data (Fig. 2) indicates that during the NE monsoon zonal winds show a positive trend on the northeastern part of the domain. Since the prevailing winds at this time are largely from the northeast or north, these trends represent a shift toward more meridional winds, and slightly weaker (since no change in the meridional component was found) in the outer border of the coastal jet (Fig. 1). During the SE monsoon, only a small portion of the north coast shows increasing zonal winds, associated with the SEC and the Somali Current, indicating

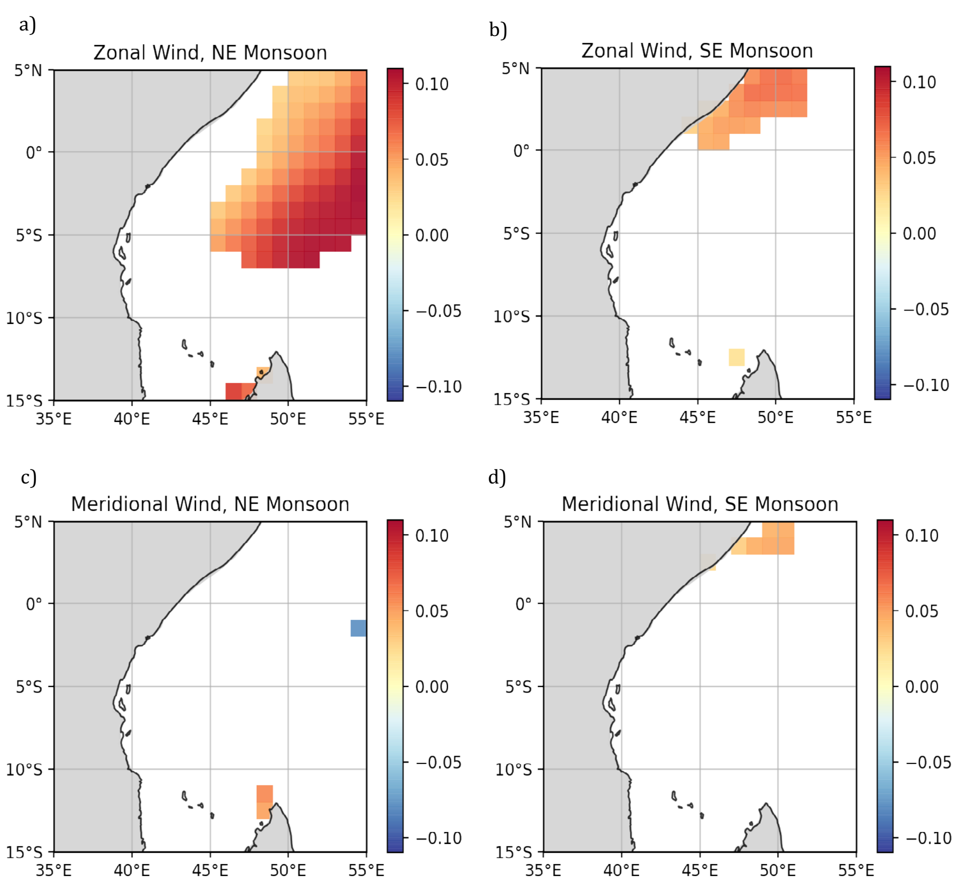

Figure 2. Linear trends in zonal (top) and meridional (bottom) wind speed from the 20th Century Reanalysis, for both NE (left) and SE (right) monsoon seasons for the period 1950-2015. Units in m/s/decade. Only significant ($p<0.05$) trends are shown.

a limited strengthening of the zonal winds in this region. No significant changes were found for the meridional winds (Fig. 2b, d). In contrast, data from the GCM ensemble do not show significant trends for the historical period anywhere in the study domain (not shown). HadSST data shows increasing trends in most of the domain in both monsoons, except a small area north of Madagascar (Fig. 3a, b). Largest trends (~0.2°C/decade) were found in the eastern equatorial region of the domain during the SE monsoon, and in the center and south western area during the NE monsoon (~0.14°C/decade). GCM historical data also show significant increasing trends in SST during both monsoons (Fig. 3c, d), with SST increasing in the northern region of the domain (~0.12°C/decade) in the Somali Current region, and lowest in the CEA during the NE monsoon. Non-significant SST trends occur on the northeast side of Madagascar, and along the Tanzanian coast. During the SE monsoon, in contrast with the HadSST data, largest trends are observed in the

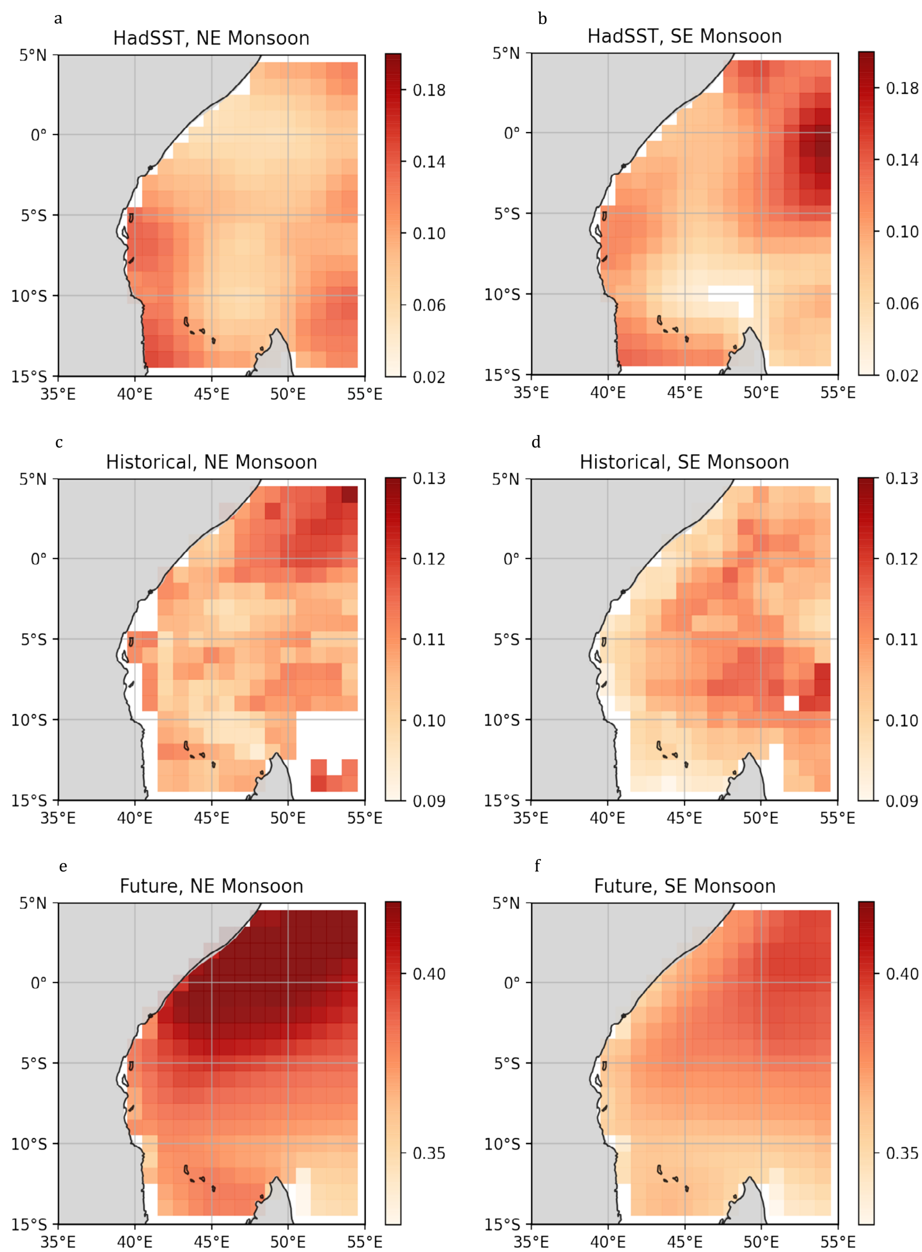

Figure 3. Linear trends in SST for NE (left) and SE (right) monsoon seasons. Top panels: HadISST1; Only significant ($p<0.05$) are shown. Middle panels: GCM ensemble mean for the historical simulations; Bottom panels: GCM ensemble mean for future projections. Only mean values of 10 or more models showing significant ($p<0.05$) trends, and with signal to noise ratio values > 1 are shown.

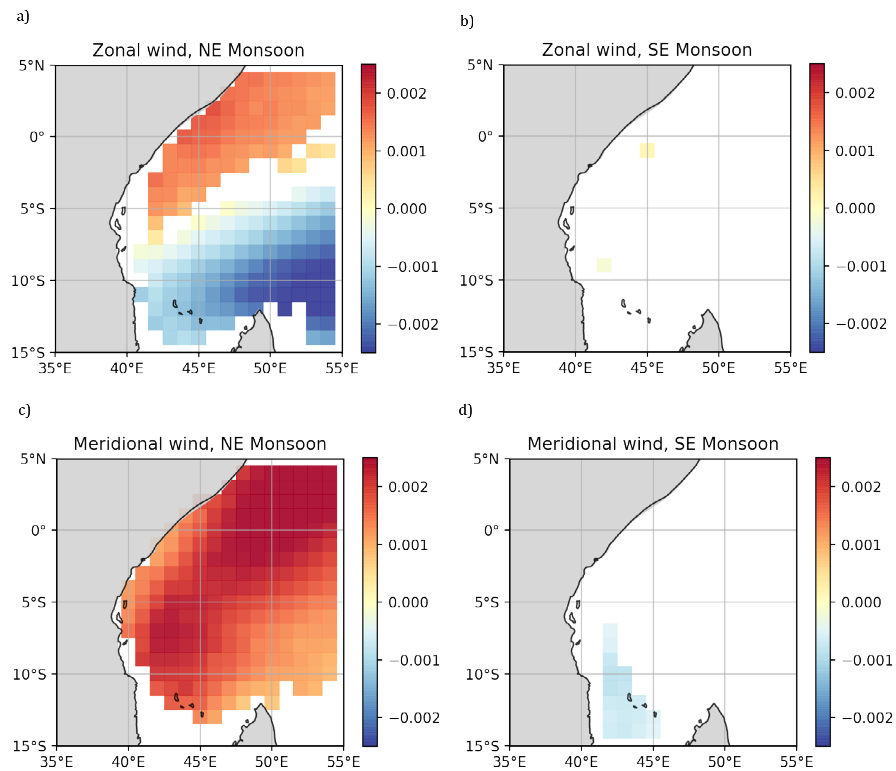

Figure 4. Future trends in wind stress (a) and signal to noise ratio (b) for the NE monsoon for the GCMs ensemble data. Only mean values of 10 or more models showing significant ($p<0.05$) trends are shown. Linear trends in zonal (top) and meridional (bottom) wind speed for GCMs ensemble future projections, for both NE (left) and SE (right) monsoon seasons for the period 2006-2100. Units in m/s/decade. Only mean values of 10 or more models showing significant ($p<0.05$) trends, and with signal to noise ratio values > 1 are shown.

central/southern eastern areas of the domain (~0.12°C/decade). Despite these differences, GMC data show a small range of trends (0.09-0.13°C/decade) within the domain, while HadSST shows a wider range, from 0.02 to 0.18°C/decade.

Future trends of winds in GCM show increasing zonal and meridional wind speed during the NE monsoon, mainly in the Somali Current region (Fig. 4a, c), which suggest weakening of the prevailing winds. This region corresponds with the region of largest SST trends (up to 0.42°C/decade, Fig. 3e) in future projections. A region of decreased zonal winds and slightly increased meridional winds is observed south of 5°S, a region with very weak climatological winds during this monsoon. During the SE monsoon, no significant trends in winds were found (Fig. 4b, d), except for weak negative trends in meridional in the southwest area. Future SST show increasing trends in the entire domain with stronger trends in the northeast corner of the domain (Fig. 3e, f), but weaker than during the NE monsoon. The range in SST trends is larger in the NE monsoon, both with minima of 0.34°C/decade in the southeast corner to >0.4°C/decade in the northern area for NE, and < 0.4 for SE. Notably, smaller trends in SST are found in the CEA.

Discussion

SST off the coast of CEA shows significant increasing trends in the last several decades as well as in future projections under anthropogenic climate change, with differences between the two monsoons, as hypothesized. Wind speed shows statistically significant trends, in the observational record, in the zonal wind for the NE monsoon, and in a small area for the SE monsoon in both zonal and meridional components. However, these trends are not replicated in the historical simulations of the climate models. In the last century, wind, the physical feature that experiences the largest variability during the year, shows significant trends only in the zonal component off the eastern side of the Somalia jet during the NE monsoon – a region with weak or zero zonal wind in the climatology. These trends indicate that the wind shows a shift toward a more meridional direction of the wind in these regions during the NE monsoon, but no change at the coast, differing from the weakening trends shown by Varela *et al.* (2015) using CSFR reanalysis data. During the SE monsoon, zonal wind has increased slightly off Somalia, strengthening the seasonal winds. Notable, these trends are not replicated in the GCM, which does not show significant trends in either monsoon. This might be due to the small long-term changes in comparison with the large variability between models. SST, on the other hand, shows significant warming during the period of study in both observational data and GCM for both monsoons, although with spatial differences. During the NE monsoon both GCM data show larger trends off Somalia, while 20CR data shows larger trends in the opposite corner of the domain. During the SE monsoon however, observations show larger trends in the eastern side of the region, while the GCMs show larger trends in the central north. While increasing SST is the dominating signal in the entire region, and they differ between model and reanalysis, trends differ between seasons in each dataset, with the historical data showing the largest trends in SST during the NE monsoon, in the same region of weakening winds.

GCM future trends, under the "business as usual" carbon path model, showed larger trends than in the last century. First, winds show significant trends in zonal and meridional winds only during the NE monsoon, indicating weakening northeast winds (as the prevailing direction is negative in both zonal and meridional components, positive trends indicate weakening of the winds), particularly in the north; these results are consistent with those found in the reanalysis data for the zonal wind. Note that the magnitude of the trends in the GCM data is small, which reflects the large variability of magnitudes (and signs) among models. The coastal regions show no significant trends in the zonal component of the wind, which is possibly a combination of small trends and low model resolution. Notably, no significant trends are projected for the SE monsoon, and only weak and sparse ones are observed in the 1950-2015 reanalysis data, despite other studies reporting trends in observations for the last decades (Mahongo *et al*., 2012). SST future trends show magnitudes up to 3 times larger than those in the 1950-2015 period, and in both monsoons, trends are smaller at the CEA southern areas. The largest SST trends are during the NE monsoon in the Somali Current region, consistent with the weakening trend in winds in this region during this season, which potentially increase the warming trends by reducing mixing.

The findings presented here suggest increased water column stability from increasing SST, especially during the NE monsoon. McClanahan (1988) indicated that the stability already observed in this season is important for biological productivity, although it is unclear if increased stability would be favourable. A potential consequence of the trends in the wind during the NE monsoon is a northward shifting of the EACC separation from the continent, where the northward flowing EACC and the southward flowing Somali Current meet, due to weakening winds. This could also shift the upwelling occurring at the coast due to the separation of these current from the coast, potentially reducing the entrainment of nutrients around Northern Kenya. However, nitrate rich water from fixation by algae (McClanahan, 1988) and island wake upwelling from Tanzanian and Kenyan islands (Roberts *et al*., 2008) might be reaching further north as the EACC reaches further north, partially compensating for the reduced upwelling. Given the resolution of the data analyzed here, a regional modeling analysis of currents and water characteristics under present and future climate would provide a more accurate insight on these changes and their implications for local conditions (see Halo *et al*., 2020, in this issue).

Finally, while consistent future changes in weakening winds and increasing SST during the NE monsoon were found in this analysis, during the SE monsoon only SST show significant increasing trends. However, given observed increasing trends (in this analysis during the SE monsoon on 20CR data and those reported by Mahongo *et al*. (2012) year-round), it would be worth further investigating the interannual to decadal variability in the conditions during this monsoon, which seems to be large and associated with climate oscillations (Mahongo *et al*., 2012), and it might have the largest implications for the marine ecosystem.

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