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Dynamic shifts in eastern boundary upwelling systems: Climate-change driven impacts on frequency, intensity and spatial patterns of upwelling

Anjaneyan Panthakka* and Jayanarayanan Kuttippurath

CORAL, Indian Institute of Technology Kharagpur, West Bengal -721302

aanjuanjaneyan@kgpian.iitkgp.ac.in

Introduction

- Eastern boundary upwelling systems (EBUS), although occupying less than 1% of the oceanic expanse, exhibit remarkable productivity, contributing significantly to global capture fisheries, accounting for up to 20% of the total yield.
- EBUS offer ecosystem, economic, and recreational benefits to approximately 80 million people residing along their coastlines and immediate hinterlands.
- EBUS's high productivity stems from large-scale atmospheric pressure systems that drive along-shore, equatorward winds. These winds, combined with the Coriolis effect, cause nutrient-rich waters to upwell from depth into the coastal zone, fueling phytoplankton blooms.

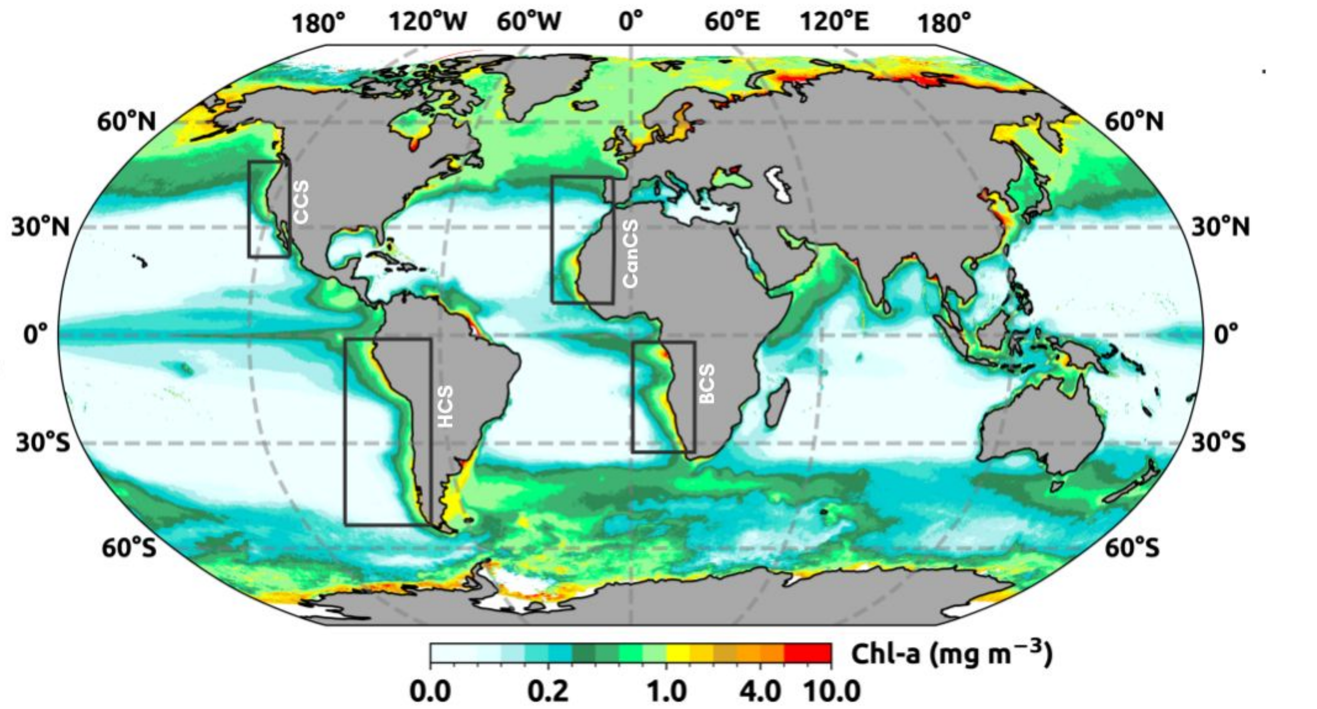

Fig. 1: Annual mean Chlorophyll-a (Chl-a) in global oceans. Four eastern boundary upwelling systems (EBUS), namely California current system (CCS), Humboldt current system (HCS), Canary current system (CanCS) and Benguela current system (BCS) are demarcated by grey box.

Objectives

- Investigate long-term changes in upwelling within EBUS regions.
- Objectively characterise upwelling dynamics across EBUS, focusing on frequency, intensity and duration.
- Examine the relationship between SST changes and upwelling events, and assess their implications for marine ecosystems and coastal communities.

Data

- Global land map at 1:10 m
- National Oceanic and Atmospheric Administration (NOAA) 1/4° Daily Optimum Interpolation Sea Surface Temperature (OISST) for period 1982–2023. (Version 2.1)
- European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) 1/4° daily wind vectors at 10 m for 1982–2023.
- European Space Agency (ESA) Ocean Colour Climate Change Initiative (OC-CCI) v5 daily Chlorophyll-a at 9 km resolution for period 1998–2023.

Methodology

Wind stress (τ):

$$\tau = (\tau_x, \tau_y) = \rho_{air} C_D V(u, v)$$

ρ_{air} is 1.255 kg m^{-3}

$$C_D = \begin{cases} 2.18 \times 10^{-3} \; for \; W \le 1 \\ \left(0.62 + \frac{1.56}{W}\right) \times 10^{-3} \; for \; 1 < W \le 3 \\ 1.13 \times 10^{-3} \; for \; 3 < W < 10 \\ (0.49 + 0.065 \times W) \times 10^{-3} \; for \; W \ge 1 \end{cases}$$

Ekman pumping (EP):

$$EP = \frac{1}{\rho f} \nabla \times \tau$$

ρ is the reference density 1025 kg m^{-3}

f is the coriolis parameter (2Ω sin φ),

Ω is the angular velocity of earth (7.2921159 x 10^{-5} rad/s)

φ is the latitude

∇ is the Del operator

- Upwelling is defined when EP values are positive and sea surface temperature (SST) decreases.
- Positive EP leads to surfacing to cold waters and a concurrent SST reductions to the seasonally variable 25th percentile (Abrahams et al., 2021) signify upwelling events.
- The detect_event() function from the heatwave package (Schlegel and Smit, 2018), which computes metrics for upwelling signals, including frequency, mean intensity and duration

Parameter	Definition
Frequency	Number of upwelling events
Mean intensity (°C)	Average temperature anomaly during the upwelling event
Total days	Annual number of upwelling days
Duration	Duration of upwelling events

Results

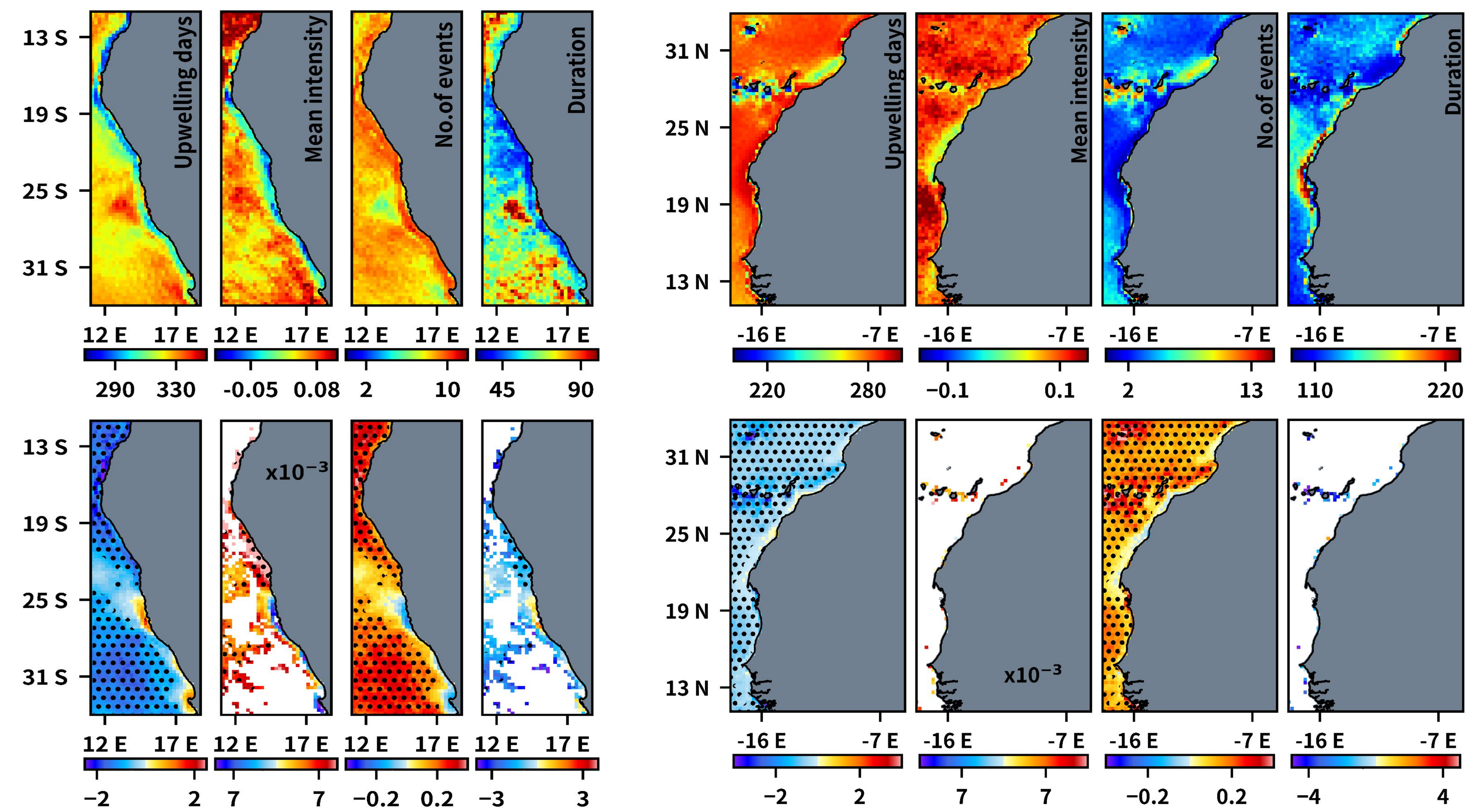

Fig. 2: (upper panel) Annual composite of upwelling days (days), mean intensity (°C), no.of events and duration (days) for BCS (left) and for CanCS (right) for the period 1982–2023. (bottom panel) Spatial trend of metrics for BCS and CanCS during the same period.

- Upwelling metrics perform better along the coastal regions than offshore.
- Upwelling metrics reveals the heterogeneity in the upwelling process in BCS and CanCS
  - BCS has stronger upwelling in southern region; with higher upwelling days (~avg.300 days in an year), higher mean intensity (drop in SST by -0.05 °C in a year).
  - Additionally, southern BCS is characterised with shorter upwelling events, thus the higher no.of events there.
  - Upwelling days in CanCS are compatible with BCS (about 300 days in an year), but weaker mean intensity points to a weaker upwelling than BCS.
  - CanCS is characterised with longer upwelling events
- Long-term trend in upwelling metrics shows mixed trends in EBUS of Atlantic Ocean.
  - In BCS, upwelling intensifies (insignificant: positive trend in upwelling days and negative trend in mean intensity) in the southern region and weakens (significant: negative trend in upwelling days) in the northern region
  - However, in CanCS the decline in upwelling is evident with significant negative trend in upwelling days throughout the coast.

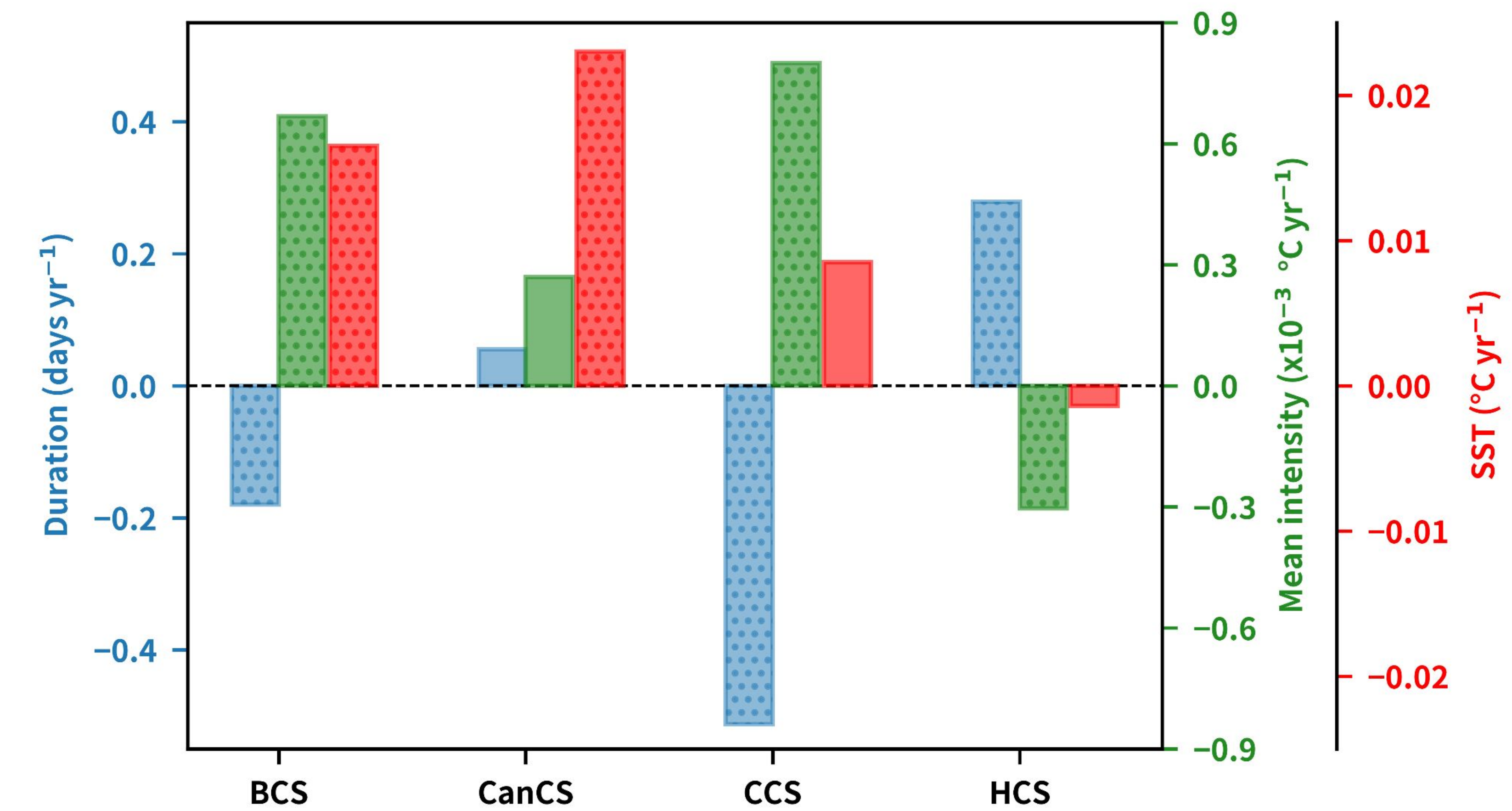

Fig. 3: Annual trend of duration (days yr^{-1}), mean intensity (°C yr^{-1}) and sea surface temperature (SST) for Benguela current system (BCS), Canary current system (CanCS), California current system (CCS) and Humboldt current system (HCS) for the period 1982–2023.

- All EBUS except HCS show signs of weakening in upwelling, as evidenced by both the decrease in upwelling days, increase in mean intensity and positive SST trend.
- Despite being primarily driven by equatorward winds along the coastline, resulting in upwelling, EBUS exhibit varying upwelling characteristics and responses to climate change.
- Highest decline in upwelling is observed in CCS, though the rise in SST there is not intense.

Conclusions

- Climate variations do not lead to increased upwelling in EBUS. However, certain coastal regions experience reinforced upwelling, slightly mitigating the impact of climate change.
- Poleward intensification in upwelling is observed in EBUS, particularly in the southern hemisphere, with the HCS exhibiting intensified upwelling despite its proximity to El Niño regions.

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