Drivers of marine heatwaves and their decadal disruption in the southwest Indian Ocean in recent decades

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In the Southwest Indian Ocean (SWIO), Marine heatwaves (MHWs) can influence marine ecosystems, tropical cyclones and regional climate including island nations and coastal areas of the Southeast Africa. Yet, their causes remain largely unknown. Using a combination of satellite observations, ECCO and other reanalysis datasets, and climate model simulations, we investigated the drivers of individual MHW events and their decadal evolution since 1982.

Warming trend increases MHW frequency (Fig. 1a-d). After the SST trend is removed, MHWs exhibit year-to-year variability and decadal variation, with a decade-long suppression of MHWs during 1992-2005 (1d). The MHW activities still show an increasing trend (1f-h). A MHW is defined as a warm SST event with SST anomalies exceeding 90the percentile and last for 5 consecutive days.

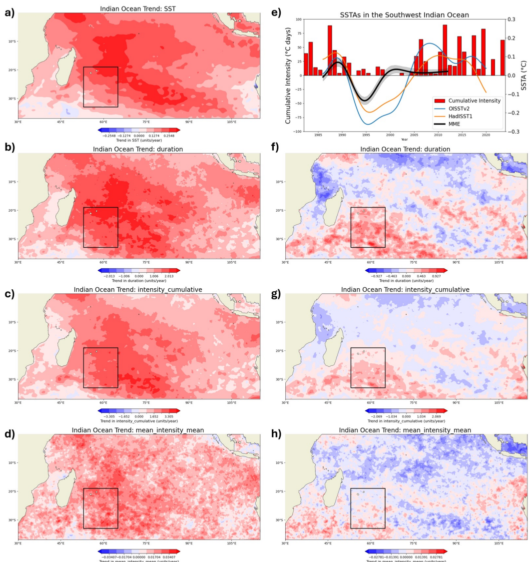
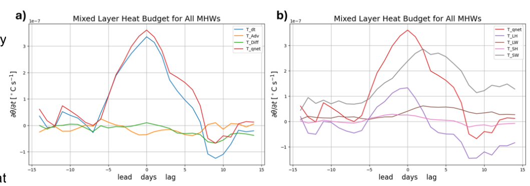


Fig. 1. (a) Linear trend of SST over the South Indian Ocean for the 1982-2024 period from OISST data. Linear trend for MHW (b) duration, (c) cumulative intensity, and (d) annual mean intensity from 1982-2024. The yearly cumulative intensity of MHWs for the SWIO is shown with the bars (red) and the 8-year low-pass SSTA for the SWIO from OISST (blue), HadISST1 (orange), and the CMIP6 MME (black)are shown in (e). The gray shading represents the 95th percentile confidence interval for the MME. After the linear trend in SSTAs are removed, the new trends from panels b-d are shown in f-h.

ECCO budget analyses for MHW composites show that surface shortwave and latent heat fluxes are the main cause for individual MHW events (Fig. 2). Weakened wind speed and increased specific humidity both act to reduce latent heat loss and increase SST. The increased humidity results from advection of the more humid air from the tropics by the southward surface wind anomalies (Fig. 3). The weakened wind speed reduces entrainment and shallows the mixed layer depth, enhancing the shortwave heating (Fig. 3).

Fig. 2. Mixed layer temperature (MLT) budget for the composite of all 47 MHW events that occurred in the SWIO region (boxed area in Fig. 1) during the ECCO era of 1992-2017. Day 0 marks the day of MHW onset, and negative (positive) days indicate the no. of days before (after) the MHW onset. (a) MLT tendency (blue), and MLT tendency induced by the net surface heat flux (red), horizontal advection (orange), diffusion (green), and subsurface processes (brown).(b) Same as (a) but for the effects of surface net heat flux (red), latent heat flux (purple), sensible heat flux (pink), longwave radiation (brown), and shortwave radiation (gray).



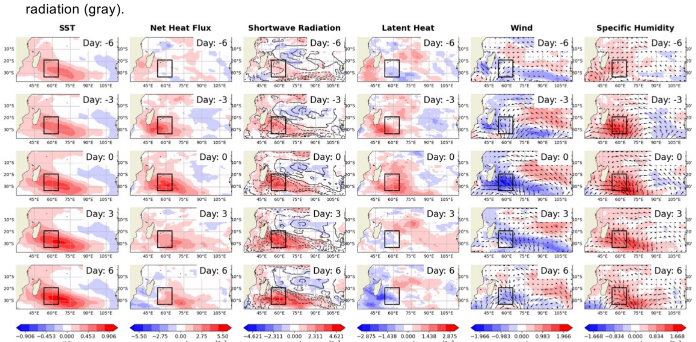


Fig 3. Mixed layer heat budget analysis for the composite of all 47 MHW events during the ECCO era of 1992-2017 at each grid point of the South Indian Ocean. Day 0 marks the day of MHW onset, and negative (positive) days indicate the no. of days before (after) the MHW onset. (a) MLT tendency; (b) MLT tendency induced by surface net heat flux (Qnet; color contours) together with MLD (line contours; positive solid and negative dashed, with an interval of xx m); (c) same as (b) but for shortwave radiation (Qsw); (d) same as (b) but for latent heat flux (QLH). All data are from ECCOv4r4. (e) surface wind velocity (vector) and wind speed (color) anomalies; (f) surface wind vector and

Atmospheric intraseasonal Rossby waves induce sea level pressure anomalies (Fig. 4) and therefore surface wind anomalies shown in Fig. 3, causing reduced latent heat loss and increase SST.

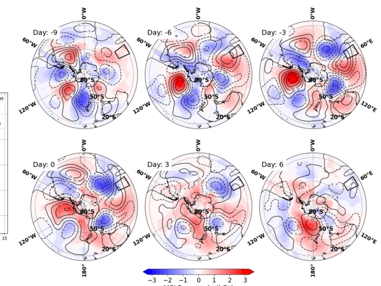


Fig. 4. Composites for mean sea level pressure (filled contours) and 200 hPa geopotential height anomalies (contours) with a 10-100 day bandpass filter during the onset and decay of all MHW events (n=91) using ERA5 data.

External forcings (especially volcanic eruption) combined with internal variability (SIOD) explain the negative SST anomalies during 1992-2005 (Fig. 5), the decade when MHW activities are suppressed. For the decades before and after, SAMV+SIOD and external forcings explain the decadal warm SST anomalies.

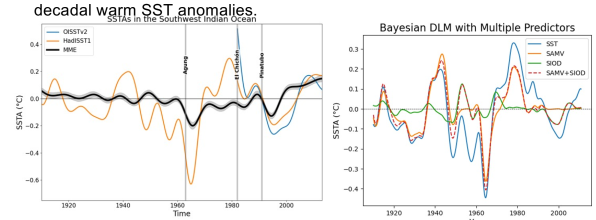


Fig. 5. (left) Time series of SWIO SSTA for OISST, HadISST and the multimodel ensemble mean (MME) from CMIP6 models. The SSTA is 8-year lowpassed. The shading indicates the 95% confidence intervals. Vertical gray bars show major volcanic eruptions with a volcanic explosivity index of at least 5 during this time period. (right) Timeseries of 8-year low-pass filtered SWIO SSTA, with the external forcing (MME) removed, and thus only represents the decadal SSTA associated with internal variability (blue), the contribution from South Atlantic Multidecadal Variability (SAMV; orange), the contribution from Subtropical Indian Ocean Dipole (SIOD; green), and their combination (dashed red).

Conclusions: (a) surface warming trend increases the frequency of MHWs; (b) surface wind anomalies associated with mid-latitude atmospheric intraseasonal Rossby waves are the main driver for individual MHW events; (c) external forcings – particularly the Pinatubo volcanic eruption – act in concert with internal climate variability modes - the Subtropical Indian Ocean Dipole (SIOD) – to drive the decadal suppression of MHWs during 1993–2005. For the decades before and after, external forcings combined with SIOD and South Atlantic Multidecadal Variability (SAMV) cause the decadal warm SST anomalies. These results highlight the importance of the interplay between external forcings and internal climate variability across multiple timescales in generating MHWs and shaping their decadal evolution. Accounting for these factors is essential for skillful predictions of MHW activity.

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