# Interannual variability and decadal change of upwelling and heat redistribution over the Indian Ocean: effects of climate modes

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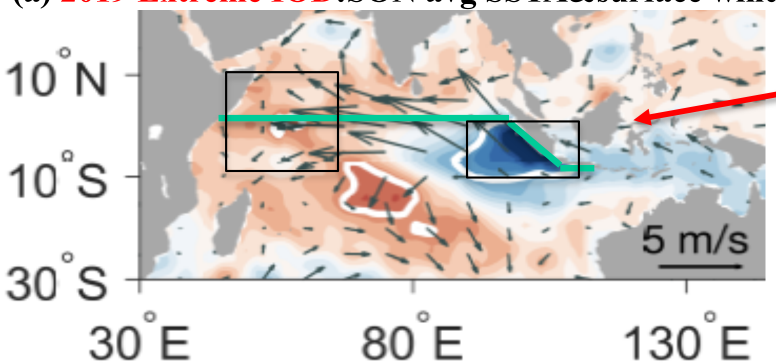
**This project studied the effects of the following climate modes**:

- **The El Nino and Southern Oscillation (ENSO), tropical Indian Ocean Dipole (IOD) & *subtropical* IOD (SIOD) - interannual timescale**
- **The Interdecadal Pacific Oscillation (IPO), decadal variability of IOD & monsoon –decadal-interdecadal timescales**
- **The Madden-Julian Oscillation (MJO) – intraseasonal timescale**

# Episodical equatorial Kelvin waves contributed to 2019 extreme Indian Ocean Dipole (IOD)

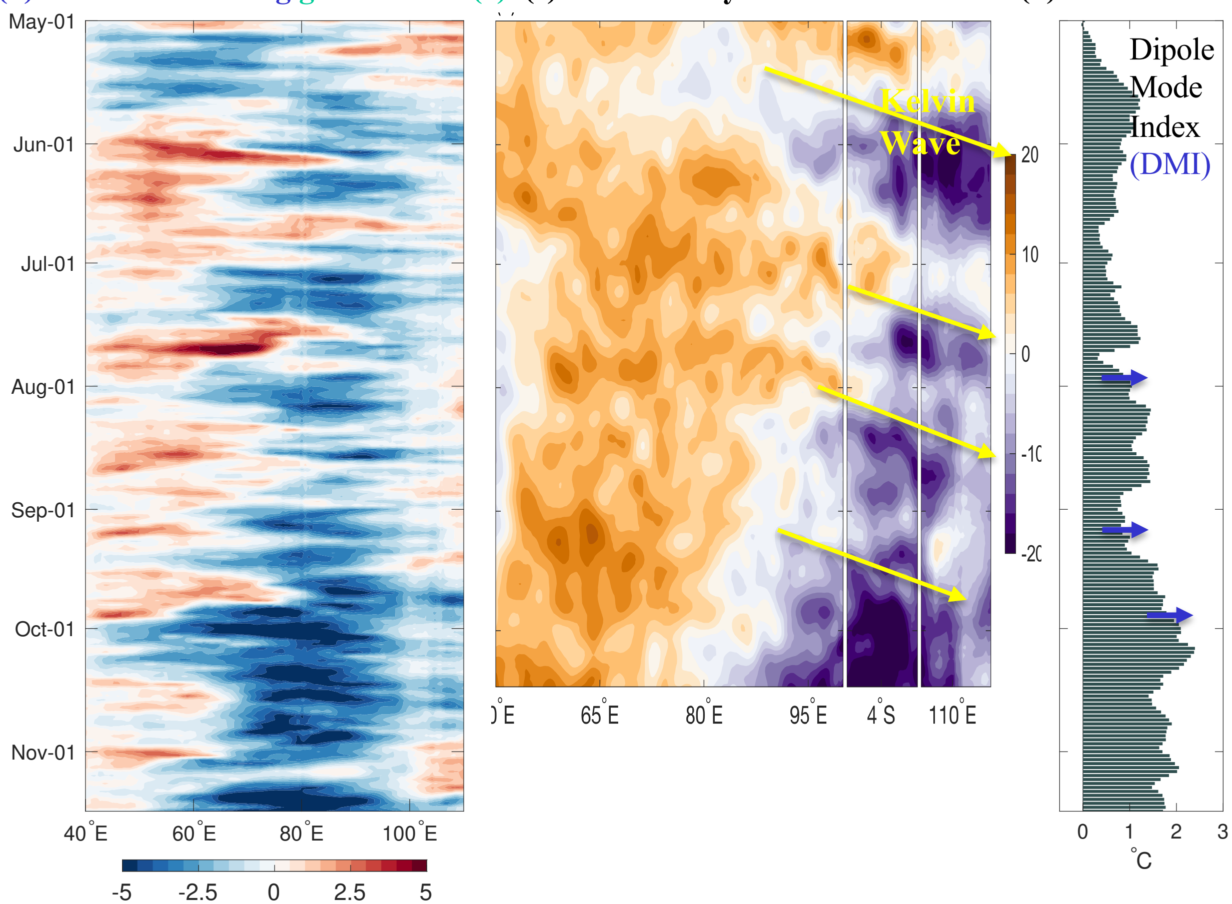
**(a) 2019 Extreme IOD:SON avg SSTA&surface wind**




The 2019 unprecedented extreme positive Indian Ocean Dipole (IOD) caused widespread disastrous impacts: e.g., East African floods, Australia vast bushfires.

*IOD is measured by Dipole Mode Index (DMI), which is seas surface temperature anomaly (SSTA) averaged in eastern box subtracts that in western box, shown in (d).*

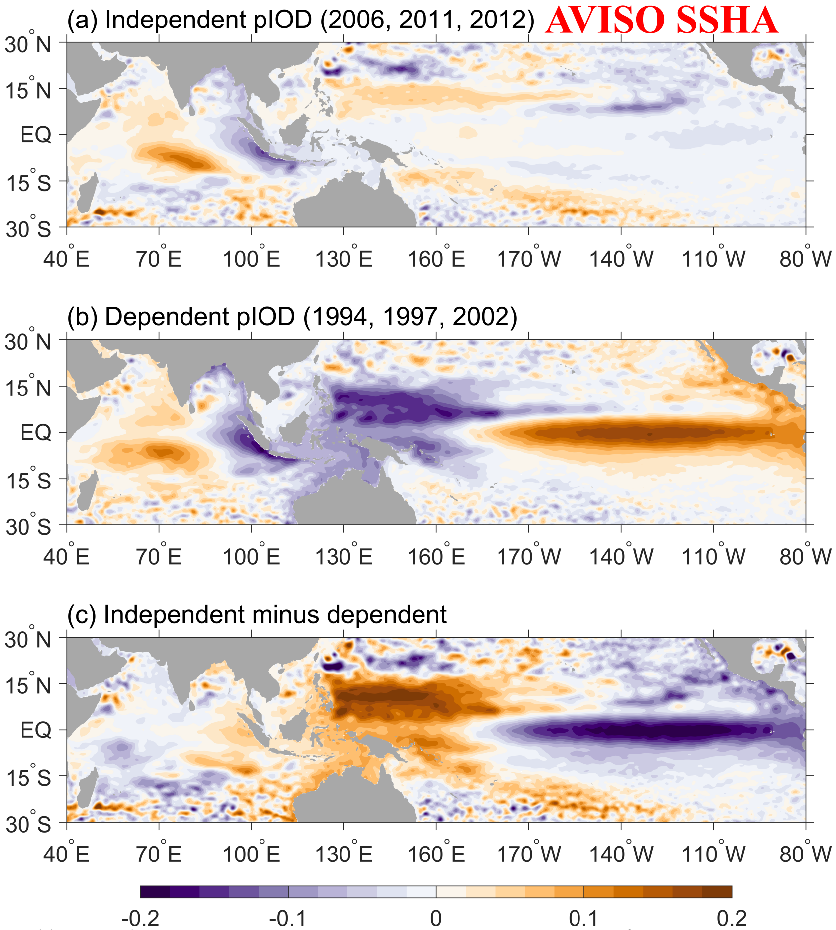
**(b) 2019 U wind along green line of (a)** **(c) AVISO daily SSHA: 2019** **(d) 2019 DMI**

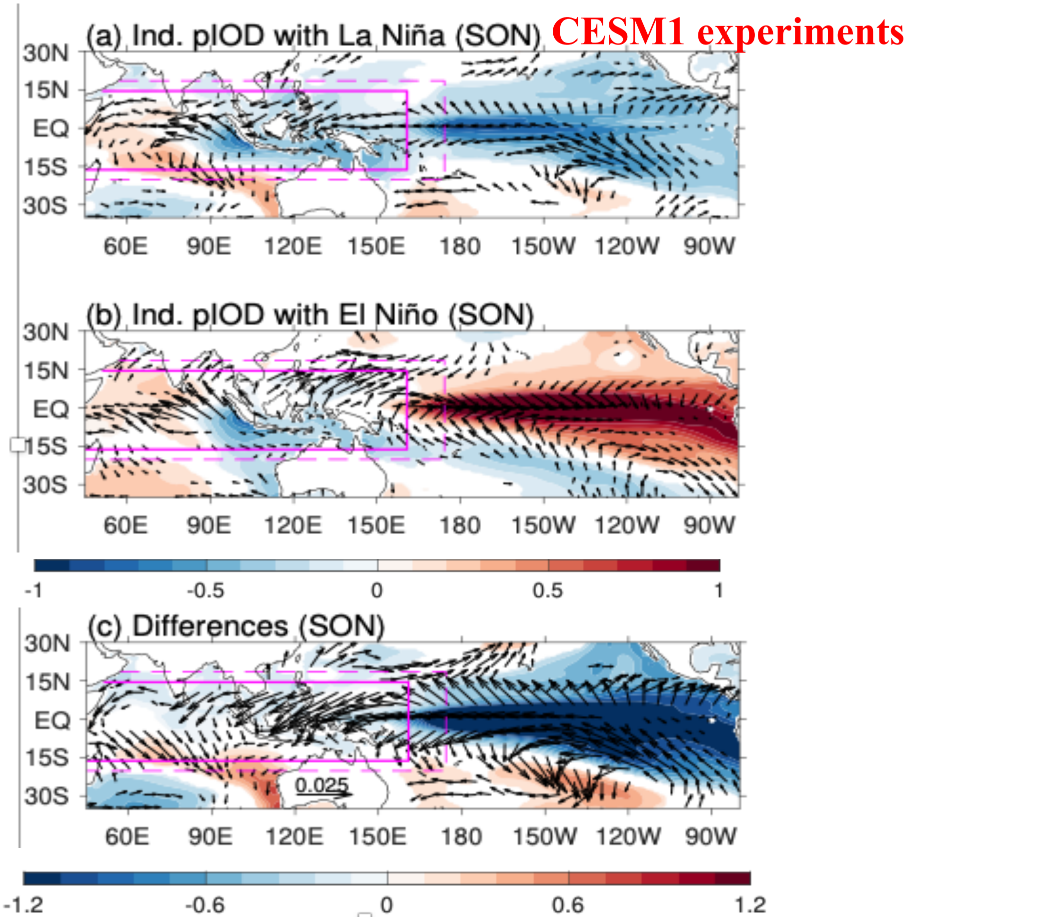



Episodical equatorial easterly wind anomalies (blue U in (b)) associated with *suppressed phase* of Madden-Julian Oscillation (MJO) drive oceanic **upwelling Kelvin waves** – indicated by negative SSHA **[purple in (c)]**, enhancing upwelling cooling in eastern equatorial basin & therefore intensify the pIOD (**DMI** in (d)). Inter-basin coupling between tropical Indian & Pacific Ocean brough the IOD to "extreme".

***From: Zhang L., W. Han and Z. Hu, 2020: Inter-basin and Multi-time Scale Interactions in generating the 2019 Extreme Indian Ocean Dipole. J. Clim., in review.***

# The IOD has diverse impacts on ENSO



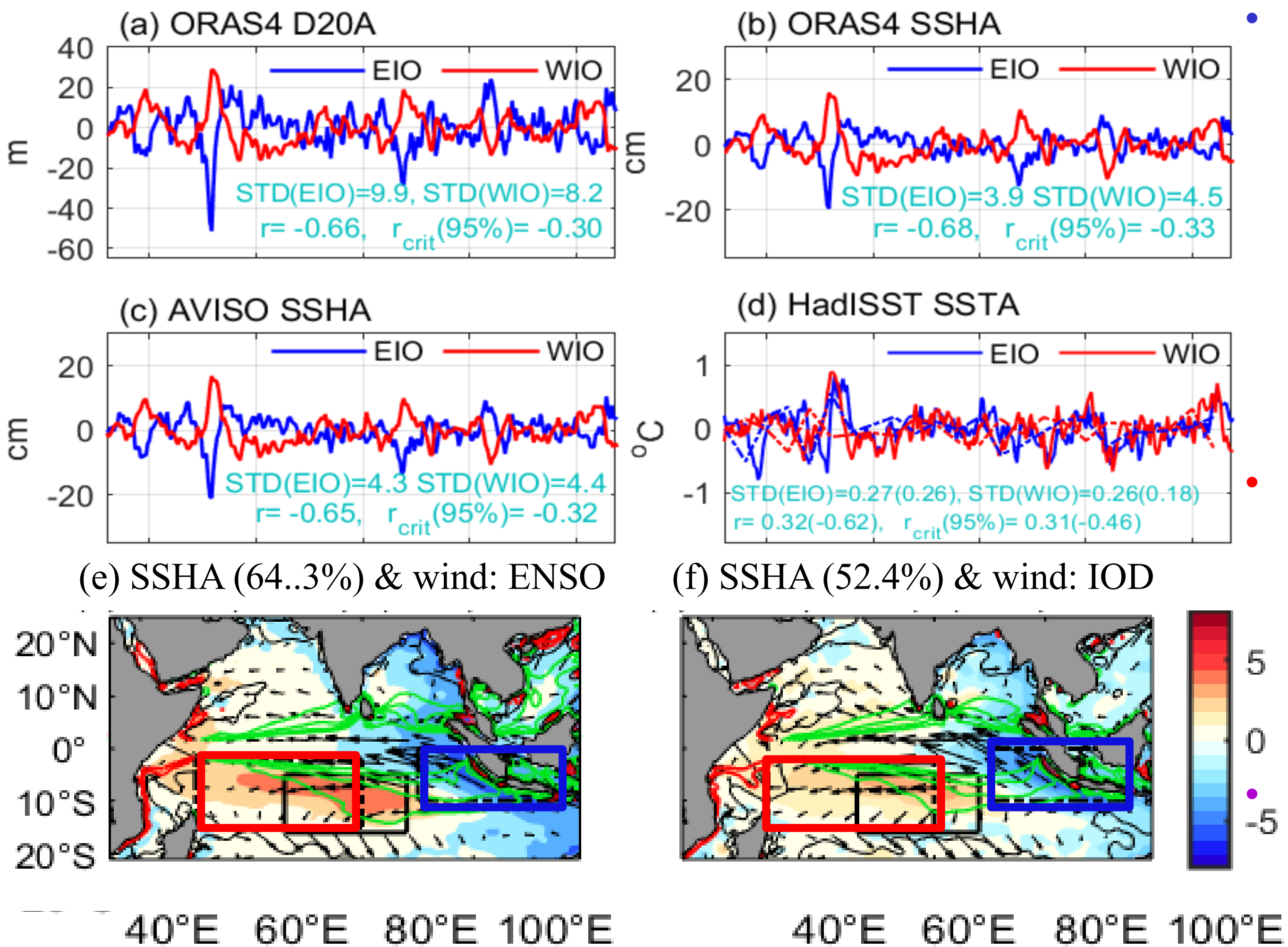




*Satellite altimeter SSHA composites: **(a)** for 3 positive IOD (pIOD) events that are **independent of ENSO**; **(b)** 3 pIOD events **dependent on ENSO**; **(c)** their difference (a) minus (b).* **The pIOD that favor inducing Pacific La Nina events show high SSHA & thus high ocean heat content (OHC) in eastern basin, as shown in (c).**

***From: Zhang L., W. Han &coauthors, 2020:Diverse impacts of Indian Ocean Dipole on El Niño-Southern Oscillation, Nature Communication, in revision.***

*SSTA & surface wind anomalies from NCAR's Community Earth System Model v1 (CESM1) experiments for: **(a) ENSO-independent pIOD that may cause La Nina**, **(b) ENSO-independent pIOD that may cause El Nino**, (c) their difference, (a) minus (b).* **SSTAs with warming (cooling) over tropical southwest Indian Ocean thermocline ridge & southeast IO off Australian coast associated with pIOD favor causing Pacific La Nina (El Nino). The SSTA pattern favors La Nina agrees with the SSHA & thus OHC anomaly (compare bottom panels of left and right column)**

# ENSO & IOD cause large-scale upwelling, SSHA & upper-ocean heat content (OHC) anomalies over tropical Indian Ocean

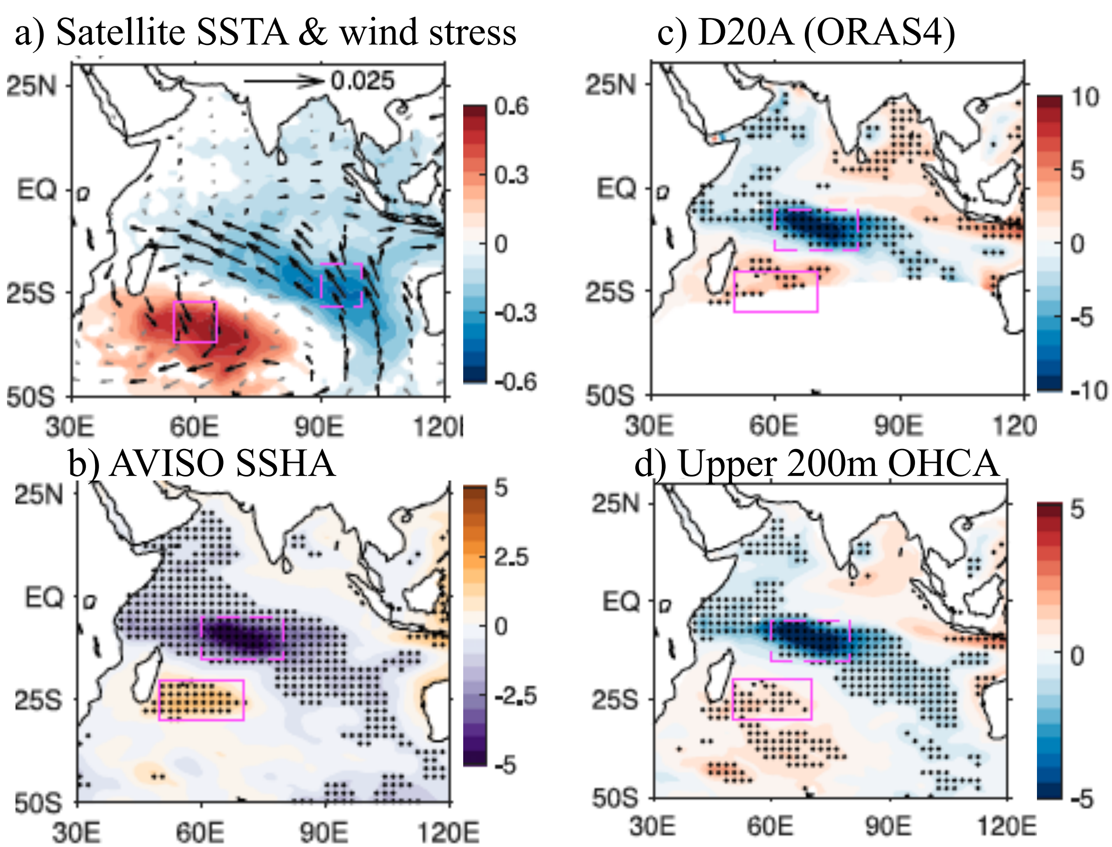



- **SSHAs can serve as reliable indicators for upwelling in tropical IO, mirroring D20 anomaly (D20A; compare blue or red lines between (a) and (c)). During SON when IOD attains its peak, SSHA is significantly correlated with SSTA (d).**
- **ENSO & IOD cause similar east-west dipole pattern of SSHA & thus OHC anomaly, redistributing heat between east and west basin of tropical Indian Ocean (e and f).**
- **When positive IOD cooccur with El Nino, they cause stronger impacts**

*Monthly anomalies (a) thermocline depth, denoted by depth of 20C isotherm (D20) from ORAS4 reanalysis, (b) ORAS4 SSHA, (c) AVISO Satellite SSHA, and (d) HadISST SSTA averaged in the Tropical WIO (red line) and Tropical EIO (blue line), mean and seasonal/interannual upwelling zones (red & blue boxes) in (e ) & (f). In (d), "dotted lines" show Sep, Oct & Nov (SON) mean SSTAs. (e)-(f): Leading EOF mode of SSHA (color), wind (vector) & Ekman pumping velocity (line contours, positive in green) associated with ENSO & IOD, respectively.*

***From: Zhang X. & W. Han, 2020: Effects of climate modes on interannual variability of upwelling in the tropical Indian Ocean. J. Clim., 33 (4): 1547–1573.***

# Subtropical Indian Ocean Dipole (SIOD) has significant impacts on heat and mass redistribution in subtropical-tropical South IO (SIO)



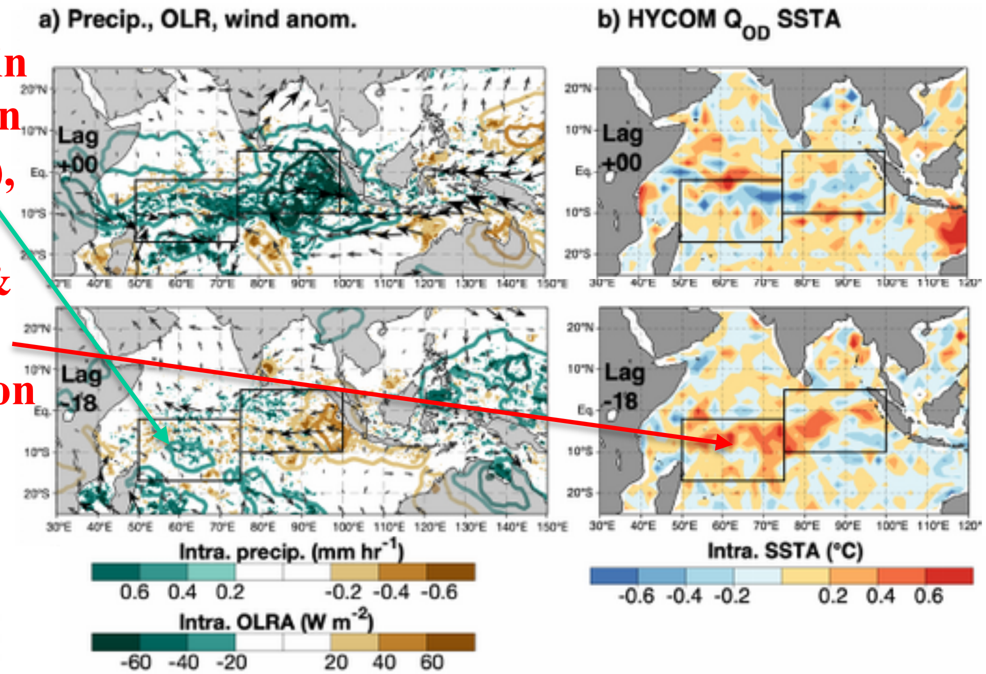

Regression of **SIOD** index onto **(a)** Satellite SSTA and surface wind stress, **(b)** AVISO SSHA, **(c)** D20A (ORAS4 reanalysis), and **(d)** upper 200m OHC anomaly (OHCA) from ORAS4 reanalysis data.

**SIOD is associated with basin-scale wind, SSTA, SSHA, upwelling (D20A) and upper OHC anomaly in the SIO, affecting upwelling and heat & mass redistribution in the upper SIO. During positive SIOD, SST, SSH, D20 and OHC increase in subtropical southwest IO, and decrease in tropical thermocline ridge region and subtropical eastern basin.**

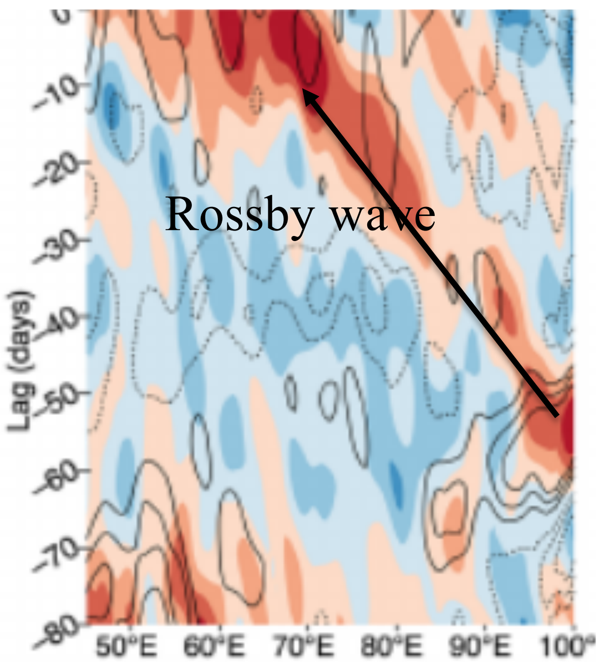
*From: Zhang L., W. Han, Y. Li, N. Lovenduski, 2019: Variability of Sea Level and Upper-Ocean Heat Content in the Indian Ocean: Effects of Subtropical Indian Ocean Dipole and ENSO, J. Clim., 32: 7227–7245.*

# Ocean dynamics help to initiate boreal winter (Nov-Apr) MJO

**(i) A MJO event was initiated in the thermocline ridge region on day -18 (bottom-left, west box), when warm SSTA induced by oceanic processes (upwelling & advection) is strong (bottom-right); Subsequently, convection propagates eastward to the warm pool (top-left; east box)**




*MJO event in 2002: **(a) P**recipitation, convection (OLR) and surface wind anomalies when MJO convection was first initiated in the thermocline ridge (bottom-left; west box) and then propagate eastward to the warm pool (top-left east box), where it peaks on day 0; **(b)** SSTA due to ocean dynamical processes (upwelling, advection & entrainment) from HYCOM model.*




**(ii) Longitude-time plot of AVISO SSHA from day -80 to day 0, showing westward propagating Rossby waves from eastern basin into the thermocline ridge region, suppressing upwelling cooling and thus contributing to the warm SSTA from day -18 to day 0.**

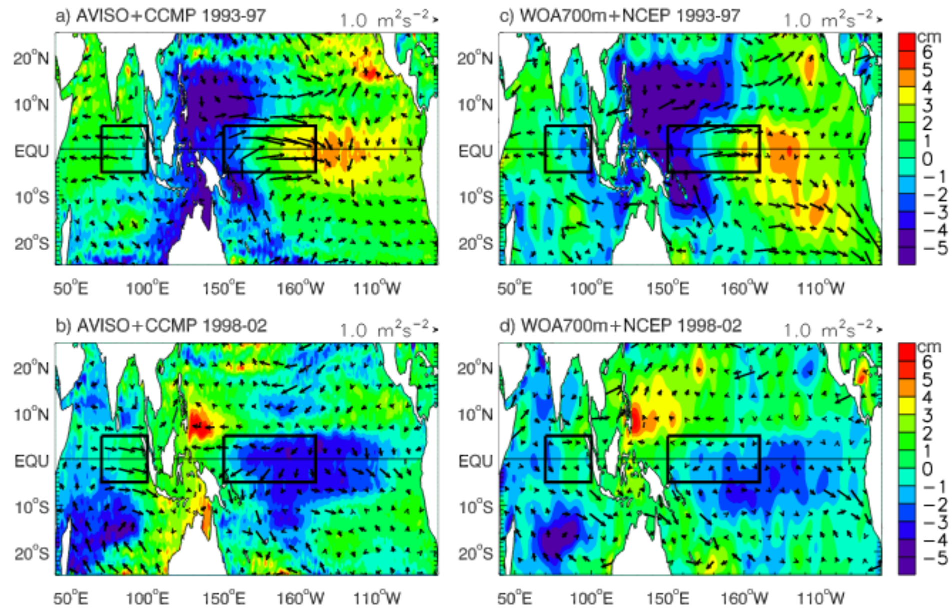
***From: West, J., W. Han, L. Zhang and Y. Li, 2020: The Role of Oceanic Processes in the Initiation of Boreal Winter Intraseasonal Oscillations over the Indian Ocean. JGR-Oceans, 125, e2019JC015426.***

**We also found that ocean dynamical processes can have a significant contribution to pre-convection warming of some boreal summer monsoon intraseasonal oscillations (MISOs).**

***West J., W. Han, and Y. Li, 2018: The Role of Oceanic Processes in the Initiation of Indian Summer Monsoon Intraseasonal Oscillations over the Indian***

**Zonal gradients of satellite SSHA along the equator are good indicators for decadal changes of Indian and Pacific Walker Cells.**

*Han W., G.A. Meehl, A. Hu, J. Zheng, J. Kenigson, J. Vialard, B. Rajagopalan, and Yanto, 2017: Decadal variability of Indian and Pacific Walker Cells: Do they co-vary on decadal timescales? J. Clim., 30, 8447-8468.*




*SSHA (with global and climatological means removed) based on monthly AVISO satellite SSHA & CCMP pseudo wind stress (arrows) averaged for (a) 1993–97 and (b) 1998–2002; (c)-(d) are as (a)-(b) but for the upper-700-m thermosteric sea level fromWOA13 data and NCEP–NCAR reanalysis wind.*

**We have also found that the effects of internal variability dominate external forcing in driving regional patterns of SSHA for both multi-decadal trend since the 1960s and decadal variability. Over the Seychelles area where sea-level variations obtain the maximum, internal variability (external forcing) contributes 81% (19 ± 2.4%) of the observed trend. For decadal SSHA, internal variability is the predominant cause, with a standard deviation (STD) ratio of externally forced/observed SSHA being 18 ± 17% over Seychelles and 17 ± 11% near the Indonesian Throughflow (ITF) area. Climate modes (IPO, decadal IOD and monsoon) account for a large fraction of observed SSHA.**

*Han W., D. Stammer, G. A. Meehl, A. Hu, F. Sienz and L. Zhang 2018: Multi-Decadal Trend and Decadal Variability of the Regional Sea Level over the Indian Ocean since the 1960s: Roles of Climate Modes and External Forcing, Climate, featured article, 6(2), 51.*

# Publications support by & acknowledged this grant

1. Zhang L., **W. Han**, G. Meehl, A. Hu, N. Rosenbloom, T. Shinoda & M. McPhaden, 2020: Diverse impacts of Indian Ocean Dipole on El Niño-Southern Oscillation, *Nature Communication, in revision*.
2. Zhang L., **W. Han** and Z. Hu, 2020: Inter-basin and Multi-time Scale Interactions in generating the 2019 Extreme Indian Ocean Dipole. *J. Clim., in review*.
3. Zhang X. & **W. Han**, 2020: Effects of climate modes on interannual variability of upwelling in the tropical Indian Ocean. *J. Clim., 33 (4): 1547–1573.*
4. West, J., **W. Han**, L. Zhang and Y. Li, 2020: The Role of Oceanic Processes in the Initiation of Boreal Winter Intraseasonal Oscillations over the Indian Ocean. *JGR-Oceans, 125, e2019JC015426*.
5. Zhang L., **W. Han**, Y. Li, N. Lovenduski, 2019: Variability of Sea Level and Upper-Ocean Heat Content in the Indian Ocean: Effects of Subtropical Indian Ocean Dipole and ENSO, *J. Clim.,* ***32****: 7227–7245*.
6. **Han W**., D. Stammer, G. A. Meehl, A. Hu, F. Sienz and L. Zhang 2018: Multi-Decadal Trend and Decadal Variability of the Regional Sea Level over the Indian Ocean since the 1960s: Roles of Climate Modes and External Forcing, *Climate, featured article, 6(2), 51.*
7. West, J. **W. Han**, and Y. Li, 2018: The role of oceanic processes in the initiation of Indian summer monsoon intraseasonal oscillations over the Indian Ocean. *J. Geophys. Res. - Oceans, 123, 3685-3704.*
8. **Han W**., G.A. Meehl, A. Hu, J. Zheng, J. Kenigson, J. Vialard, B. Rajagopalan, and Yanto, 2017: Decadal variability of Indian and Pacific Walker Cells: Do they co-vary on decadal timescales? *J. Clim., 30, 8447-8468.*

## Publications: PI partially supported by & acknowledged this grant

- Shinoda, T., **W. Han**, L. Zamudio, X. Feng, 2020: Influence of atmospheric rivers on the Leeuwin Current system. *Clim. Dyn., 54, 4263–4277.*
- **Han W.,** Detlef Stammer, & coauthors, 2019: Impacts of basin-scale climate modes on coastal sea level: a review. *Surveys in Geophysics, 40, 1493–1541.*
- Kido, S., T. Tozuka, and **W. Han**, 2019a: Experimental assessments on impacts of salinity anomalies on the positive Indian Ocean Dipole. *J. Geophys. Res., 124, 9462–9486.*
- Kido, S., T. Tozuka, & **W. Han**, 2019b: Anatomy of salinity anomalies associated with the positive Indian Ocean Dipole. *J. Geophys. Res., .124, 8116-8139.*

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- Kenigson, J., **W. Han**, B. Rajagopalan, Yanto, and M. Jasinski, 2018: Decadal Shift of NAO-Linked Interannual Sea Level Variability along the US Northeast Coast. *J. Clim., 31, 4981-4989*.
- Tozuka, T, M. Feng, **W. Han**, and S. Kido and L. Zhang, 2020: The Ningaloo Niño/Niña: Mechanisms, Relation with Other Climate Modes and Impacts. Book chapter in "Tropical and Extra-tropical Air-Sea Interactions", *S. Behera eds, ISBN: 9780128181560*.
- Lee T., J.T. Farrar, T. Durland, S. Arnault, B. Meyssignac and **W. Han**, 2018: Monitoring and interpreting the tropical oceans by satellite altimetry. Chapter 7 of Satellite Altimetry Over Oceans and Land Surfaces, *Stammer and Cazenave Eds., CRC Taylor and Francis Group, LLC. ISBN-13: 978-1-4987-4345-7.*