Prolonged Westerlies in the Equatorial Indian Ocean: Atmospheric Drivers and Upper-Ocean Responses

Prasad Thoppil
Ocean Sciences Division, U.S. Naval Research Laboratory
Stennis Space Center, MS 39529, USA.
prasad.g.thoppil.civ@us.navy.mil

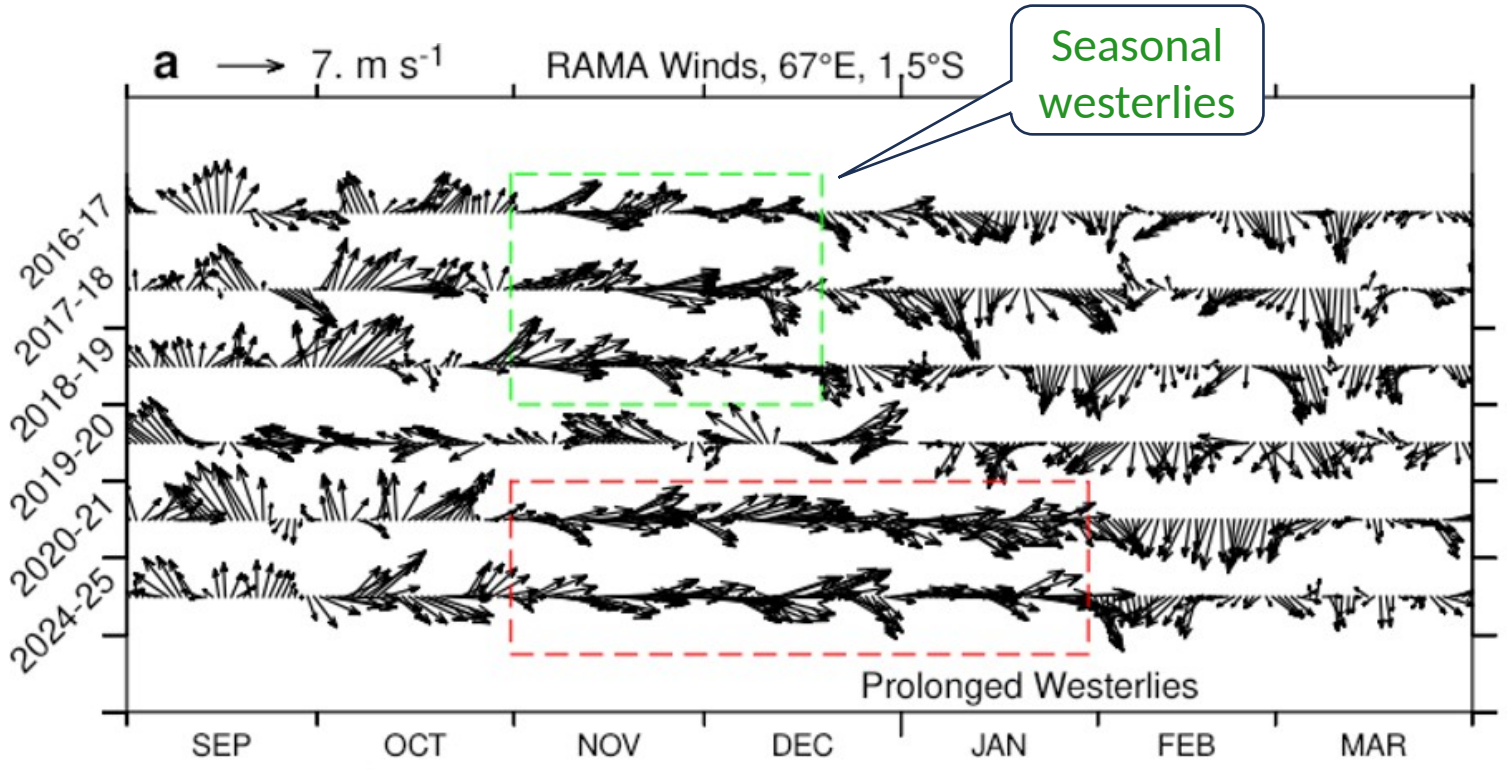
Carolyn Reynolds & Stephanie Rushley
Marine Meteorology Division, U.S. Naval Research Laboratory
Monterey, California

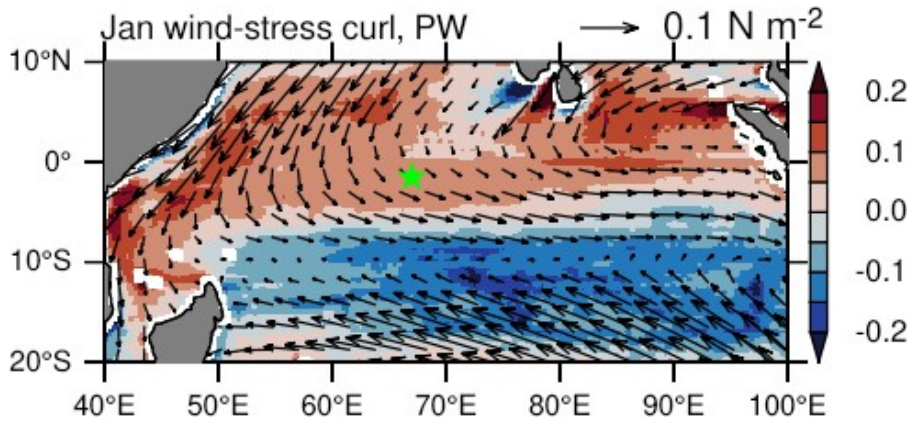
ONR funding: Scales of Ocean Atmosphere Interactions in the Western Pacific

Advances in Coupled Ocean Modeling, Data Assimilation and Predictions
Joint CP-TT/DA-TT Workshop, Oct 26-30, ECMWF, UK

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited

Prolonged Westerlies (PW) in the Indian Ocean





Prolonged westerlies (PW): In 2020-21 and 2024-25, westerlies persisted into late January, beyond their typical seasonal period.

- **Seasonal cycle**: Equatorial Indian Ocean westerlies typically occur during the spring and fall transitions.
- **2019-20**: Strong easterlies prevailed during the positive Indian Ocean Dipole (IOD) event.

Prolonged Westerlies (PW)

Outline:

1. **ENSO & IOD modulation of PW events.**
2. **Madden-Julian Oscillation (MJO) and tropical cyclones (TCs) forcing.**
3. **Kelvin and Rossby wave response.**
4. **Thermocline depth response**
5. **Equatorial current response**
6. **Sea surface temperature (SST) response.**
7. **Summary and conclusions.**

Analysis approach:

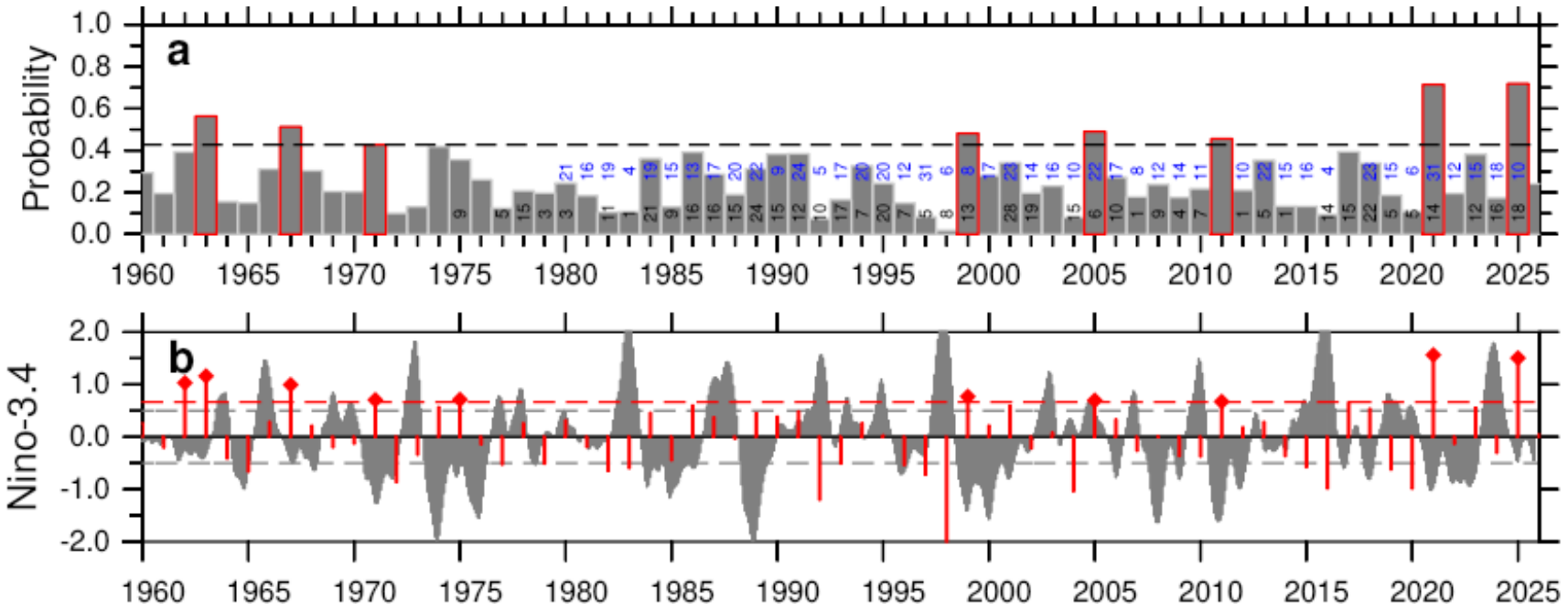
- **Composite analysis:** Five PW events (1999, 2005, 2011, 2021, and 2025) identify common atmospheric and oceanic characteristics.
- **Case study:** The strong 2020–2021 PW event reveals temporal evolution and processes not captured by composites alone.
- **Data:** ERA5, ORAS5, NAVGEM, GOFS, IBTrACS, AMSR-2, RAMA, OSCAR, EN4, OLR.

ENSO/IOD Modulation of PW events

Probability of westerly wind days in January.

PW years: Probability > 90th percentile (43%).

PW years: 1963, 1967, 1971, 1999, 2005, 2011, 2021, 2025



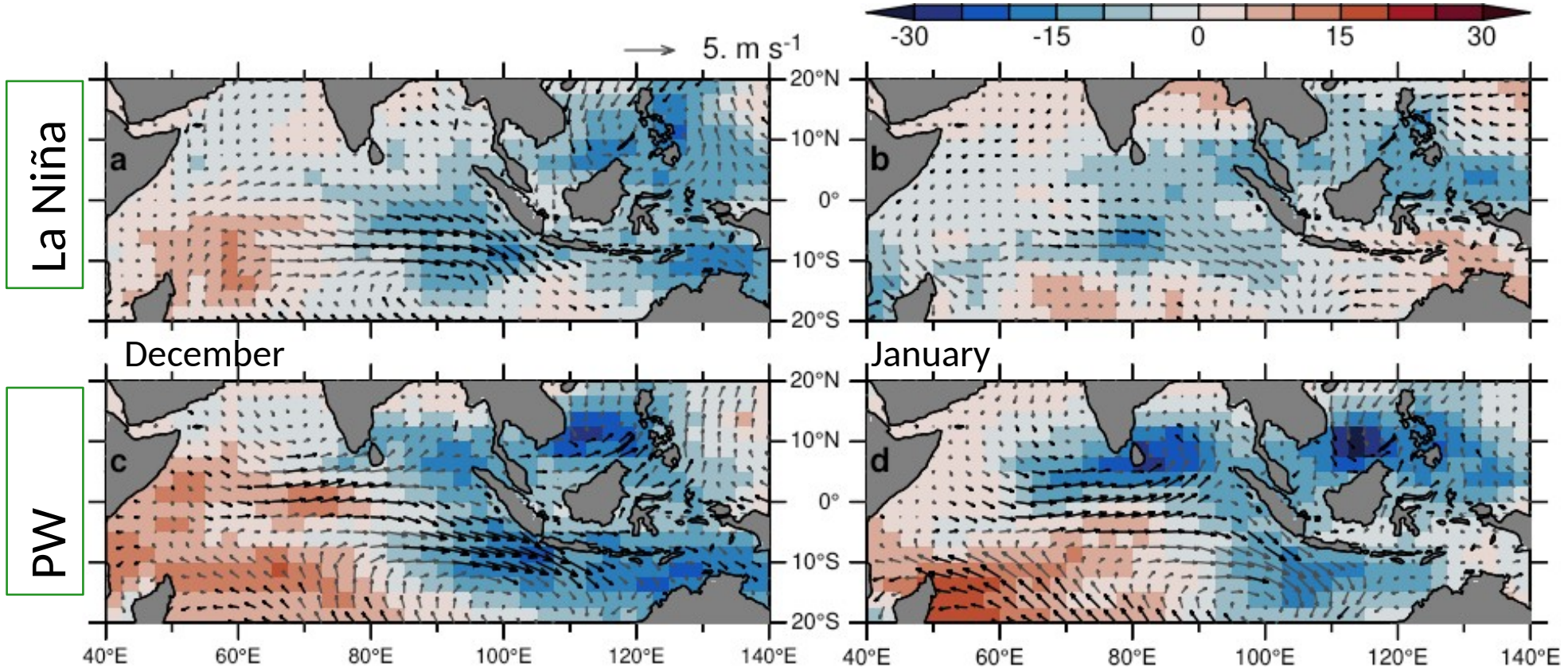
TCs days
MJO days in phases 1–4

u-wind anomalies > 1 std dev.

- **La Niña association:** 6 of 8 events occurred during La Niña conditions.
- **Favorable background:** Persistent, multi-year La Niña supports PW development, including in 2020–21 event.
- **Indian Ocean influence:** The 2004–2005 PW event occurred during weak El Niño with a negative IOD, highlighting the role of regional influence.

ENSO modulation of PW events

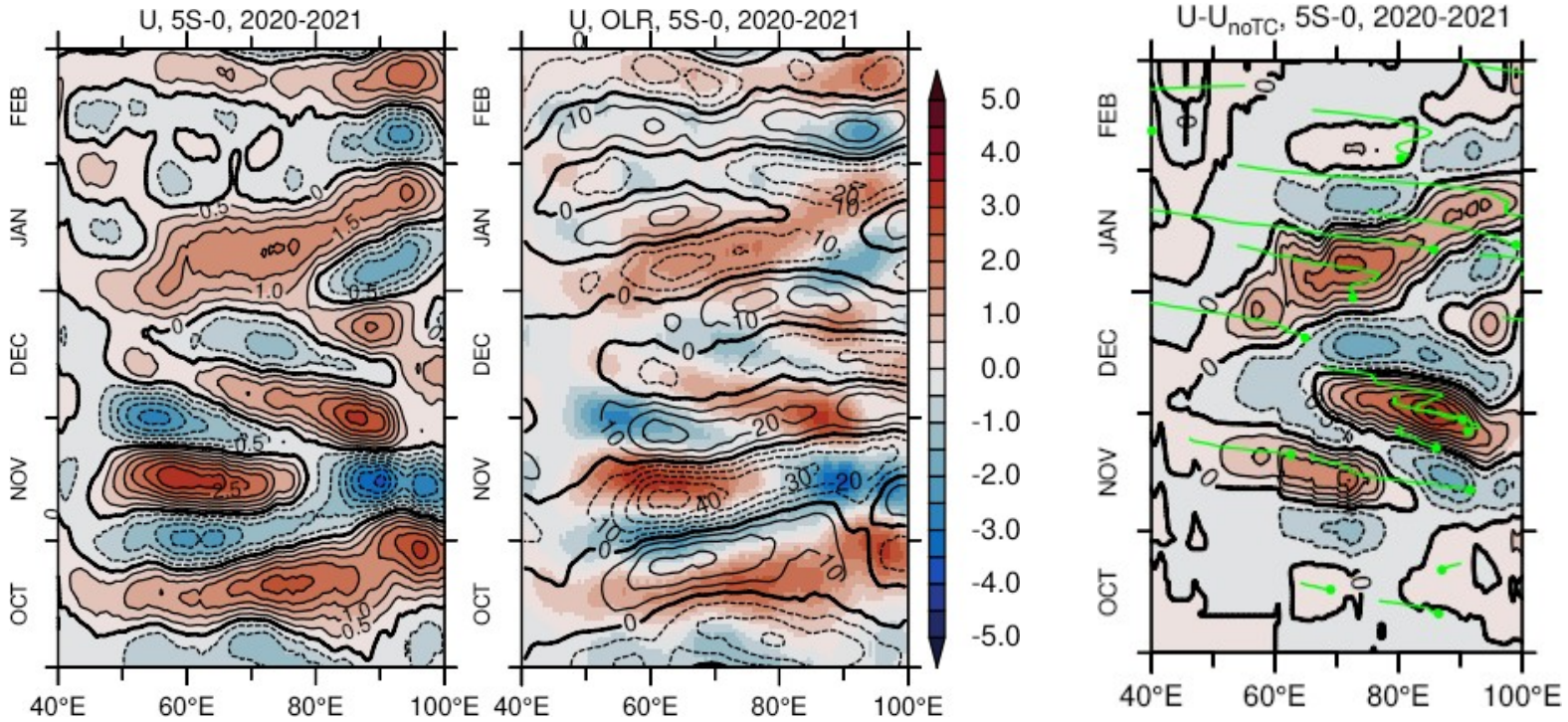
Monthly mean anomalies of winds and outgoing longwave radiation (OLR; W m^{-2}) for composite La Niña years and PW years.



- **La Niña alone is insufficient**: Both composites show enhanced convection over the Maritime Continent and equatorial Indian Ocean westerly anomalies in December.
- **Persistence distinguishes PW events**: Westerlies weaken by January in **La Niña** years but remain strong and zonally coherent during PW events.
- **Additional forcing matters**: Intraseasonal variability and episodic atmospheric forcing may sustain the westerlies into late January.

Linking PW to MJO and Tropical Cyclones

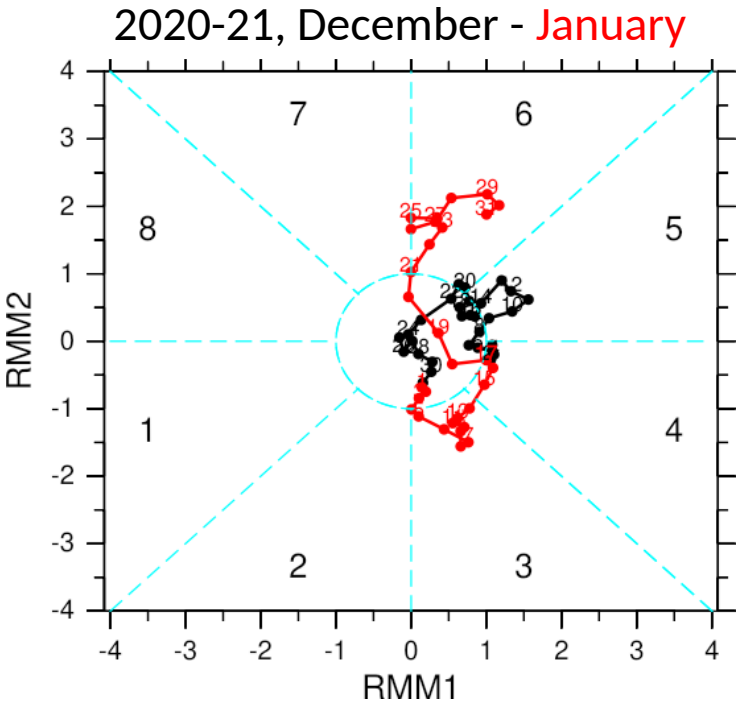
20–90-day Lanczos bandpass-filtered anomalies of 10-m zonal wind and OLR



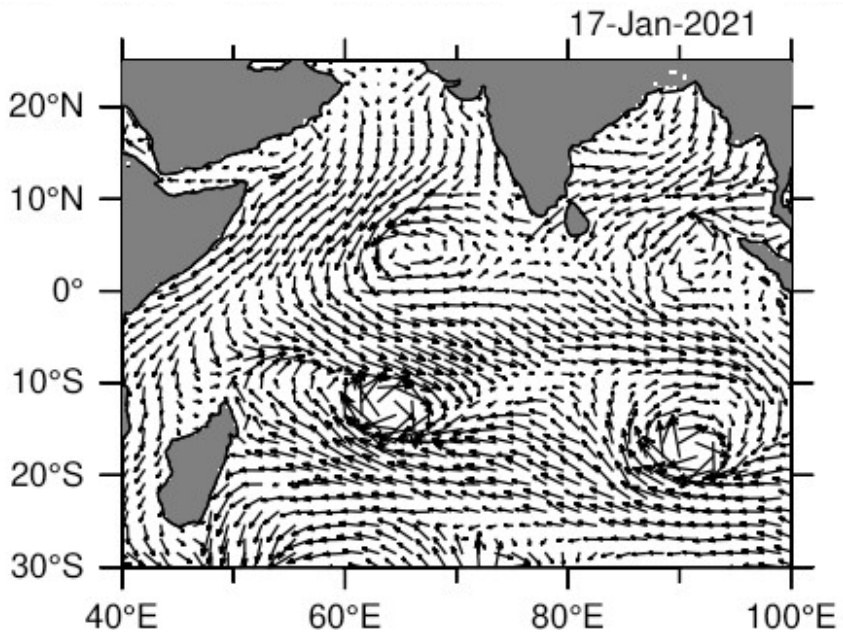
- **MJO alone is insufficient**: The weak MJO signal suggests that other atmospheric processes help sustain the 2020–2021 PW event.

- **Tropical cyclones drive key wind anomalies**: Successive TCs contribute strongly to westward-propagating anomalies in November–December and eastward-propagating anomalies in December–January.

TC removal weakens the westerly peak: Removing TC-related winds substantially reduces the December–January westerly maximum, highlighting their contribution to PW

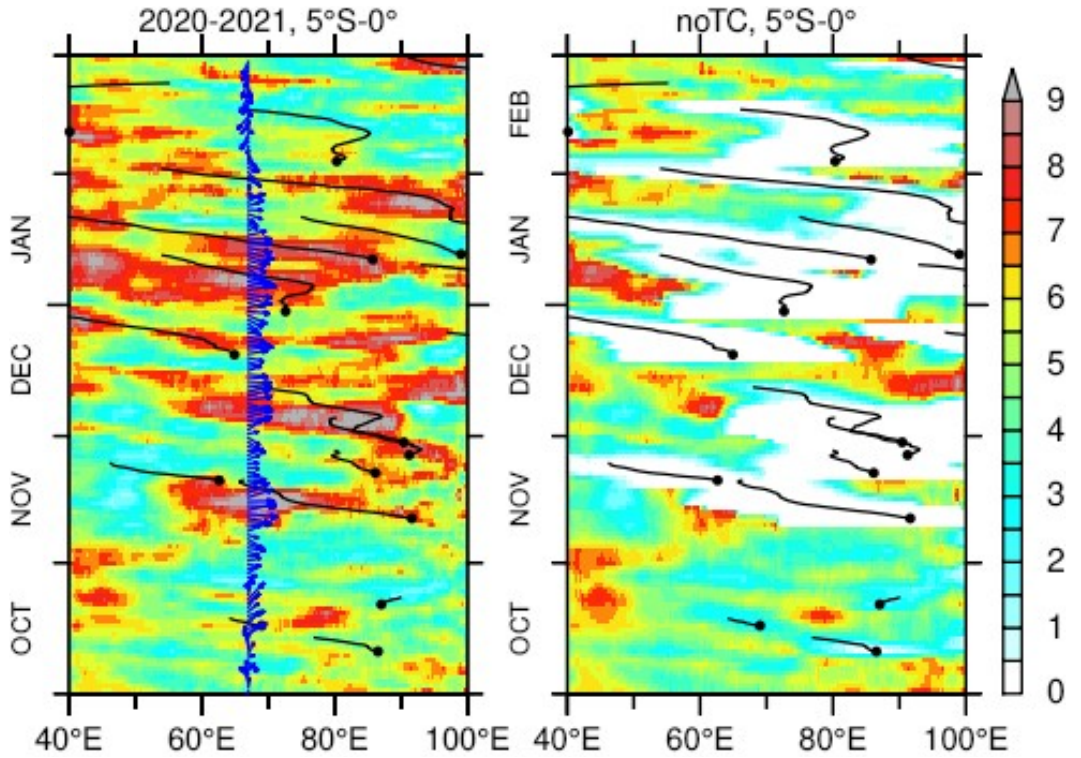


Linking PW to MJO and Tropical Cyclones



Tropical cyclones can generate equatorial westerly winds, particularly when they form close to the equator, and have been shown to enhance the equatorial westerlies.

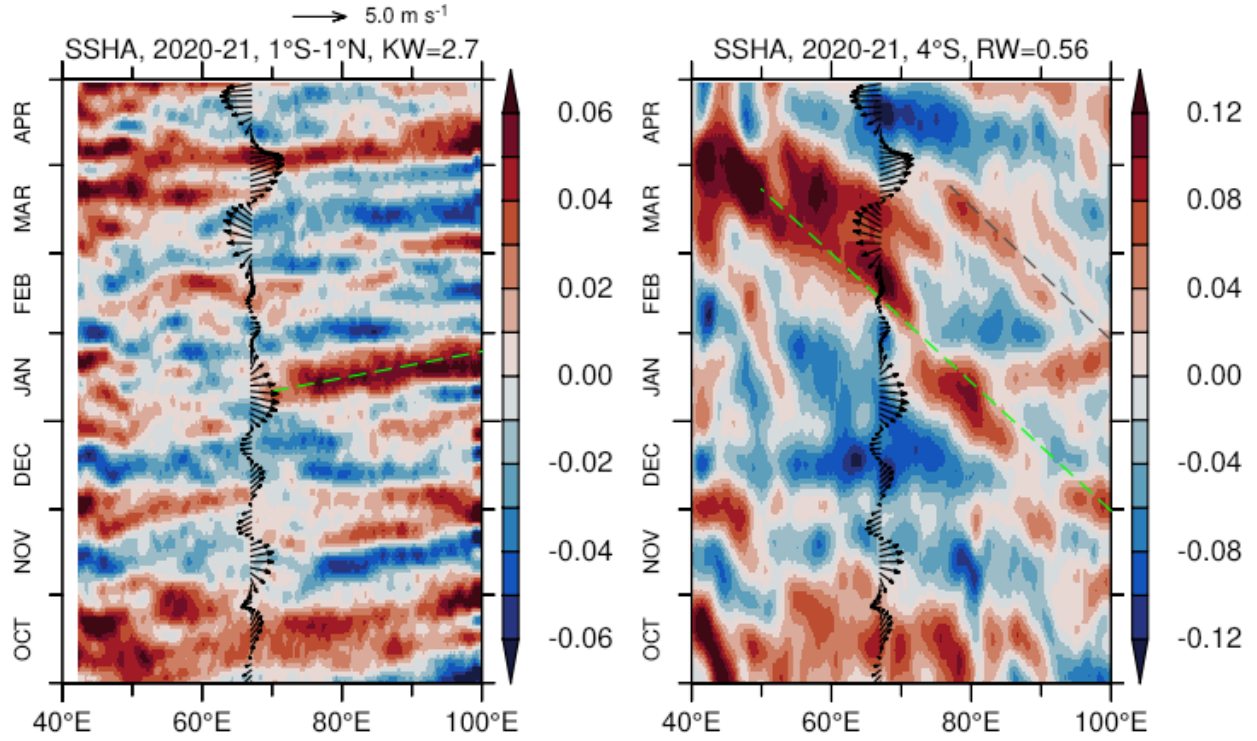
- **TCs generate strong equatorial winds**: AMSR-2 observations show wind events exceeding 7 m s^{-1} aligned with cyclone tracks.
- **Successive cyclones reinforce westerlies**: Repeated cyclone activity likely helped sustain the 2020–2021 PW event.



Removing winds within 2,000 km of IBTrACS tracks eliminates strong episodic wind events, revealing the contribution of TCs to the PW.

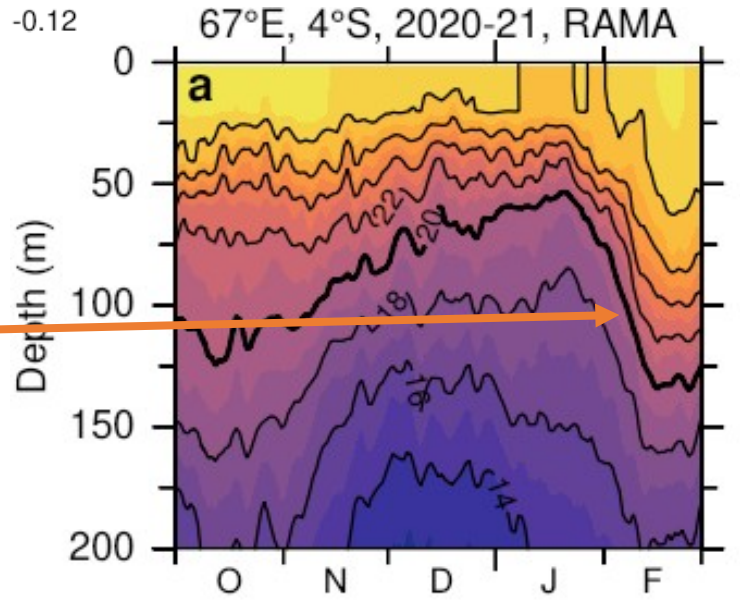
PW excitation of Kelvin and Rossby waves

Downwelling Kelvin waves: Strong positive SSHA east of 70°E in January 2021, with a phase speed of 2.7 m s^{-1}, close to the theoretical first-baroclinic speed.

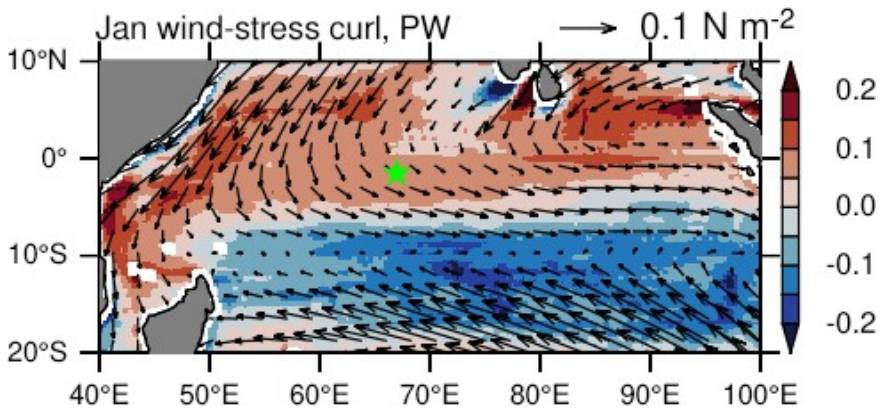


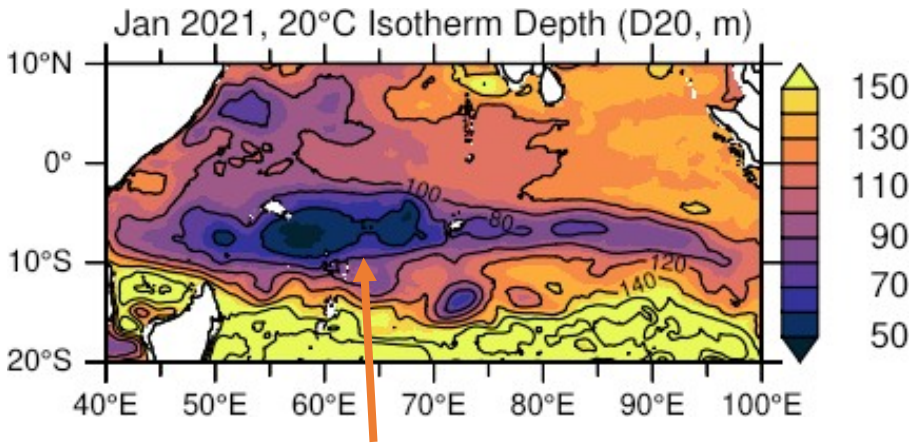
Rossby-wave response: Weaker westward-propagating SSHA anomalies emerge near 4°S following Kelvin-wave arrival at the eastern boundary.

- **Thermocline deepening**: A westward-propagating downwelling Rossby wave arriving from the east in February further deepens the thermocline.
- **Possible local wind forcing**: Strengthening SSHA anomalies in the central-western basin during westerly relaxation suggests additional wind-driven thermocline adjustment.

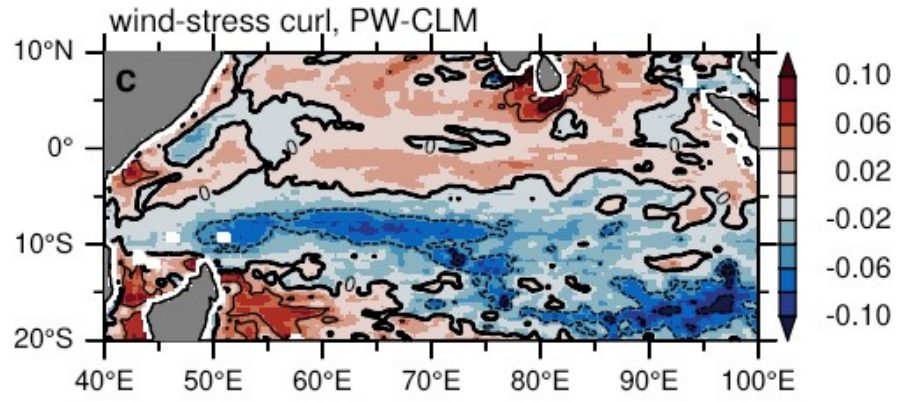


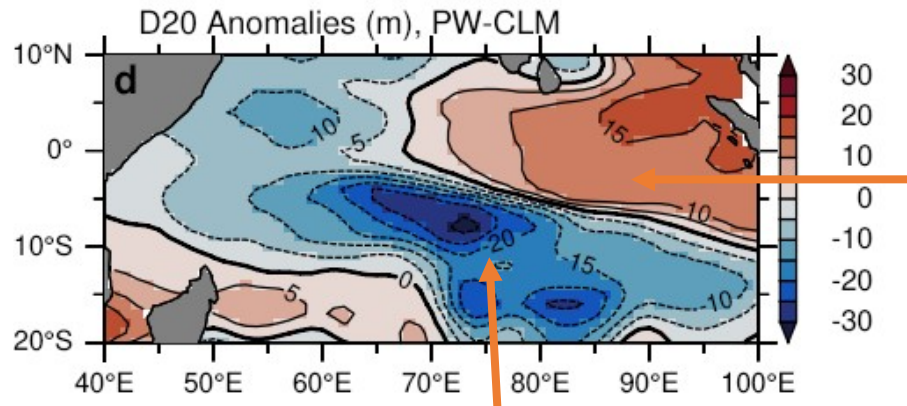
Westerly wind modulation of thermocline depth





The Seychelles–Chagos Thermocline Ridge (SCTR) is a persistent upwelling region maintained primarily by negative wind-stress curl, producing a domed thermocline (5°–15°S).



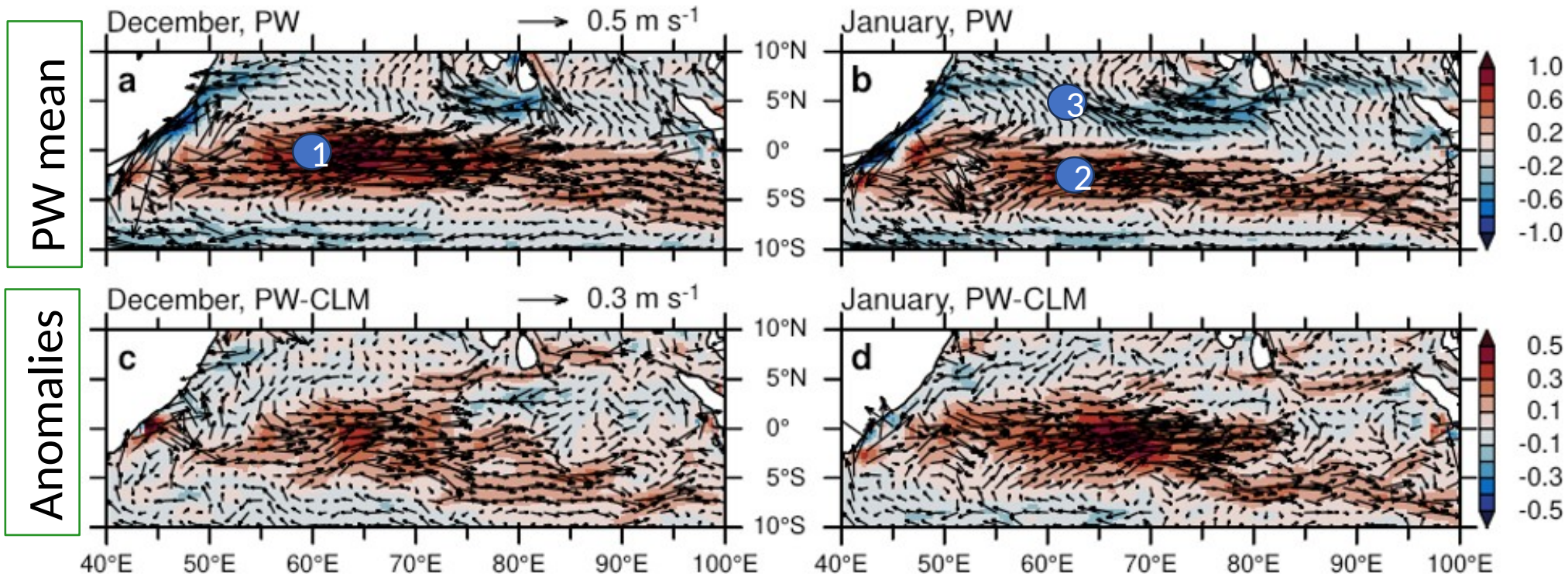


Enhanced SCTR upwelling: D20 shoals by ~20–25 m during PW, consistent with stronger negative wind-stress curl and Ekman divergence.

Opposite eastern-basin response: D20 deepens by ~15 m, consistent with downwelling Kelvin waves driven by equatorial westerlies.

Response of equatorial currents

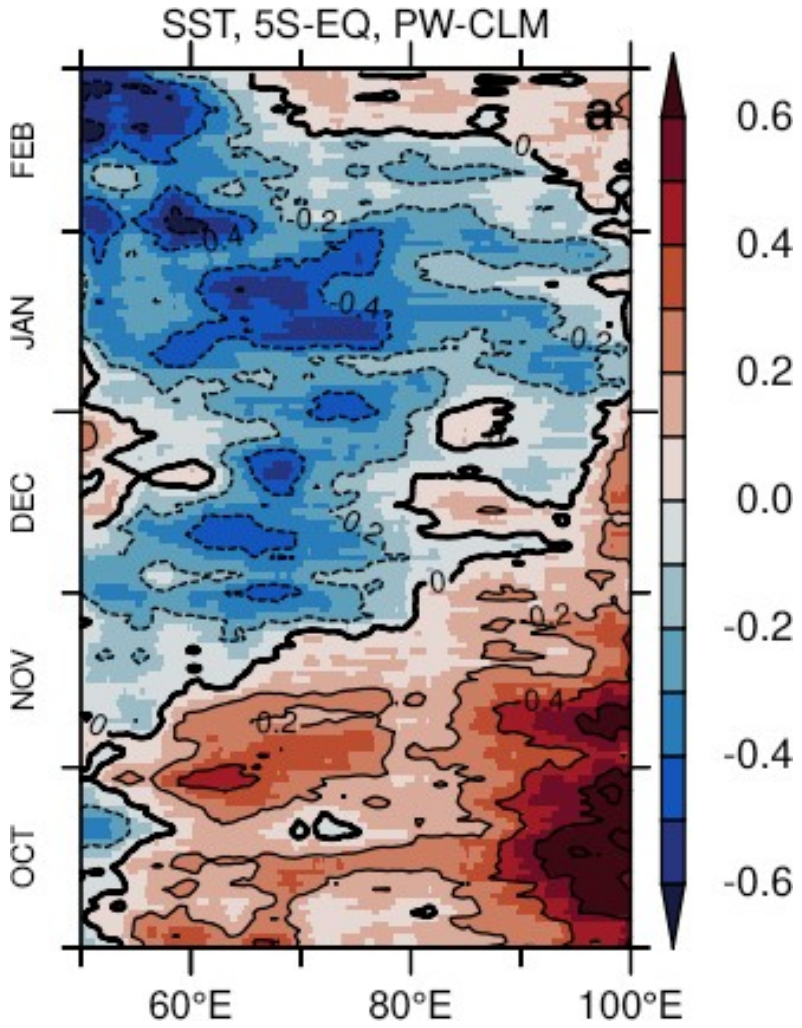
(1) Wyrtki Jet.
(2) South Equatorial Counter Current (SECC).
(3) North Equatorial Current.



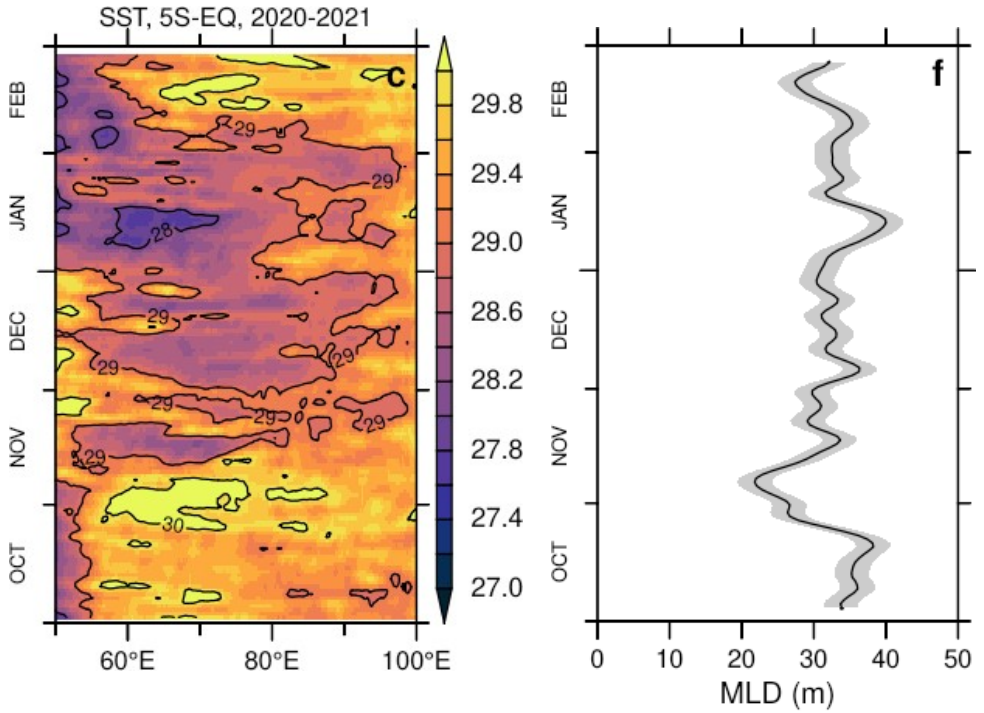
- **Stronger eastward currents**: PW events produce equatorial current anomalies of 0.2–0.4 m s^{-1}, strengthening the Wyrtki Jet in December and SECC in January.
- **SECC intensifies into January**: Eastward current anomalies increase by 43%, from 0.16 to 0.23 m s^{-1}.
- **Wind-driven response**: Persistent westerlies enhance eastward currents through direct wind forcing and Ekman convergence.

Data: Ocean Surface Current Analysis Real-time (OSCAR).

Response of SST

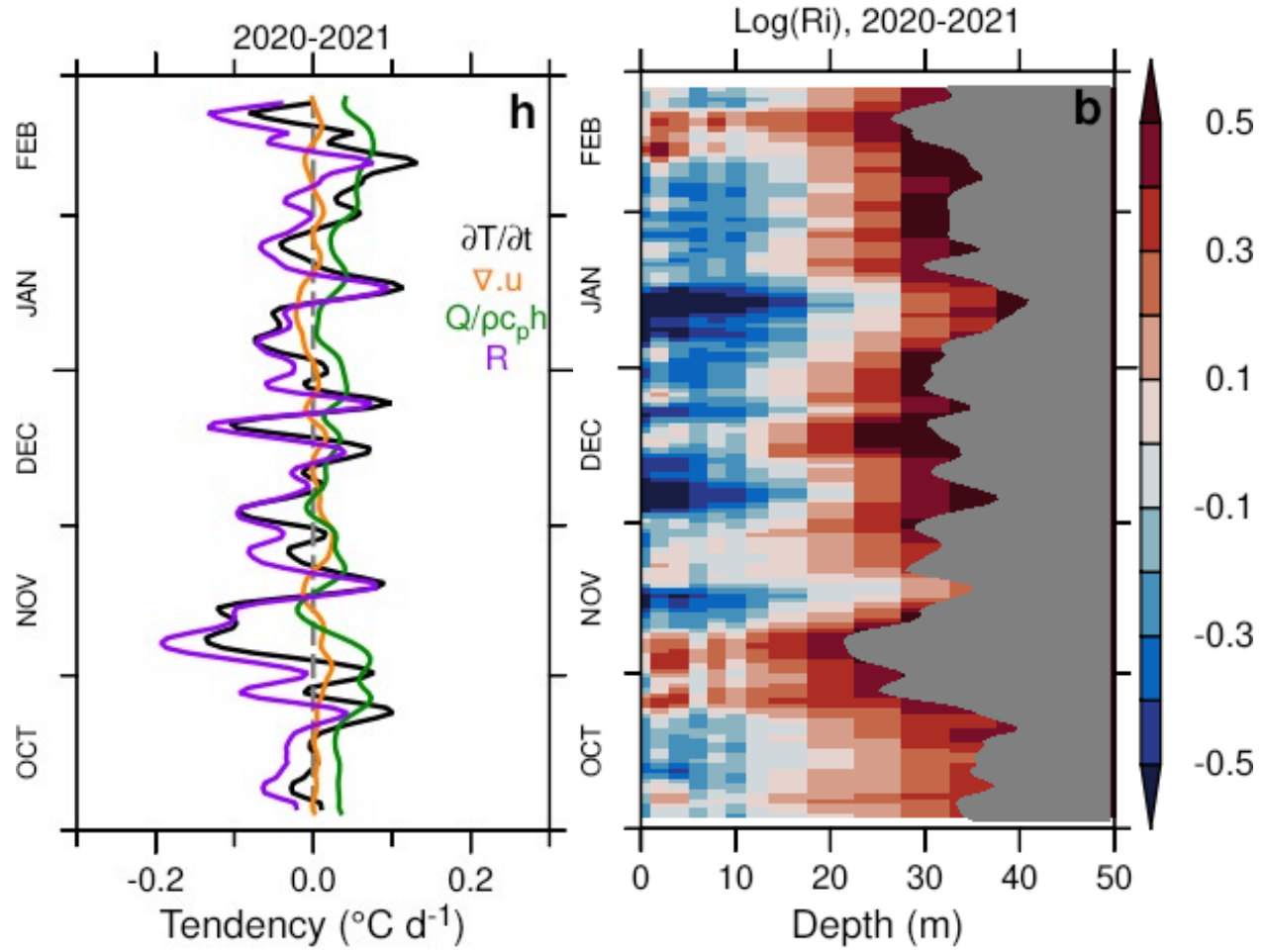


- **Equatorial SST cools during PW**: Local anomalies reach −0.4 to −0.5°C, with area-averaged cooling increasing from −0.17°C in December to −0.32°C in January.
- **SST cooling persists despite stronger eastward currents**: Enhanced currents do not translate into substantial zonal advective warming.



- **Deep mixed layer during PW**: In 2020–2021, SST decreases from ~30°C in November to ~29°C in December, remaining relatively stable through January as MLD reaches ~30 m.

Response of SST to PW



$$\frac{\partial T}{\partial t} = \frac{Q_0}{\rho c_p h} - u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} + R$$

Richardson number ,
the buoyancy frequency,
, vertical shear of horizontal velocity.

- **Ocean dynamics dominate SST tendencies**: The residual term closely tracks SST tendency and generally cools the mixed layer, while surface heat flux provides modest warming.
- **Persistent westerlies suppress SST variability**: Enhanced vertical mixing and entrainment likely damp SST fluctuations; weak zonal SST gradients limit zonal advection.
- **Low Richardson numbers favor shear-driven mixing**: Sustained winds and stronger currents coincide with low Ri in the upper 20 m during December–January, supporting enhanced mixing.

Summary: Prolonged westerlies in the equatorial Indian Ocean

- **Climate drivers:** 6 of 8 PW events coincide with La Niña. Intraseasonal variability and successive tropical cyclones may help sustain westerlies from December into late January.
- **Equatorial wave dynamics:** Downwelling Kelvin waves deepen the eastern-basin thermocline, while wind-stress curl and Rossby-wave dynamics contribute to thermocline variability in the southwestern Indian Ocean.
- **Circulation response:** PW strengthens eastward equatorial currents, including the Wyrtki Jet and SECC, with anomalies reaching 0.2–0.4 m s^{-1}.
- **SST response:** Equatorial SST cools by ~0.4–0.5°C in the composite. The heat budget points to ocean dynamics as the dominant influence on SST tendency, with enhanced mixing a plausible contributor.