

NASA Ocean Physics State of Science Overview

Tony Lee¹

with contributions from Severine Fournier¹, Matt Archer¹, Josh Willis¹, Bia Villas-Bôas², & Shineng Hu³

¹Jet Propulsion Laboratory, California Institute of Technology

²Colorado School of Mines

³Duke University

Topics covered:

1. Ocean surface tides, internal waves, wave-wind-current interactions
2. Air-sea coupling and climate variability (focusing on ENSO)
3. Mission concepts for advancing the understanding of 2.

Trend in the M_2 ocean tide observed by satellite altimetry

Ray and Schindelegger (2025), Opel, Schindelegger, & Ray (2024), Zhao (2023)

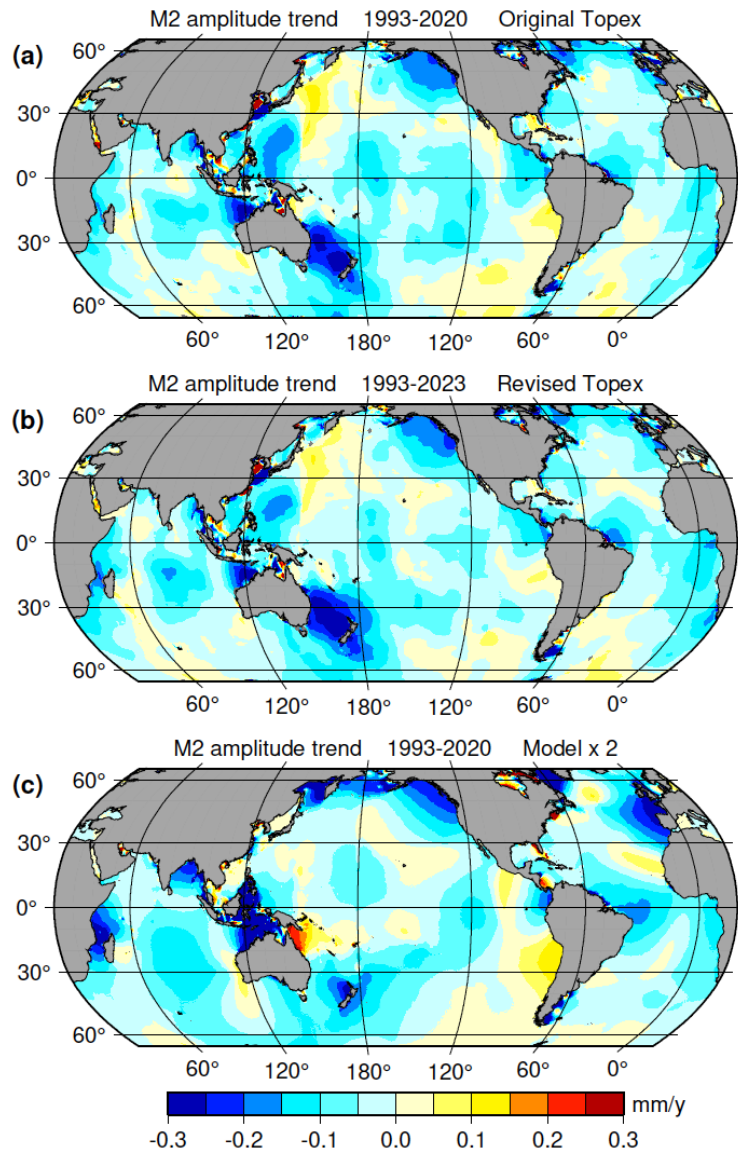


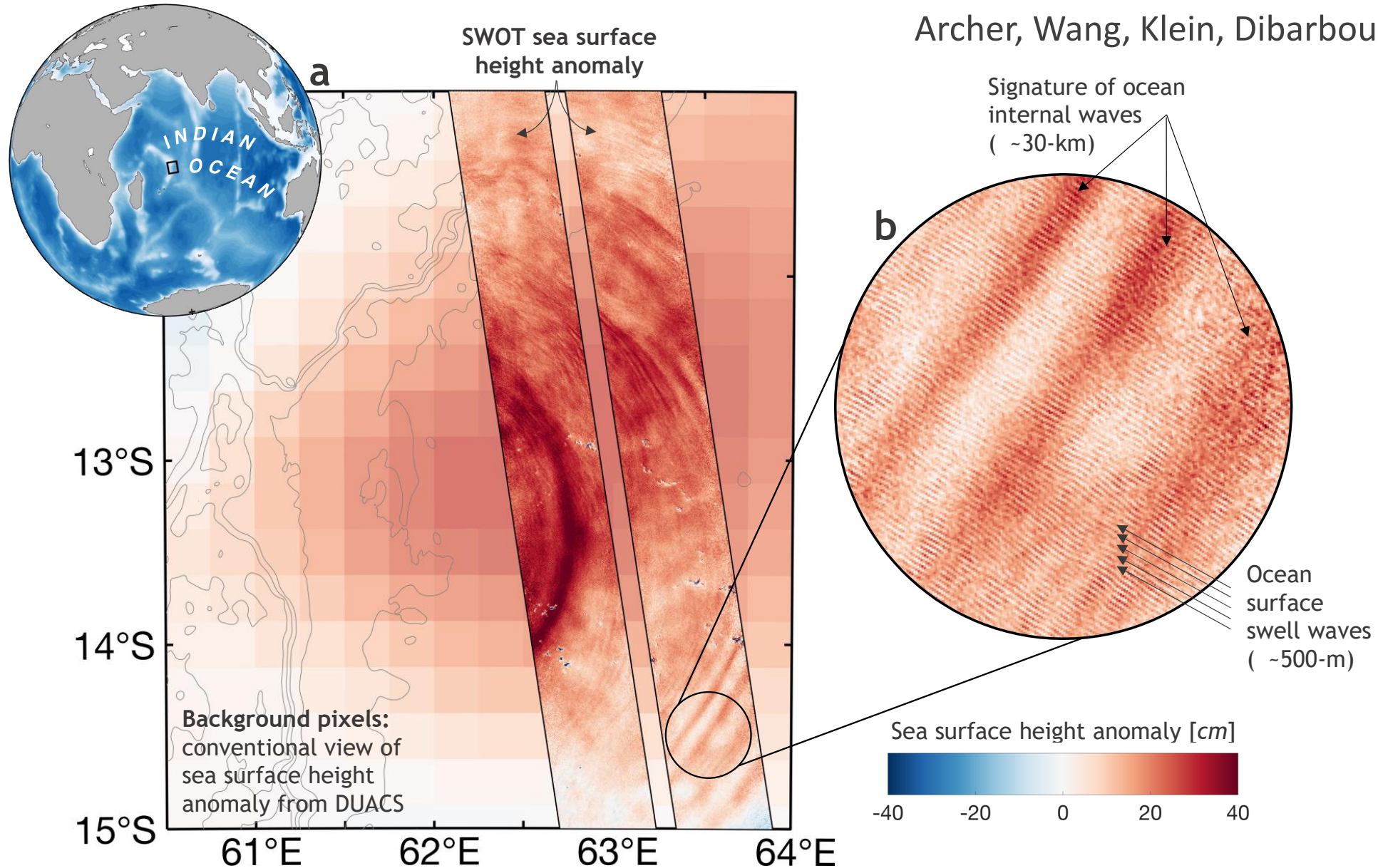
Fig. 2 Trends (mm/y) in the M_2 ocean tide amplitudes, (a) deduced from altimetry over 1993–2020, reproduced from Opel et al. (2024); (b) updated here from altimetry over 1993–2023, with revised TOPEX data; and (c) deduced from two ocean models by Opel et al. (2024), a 3-D model with changing stratification and a 2-D model with sea level rise. The amplitudes in (c) have been scaled by 2. Data of panels (a,b) have been adjusted for DAC errors, as described in Section 3.

- M_2 surface (semi-diurnal) tide is the largest tidal component in the world ocean.
- Altimetry data reveal 3-decade trends in M_2 tide, with a predominant decreasing amplitude.
- Contributed by increasing stratification in a warming ocean that enhances surface-to-internal tidal conversion.
- **Importance to ocean physics:**
 - mixing and energy transfer;
 - sea level anomaly with removal of tides.
- **Observing system implication:** Importance of continuing reference altimetry mission.

SWOT unveils global submesoscale dynamics for the 1st time

Examples: internal waves & swells

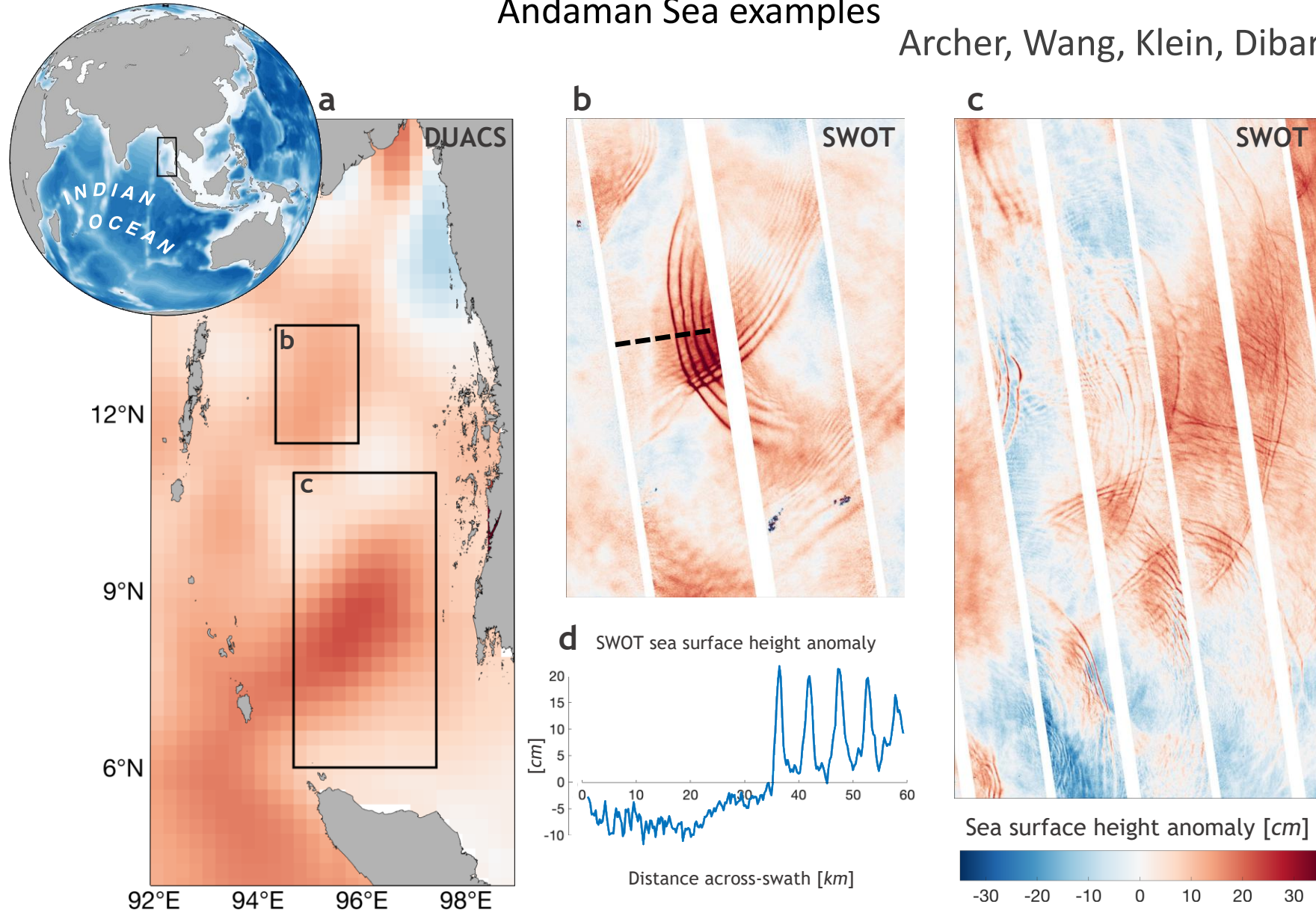
Archer, Wang, Klein, Dibarboure, & Fu (2025)



SWOT measures the amplitudes of internal solitary waves

Andaman Sea examples

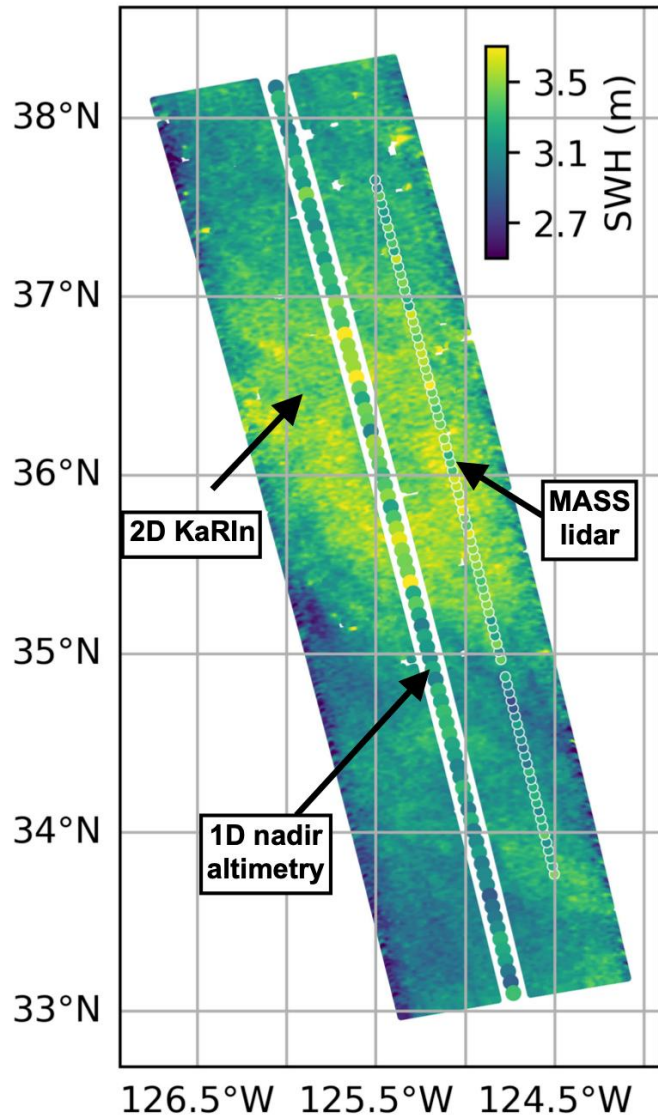
Archer, Wang, Klein, Dibarboure, & Fu (2025)



Check out the animation for SWOT small-scale features: <https://svs.gsfc.nasa.gov/5538/>

SWOT provides the 1st global 2D maps of km-scale significant wave height (SWH), elucidating wave-wind-current interactions

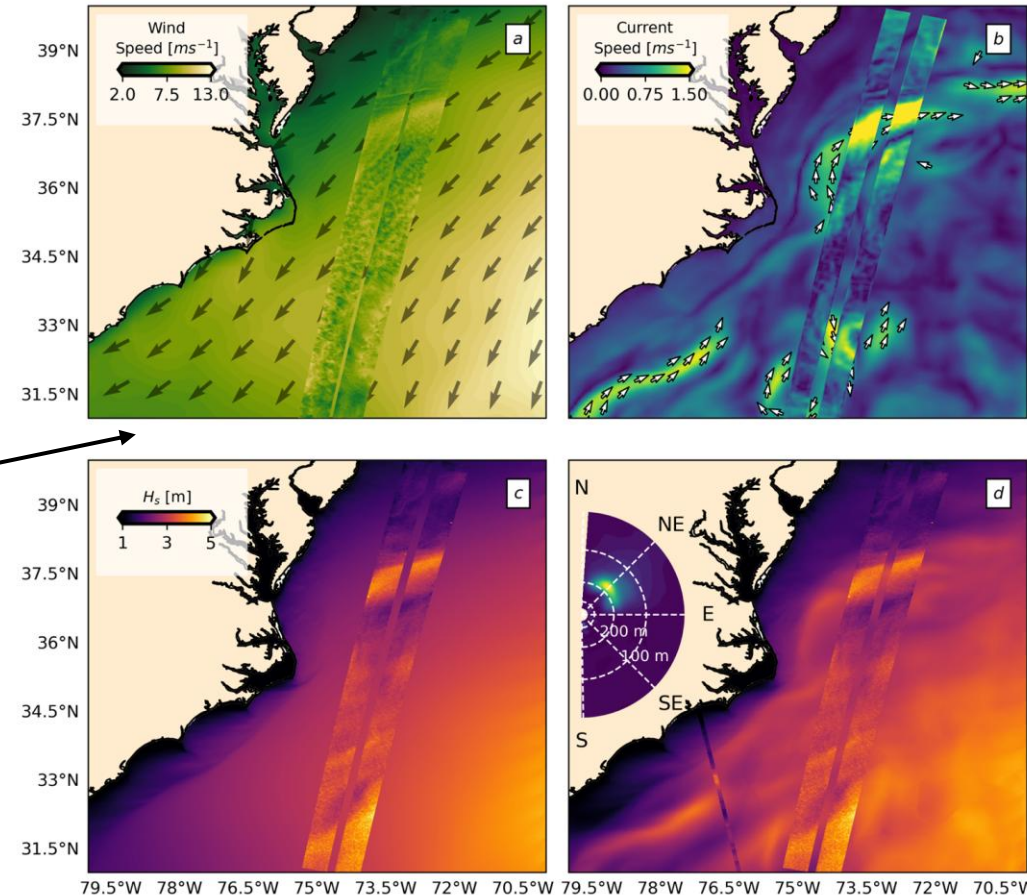
Villas Bôas, Marechal, & Bohé (2025), Bohé et al. (2025)



SWOT and airborne MASS observations reveal complex spatial gradients—driven by winds, **wave–current interactions, and wave group modulation**—that challenge existing assumptions in remote sensing and modeling.

SWOT captures sharp sea-state gradients as northeast-propagating swell interacts with the Gulf Stream, providing the first **observational evidence** of 2D features previously seen only in numerical simulations.

WaveWatch III simulations without (c) and with (d) current forcing suggest that the increase in SWH is mostly driven by current refraction and not winds.



Advance understanding of air-sea interactions & prediction of climate variability, e.g., ENSO — the largest disruptor of the Earth system on interannual time scales

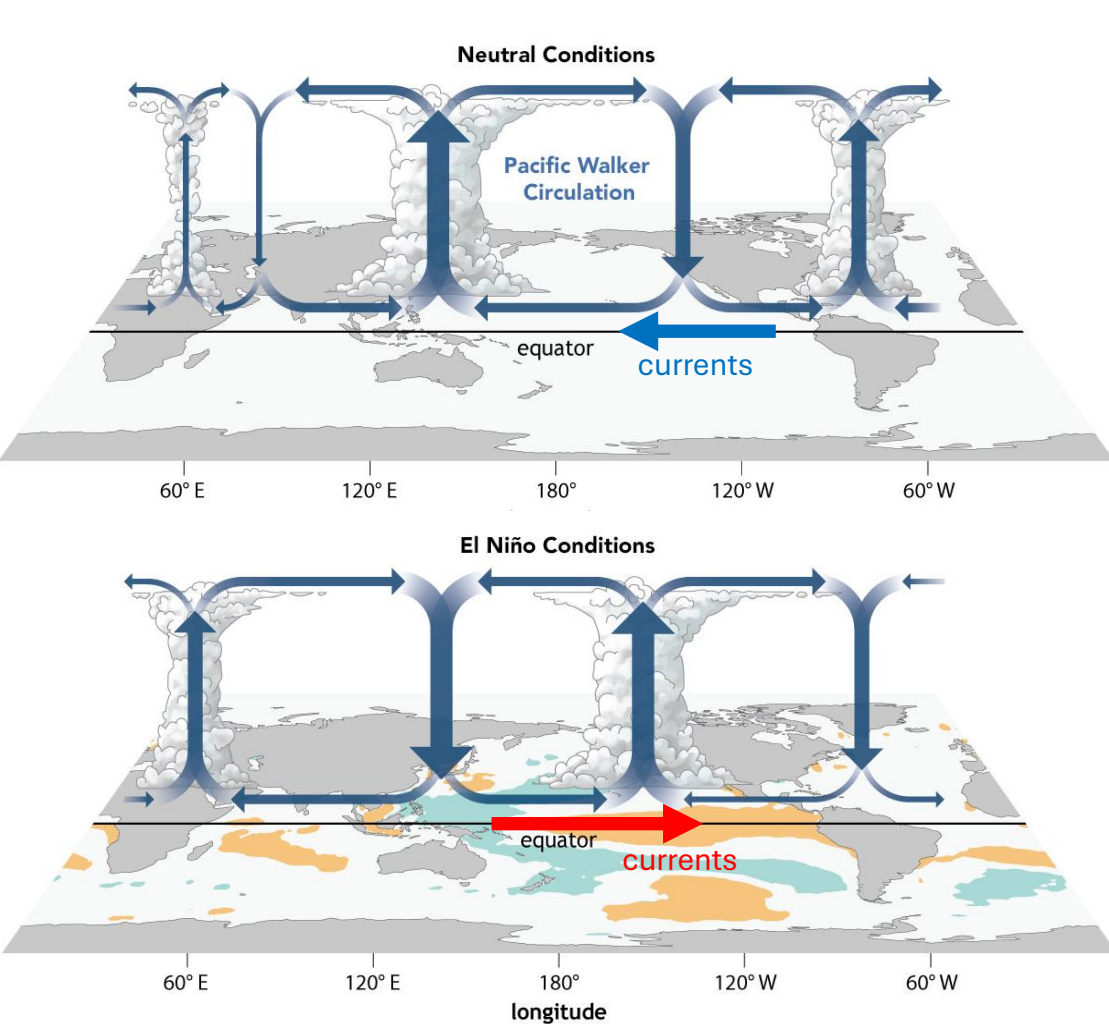
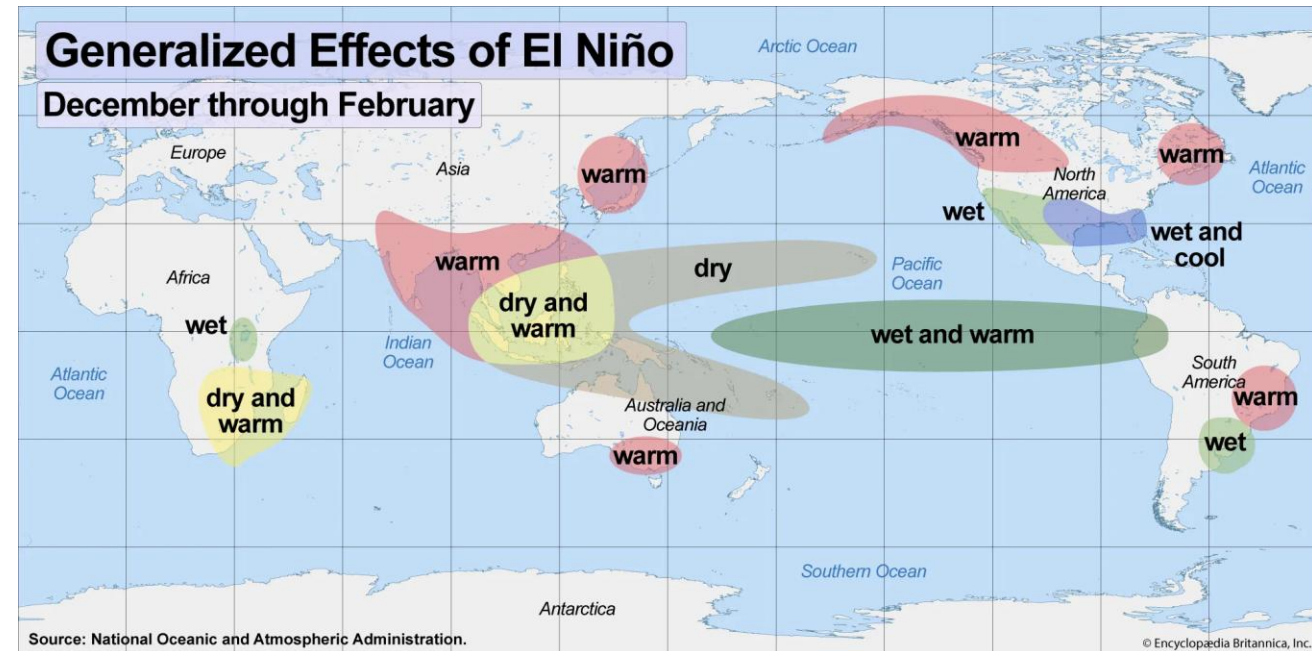


Image credit: <https://science.nasa.gov>



NASA has revolutionized ENSO theory & observation:

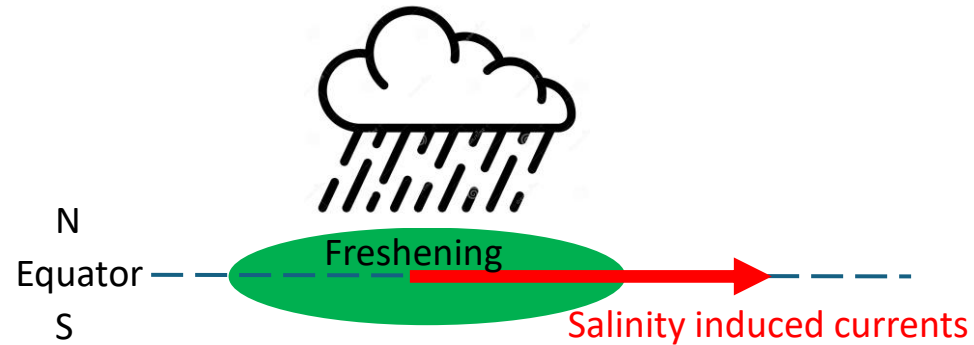
- Delayed (Action) Oscillator theory (Suarez & Schopf 1988).
- Altimetric sea surface height (SSH) observation since 1992 is a game changer for evaluation & improvement of theories & models.

Continuing advancement of process understanding & prediction (examples in the next 2 slides).

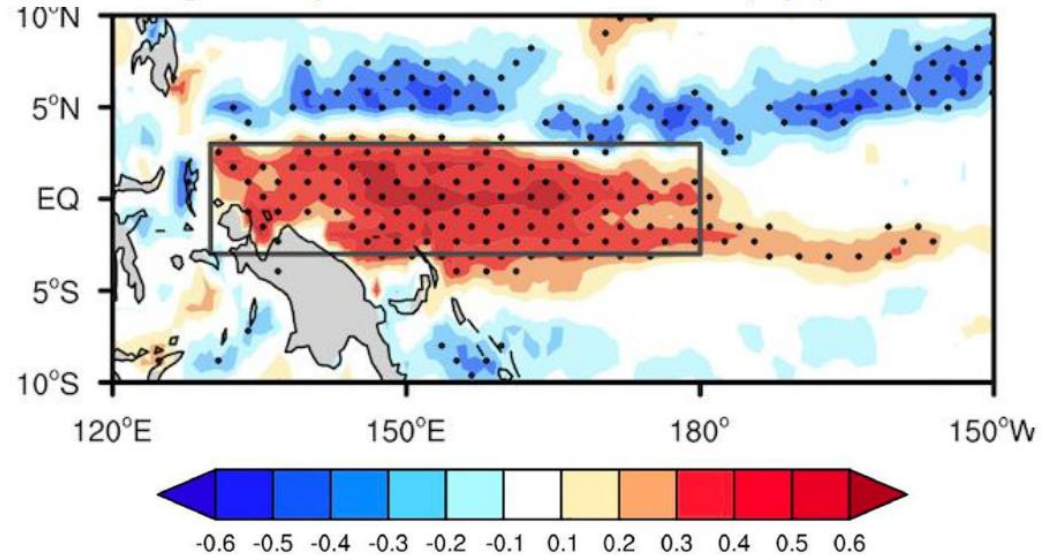
Salinity & ENSO: salinity-induced equatorial currents favors extreme El Niño

Classical ENSO theories do not consider salinity.

Liu, Hu, & McPhaden (2025) identify a new ocean salinity precursor of extreme El Niño to potentially enhance El Niño forecast skill.



Correlation between spring (MAM) salinity-induced surface zonal geostrophic current and winter (DJF) Niño3.4

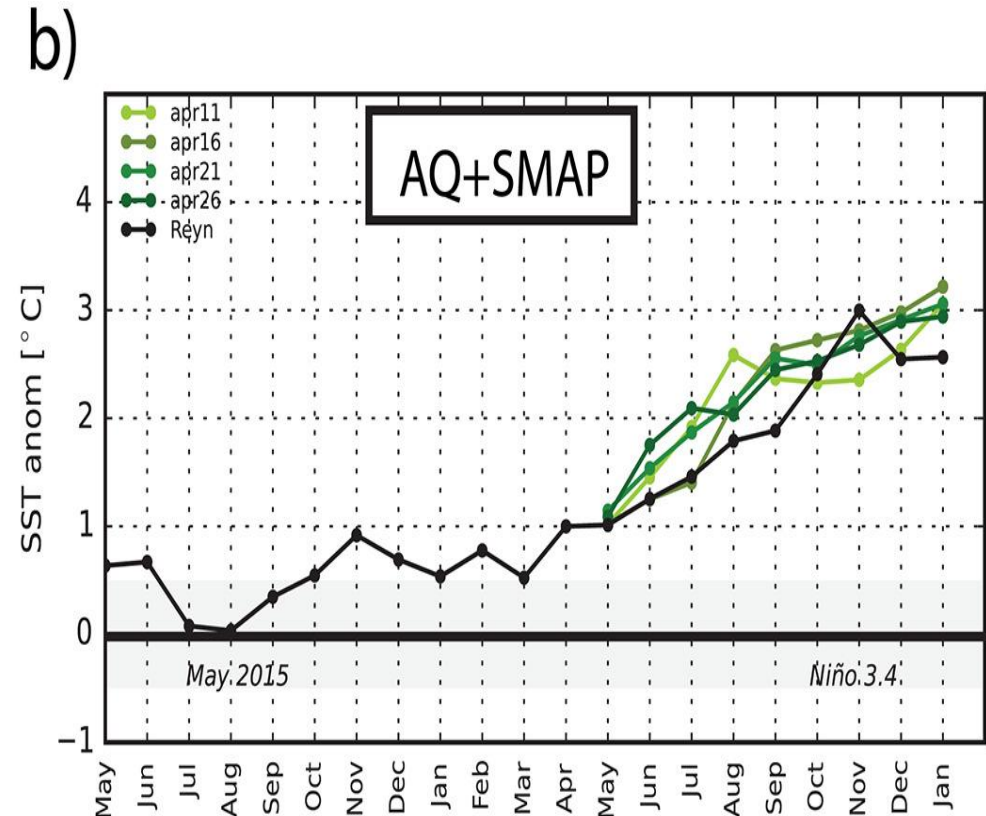
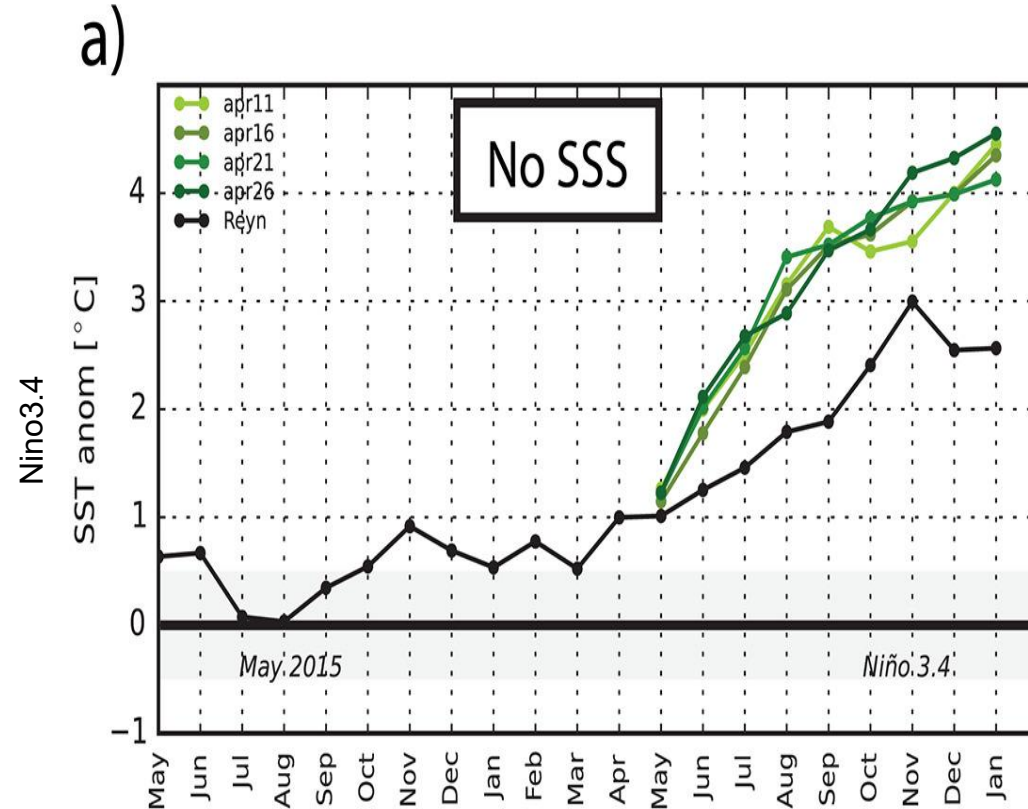


- Observational analysis: reveals that El Niño is preceded by a spring salinity pattern and associated ocean currents in the western Pacific.
- Model sensitivity experiment: imposing spring salinity anomalies almost doubles the probability of extreme El Niño.
- Inter-model comparison: a model with a higher sensitivity to salinity-induced currents tends to simulate a stronger ENSO.

Salinity from space improves El Niño prediction:

case studies from NASA GEOS Seasonal Forecast System

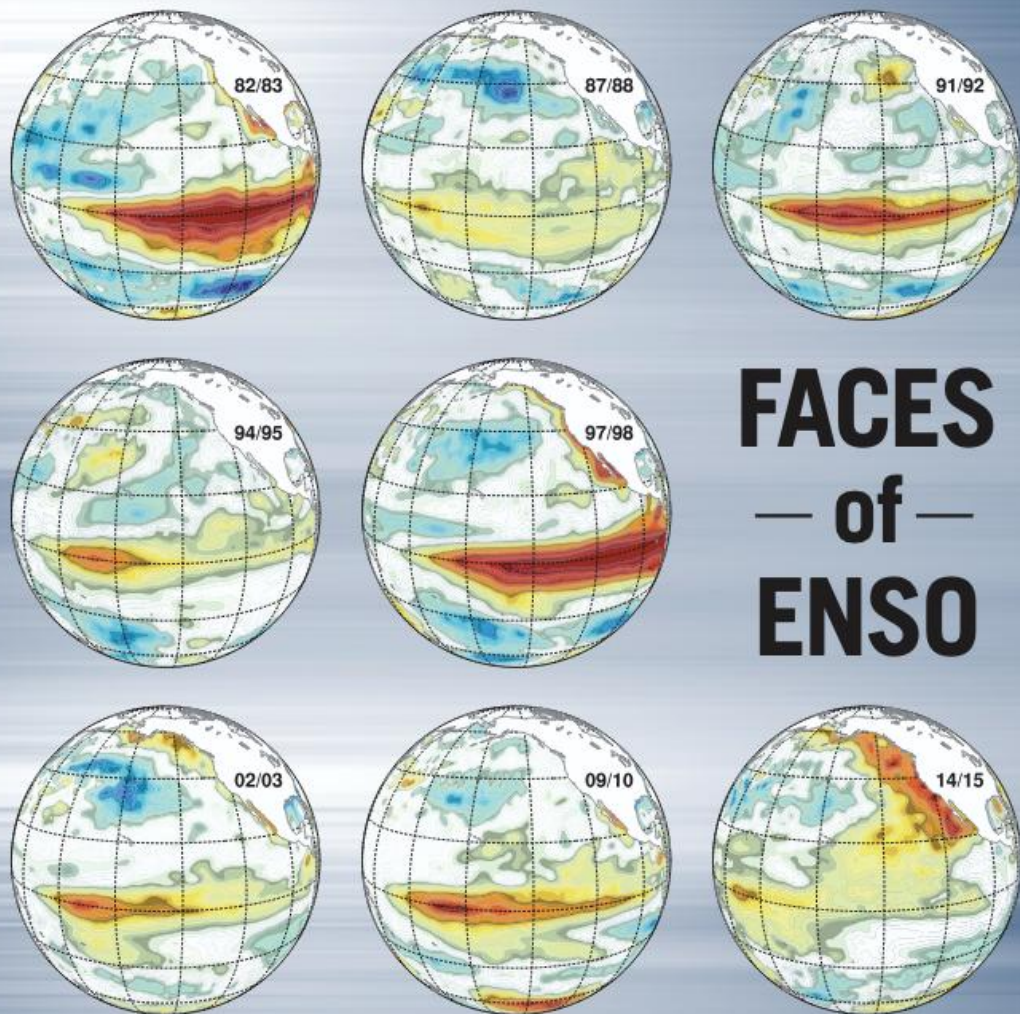
Hackert et al. (2020), also see related work by Hackert et al. (2014, 2019)



TESTS FOR HI-RES NWP

HURRICANES AND CLIMATE

IMPROVING CMIP ENSEMBLES



ARTICLES

UNDERSTANDING ENSO DIVERSITY

BY ANTONIETTA CAPOTONDI, ANDREW T. WITTENBERG, MATTHEW NEWMAN, EMANUELE DI LORENZO, JIN-YI YU, PASCALE BRACONNOT, JULIA COLE, BORIS DEWITTE, BENJAMIN GIESE, ERIC GUILYARDI, FEI-FEI JIN, KRISTOPHER KARNAUSKAS, BENJAMIN KIRTMAN, TONG LEE, NIKLAS SCHNEIDER, YAN XUE, AND SANG-WOOK YEH

Improved determination of ENSO predictability, teleconnections, and impacts requires a better understanding of event-to-event differences in ENSO spatial patterns and evolution.

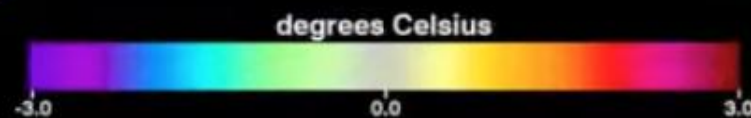
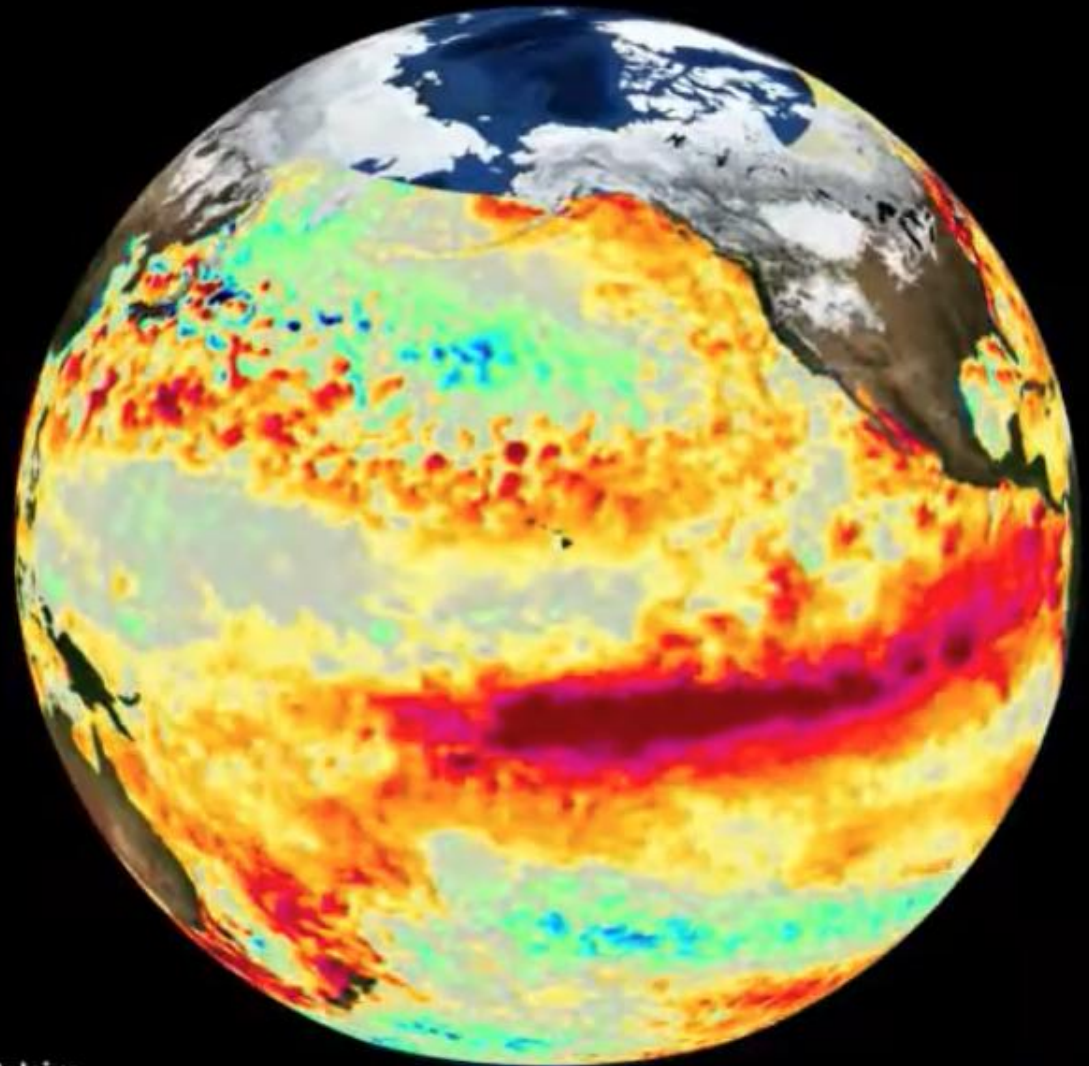
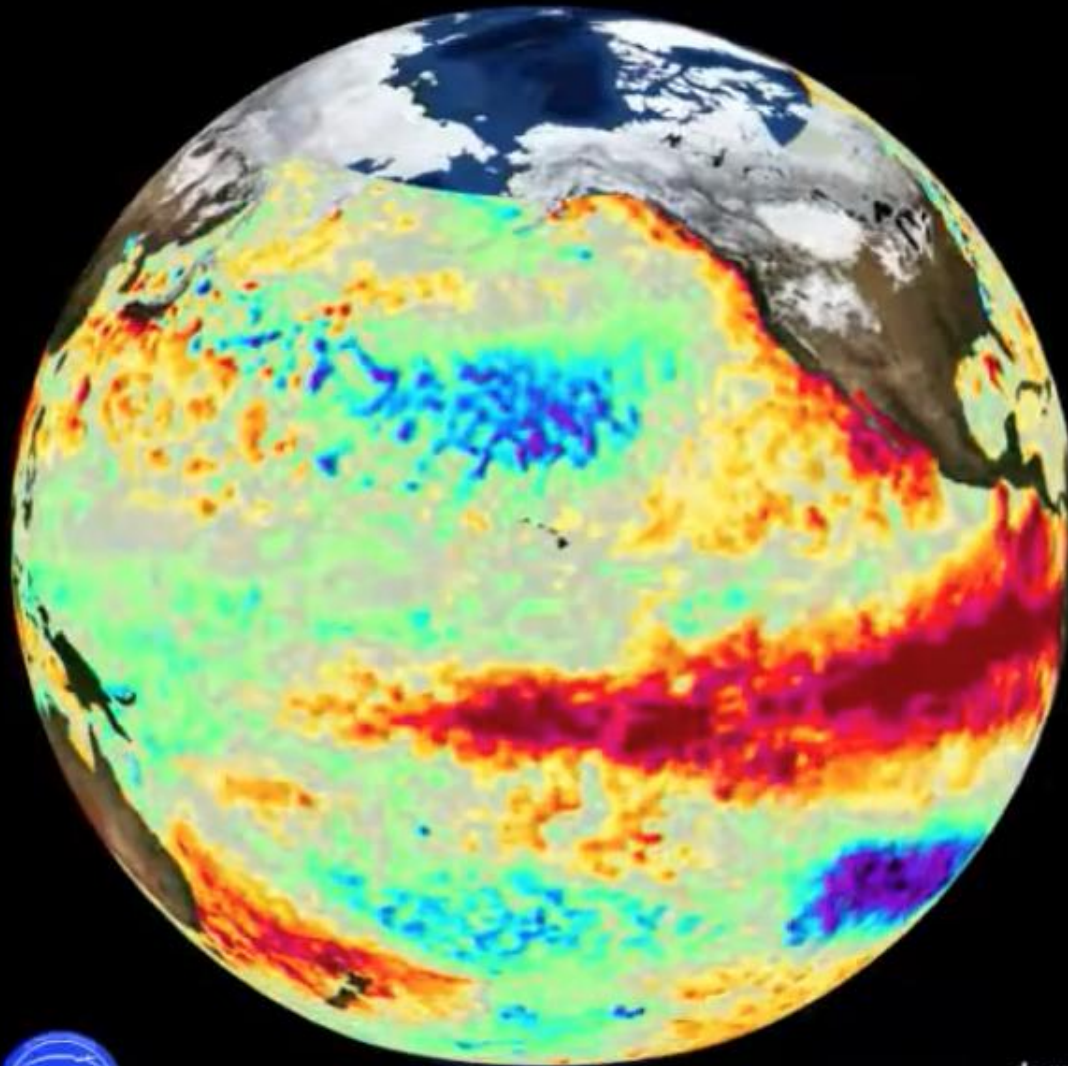
El Niño–Southern Oscillation (ENSO) is a naturally occurring phenomenon in the tropical Pacific that has global impacts of great relevance to society. The term *El Niño* refers to warming of the tropical Pacific Ocean occurring every 2–7 yr, while the opposite cold phase is known as *La Niña*. Anomalous warming or cooling conditions are associated with a large-scale east–west sea level pressure seesaw, termed the Southern Oscillation, which represents the atmospheric manifestation of the coupled ENSO phenomenon (McPhaden et al. 2006). ENSO events differ in amplitude, temporal evolution, and spatial pattern. While differences among ENSO events have been known for many years, a renewed interest in this diversity was stimulated by Larkin and Harrison (2005) and Ashok et al. (2007), who highlighted an unusual sea surface temperature anomaly

(SSTA) pattern over the tropical Pacific during the summer of 2004 that was associated with remote impacts on surface air temperature and precipitation different from those related to “typical” El Niño conditions. Because of the similarity and differences from a typical El Niño, Ashok et al. (2007) named this pattern *El Niño Modoki* (a Japanese word that means similar but different) and argued that it is a different type of El Niño. Significant research has since been conducted to identify, describe, and understand these “El Niño types,” spurring debates on whether there are indeed two distinct modes of variability, or whether ENSO can be more aptly described as a diverse continuum. In this article, we report on advances in understanding ENSO diversity, drawing from community discussions that took place at the U.S. CLIVAR ENSO Diversity Workshop held in Boulder, Colorado,

Sea Surface Temperature Anomaly (SSTA)

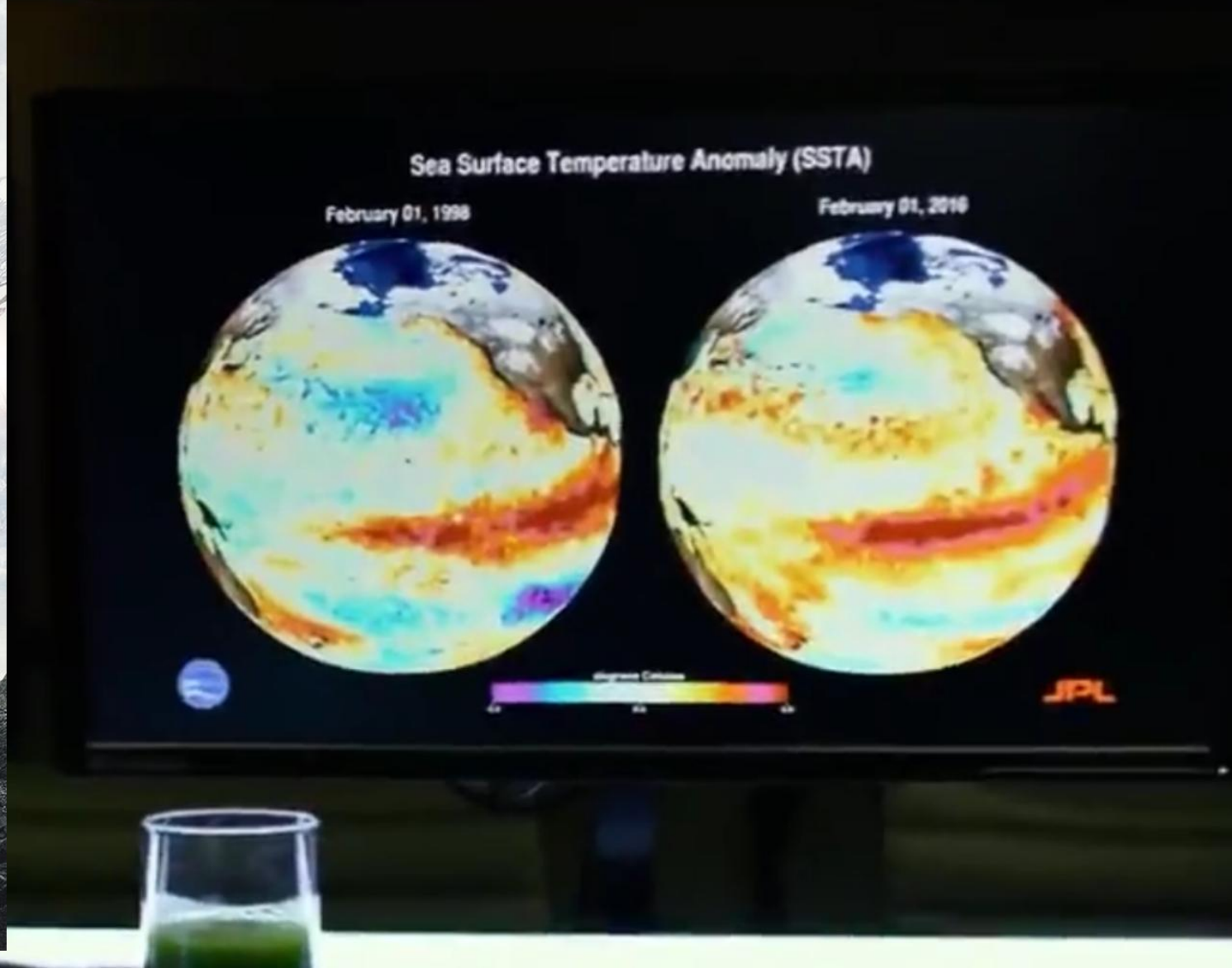
February 01, 1998

February 01, 2016



JPL

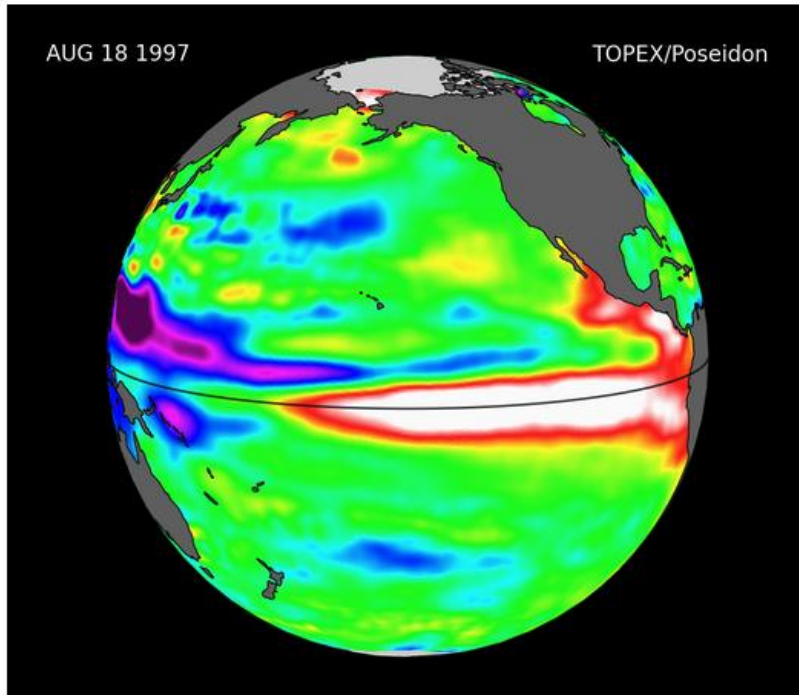
SCREENSHOT FROM A BLOCKBUSTER MOVIE



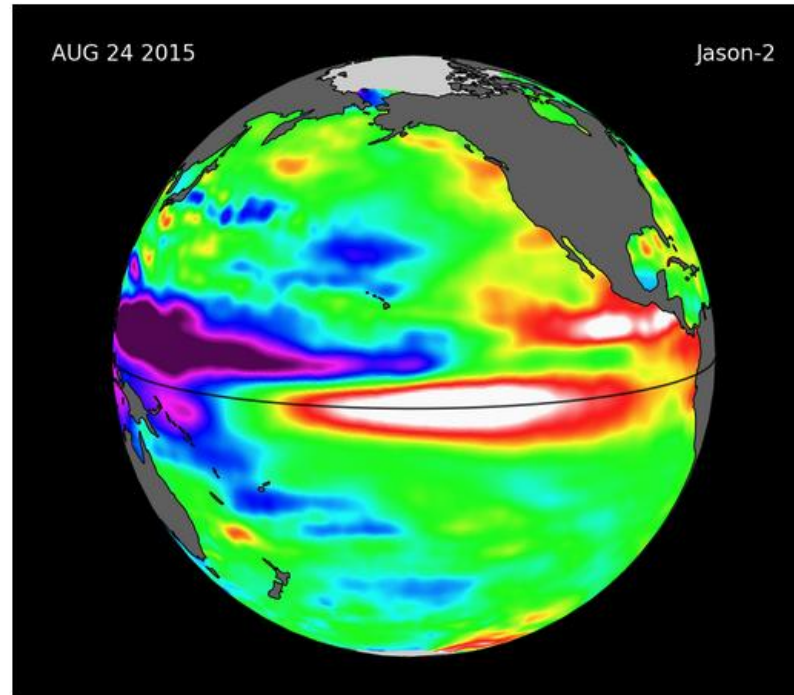
How big is the 2026 El Niño?

Comparison of sea surface height anomalies for 3 big El Niño events in the altimeter era

August 1997 (TOPEX/Poseidon)



August 2015 (Jason-2)



August 2026 (Sentinel-6 MF)

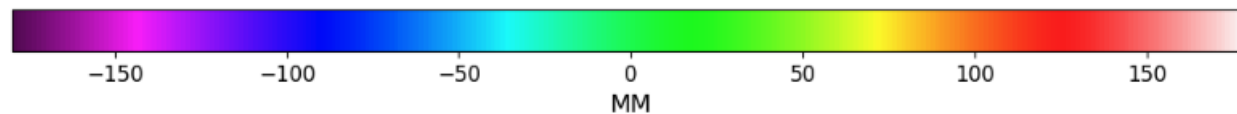
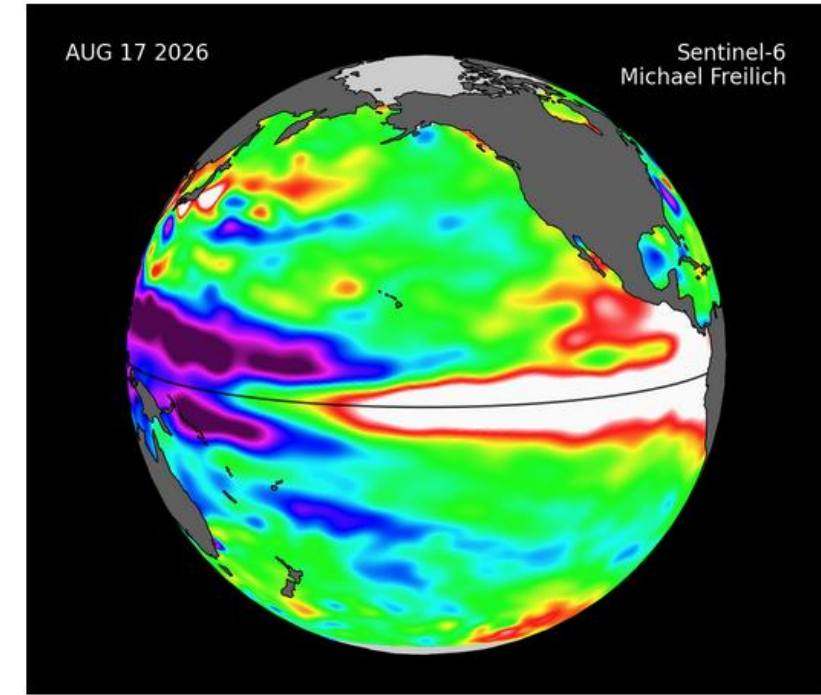


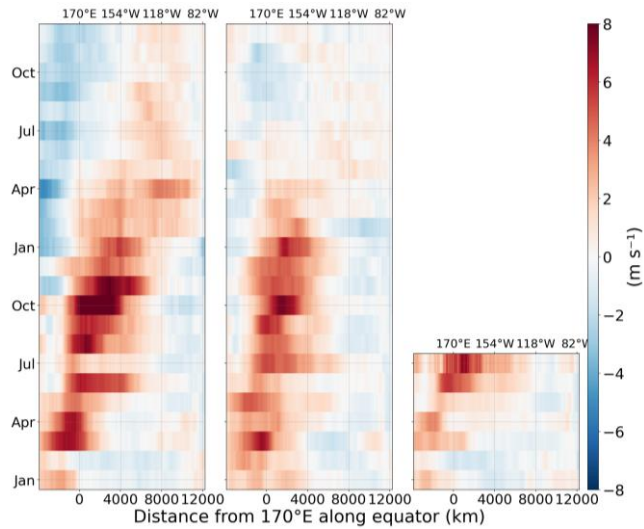
Image credit: <https://sealevel.jpl.nasa.gov>

The 2026 El Niño had a moderate growth in spring followed by a rapid intensification by summer

Multi-event, multi-parameter comparison for the state of the equatorial Pacific (2°S-2°N)

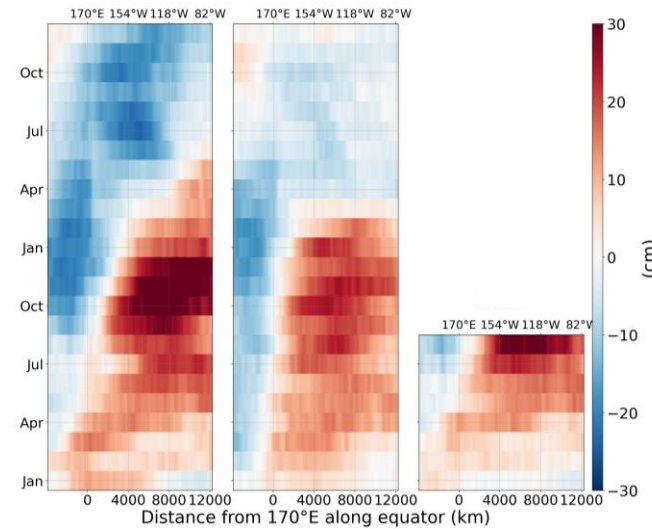
Zonal wind anomaly (CCMP)

1997-98 2015-16 2026

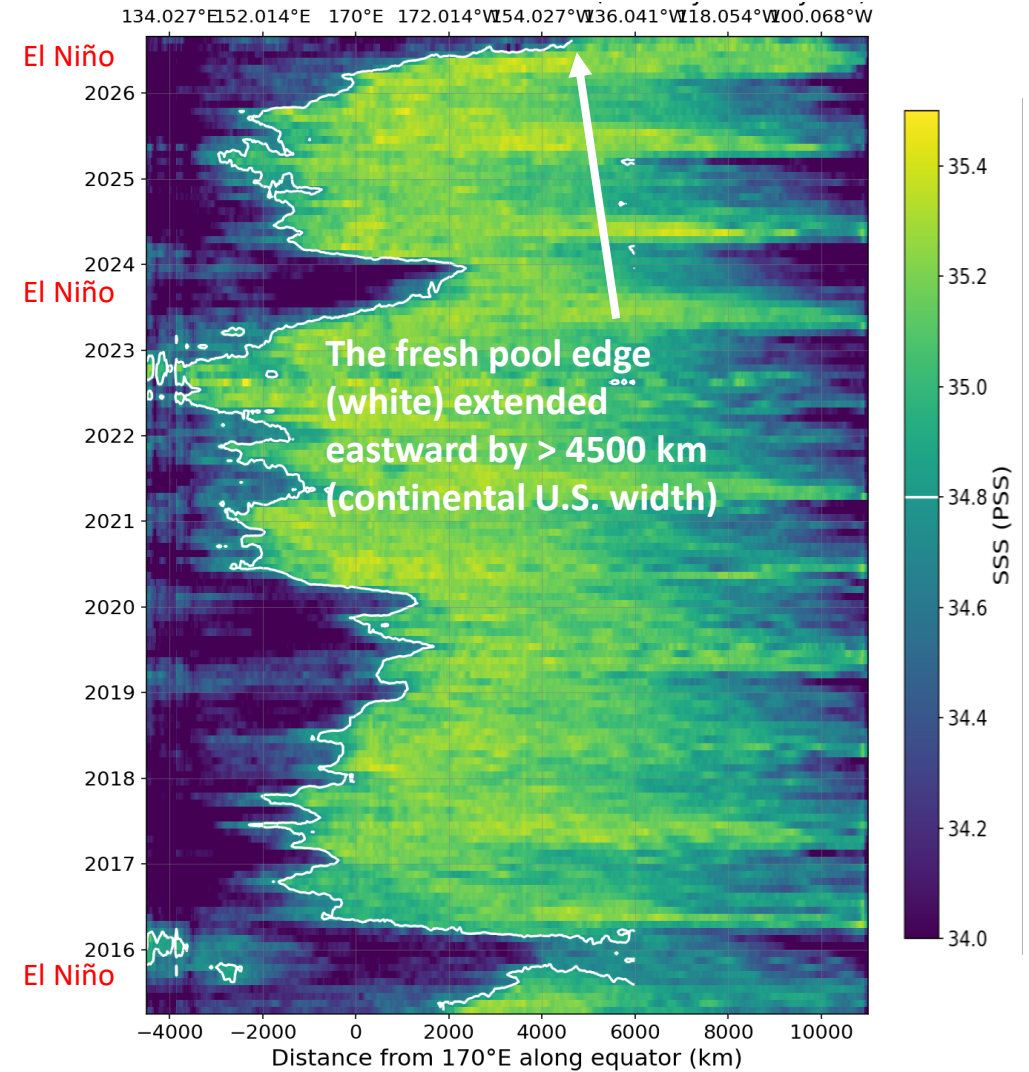


Sea surface height anomaly (NASA)

1997-98 2015-16 2026

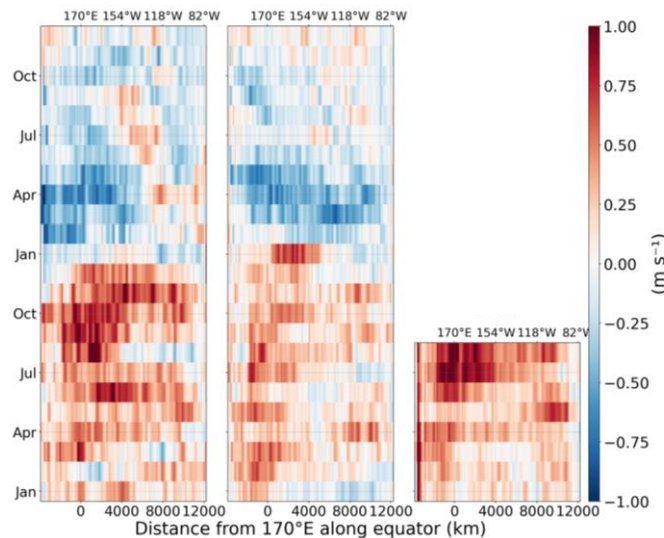


Sea surface salinity anomaly (SMAP RSS)



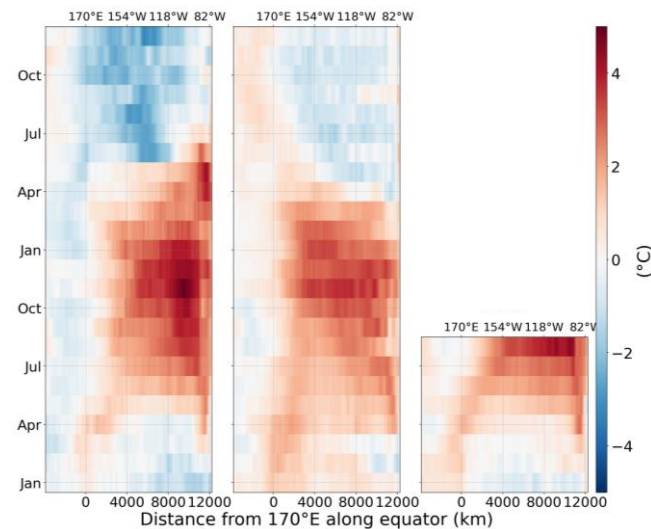
Zonal current anomaly (OSCAR)

1997-98 2015-16 2026



SST anomaly (NOAA OISSTv2)

1997-98 2015-16 2026

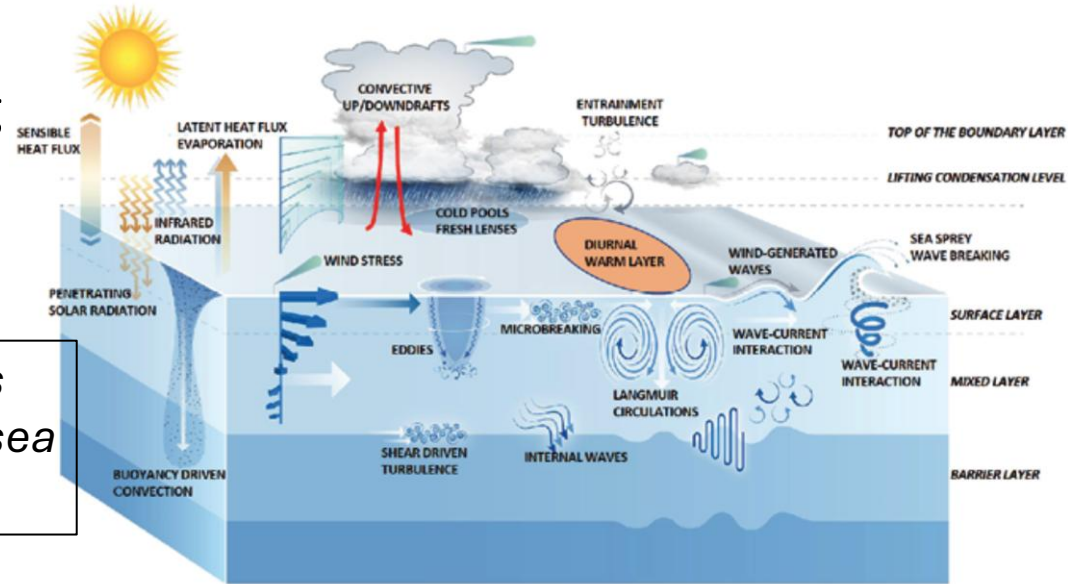


Credit for figures: Severine Fournier

Mission concepts & instrument assets for advancing hydrosphere science related to air-sea interactions

Observing air-sea interactions are crucial for understanding & predicting weather & climate variability (incl. extreme events), but significant observing capability gaps exist.

Figure from U.S. CLIVAR report Aug. 2023. Some key processes that govern transfer of heat, moisture, & momentum in the air-sea transition zone. Courtesy of Chidong Zhang.



Two synergistic mission concepts for observing air-sea interactions:



Observing air-sea **thermodynamic coupling** through coincident high-resolution measurements of SST, wind speed, near-surface temperature & humidity.



Observing air-sea **mechanical coupling** through coincident high-resolution measurements of ocean-surface vector winds & currents.

The related airborne instruments (e.g., DopplerScatt) are poised to enhance hydrosphere science.

SWOT observations of small-scale ocean features <https://svs.gsfc.nasa.gov/5538/>

