Tropical Pacific Observing System (TPOS) Equatorial Pacific Experiment (TEPEX)

Contributors: NOAA CPO/CVP, GOMO, OAR (PMEL, PSL, GFDL)
and NCAR, CU, CSU, SIO, UW, NASA

Key Points

- The tropical Pacific plays a central role in global weather and climate. ENSO, the strongest interannual climate signal, and the MJO, the strongest intraseasonal signal, both shape high-impact environmental events worldwide. ENSO and the MJO interact with each other in the tropical Pacific. Accurate detection, description and modeling of both phenomena is critical to subseasonal to interannual predictions.
- Among the important processes of ENSO, two stand out as inadequately understood and poorly represented by numerical models. One is equatorial upwelling and mixing in the eastern Pacific cold tongue, the other is the zonal movement of the western Pacific warm pool. Both involve active air-sea interaction. They are the primary targets of TEPEX.
- TEPEX emerged from wide discussions in the science community and was recommended by TPOS 2020 as an urgently needed action to advance our understanding and prediction of global variability from subseasonal to interannual timescales, and to inform the evolution of the sustained observing system. TEPEX provides opportunities for multidisciplinary studies of the tropical ocean and atmosphere. It is envisioned as an internationally collaborated and coordinated program and serves as the first field campaign of the WCRP Global Precipitation Experiment (GPEX).
- TEPEX is planned for 2026 - 2028. Its preliminary plan capitalizes on major ongoing upgrades to the TAO moored array and new observing technologies, and has been focused by several years of pre-field modeling studies.
- The field observations of TEPEX in regions without previous comprehensive air-sea interaction field campaigns will enable the global research and operation communities to tackle physical processes key to ENSO prediction through improvement of fundamental understanding and prediction models.

Motivation

ENSO and the MJO are strong influences on global environmental extremes including precipitation, wildfire, tropical cyclones, flooding, droughts, and heat waves. They also influence marine biological productivity, air quality, and the global carbon cycle. Accurate predictions of ENSO and the MJO are essential to mitigate the societal impacts of multiple environmental events in a changing climate.

Our current prediction models, however, do not adequately represent processes key to ENSO and the MJO, and their interactions. Prediction models misrepresent the cold tongue and warm pool in ways that have far-reaching effects on global precipitation, energy and carbon budgets, and circulation patterns. In consequence, ENSO and MJO prediction skills are limited and do not meet societal needs. Improvement of ENSO and MJO prediction must be based on a solid understanding of their central mechanisms, to enable implementation of these factors into the global models. Detailed in situ observations from targeted field campaigns are the foundations for such understanding.

Variability of the East Pacific cold tongue and West Pacific warm pool dominate the zonal sea surface temperature (SST) gradient that plays a central role in ENSO and helps determine the eastward extent of MJO events. Accurate representations of processes controlling the variability of the cold tongue and the warm pool are critical for enhancing prediction skills at the global scale and intraseasonal to interannual timescales. Both the maintenance and variability of the cold tongue and warm pool are actively involved with air-sea interaction (Fig. 1) through the air-sea transition zone, which includes the upper ocean, air-sea interface, Marine Atmospheric Boundary Layer (MABL) as a single identity. Rainfall, surface winds, and modulation of solar radiation by clouds govern the input of freshwater, momentum, and energy to the ocean. The oceanic response to these disturbances is regulated through the upper-ocean stratification of temperature, salinity, and velocity which determine the extent to which the surface inputs penetrate vertically and are transported horizontally. The consequent distributions of the upper-ocean heat content and sea surface temperature (SST) feed back to the atmospheric wind, clouds, and rainfall. Strong horizontal gradients in SST exist in both the cold tongue (in the meridional direction) and the eastern edge of the warm pool (in the zonal direction). The air-sea interaction processes uniquely acting upon the strong SST gradients in these two regions cannot be fully understood based on data obtained from elsewhere.

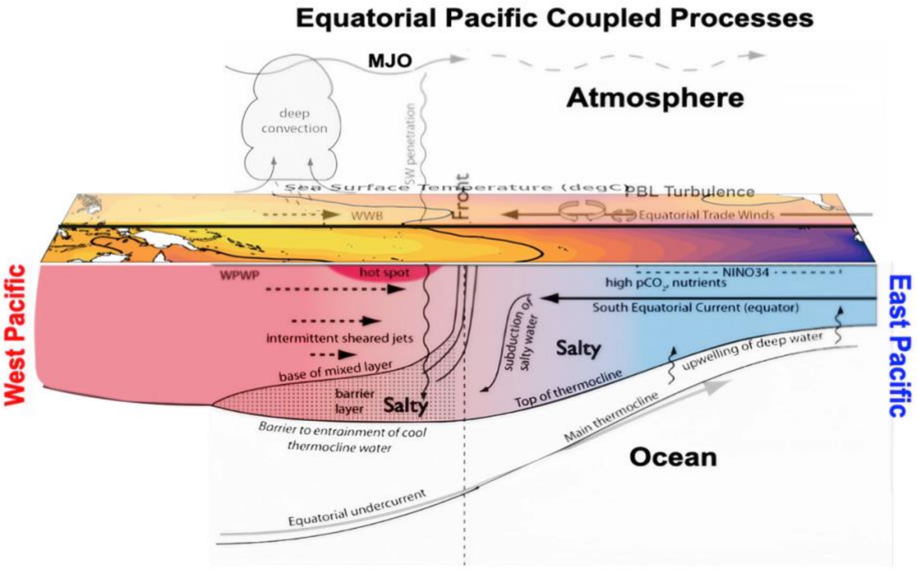


Figure 1. Illustration of air-sea interaction processes of the equatorial Pacific (From Brown et al. 2014)

Goal and Objectives

The overarching goal of TEPEX is to enhance our understanding of the key processes for the intraseasonal to interannual variability of the tropical Pacific, especially those that govern the evolution of ENSO, thereby to provide robust information guiding improvement of ENSO prediction. This goal will be achieved through three related efforts: (1) Conduct field observations targeting two regions: the equatorial cold tongue of the eastern Pacific and the eastern edge of the warm pool of the central Pacific, (2) Combine observational analysis and numerical modeling to dissect the detailed processes critical to air-sea interaction of the equatorial Pacific and ENSO dynamics, and (3) Apply these gains to model advancement: new parameterizations of ocean vertical mixing, and explicitly-modeled freshwater- salinity coupling.

Physical basis

The physical processes of the cold tongue and warm pool share many commonalities (e.g., strong surface winds, air-sea fluxes, upper-ocean mixing, MABL response to SST fluctuations). They also have their unique aspects. Their specific processes that need special attention for the planning of TEPEX field observations are discussed below.

The cold tongue exists despite strong local solar warming because of intense upwelling of cold water and downward transport of heat by ocean mixing. This two-way communication of energy, momentum, and water properties between the sea surface and the thermocline couples the atmosphere to "ocean memory" that shapes ENSO. Air-sea and ocean processes determine the height, stability, and cloudiness of the local MABL, which determine how effectively the thermocline memory and MABL properties will be connected to the troposphere and thereby influence atmospheric general circulation. Locally, gradients of surface pressure - modulated by the SST gradient - competes with the tropospheric pressure gradient in driving the surface wind. The penetration of tropospheric momentum into the MABL and to the surface depends on MABL instability, which is mainly determined by SST. Local and remote factors modulating upwelling, and its role in regulating SST, air-sea fluxes, their spatial gradients, and their influence on stability, height, and cloudiness of the MABL are all largely unconstrained by *in-situ* or satellite observations, and therefore cannot be confidently modeled or simulated. TEPEX will provide the physical basis to underpin and advance the next generation of models and observing networks in the cold tongue.

The zonal movement of the warm pool at its eastern edge is forced by surface zonal winds and controlled by several factors (e.g., directly forced surface current, oceanic Kelvin waves, Ekman divergence, and the asymmetry in wind responses to the ocean). A special feature of the warm pool is the episodes of strong surface westerly wind events (WWEs) and strong rainfall events that are often closely related through, for example, the MJO. The counter-effects of enhancing ocean mixing by WWEs and weakening mixing by the barrier layer due to surface freshwater input by rain are perhaps among the most difficult to be accurately reproduced by numerical models. This difficulty is compounded by the multi-scale variability (the MJO, equatorial waves, extratropical intrusions) in the atmosphere, their interactions, and their ocean responses.

Hypotheses

Decades of shipboard, moored, and satellite observations, as well as recent modeling results, have spurred new ideas for understanding and representing relationships between subsurface mixing, air-sea fluxes, surface forcing, and MABL response in the air-sea transition zone. They also prompted new hypotheses for the role of equatorial mixing and freshwater input in the Pacific coupled ocean-atmosphere system. The following hypothesized processes are proposed to guide TEPEX field observations:

1) Upwelling and Mixing

In the eastern Pacific cold tongue, persistent vertical shear between the surface westward South Equatorial Current and the eastward Equatorial Undercurrent in the thermocline creates an unstable regime below the surface mixed layer that is primed to mix vigorously. Surface-trapped currents in the afternoon warm layer set off a diurnal cycle of downward-propagating turbulence that reaches far below the ocean surface mixed layer into the upper thermocline. The resulting deep vertical mixing transports surface heat downward and cold water upward, cooling the surface and allowing the cold tongue to extend much further west than simple flow along the upward-sloping thermocline would imply. Thus, mixing drives efficient surface-thermocline communication even where the wind stirring does not reach the depth of the thermocline (Fig. 2). Mixing carries ocean memory to the atmosphere, enabling large-scale ocean-atmosphere coupling (Bjerknes feedbacks), and providing a path for carbon-rich water to reach the surface resulting in CO_2 outgassing, and sustaining the cold tongue's productive fishery.

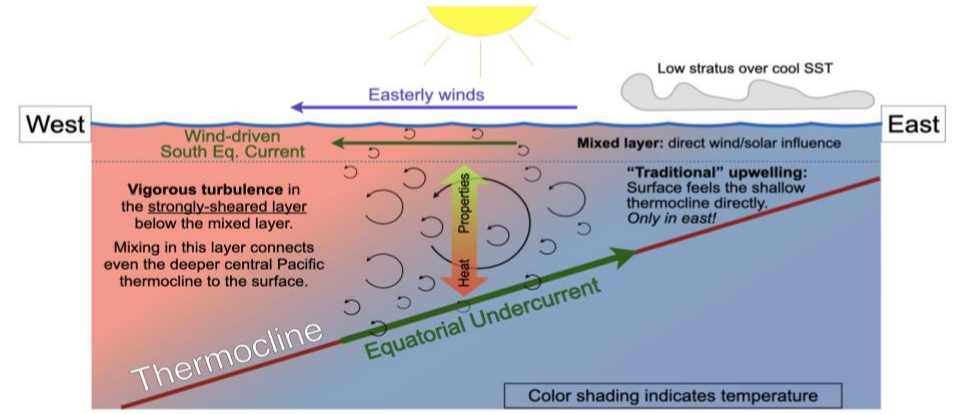
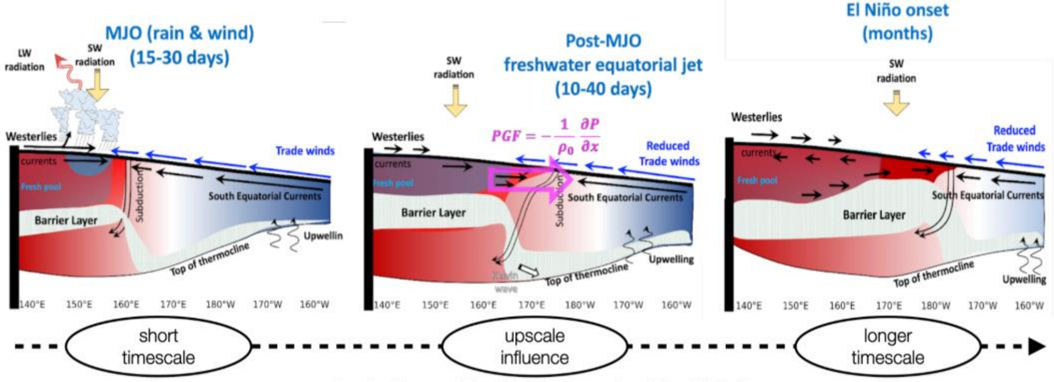


Figure 2 Schematic illustration of vertical-shear driven mixing in the cold tongue.

In contrast, in the region of the eastern edge of the warm pool, mixing is primarily driven by surface wind and inertial waves. Because of substantial surface freshwater due to rainfall, salt-stratified barrier layers can form, lasting until being eroded by subsequent strong surface wind forcing. Weakened or diminished mixing across the pycnocline increases the efficiency of wind-forced surface current responses.

2) Roles of surface freshwater input

In addition to forming salt-stratified barrier layers that inhibit entrainment of cold water from below and enhance surface warming, surface freshening from rainfall can also stabilize the upper ocean and generate density gradient-driven surface pressure jets along the equator that expand the warm pool eastward. The expanded warm pool can support further eastward propagation of subsequent atmospheric events, such as the MJO, and their associated westerly wind forcing, thus strengthening equatorial downwelling oceanic Kelvin waves that deepen the thermocline in the central and eastern Pacific. Such multiscale air-sea interactions, as illustrated in Fig. 3, are among the processes likely contributing to the onset of El Niño. However, this process is absent from the cold tongue region because of its weak precipitation.



Based on Kerns and Chen (2021) and Jauregui and Chen (2023a,b)
https://orca.atmos.washington.edu/publications.php

Figure 3 Schematic illustration of one of the hypothesized multiscale air-sea interactions of the warm pool. MJO precipitation and westerly winds induce eastward propagating oceanic Kelvin waves that deepen the thermocline and upper ocean barrier layer (left). During the post-MJO phase, surface warming and freshwater generate a large-scale zonal gradient in upper ocean pressure, which induces a strong easterly current (middle). Consequently, the warm pool is expanded eastward, and the trade wind is relaxed during the onset of El Niño (right).

3) Air-sea coupling

Air-sea coupling of the warm pool is empowered especially by its episodic, very strong precipitation events. Variations in surface wind, rainfall, radiation, and other quantities crucial to the atmospheric forcing of the ocean are often closely related to atmospheric deep convection. The oceanic feedback to the atmosphere through SST anomalies and air-sea fluxes is received by the MABL and manifested by the responses in atmospheric convection. In contrast, non-precipitating processes dominate air-sea coupling of the cold tongue. Variations in upwelling and mixing produce SST anomalies gradients on subseasonal to interannual scales. Through air-sea fluxes, atmospheric responses in near-surface moisture, temperature, pressure, boundary layer stability and height, and cloudiness determine the strength of turbulent mixing in the MABL. The consequential surface pressure gradient, tropospheric pressure gradient (measured at the top of the MABL), and cloud-enhanced vertical mixing of tropospheric momentum into the AMBL compete to drive surface winds, closing the interaction loop between the thermocline, air-sea transition zone, and the troposphere.

Guiding Questions for TEPEX

1. What controls the strength and extent of the thermocline variability and upper-ocean shear/ stratification? What are the relative roles of upwelling, mixing, and surface forcing in this?
2. What processes control the emergence, strength, persistence, and pattern of SST anomalies? What are the relative roles of upwelling, mixing, thermocline anomalies, upper-ocean stratification, and surface forcing in this?
3. To what extent - and by what mechanisms - do changes in SST and air-sea fluxes, especially across the sharp front of the cold tongue and the eastern edge of the warm pool, co-evolve with the other properties in the air-sea transition zone? To what extent does the variability of the air-sea transition lead to the fluctuations in atmospheric convection and cloudiness and in the thermocline?
4. What are the roles of oceanic and atmospheric propagating phenomena (e.g., TIW, MJO, equatorial waves, inertial oscillations) in equatorial air-sea coupling? Do these processes connect the warm pool east edge with the cold tongue?
5. To what extent can the identified processes in the air-sea transition zone key to equatorial air-sea coupling be inferred or diagnosed from the sustained TPOS and routinely observed for accurate ENSO prediction?

Field Observation Strategy

TEPEX-Central: eastern edge of warm pool (across the 28.5°C isotherm, typically 160°E - 160°W, 5°S – 5°N	**TEPEX-East: cold tongue** (140°W, 2°S – 5°N)
Boreal Spring (March – May) 2026	One year starting from boreal fall 2026 (three ship cruises, six-month apart)
Ship observations of the air-sea transition zone (including ocean mixing, convective clouds, and precipitation), the thermocline, and the tropospheric profiles	
UxS (underwater, surface, and aerial drones) observations of the air-sea transition zone	
Aircraft observations of the air-sea transition zone	enhanced moorings for ocean mixing
Land-based observations of the MABL and atmospheric convection	
Argo floats, surface drifters, TAO array	

Satellite observations of SST, SSS, wind, rainfall, cloudiness, water vapor, etc.
Real-time forecasts and state-estimation will guide the field operations and provide early interpretation and quantification of the value and impact of the field observations.

Outcomes:

a) **Advance fundamental understanding.** TEPEX will provide comprehensive, co-located in situ observations that will, through testing the proposed hypotheses, bring improved process-level understanding of the cold tongue and warm pool in the context of the air-sea transition zone across dynamical regimes; It will also pursue broaden scientific scopes into oceanic biogeochemistry and atmospheric chemistry;

b) **Guide model development.** TEPEX observations will provide the base for iterative implementation and evaluation of prediction model improvement: parameterizations of ocean vertical mixing and explicit coupling of freshwater and salinity, and for constraining large eddy simulations (LES) to produce observational proxies to assist model development;

c) **Guide observing system design**. TEPEX observations will help determine the variables and their spatial and temporal scales that must be sampled by the TPOS observing systems and satellite observations to produce adequate data for diagnostics of the air-sea transition zone over the cold tongue and warm pool and for accurate ENSO prediction.

Impacts:

The international TPOS 2020 observing system redesign identified the processes targeted by TEPEX as key to realizing the potential global prediction skill depending on intensely coupled tropical Pacific air-sea interaction. Observational, technical, theoretical, and modeling advances of recent years have prepared us to accomplish the goals laid out above. The insight gained through TEPEX co-located measurements of the air-sea transition zone and its interaction with the thermocline and troposphere will lead to more complete and more effective ocean-atmosphere monitoring of the region by the sustained observing system. The advanced observing system, understanding, and models in combination will lead to more accurate prediction of the Pacific ocean-atmosphere coupled system of a wide range of timescales. This advanced observation-understanding-prediction enterprise would have far-reaching societal benefits. It is the foundation for mitigation of the impact of extreme environmental events modulated by ENSO and the MJO (floods, droughts, wildfire, heat waves, marine heat waves, tornados, tropical cyclones, coastal inundation, etc.), better management of natural resources (fisheries, coral reefs, etc.), design of sound and sustainable climate solutions (clean energy, reforestation, aquaculture, CO_2 removal, etc.), and global/regional equality for vulnerable populations.

TEPEX will serve as the first field project of the WCRP Global Precipitation EXperiment (GPEX) and Precipitation Prediction Grand Challenge (PPGC), a WMO Ocean Decade Action. TEPEX will provide experience and lessons learned to pave the road for the long-term success of GPEX and PPGC.

TEPEX will promote diversity, inclusion, and equality by actively recruiting and supporting participants who are early-career and from underrepresented groups in geoscience to help build a more representative future workforce. TEPEX is envisioned as an international program that promotes collaborations and coordination among the countries/regions of the Pacific Rim to advance their common interests in the ability to predict the Pacific ocean and atmosphere to benefit society.