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

EXECUTIVE SUMMARY

- 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 affect 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 are critical to subseasonal to interannual predictions.
- Among the important processes of variability in the tropical Pacific, two stand out as inadequately understood and poorly represented by numerical models. One is equatorial upwelling and mixing critical to formation and changes in the tongue of cold surface water in the eastern equatorial Pacific; the other is the zonal movement of the eastern edge of the Warm Pool in the central Pacific that limits the location of the eastward development of deep convection in the atmosphere. Both involve active air-sea interaction. The large-scale SST gradient between these two enables the Bjerknes feedback, crucial to ENSO. 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 capabilities 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 has the potential to serve as an anchor field project of the WCRP Global Precipitation Experiment (GPEX).
- TEPEX is planned for 2026 - 2027. Its preliminary plan leverages 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 goal is to better understand the processes that shape tropical Pacific variability, and to learn how to take maximum advantage of the sustained observing system that samples over time scales longer than those to be covered in an intensive field campaign.
- The field observations of TEPEX in regions that currently lack comprehensive air-sea interaction field campaigns will enable the global research and operational communities to address key physical processes essential to ENSO prediction. This will be achieved through improvements in both fundamental understanding and the representation of these processes in prediction models.

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1. INTRODUCTION

The international Tropical Pacific Observing System (TPOS) 2020 project over the course of seven years identified tropical Pacific observations needed to improve global prediction skills and to meet global carbon dioxide assessments called for by the Paris Agreement (Cravatte et al. 2016, Kessler et al. 2019, 2021). TPOS-2020 envisioned a TPOS that was more capable and sustainable, and a pathway for improving the operational system through both pilot and process studies. Critically, TPOS-2020 recommended intensive field campaigns to resolve processes responsible for the evolution of the coupled ocean-atmosphere climate system that were neither well captured by the TPOS nor well represented in operational numerical prediction models. Two process study domains were identified: the eastern edge of the Pacific warm pool (hereafter as the Warm Pool) and the Cold Tongue. Process studies in these two domains, referred to collectively as the TPOS Equatorial Pacific Experiment (TEPEX), are the subject of this Science Plan.

Observational, technical, theoretical, and modeling advances of recent years have prepared us to accomplish the goals laid out below. The insight gained through TEPEX co-located measurements of the Air-Sea Transition Zone (ASTZ; Clayson et al. 2023) and its interaction with the thermocline and free troposphere will lead to more complete and more effective ocean-atmosphere monitoring of the region by the sustained observing system. The combination of advancements in the observing system, model representation, and physical understanding of the Pacific ocean-atmosphere coupled system will lead to more accurate prediction over a wide range of timescales. This advanced observation-understanding-prediction enterprise will have far-reaching societal benefits. It is the foundation for mitigation of the impact of extreme environmental events (floods, droughts, wildfire, heat waves, marine heat waves, tornados, tropical cyclones, atmospheric rivers, coastal inundation, etc.) modulated by El Niño-Southern Oscillation (ENSO) and the Madden-Julian Oscillation (MJO), better management of natural resources (fisheries, coral reefs, ocean carbon sink, etc.), design of sound and sustainable climate solutions (clean energy, reforestation, aquaculture, marine carbon dioxide removal, etc.), and global/regional equality for vulnerable populations.

TEPEX is envisioned as an international program that promotes collaborations and coordination among the countries/regions of the tropical Pacific and Pacific Rim to advance their common interests in the ability to predict the Pacific ocean and atmosphere to benefit society. The eastern edge of the Warm Pool (EEWP) migrates zonally thousands of kilometers, crossing national boundaries of many Pacific Islands, including islands of the Republic of Kiribati. TEPEX offers an opportunity to work directly with the Pacific Community (https://www.spc.int/), an organization formed in 1947 and currently owned and governed by 27 country and territory members that is the principal scientific and technical organization in the Pacific region. With relevance to multiple U.S. agencies and emerging international collaborations, TEPEX has the potential to serve as an anchor field project of the Global Precipitation Experiment (GPEX), a lighthouse activity of World Climate Research Programme (WCRP), and the first field project of NOAA's Precipitation Prediction Grand Challenge (PPGC), a WMO Ocean Decade Action.

2. BACKGROUND

Variability of the Pacific Cold Tongue and Warm Pool dominate the sea surface temperature (SST) gradients that are critical to ENSO and help determine the eastward extent of MJO events. Accurate representations of processes controlling the variability of the Cold Tongue and 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 consist of active air-sea interaction processes (Fig. 1) through the ASTZ, which includes the upper ocean, air-sea interface, and marine atmospheric boundary layer (MABL) as a single entity. Rainfall, surface winds, and modulation of solar radiation by aerosols and clouds govern the input of freshwater, momentum, and energy into the ocean. The oceanic response to these fluxes is regulated through the upper-ocean stratification of temperature, salinity, velocity, and mixing which determine the extent to which the surface inputs penetrate the ocean vertically and are transported horizontally. The consequent distributions of the upper-ocean heat content and SST feed back to the atmospheric wind, stability, clouds, and rainfall. Strong horizontal gradients in SST exist in both the Cold Tongue (in the meridional direction) and the EEWP (in the zonal direction). The air-sea interaction processes uniquely acting upon the strong SST gradients in these two regions cannot be understood based on data obtained from elsewhere.

3. SCIENTIFIC PROBLEMS AND 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 ASTZ. They also prompted new questions and hypotheses for the role of equatorial mixing and freshwater input in the equatorial Pacific coupled ocean-atmosphere system. The dominant physical processes common to both the Cold Tongue and Warm Pool involve the surface winds, air-sea fluxes, upper ocean mixing, and response of the

MABL to local SST fluctuations. There are also processes unique to each region (e.g. below-mixed-layer mixing in the Cold Tongue, barrier layer formation and the development of atmospheric convection in the Warm Pool). The processes that need special attention for the planning of TEPEX field observations are discussed below in two parts: TEPEX-Eastern Pacific (TEPEX-E), and TEPEX-Central Pacific (TEPEX-C).

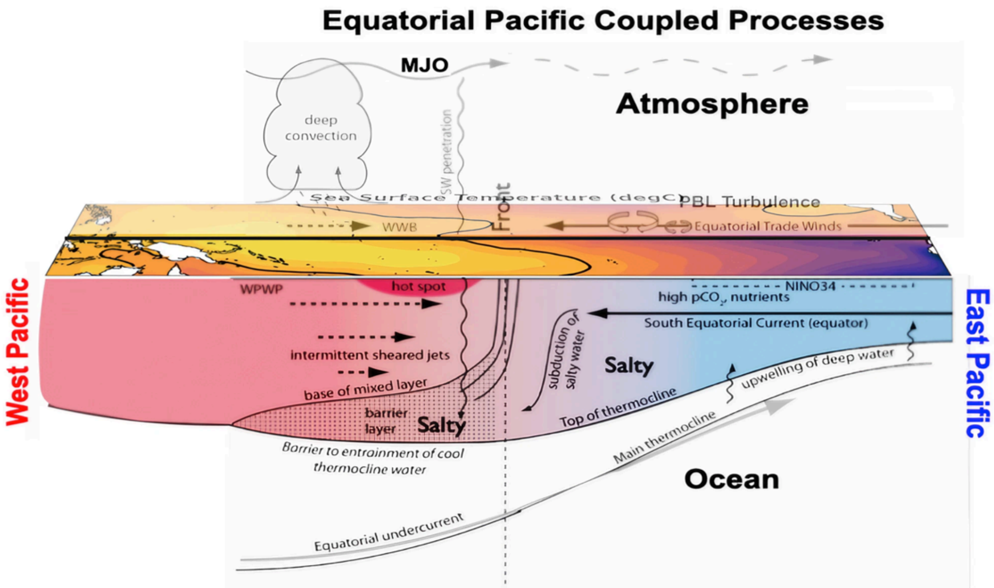

Figure 1. Illustration of air-sea interaction processes of the equatorial Pacific (Adapted and modified from Brown et al. 2015).

3.1 TEPEX-E: Cold Tongue Mixing and Coupling to the Atmosphere

A. Ocean Mixing

The Cold Tongue exists despite strong local solar warming because of intense upwelling of cold water and downward transport of heat by ocean mixing which reaches down to the thermocline. 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 (Fig. 2a).

Early coupled models were relatively successful in simulating ENSO oscillations using extremely simple parameterizations of ocean-atmosphere interaction: the ocean memory was contained in thermocline depth alone, with a shallow thermocline implying cooler local SST; the resulting zonal gradient drove wind anomalies that enabled coupled (Bjerknes) feedbacks (McCreary and Anderson 1984; Zebiak and Cane 1987). But such a direct connection between the thermocline and the surface is not a useful framework in locations where the top of the thermocline is multiple 10s of meters below the surface mixed layer, as is between 125°W to 170°W in the cool season of boreal Fall (Fig. 2b). Cool SST extending well west of the shallow thermocline region requires other processes that can enable this connection.

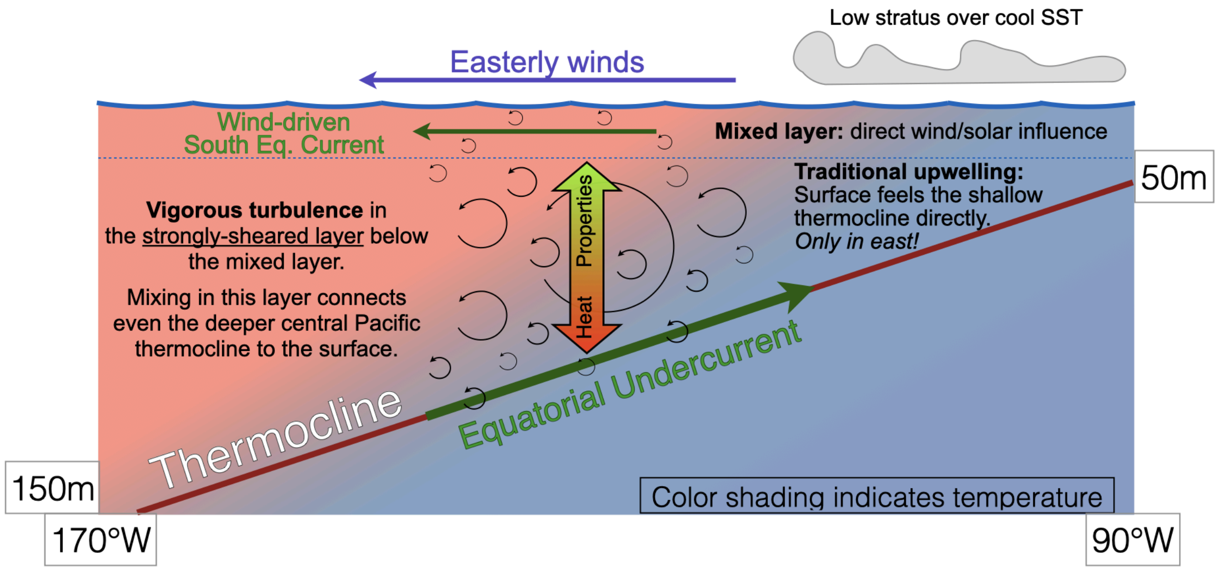

Figure 2a. Schematic vertical shear-driven mixing in the Cold Tongue. The layer between the thermocline and the mixed layer is strongly sheared and weakly stratified (Fig. 2b), thus with a gradient for mixing to work on and background shear to enable turbulence.

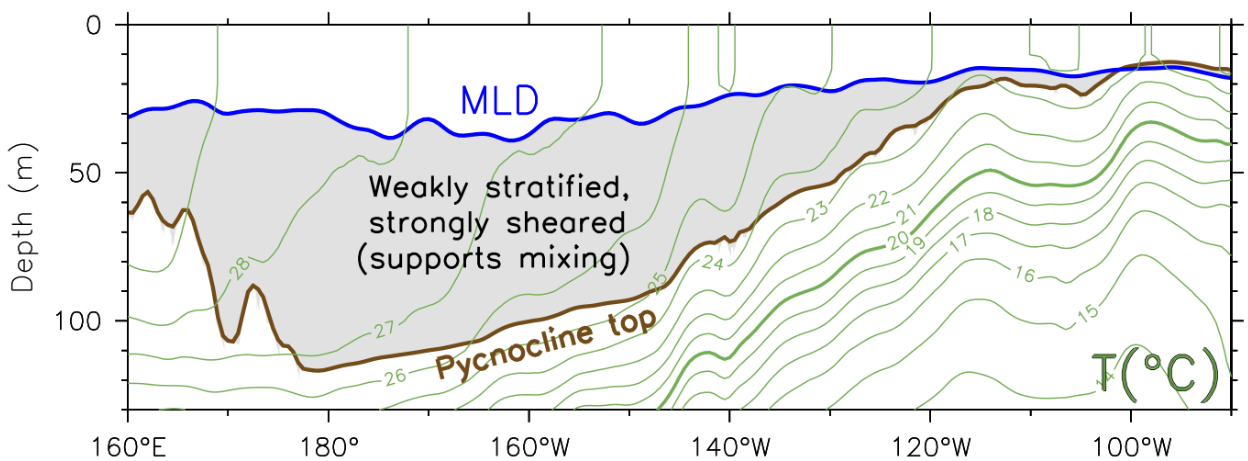

Figure 2b. Zonal section of mean temperature along the equator from the MIMOC climatology (Schmidtko et al., 2013). The gray-shaded region between the explicitly-analyzed mixed layer depth (MLD), and the top of the pycnocline (defined as the depth of N^2=2x$10^{-4}s^{-2}$) defines the weakly-stratified, strongly-sheared layer that can support shear-driven turbulent mixing.

In the Pacific Cold Tongue west of 120°W, persistent vertical shear between the surface westward wind-driven South Equatorial Current and the eastward Equatorial Undercurrent (EUC) in the thermocline creates an unstable regime below the surface mixed layer that is primed to mix vigorously (gray shading in Fig. 2b; Gregg et al 1985, Moum and Caldwell 1989, Lien et al 1995, Moum et al 2013, and others). 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 (Smyth and Moum 2013, Pham et al 2017, Smyth et al 2021, Masich et al. 2021, Moum et al 2022). Vertical mixing thus transports surface heat downward (Holmes et al 2019, Cherian et al 2021, Deppemeier et al 2021, 2022), cooling the surface and allowing the Cold Tongue to extend much further west than expected from advection along the upward-sloping thermocline.

Historically, attempts to quantify the role of "upwelling" in controlling SST change in the Cold Tongue focused on measuring vertical velocity *w* (e.g., Weisberg and Qiao 2000). This is an incomplete lens to describe the Cold Tongue because it obscures the crucial role and effects of mixing as discussed above.

Equatorial upwelling *w* consists of two components, one of which is primarily associated with the upward slope of the EUC (roughly along the 20°C isotherm; Fig. 2b). The eastward jet closely follows the shoaling thermocline, and its along-isotherm flow therefore conserves the heat of water parcels; it cannot directly affect SST except where the thermocline is very shallow in the far east where shallow wind stirring can couple the surface to the nearby thermocline (Fig. 2a). This along-isotherm flow is the adiabatic part of *w*, which is found to be about two-thirds of the total (Bryden and Brady 1985, Deppenmeier et al. 2021). The other one-third is diabatic, accomplished by vertical exchanges of water parcels across isotherms, transmitting heat downwards, cooling the surface and warming the thermocline.

This mixing-driven heat exchange, especially in the upper thermocline and into the weakly-sheared layer directly above (Fig. 2b), is driven primarily by shear driven vertical mixing, not adiabatic upwelling. Attempts to improve our understanding and model representation of equatorial mixing have been made using observations at 0º,140ºW (Moum et al 2013, Warner and Moum 2019, Smyth et al 2021) and LES (Large Eddy Simulation, Pham et al 2017, Whitt et al 2022). These observations and simulations have shown a strong seasonal variability of mixing, strongest in boreal fall when the zonal winds and vertical shear are larger. But a full description has been hampered by inadequate temporal resolution that would allow the connection of local and remote forcing to be quantified. In addition, spatial variations are likely important but unmeasured, including the background velocity structure on the flanks of the EUC and across the front near 2°N. The limited observations of equatorial mixing and its impacts on the large scale reveal biases in state-of-the-art ocean and climate models (Deppenmeier et al 2022). Thus, a central purpose of the field program is to provide targeted observations to guide mixing parameterization improvement.

Global ocean models that underpin seasonal forecasting use tunable mixing parameterizations that date back to the 1990s and are ripe to be revisited. Direct process-level comparisons between observations and the results given by mixing parameterizations are crucial to advancement. Evaluation of vertical mixing-induced ocean turbulent heat fluxes requires observations of seasonally and meridionally varying shear, stratification, and mixing, rather than typical indirect comparisons of the response of mean state variables such as temperature to changes in the parameterized mixing. The TEPEX-E campaign will provide the data necessary for these direct comparisons to refine mixing parameterizations and improve models.

Hypothesis: Shear-driven mixing enables efficient surface-thermocline communication even where the wind-driven stirring does not reach the depth of the thermocline west of 120°W (Fig. 2b).

Observational Needs:

Targeted observations to guide mixing parameterization improvement will require expanding observations of mixing processes as well as their large scale forcing beyond the 0°,140°W site, especially to include the meridional flanks of the EUC and into the tropical instability wave zone, thus to about 3°N. Seasonally-varying time series of mixing in the context of surface forcing, shear, and stratification spanning the equatorial zone at 140°W will be needed. Ideally profiles of these aforementioned variables will be co-located. To maximize the chances to sample the strong-mixing season, even in the unlikely event of an El Niño, the TEPEX-E field campaign is intended to last a full year, beginning in boreal fall and extending through the next year.

We note the practical difficulties of measuring total *w* in a context where the target is the short-term (less than monthly) and local interactions of the multiple processes influencing SST in the Cold Tongue. It may not be necessary or possible to measure upwelling directly to test the above hypothesis. Since vertical velocity is far smaller than can be measured directly, it must be estimated by downward integration of the horizontal divergence. These velocity measurements are noisy, and do not extend to the surface where divergence is largest. The results have been interpretable only over long time or large regional averages, and still have large uncertainties (Bryden and Brady 1985; Weisberg and Qiao 2000; Meinen et al. 2001; Johnson et al. 2002). While these studies have taught us much about the structure of upwelling in the tropical Pacific, the vertical velocity measurements advocated in the formerly known “Pacific Upwelling and Mixing Physics” (PUMP) project have broadened to include the diabatic exchanges.

B. Air-Sea Sea Interaction and the MABL

Ocean mixing and upwelling influence SST and therefore air-sea fluxes modulated by the ocean surface waves, which in turn influence the height, stability, turbulence, and cloudiness of the local MABL (Small et al. 2005, Schneider 2020). Though some components of these feedbacks can be observed from satellites (Chelton et al. 2001), the coupled processes including the role of ocean mixing on SST, as well as its impacts of SST on fluxes, MABL structure and stability, and clouds, are neither well observed operationally (see satellite discussion of Section 11), nor well constrained in models or reanalyses. Ocean waves and currents impact the surface stress and therefore the momentum flux between atmosphere and ocean, which are also not well constrained by satellites. Errors on the order of 15-20% in surface stress due to neglecting waves and currents (Iyer et al. 2022; Sauvage et al. 2023) need to be accounted for in bulk algorithms because they can lead to larger errors in estimates of adiabatic upwelling across the Cold Tongue. While stable to neutral MABLs have been observed and used to train bulk flux algorithms, more data from the Cold Tongue region will help bolster these flux algorithms that are relied upon for research, satellite, and NWP activities.

<u>Hypothesis</u>: Surface fluxes, MABL stability, and the interaction of waves at the air-sea interface determine how effectively the thermocline memory is communicated to the MABL, how vigorously the MABL is connected to the free troposphere, and thereby how the Cold Tongue influences atmospheric general circulation. Waves at the air-sea interface modulate the exchange processes and energy transfer, impacting the overall stability and mixing within the MABL.

<u>Observational Need:</u> Time series measurements of the surface energy budget are needed using bulk quantities in most places, but direct eddy covariance fluxes (including wave effects) are needed in at least a few places on and off the equator to better understand and constrain the underlying physical processes. Flux measurements should be colocated where ocean mixing data are collected.

C. Local and Remote Atmospheric Forcing and Response

Thermocline to tropospheric exchange in the Cold Tongue regulates cloud feedbacks, global circulation, and downstream weather and climate patterns. ENSO is sensitive to surface radiation anomalies related to cloudiness. Clouds here respond to ocean-mixing modified SST via MABL processes. Additionally, satellite measurements show that shortwave cloud radiative feedbacks north of the Pacific Cold Tongue in the ITCZ are the strongest of the global ocean (and second only to the Warm Pool in longwave, Henderson et al. 2013). Compared to the rest of the globe, the cloud feedbacks in this region are also the most uncertain and biased in models (both longwave and shortwave, Andrews et al. 2015, Cesana and Del Genio et al. 2021). These cloud feedbacks are modulated by SST anomalies from the Cold Tongue and by the SST front near 2°N that shifts with Tropical Instability Waves (TIWs). Cloud-radiative feedbacks affect the atmospheric general circulation (Zelinka and Hartmann 2012, Zelinka et al. 2018, Vogel et al. 2022), and contribute to climate model uncertainty (Zelinka and Hartmann 2011, Bony et al. 2015, Meyers et al. 2021, Vogel et al. 2022).

The local SST gradients associated with the Cold Tongue and its TIWs interact and compete with larger scale tropospheric processes (e.g. the MJO) to establish the low-level pressure fields that drive winds, which influence convergence, cloudiness, and the upper ocean. While the cold SST of the central Cold Tongue can isolate a thin stable MABL, penetration of tropospheric momentum into the MABL that increases surface wind speed can occur with low-level warming (e.g. as southeasterly trade winds pass over the SST front; Chelton et al., 2001). Downward momentum transport depends on MABL stability and the low-level wind profile, which are determined by SST, air-sea fluxes, subsidence aloft, and geostrophic processes in the troposphere.

Additionally, MJO convection (precipitation) anomalies in the ITCZ that reach the Cold Tongue region cause strong teleconnections to the North American jet stream blocking patterns and extreme weather (Henderson et al. 2017), highlighting the importance of constraining Cold Tongue SST impacts on MJO convection. Though this convection does not happen directly overhead of the Cold Tongue, the Cold Tongue shapes the location and extent of the ITCZ and therefore its MJO teleconnections. Air-sea interactions in this region can also affect decadal variability through cold tongue intensity, northern ITCZ shifts, and cross-equatorial winds (Levine et al 2018, Hu and Fedorov 2018)

Local and remote factors modulating cloudiness and the troposphere above the Cold Tongue are largely unconstrained by *in-situ* or satellite observations. The processes involved, such as ocean mixing, MABL response, atmospheric convection, S2S variability, and teleconnections, cannot currently be confidently or comprehensively characterized by observations, research models, or operational forecasting systems. This motivates a detailed observation-backed study from the thermocline through the troposphere.

Hypothesis: The chain of local and remote processes outlined in A-B above constraints upper ocean mixing in the Cold Tongue that is the main from-below control of SST. This imprints on the local MABL, then to the free atmosphere, and in turn produces cloudiness and surface wind anomalies that further modulate SST and upper ocean conditions.

Observational Need: When and where possible, full soundings of the troposphere and cloud property data are needed. Observations from the TPOS sustained arrays and from TEPEX also need to be contextualized by larger scale observables and reanalysis to better quantify and understand the relative strengths of local and remote factors on Cold Tongue ocean mixing and its imprint on the atmosphere, including locally, nearby in the ITCZ, and downstream. TEPEX-E activities are designed to determine how well these processes can be inferred or diagnosed from the future sustained observing system.

D. BGC & Aerosols

Shear-driven turbulent mixing (Fig.2) represents a critical two-way (both upwards and downwards) pathway for the vertical exchange of biogeochemical properties and fertilizing phytoplankton production that sustain ecosystem productivity and habitability in the tropical Pacific and its strength as the largest source of natural carbon to the atmosphere (Ryan et al 2002, Vichi et al 2008, Pittman et al 2022). Much of the carbon arrives from the west in the EUC before it is upwelled to the surface (Murray et al 1994). Conversely, shear-driven mixing results in a downward oxygen transport from the mixed layer into the upper thermocline (EUC) in the eastern and central equatorial Pacific (Eddebbar et al 2024). The latter may play a key role in the expansion of the tropical eastern Pacific oxygen minimum zones (Oschlies et al 2018, Levy et al 2022).

Vertical exchanges and their transport of low oxygen / high nutrient waters to the surface may also have substantial impacts on atmospheric chemistry and solar absorption near the surface that regulates SST, the marine boundary layer, and the free troposphere through air-sea exchange of reactive trace gasses. Aircraft observations in the eastern tropical Pacific suggest major missing sources of nitrogen oxides (NOx); but need to be confirmed by in situ trace gas flux measurements. These NOx sources could react in the atmosphere to reduce the global methane lifetime by more than 10% (Travis et al., 2020; Guo et al., 2023). Upwelled nutrients such as chlorophyll also change the vertical profile of solar absorption in the water, which is critically important to constrain estimates of skin SST from subsurface water temperature measurements such as on the TPOS array (Murtugudde et al. 2002, Gildor et al. 2003, Wetzel et al. 2006, Tian et al. 2018, 2019). Accurate surface flux estimates rely heavily on the accuracy of estimated skin SST by these means. Finally, sources of marine-sourced sulfur containing gasses such as dimethyl sulfide and methanethiol, which are precursors to cloud condensation nuclei (CCN), are also strongly linked to upwelling of nutrient rich waters and phytoplankton activity. These BGC, aerosol, and CCN processes are not well understood or parameterized in models currently, nor are their interactions with cloud, atmospheric, and ocean feedbacks. Operational forecast models are already moving toward aerosol and BGC coupling, but lack observational guidance. TEPEX observations of these processes and their feedbacks will advance understanding and prediction capability.

Hypotheses: Ocean mixing plays a strong role in modulating the downwelling of oxygen as well as the upwelling of carbon- and sulfur-containing gasses that are precursors to CCN. This sustains oxygen minimum zones at depth, drives intense surface CO_2 outgassing, in addition to affecting cloud processes and surface solar radiation absorption in this region. In turn, ocean mixing and upwelling also regulate chlorophyll variations of the near-surface water, which determines the vertical profile of penetrative solar radiation, SST, fluxes, and ENSO variability.

Observational Needs:

Vertical transport of nutrients and carbon carried from the subtropics via the EUC to the Cold Tongue mixed layer is well-documented but factors controlling transport variability (whether by the source waters, along the pathways to the subsurface eastern Pacific, or the local vertical processes) remains uncertain. The buildout of BGC-Argo will help with the first two of these issues, and quantification of vertical ocean mixing described in part A above will help with the third. Shipboard measurements of the chemical species, including their vertical distribution in the water and surface fluxes, are necessary to build a predictive understanding of the specific connections between Cold Tongue vertical mixing, BGC transport, solar radiation absorption in the water, SST, and the lifetime of greenhouse gasses in the atmosphere.

The aerosol processes must be better constrained by observations before they can be parameterized in observation-based bulk flux algorithms or in coupled modeling systems. Understanding how air-sea exchange leads to natural sources of aerosols, aerosol precursor gasses, and CCN in these regions where the atmosphere is relatively free of CCN will be important for understanding feedbacks between ocean processes and climate-relevant cloud and radiative processes.

Summary

The current inability to accurately characterize, explain, or model the coupled Cold Tongue system in present or past day conditions inhibits confident predictions of the future dominant ENSO state, the Hadley Cell extent, monsoons, ITCZ location, and S2S climate variability including the MJO (Donohoe et al. 2013, Jiang and Zhu 2018, Seager et al. 2019, Warner and Moum 2019, Donohoe et al. 2019, Song and Zhang 2020, Liao et al. 2021, Kang et al. 2018, 2023). TEPEX-E observations and interpretations will illuminate the debates over whether anthropogenic climate change will drive the Pacific more toward La Niña or El Niño conditions in the future, and about how to reconcile past vs. current conditions. The uncertainty in these arguments hinges on the inability to constrain how the coupled Cold Tongue system regulates momentum, heat, and moisture across the Pacific and vertically, limiting confident predictions. Observations from TEPEX-E will push forward our models of the air-sea coupled Cold Tongue region to diagnose past and present Pacific climate variability more confidently, and to enable more accurate predictions of ENSO and its global impact on future weather and climate.

TEPEX-E will provide the observational and process-oriented basis to underpin and advance the next generation of ocean, atmosphere, and air-sea coupled models and observing networks in the Cold Tongue.

3.2 TEPEX-C: Eastward Expansion of the Warm Pool (EEWP)

Because deep atmospheric convection supported by surface heat fluxes is limited to regions where surface water temperatures are greater than about 1°C above the tropical mean SST (or roughly 28°C in the observed present-day climate; Izumo et al. 2019), the EEWP acts as a boundary for eastward propagating atmospheric convection along the equator (Fig 3). When the EEWP shifts zonally both on intraseasonal (e.g., the MJO) and interannual (e.g., ENSO) timescales, it leads to the zonal shifts of atmospheric deep convection. The zonal location of tropical deep convection is a key factor for its effect on global precipitation through mesoscale convective system (**MCS**) development and their influence on teleconnections (Galarneau et al. 2023). Better predictions of EEWP shifts on a range of time scales therefore could lead to improved prediction of precipitation across the world.

This tight linkage between the EEWP and the zonal limit of rainfall on the equator (Fig. 3) leads to a strong zonal freshwater (i.e., surface salinity) gradient slightly east of the EEWP and shallow freshwater stratification within the Warm Pool (Bosc et al. 2009). As a result, a western Pacific Fresh Pool is located within the Warm Pool, with potentially important consequences (Fig. 4). Particularly near the eastern edge of the Fresh Pool, the surface mixed layer depth tends to be defined by a shallow halocline that isolates the warm surface from the cooler thermocline waters (Bosc et al. 2009). This freshwater stratification acts as "barrier layer" (Lukas and Lindstrom 1991), which inhibits entrainment of cold water from below into the surface mixed layer, while stabilizing the upper ocean and thinning the surface mixed layer, and together enhancing surface warming and currents (Anderson et al. 1996). While rain puddles can form barrier layers (Thompson et al. 2019; Shackelford et al. 2022; 2023), the largest and most persistent barrier layers are formed when surface intensified eastward currents tilt the background zonal freshwater gradient into vertical salinity stratification (Cronin and McPhaden 2002). A major finding of the TOGA COARE experiment was that salinity played an active role in maintaining and warming the Warm Pool, thereby coupling the hydrological cycles in the ocean and atmosphere. Now, thirty-some years later, we ask how this coupled hydrological cycle, which is intimately tied to the eastern edge of the Fresh Pool and thus to the EEWP, may play a role in the physics governing the zonal migration of the EEWP.

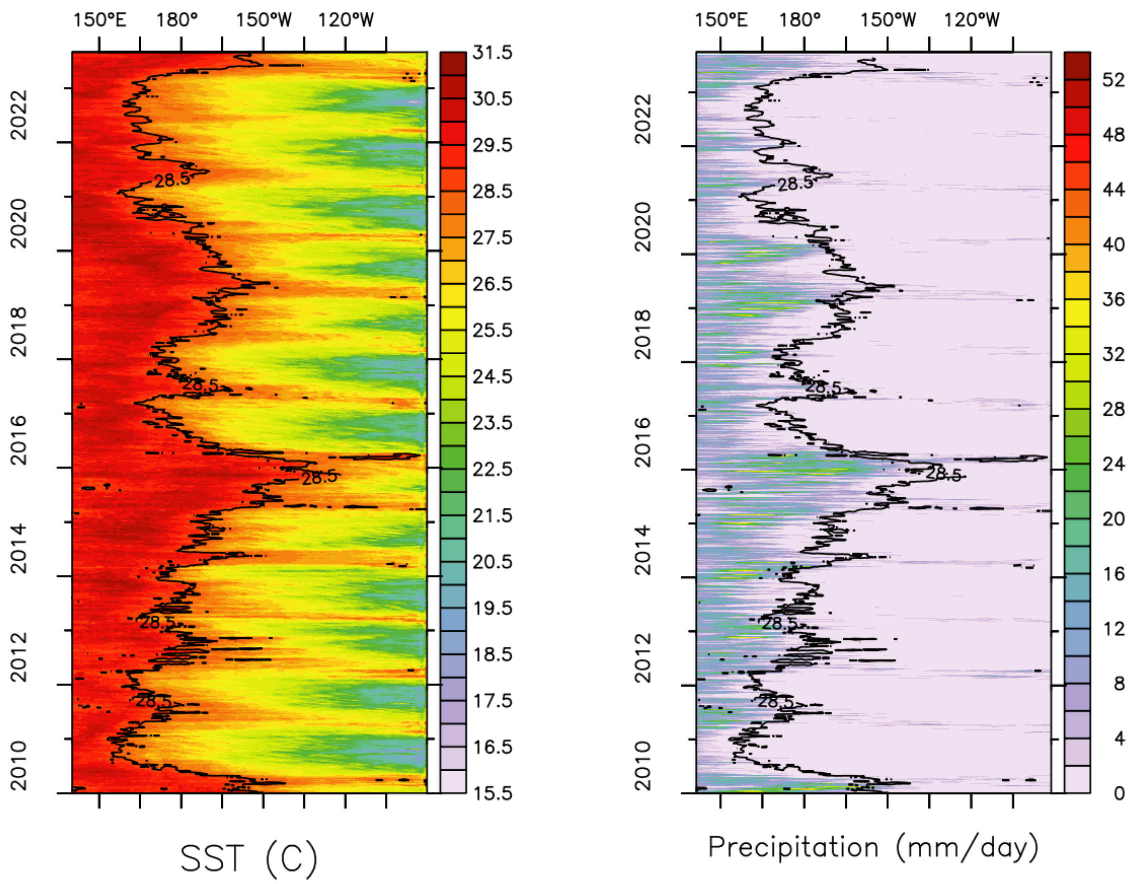

Fig. 3. Time - longitude diagram of the equatorial Pacific time series from 2010 to 2023 for (left) SST (˚C) and (right) Precipitation (mm/day). The SST 28.5˚C isotherm, marking the EEWP is overlaid on both. Longitude axis is shown at the top of each panel. Weekly 1°x1°-gridded SST are from the NOAA Optimum interpolation (OI) version 2.1 SST analysis (Huang et al. 2021). Monthly 2.5°x2.5°-gridded precipitation estimates are from the NOAA Climate Prediction Center (CPC) Climate Anomaly Monitoring System and OLR Precipitation Index merged precipitation (Janowiak and Xie 1999). Both the OISST and CAMS-OPI data sets were accessed via the Asia-Pacific Data-Research Center website (http://apdrc.soest.hawaii.edu/).

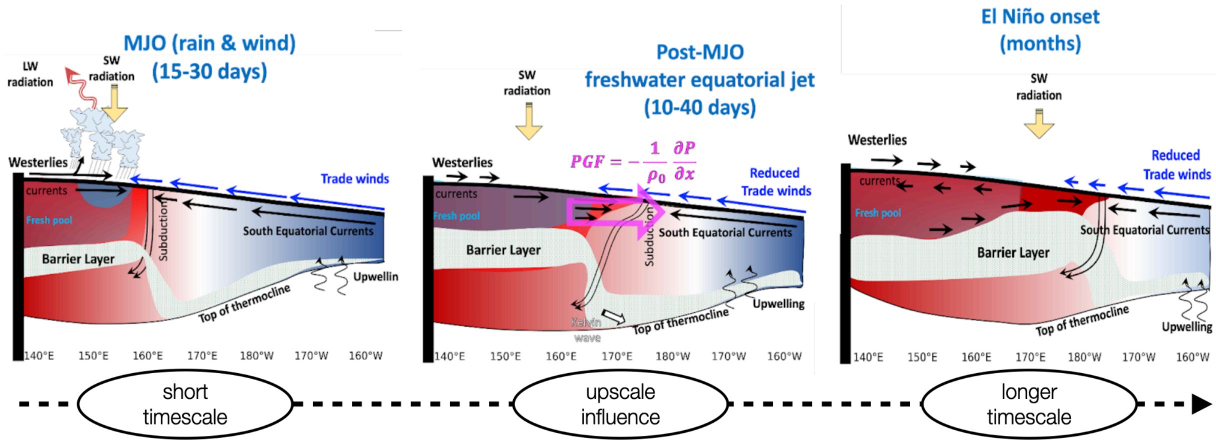

Figure 4 Schematic illustration of one of the hypothesized multiscale air-sea interactions of the Warm Pool along the equator. MJO precipitation and westerly winds induce eastward propagating oceanic Kelvin waves that deepen the thermocline and upper ocean barrier layer (left). During the post-MJO phase, surface warming of the shallow freshwater-stratified surface layer generates a large-scale zonal gradient in upper ocean pressure due to changes in the surface height and density, which induces a strong eastward current (middle) in addition to that forced by the surface wind. Consequently, the Warm Pool is expanded eastward, and the trade wind is relaxed during the onset of El Niño (right). This in turn allows more eastward propagation of MJO convection and more and stronger WWEs (a positive feedback). Adapted from Kerns and Chen (2021) and Jauregui and Chen (2024a, 2024b).

Observational evidence and model-based diagnoses of the upper ocean heat budget associated with EEWP zonal shifts have demonstrated the critical role of zonal heat advection and the processes that create both the zonal surface currents and shape the zonal gradients (Brown et al. 2015; Drushka et al. 2015; Lengaigne et al. 2002; Puy et al. 2019). On the equator, the lack of Coriolis turning allows zonal surface currents to be directly forced by zonal wind stress and pressure gradients. When the surface layer is thin, as it is when the shallow halocline and barrier layer exist, the wind energy can channel into an intense surface current. Eastward fresh jets can be driven not only by westerly wind events near the eastern edge of the Fresh Pool but also by the pressure gradient associated with the salinity gradient itself (Roemmich et al. 1994). These salinity-gradient driven fresh jets can exist even in the absence of a westerly wind stress (Jauregui and Chen 2024b). Not all zonal pressure gradients and resulting current anomalies, however, are associated with a surface salinity gradient. Wind stresses (both zonal and meridional) that give rise to mass convergence or divergence within the ocean will result in deformation of the subsurface pycnocline resulting in a set of transient equatorial waves that have remote impacts. Eastward propagating equatorial Kelvin waves generated in the Warm Pool region are particularly important for changing the thermocline depth in the central and eastern equatorial Pacific and impacting the equatorial Cold Tongue (Kessler et al. 1995). The processes associated with the zonal advection of the EEWP are thus quite complicated, with zonal current anomalies generated by wind forcing directly and indirectly, and by pressure gradients associated with surface and subsurface density gradients. *Understanding the processes that generate and maintain these surface jets, and the zonal gradients of upper ocean heat content (i.e., temperature) that they act upon, remains incomplete*. This is especially true for subseasonal timescales where EEWP zonal shifts can affect MJO global teleconnection patterns and MJO-ENSO interactions.

The system is further complicated by the fact that the ocean and hydrological cycles can be coupled in multiple ways. For example, the location of the EEWP impacts the fetch of the surface wind patterns leading to feedbacks on the oceanic equatorial wave response and zonal advection of the EEPW (Kessler and Kleeman 2000). Likewise, as shown in Fig. 4, the EEWP can lead to atmospheric convection patterns which result in fresh jets that advect the EEWP, affecting the overlying atmospheric convection patterns (Jauregui and Chen 2024b). To understand these feedbacks, it is important to understand the processes affecting the circulation and heating patterns in both the atmosphere and ocean. In the ocean, the processes that set up the zonal currents and their shears that affect ocean turbulent mixing (Skyllingstad et al. 2000) are sensitive to the mixed layer depth, which can be defined by the freshwater stratification, and surface density gradients (Cronin et al. 2000). The surface waves interact with the near-surface wind, current, and stratfication to influence the air-sea fluxes of momentum and heat, vertical shear and buoyancy, and thus the near-surface mixing. In the atmosphere, the strength and zonal extent of the wind forcing can depend critically upon the horizontal organization and vertical structure of the convection (e.g., Tung and Yanai 2002; Miyakawa et al. 2012).

Direct observation of the above processes is challenging. There are few observations of the upper ocean current profiles that extend into the surface layer and none that are co-located with salinity profiles that resolve both horizontal and vertical gradients at the required temporal scale. Argo profiling floats and some moorings can observe changes to vertical profiles of temperature, salinity, and momentum driven by these processes, but their coarse temporal (Argo) and spatial (Argo, moorings) sampling limits understanding of these feedbacks to relatively large spatial and long temporal scales. Remote observations from satellites have the advantage of higher spatiotemporal sampling but cannot provide information on the formation of barrier layers or the strength of ocean mixing below the surface. Direct observations of the MABL, air-sea flux, and surfae waves are even more challenging given the need for surface-based instruments for calibration and validation, while satellite retrievals of MABL properties are limited to coarse vertical and temporal resolutions. Hence, much of our understanding of the processes that regulate ocean-atmosphere coupling, especially at smaller and shorter spatiotemporal scales important for EEWP zonal shifts, is based on model output or model-aided reanalysis products and thus includes uncertainties arising from subgrid scale parameterized processes. *How these processes at the EEWP influence the initiation, organization, and spatial and temporal scales of atmospheric convection that drive global teleconnection patterns remains a key gap in our understanding of the global energy and water cycles.*

The gaps in our process understanding at the EEWP can be summarized with the following science questions:

- What are the structures and scales of variability of the ASTZ (e.g., temperature, humidity, wind, precipitation, aerosols, clouds, surface fluxes, salinity, currents) leading to changes in upper ocean stratification, surface warming, and eastward density current that matter the most to the EEWP zonal shifts?
- How does barrier layer thickness and stability modulate wind-driven surface jets and ocean Kelvin waves?
- How does the ASTZ change across strong SST and salinity gradients?
- How do changes in atmospheric convection and its organization in response to EEWP zonal shifts participate in maintaining or extending those shifts?
- What is the role of ocean biogeochemical processes in the air-sea coupling and Warm Pool variability?

In summary, our understanding of the processes that regulate zonal gradients of atmospheric convection, humidity as well as ocean temperature and salinity is incomplete owing to 1) uncertainties in the abilities of models to adequately simulate the above-mentioned processes and feedbacks, 2) a lack of well-resolved observations in space and time to ascertain the relative contributions of momentum fluxes and salinity effects in maintaining surface jets, and 3) a lack of observations to document the changes in surface freshening and heating, cloud system development, and convective momentum transports throughout the ASTZ following EEWP expansion. It is expected that through a TEPEX-C field campaign that resolves these processes, we will be able to improve not only our understanding of the physics governing the zonal motion of the EEWP and its cloud systems, but also the model physics.

3.3 Complementary but independent field campaign components

The TEPEX field campaign addresses the objectives of TEPEX-E and TEPEX-C. The two components of the campaign target processes that are neither well understood or observed in their complexity, nor well represented in models. TEPEX-E provides the opportunity to deepen our understanding of the spatio-temporal scales of diabatic upwelling and shear-driven mixing, their impacts on SST, and their interaction the MABL and cloudiness, which promises advances in parameterizations of ocean mixing, air-sea flux/coupling, marine boundary layer, and cloud-radiative feedbacks for weather and climate models in the next decade. Through exploration of the coupling between the troposphere (especially rainfall) and ocean mixed and barrier layers that support expansion and contraction of the Warm Pool, TEPEX-C provides new knowledge that guides the development of numerical models to better represent the effect of freshwater input on air-sea coupling. These two focus areas are the heartbeat of tropical Pacific variability, which impacts global weather and climate patterns. Both campaigns have intense short-term field measurement components (similarities and differences shown in Table 1) and both build off the TPOS mooring array.

4. OVERARCHING GOAL

The overarching goal of TEPEX is to enhance our understanding of the key processes behind intraseasonal to interannual variability of the tropical Pacific, especially those that govern the evolution of ENSO and thereby to provide robust guidance for improvement of ENSO simulation and prediction, and for the future evolution of the sustained observing system. 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 EEWP of the central Pacific.
2. Combine observational analysis and numerical modeling to dissect and better understand the detailed processes critical to air-sea interaction of the equatorial Pacific and ENSO dynamics.
3. Use the observational data to advance model representation of the key processes governing the climate state of the tropical Pacific.

5. FIELD OBSERVATIONS

The goal of TEPEX is to observe ocean-atmosphere coupled processes responsible for Cold Tongue and Warm Pool variations. TEPEX field observations will include two major phases. The first phase will focus on the EEWP in the central Pacific (TEPEX-C) starting spring 2026 or 2027, the season when WWBs and EEWP zonal shifts are most pronounced, and the second phase on mixing and upwelling of the eastern equatorial Pacific (TEPEX-E) in fall 2026 through fall 2027. These time periods are sufficiently long to sample intraseasonal variability for a given ENSO phase. Conducting both components of TEPEX during ENSO neutral or La Niña conditions maximizes the likelihood of observing the strong-tradewind/high-shear/active-TIW mixing regime typical of boreal fall for TEPEX-E, and observing intraseasonal zonal shifts of the EEWP for TEPEX-C. However, the measurements described in this document will be useful and informative regardless of the ENSO phase.

For TEPEX-C, ENSO phases can shift the longitude of the EEWP farther west or east than its climatological location. These shifts can be accommodated by repositioning ships and adapting flight plans and uncrewed systems to the actual EEWP location. Furthermore, intraseasonal zonal shifts of the EEWP occur regularly across all ENSO phases (Fig. 3) and indicate a high likelihood of sampling one or more intraseasonal Warm Pool expansion or contraction events.

For TEPEX-E, the year-long deployment of assets assures that the campaign will measure various seasonal conditions, even in the case that El Niño should be present during part of it. For example, even if one of the fall TEPEX-E cruises coincides with a shift toward El Niño conditions, which will probably inhibit the mixing regime and limit the TIW activity we seek to sample, the other fall cruise is unlikely to again sample El Niño conditions since most El Niño events last one year, ending before the next boreal Fall. If such variations of ENSO phase from one fall to the next occur, they can provide the opportunity to study near-equator ocean mixing with and without the influence of El Niño, which can be helpful for developing model test cases (Section 7).

The field requirements for each campaign are listed in Table 1.

Table 1. Field Observation Strategy

<table>
<tr><th>TEPEX-C: eastern edge of the Warm Pool
(across the 28.5˚C isotherm, typically 160˚E - 160˚W, 5˚S – 5˚N)</th><th>TEPEX-E: Cold Tongue upwelling and mixing
(140˚W, 2˚S – 5˚N)</th></tr>
<tr><td>Boreal Spring (March – May) 2026 through 2027</td><td>One year: boreal fall 2026-2027 (three ship cruises, six-month apart)</td></tr>
<tr><td colspan="2">Ship observations of the ASTZ (including ocean mixing, convective clouds, and precipitation, MABL profiles), as well as through the thermocline and free troposphere</td></tr>
<tr><td colspan="2">UxS (underwater, surface, and aerial drones) observations of the ASTZ</td></tr>
<tr><td>Aircraft observations of the ASTZ (dropsondes, AXBT)</td><td rowspan="2">N/A</td></tr>
<tr><td>Land-based observations of the MABL and atmospheric convection (Tarawa or Nauru)</td></tr>
<tr><td colspan="2">Enhancements to the TAO mooring array, e.g., for additional current profiles, mixing profiles, zonal resolution, direct covariance fluxes</td></tr>
<tr><td colspan="2">Argo floats, surface drifters, XBTs, TAO array with Recap moorings</td></tr>
<tr><td colspan="2">Satellite observations of SST, SSS, SSH, wind, rainfall, cloudiness, water vapor, etc.</td></tr>
<tr><td colspan="2">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.</td></tr>
</table>

One guiding principle of the TEPEX field campaign is to treat the upper ocean, air-sea interface, and the MABL as an integrated single identity, i.e., the ASTZ. The design and coordination of the TEPEX field observations require simultaneous and collocated measurements of the ASTZ using combinations of conventional (ships, aircraft, moored buoys, etc.) and new uncrewed systems (UxS) observing technologies. The second guiding principle is for observational and modeling teams to work together in all planning, field work, and research activities.

5.1 TEPEX-C

An optimal time for TEPEX-C is boreal spring. Active MJO events are closer to the equator in boreal spring (Zhang and Dong 2004; Kerns and Chen 2020) and can more effectively force the equatorial Kelvin waves and surface density current and hence the zonal motion of the Warm Pool (Jauregui and Chen 2024a). The ENSO spring prediction barrier remains an unsolved problem (Jin et al 2022) due to problems such as misrepresentation of state-dependent westerly wind events in climate models (Lopez and Kitman 2014). Observations from TEPEX-C in boreal spring may shed new light on this issue in the context of whether the freshwater-generated surface current may act to help break the barrier.

TEPEX-C science questions introduced in Section 3 are repeated below to identify observations needed to answer these questions. :

A. What are the structures and scales of variability of the ASTZ (e.g., temperature, humidity, wind, precipitation, aerosols, clouds, surface fluxes, salinity, currents) leading to changes in upper ocean stratification, surface warming, and eastward density current that matter the most to the EEWP zonal shifts?
B. How does barrier layer thickness and stability modulate wind-driven surface jets and ocean Kelvin waves?
C. How does the ASTZ change across strong SST and salinity gradients?
D. How do changes in atmospheric convection and its organization in response to EEWP zonal shifts participate in maintaining or extending those shifts?
E. What is the role of ocean biogeochemical processes in the air-sea coupling and Warm Pool variability?

Table 2 lists the envisioned variables needed to be observed to address these questions, observational requirements, and potential platforms and sensors that may provide the needed variables.

Table 2. TEPEX-C Field Observation Requirements (see Section 11 for complementary satellite measurements)

TEPEX-C Question	Variables needed to be observed	Observational requirement	Potential platforms/sensors	Notes
A, B	Time series of air-sea fluxes, ocean vertical profiles for T, S, U, V at fixed or roaming locations	Resolves subdiurnal variability, mixed layer properties and depth, and profiles down to below the EUC from weeks up to multiple years, Collocated and resolving upper ocean stratification	Moored buoys (recap TAO array), ships, UxS	UxS deployment can be multiple months
A, B	Subsurface turbulence	Eulerian time/depth vertical profiles of (TKE, turbulent dissipation rate of heat χ) through EUC	Ships	
A, D	Vertical profiles of tropospheric temperature, humidity, aerosols, and winds (u, v)	Need 3-4 fixed locations with 3- (preferred) or 6-hourly (acceptable) frequency	Land-and ship-based radiosondes and UAS	Can be used as forcing fields for modeling experiments
C	Vertical profiles across the ASTZ (ocean temperature, salinity, currents, air-sea fluxes, air temperature humidity, pressure, and winds)	Collocated measurement within a given distance along lines crossing strong gradients	Coordinated UUV, USV, and UAV; Airborne atmospheric and oceanic profilers	Coordinated UxS can be deployed from research vessels
C	Distributed measurements of surface pressure and near-surface temperature, humidity, winds, and radiation (down & up) across horizontal gradients of temperature, salinity and current	Characterize sea surface inhomogeneity contributions to atmospheric buoyancy fluxes and boundary layer convergence, and surface fluxes of heat, momentum, and moisture; upper-ocean currents and vertical velocity	USV, moorings, drifters, Argo floats, airborne remote sensing of surface properties	Drifters will diverge away from the equator. Most platforms cannot measure all parameters. Will rely upon mapping.
C	Ocean surface directional wave spectra	Coincident or overlapping with surface meteorology, and ocean surface current observations	USVs, surface drifters, aircraft-mounted laser or wide-swath radar altimeters, surface mooring	Can be used to refine bulk flux algorithms
D	2D and 3D Eulerian time series of clouds and precipitating convection	Precipitation radar: 10-minute sampling, with tilt angles fine enough to achieve preferably 0.25 km vertical resolution of convection in the lowest 5 km of the atmosphere.	Land- and ship-based precipitation radars, whole-sky cameras, vertically pointing Doppler lidars and microwave radiometers	

TEPEX-C Question	Variables needed to be observed	Observational requirement	Potential platforms/sensors	Notes
E	Ocean color, turbidity, chlorophyll, backscatter penetrative, shortwave; Surface gas/water isotope exchange.	Eulerian, time/surface and time/depth/height	Ship, autonomous vehicles, moored buoys	

5.2 TEPEX-E

The specific questions to be addressed by TEPEX-E field campaign observations that cannot be answered by the existing operational observing system or modeling tools are:

A. How does diabatic ocean mixing connect the thermocline and the ocean mixed layer in the Cold Tongue? What local and remote influences govern the strength and occurrence of this mixing? How does adiabatic upwelling driven by surface divergence contribute to vertical transport?
B. How are the resulting ocean property changes communicated to and through the ocean mixed layer from below? How do these modulate the surface fluxes? Also the reverse: How does the surface forcing affect the ocean sub-mixed-layer mixing? (e.g. by changing the shear and stratification).
C. How do the surface properties modified by ocean mixing influence the MABL? What are the differences between the two regimes of the eastern equatorial Pacific: the stable equatorial cold tongue vs the warmer off-equator region where convection connects the MABL with the overlying troposphere? What changes in MABL are coherent with the observed SST?
D. How does the troposphere respond to forcing from below, and how does this feed back to modify the surface fluxes? How do local ocean forcing and larger-scale atmospheric forces interact in the troposphere above the Cold Tongue?

The observational requirements to these four questions are listed below in Table 3.

The next-step practical questions are whether the observed processes can be:

- better parameterized or represented in operational models.
- detected or inferred from the sustained observing system.
  (What changes to the observing system would enable this detection?)

The ultimate broader impacts of TEPEX-E are:

- How does variability due to internal processes of the east Pacific Cold Tongue communicate upwards and away from the region?
- What downstream impacts can be better predicted based on improved characterization of the Cold Tongue?

Table 3. TEPEX-E Field Observation Requirements

	Variables needed to be observed	Observational requirement	Potential platforms	Notes
A, B	**Ocean Kinematics & Thermodynamics**: ocean currents and vertical, zonal, and meridional structure of shear, turbulence, T, S, stratification	Eulerian time/depth vertical profiles from near-surface past EUC; turbulence needed between mixed layer and thermocline	moored and autonomous, supplemented by ship	Preference to have fixed locations for long periods of time for budgets
B, C	**Surface Energy Budget:** fluxes of radiation and, heat/momentum/moisture, rain, solar penetration absorption, skin/subskin SST, surface 2D wave spectra / bulk properties, surface currents	Eulerian surface time series at fixed locations	moored and autonomous, supplemented by ship and UxS	Direct (eddy covariance) fluxes needed at some locations
C	**MABL:** Ta, qa, Pa, wind, stability, shear, turbulence	Eulerian time/height vertical profile	ship and UxS, possibly moored	moored needs development
D	**Free Troposphere:** Ta, qa, Pa, wind	Eulerian time/height vertical profile	ship and UxS	needed for research and to initialize models
C, D	**Cloud Properties**: cloud base/top height, LWC, LWP, microphysics, rain, radiation	Eulerian time/height vertical profile	ship and UxS, possibly moored	moored needs development
B, C	**BGC & Aerosols**: nutrients, CO_2, NO, NO2, O_2, O_3, Chl, pH, fluorescence, optical backscatter, turbidity, isotopes, aerosols	Eulerian time, surface, vertical profiles through MABL and into clouds, ocean surface layer vertical profiles	ship-based, moored, UxS	UxS and mooring capability still in development, but BGC Argo is further along

6. DATA ANALYSES

TEPEX observations will be open to public use after 6 months of post-field data quality control period. The broad research community is encouraged to collaborate with TEPEX PIs who are responsible for taking the observations in data analyses. It would be productive to combine the TEPEX observations with other past and existing data to reach a more comprehensive understanding of the equatorial Pacific coupled system beyond what the TEPEX data alone can achieve. It is highly recommended to focus on the entire ASTZ in data analysis instead of treating the atmosphere, ocean and their interface individually as often practiced in the past. It would be beneficial to conduct data analyses with the modeling efforts (see section 7) in mind to yield products that can be used as initial and/or boundary conditions, validations, and guidance to improvement of numerical models. Innovative data analysis procedures that can be applied to model diagnosis would be highly welcome. Combined efforts of data analyses and modeling are encouraged.

7. MODELING

7.1 The Role of Models

Current-generation Earth system models are designed and built by the community to help improve our understanding and prediction of the Earth system. They include numerical models for the atmosphere, ocean, land, and sea-ice, which are coupled to exchange forcing fields across their interfaces. Operational Numerical Weather Prediction (NWP) centers around the world strive to extend their forecast skill beyond the weather time scale of a week, requiring them to not only use an atmospheric model for forecasting as traditionally done, but to also include other domains of the Earth system in the forecasting system. Longer-term subseasonal-to-seasonal (S2S) and seasonal to decadal (S2D) predictions typically require global coupled ocean-atmosphere models, in order to capture the oceanic memory and large-scale air-sea interactions that provide most of the predictability at seasonal and longer time scales. For these longer-term predictions, the accuracy of the coupled model's *climate* simulation becomes increasingly important, in order to limit the emergence of model biases that could otherwise limit the effectiveness of data assimilation and distort the predictable climate signals.

7.2 Opportunities For Model Improvement

The dynamics, physics, and biogeochemical interactions within the coupled marine boundary layer are complex, with many nonlinear processes impacting the individual boundary layers and the exchanges of momentum, heat, mass, and tracers across their interface. The potential value of TEPEX for providing a unique coupled boundary layer dataset in the Tropical Pacific Ocean is immense, to help advance understanding of the complex air-sea interactions and climate variability in the equatorial Pacific. This improved fundamental understanding will then be used to evaluate and refine the parameterized processes in coupled models, which will help to advance the simulations, assimilations, and forecast/projection systems used for subseasonal-to-decadal climate predictions.

In atmosphere models, the parameterizations of cloud entrainment and detrainment, microphysical processes, and radiative transfer influence individual cloud lifecycles as well as the horizontal and vertical organization of ensemble cloud systems. Large-scale cloud organization and cloud-aerosol interactions, in turn, affect tropospheric heating and moistening, cloud-radiative feedbacks, convective momentum transports, the processing and transport of aerosols, and the distributions of rainfall location, frequency, and intensity — all of which shape the heat, freshwater, and momentum fluxes at the ocean surface, which contribute to EEWP zonal shifts and Cold Tongue mixing. Because most of these parameterized processes cannot be directly measured, they must be estimated through their effects on the MABL and lower free tropospheric thermodynamic variables. Their parameterization typically relies upon statistical analysis of well-constrained LES simulations and testing in a hierarchy of model experiments, as described below.

In ocean models, the representation of vertical mixing affects a multitude of processes, including deep cycle turbulence and diabatic upwelling (Cherian et al 2021; Deppenmeier et al. 2021, 2022), barrier layer formation (Wei et al., 2022; Liu et al., 2022), and nutrient exchanges between the surface and subsurface (Gnanadesikan et al., 2001; Eddebbar et al., 2024). Vertical mixing must be parameterized in any operational model due to its small spatial and short temporal scales. Current ocean mixing parameterizations, which stem from the 1980s and 1990s and the limited data available at that time (Pacanowski and Philander, 1981, Gaspar et al, 1990, Blanke and Delecluse, 1993, Large et al, 1994), exhibit substantial biases compared to mixing observations at the only location with longstanding mixing measurements at 0°N, 140°W (Deppenmeier et al, 2022). Hence, they are ripe for revisiting.

Improving model representations of upwelling and mixing in the equatorial Pacific Cold Tongue (e.g. the TEPEX-E region) is crucial for simulating the vertical processes that determine the SST, carbon fluxes, and biological productivity in this region, and that play a central role in the ocean/atmosphere feedbacks that are essential for improving ENSO predictions. Progress has been made in understanding the spatio-temporal variability of off-equatorial mixing, and mixing's contribution to diabatic upwelling, based on modeling studies funded by the pre-field campaign. These studies have shown substantial variability of mixing that reaches the thermocline and contributes to diabatic upwelling (Cherian et al, 2021, Deppenmeier et al 2021, 2022). Recent advances have pointed to the roles of wind stress, TIWs, and the diurnal cycle in driving cold tongue mixing (Holmes and Thomas 2015; Masich et al. 2021; Whitt et al 2022; Smyth et al 2013, 2021; Moum et al 2022), but more observational evidence is needed off the equator, as the equatorial undercurrent (which tapers sharply poleward) largely determines the background shear that helps to enable mixing.

Farther west, improving simulations of zonal excursions of the Warm Pool (e.g. in the TEPEX-C region) is crucial for representing the air-sea interactions that govern the onset, development, and intensity of MJO and ENSO events and their global teleconnections. The coupled GCMs used for climate predictions may not properly simulate the enhanced salinity-stratified barrier layers that often develop during MJO active phases and during the onset of El Niño events, when increased rainfall and

WWE-induced eastward tilting and intensification of the background salinity profile can shoal the mixed layer at the warm pool's eastern edge. A forecast model that underestimates this effect could see a reduced sensitivity of the near-surface currents and thermal advection to changes in the trade winds, contributing to under-forecasts of subsequent MJO events and/or the developing El Niño (see reviews by Cravatte et al. 2016 and Kessler et al. 2019, 2021). Detailed observations are needed to support systematic assessments of the simulated ASTZ and its variability at the EEWP, including the physical parameterizations and lateral/vertical resolutions needed to realistically simulate the surface fluxes, ocean mixing, rainfall, cloud-radiative feedbacks, solar penetration, convective momentum transport, and winds in this critical region.

7.3 Specific TEPEX Observations Needed to Better Constrain Simulations

The TEPEX campaign aims to better constrain key aspects of models that are thought to be limiting simulations, forecasts, and projections of weather and climate at weekly-to-decadal scales. These include accurate representation of the spatiotemporal scales, distributions, and cross-correlations of variations in ASTZ variables, which is crucial not only for evaluating simulations, but also for developing observational sampling and physical parameterization schemes, and providing informative priors for data assimilation and forecast initialization. Specific examples include (1) the intensities, scales, durations of rain events, wind gusts, surface heat fluxes, transient subsurface shears, and downward mixing of ocean heat driven by the diurnal cycle, atmospheric convection, the MJO, TIWs, and tides; (2) the space/time scales of salinity-stratified barrier layers and WWE-induced currents and shears; (3) the meridional width and meaders of the EUC; (4) the scales and drivers of thin alternating vertical layers of relatively high/low shears and stratification above the thermocline; and (5) the balance of terms in the subsurface thermal, haline, momentum, moisture, and tracer budgets, particularly at scales finer than the grid scale of the forecast models.

Better understanding these factors will help to further establish the **resolutions** (horizontal, vertical, time, and process comprehensiveness) required for models to adequately capture the essential physical and biogeochemical features and nonlinearities of the equatorial Pacific climate system, and its sensitivities to initial conditions and external forcings. In particular, TEPEX will help to establish the grid spacings, time steps, and coupling intervals that are needed to explicitly represent the atmospheric and oceanic boundary layers, TIW shears, fresh pools, barrier layer intensities, thermocline structure, surface fluxes, and mixing distributions.

Once vetted against TEPEX observations, these high-resolution models can then serve as touchstones for the global models used for forecasts and projections, which require more extensive use of parameterizations due to their coarser resolutions and time steps. Key model parameterizations that can be targeted by TEPEX include the representation of (1) upper-ocean vertical mixing driven by SEC/EUC and transient shears, Langmuir turbulence, and the diurnal cycle, given the coarse-grained simulated shears and stratification; (2) solar penetration into the water column, including its interaction with biological turbidity; (3) atmospheric deep convection, including convective aggregation, lateral entrainment of environmental air into convective plumes, and convective momentum transport (vertical transport of horizontal momentum), as a function of the coarse-grained atmospheric fields; (4) atmospheric shallow convection, and its interaction with the surface fluxes of heat and moisture; (5) cloud physics and cloud-radiation interactions across deep and shallow convective regimes, and their relation to the diurnal cycle; and (6) the surface fluxes of heat, momentum, freshwater, aerosols (e.g. sea salt), and BGC tracers, as mediated by unresolved surface waves, Langmuir circulations, tides, wind gusts, and aspects of the diurnal cycle, as a function of the coarse-grained simulated fields.

7.4 A Hierarchical Modeling Approach to Both Inform and Leverage TEPEX

The path to model improvement involves several steps (Fig. 5) — in which constrained, high-resolution, limited-area simulations serve as intermediaries between detailed process observations and the coarse-resolution global coupled GCMs (CGCMs) used for climate predictions. If provided with sufficient initial and boundary conditions, the extremely high-resolution, limited-area large eddy simulations (LES), cloud-resolving models (CRM), and single-column models (SCM) can be used to target, with high fidelity, the same regimes sampled in the observations. These two complementary insights into *detailed* processes will be critical for evaluating the process *parameterizations* used in coarser models, and will allow the insights from the process studies to influence the full model hierarchy — all the way to the models used for predictions.

The LES/CRM/SCM simulations can be used to evaluate high-resolution regional ocean/atmosphere simulations of the broader equatorial Pacific region, which can in turn be used to benchmark coarser-resolution global atmospheric & oceanic GCMs (AGCMs & OGCMs) that are driven by near-surface observations. Finally, the single-component AGCM/OGCM simulations can be used to benchmark global CGCMs, that are either nudged toward observations or freely-evolving. A schematic of the information flow in this model development approach is:

Detailed process observations + LES/CRM/SCM simulations

→ high-resolution regional OGCMs and AGCMs

→ coarser-resolution OGCMs and AGCMs

→ CGCMs

→ forecast systems and future projections

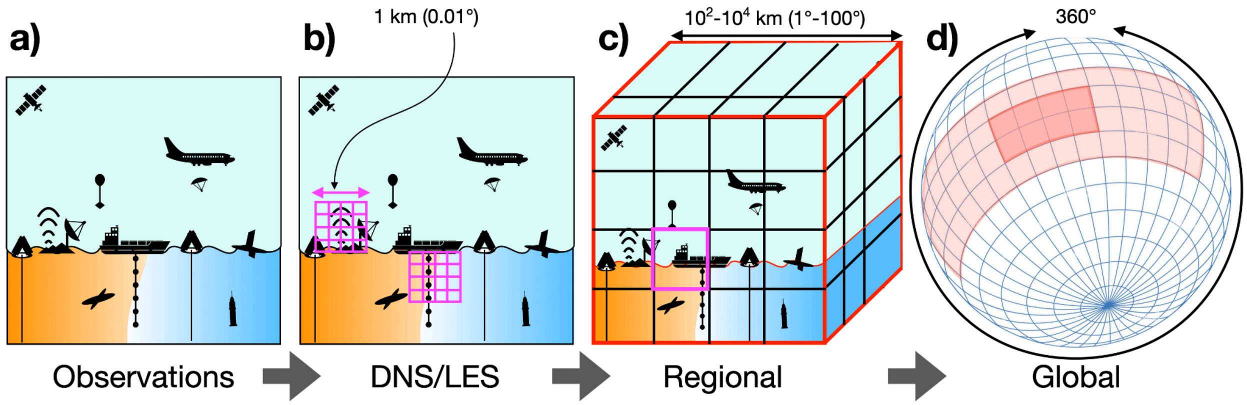

Figure 5. Schematic illustration of how TEPEX observations will be used for model development. a) Observations measure targeted phenomena throughout the ocean and atmosphere and at the air-sea interface. b) DNS/LES models (magenta grid boxes) simulate targeted phenomena to generate their statistical properties to improve their parameterization. c) Parameterizations developed or refined through DNS/LES modeling are incorporated into and tested in regional and single-column simulations of observational test cases whose large-scale forcing (red 3D domain limits) is defined through assimilation of all available observations, including those from TEPEX. d) Parameterizations developed in a–c are evaluated in global models for their ability to improve the mean state and major modes of climate variability. Magenta box in c) schematically compares LES domain to regional model domain; lighter and darker red polygons in d) schematically compare larger and smaller regional model domains to global model domain.

7.5 Developing Well-Constrained Test Cases for Models

A major goal of TEPEX is to help coordinate observations and reanalyses to develop robust test cases for a hierarchy of models including LES, CRM and SCM, providing:

- **Clear observational targets** for the LES/CRM/SCM simulations, within the near-equatorial study volume and observing period. These would include observations and reanalysis estimates of the evolving 3-dimensional state within the volume for *mass* (water liquid/vapor/ice, air, salt, biogeochemical tracers), *energy* (heat and temperature, gravitational potential energy, TKE, surface wave spectrum, upper-ocean vertical profiles of penetrative shortwave radiation), and *momentum* (vector winds and currents). Relevant statistics for these state variables would include (a) the spatial and temporal *scales, features, and* *distributions* of variability, and (b) the *cross-correlations and cross-spectra* among variables, locations, and times.

- **Comprehensive tests** for these simulations over diverse regimes, including extreme and compound events. To thoroughly exercise the models, TEPEX will endeavor to sample a wide and representative range of conditions along the equator, including: day/night; cloudy/sunny; rainy/clear; strong/weak barrier layer; strong westerly/easterly winds and weak winds; cold/warm TIW phases and TIW fronts; stronger/weaker ocean mixing; active/inactive convective phases (seasonal cycle, MJO, ENSO); strong/weak SST gradients; and shallow/deep mixed layer, thermocline, and EUC regimes (e.g. El Niño / La Niña).
- **Comprehensive initial and boundary conditions** for the simulations. These would include observations and reanalysis estimates of the *initial* 3-dimensional state of the study volume, as well as the *values and fluxes* of mass, energy, and momentum at the volume boundaries.

The detailed TEPEX observations can be used to refine and validate the LES/CRM/SCM benchmarks, which can then be used to evaluate broader-scale models. For each model resolution, this assessment could proceed via an assimilation and forecast framework, as follows:

1) **Data assimilation** of the available observations (TEPEX and ancillary) over the study volume and period, using an oceanic, atmospheric, or coupled model. This would provide both a *reference solution* for evaluating subsequent simulations, and *reanalysis increments* in the mass/energy/momentum budgets that can be used to pinpoint model process errors as discussed above. The assimilation technique itself could range from simple (e.g. nudging toward a target SST) to sophisticated (e.g. a 4d variational method or a multivariate ensemble Kalman filter, assimilating sparse and heterogeneous observations in both space and time).
2) **Ocean-only ensemble reforecasts** of the study volume and period, with prescribed atmospheric forcings. These reforecasts could be initialized through data assimilation (1), and then proceed without subsurface constraints over the next few months (apart from lateral boundary conditions provided from an oceanic reanalysis), with surface boundary conditions (surface air temperature and humidity, radiative fluxes, wind stress and speed, and precipitation) imposed from an atmospheric reanalysis. The ocean solutions would then be compared to the observations, high-resolution benchmark simulations, and reanalyses in the TEPEX region. Oceanic variables of interest would include the SST, SSS, SSH

(obtainable from existing satellite altimetry), surface currents, wave spectra, and ocean color; the vertical profiles of subsurface temperature, salinity, currents, penetrative shortwave, turbidity, and turbulent dissipation; and the column and layer budgets for temperature, salt, momentum, and TKE. Key diagnostics would include the scales, distributions, and cross-relationships among these variables across space and time.

3) **Atmosphere-only ensemble reforecasts** of the study volume and period, with prescribed SST. These reforecasts could be initialized through data assimilation (1), and then proceed without atmospheric constraints over the next few months (apart from lateral boundary conditions provided from an atmospheric reanalysis). The atmospheric solutions would then be compared to the observations, high-resolution benchmark simulations, and reanalyses in the TEPEX region. Atmospheric variables of interest would include the surface wind stress and heat flux components; the near-surface air temperature, winds, and humidity; profiles through the MABL and troposphere of temperature, humidity, winds, precipitation, cloud liquid/ice, and radiative fluxes; and column budgets of moist static energy (MSE) and convective available potential energy (CAPE). Key diagnostics would include those in (2).

4) **Coupled ocean/atmosphere ensemble reforecasts** of the study volume and period. These would be initialized as in (2) and (3), and then proceed without atmospheric, oceanic, or subsurface constraints over the next few months, with lateral boundary conditions provided from atmosphere/ocean reanalyses. The forecast skill and the *statistics* of variability in the reforecasts would then be compared to the observations, high-resolution benchmark simulations, reanalyses, ocean-only reforecasts (2), and atmosphere-only reforecasts (3) in the TEPEX region. All of the variables and diagnostics in (2) and (3) would again be of interest.

8. DATA ASSIMILATION AND FORECASTS

The proposed field campaign will also help create a unique collocated ocean-atmosphere coupled boundary layer profile dataset that will facilitate scientific discovery that has the potential to result in major improvements in both the modeling and prediction of this region. These observations will enable verification of coupled forecasts and improvement of coupled data assimilation capabilities in the forecasting systems. Current operational ocean-atmosphere forecasting systems have mostly independent data assimilation schemes with the modeling components initialized separately. Yet, operational centers are developing ‘seamless prediction’ systems to predict from weather to climate timescales, and the challenge to initialize the coupled system accurately and consistently becomes particularly relevant. Coupled state estimates are not only useful for initializing forecasts, but also for providing physically consistent reanalysis products that can include conservation of mass and energy.

The field campaign will generate a dataset of the coupled ocean-atmosphere boundary layer in the Tropical Pacific to study the evolution of the coupled boundary layer (BL), characterize the statistics of the BL evolution, and produce value-added datasets of the coupled BL that can be used for model verification and coupled data assimilation. This will be accomplished through:

- coupled DA advancement and experiments;
- forecast products and services that TEPEX aligns with and can improve;
- forecast support for the field campaign - to guide placement of assets and evaluation of conditions.

9. DATA MANAGEMENT

9.1 Data Policy

TEPEX adopts a timely release and free/open sharing data policy. The TEPEX data policy should be in compliance with the WMO Resolution 40 on the policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities: *"As a fundamental principle of the World Meteorological Organization (WMO), and in consonance with the expanding requirements for its scientific and technical expertise, the WMO commits itself to broadening and enhancing the free and unrestricted international exchange of meteorological and related data and products."* Additional TEPEX data policy requires:

- TEPEX Data (field observations, operational observations, satellite data, reanalyses, and model output) Archive Centers (TDACs) will be established and maintained at designated institutes.
- Within 12 months following the end of the field campaign, all data shall be promptly provided by TEPEX investigators responsible for data acquisition to other TEPEX investigators upon request with notification of the intent of data use.
- Data must be formatted and provided in universally readable and accessible netCDF files except for the case of imagery or those that cannot otherwise be converted to netCDF.
- All TEPEX investigators participating in the field campaign are required to submit their field data to one of the TDACs no later than 12 months following the end of the field campaign.

- During the first 12 months following the end of the field campaign, all TEPEX data will be accessible only to TEPEX investigators to facilitate inter-comparison, inter-calibrations, and quality control checks, as well as an integrated interpretation of the combined data set. No public release of the data (sharing with non-TEPEX colleagues, conference presentations, publications, commercial and media use, etc.) is allowed without the permission of TEPEX PIs who are responsible for making the observations.
- Quality control procedures should be carried out by TEPEX investigators within 12 months following the end of the field campaign, unless unforeseeable issues emerge. After that, TEPEX field data will be made publicly available to the broader scientific community. Any remaining data quality issues and information about data whose release will be delayed beyond 12 months following the end of the field campaign should be made clear in the data documentation files. Improving TEPEX data quality will be a continuous effort. The suitability of the released data for scientific investigations and publications should be decided at the discretion of the TEPEX investigators responsible for field data collection and quality control and data users.
- The authorship decision for publications resulting from using TEPEX data should follow the ethical rules of the journals and professional organizations (e.g., AGU, AMS). TEPEX investigators responsible for field data collection are encouraged to make contributions to data analysis and writing of manuscripts, in addition to providing the data, to be co-authors of publications using TEPEX data.
- The following acknowledgements are suggested to be included in all publications using TEPEX data: The xxxx data were collected as part of TEPEX by investigator(s) YYYY (if YYYY is not a co-author) under the support by wwww. The data are archived at AAAA which is maintained by ZZZZ.

9.2 Data Archive

As noted in the TEPEX data policy, TDACs will be established and maintain all data. Initially, a designated institute can potentially be responsible for this mission and provide TEPEX websites, where all data can be retrieved. Note that data can be opened to the public through the PIs' own sites. However, the inventory for all data sets and links to such individual sites are provided at the TEPEX websites. Namely, it is possible for users to find and access all data via the TEPEX websites. Eventually, TEPEX data will be archived at NCEI and other data repositories.

It is desirable that all archived data have the standard formats and metadata templates to assist efforts of data assimilation, model forcing, evaluation and improvement, and data intercomparisons. It is also desirable to have user-friendly interfaces that allow

easy selection of data based on the need in terms of variables, sensors, platforms, time and location. An example of such interface is
https://orca.atmos.washington.edu/dynamo_legacy/

10. READINESS AND SYNERGY

TEPEX is ready to take place because:

- TPOS 2020 provided solid scientific justifications for the need of field observations that will be taken by TEPEX.
- New observing technologies have developed to make field observations of some key variables feasible at an acceptable cost that were not available previously.
- Deficiencies in numerical models in representing the key processes to be targeted by TEPEX observations have been well documented.

There are excellent synergies between TEPEX and other existing projects and programs:

- JAMSTEC is planning for a field project in early 2025 in which R/V Mirai will take observations of air-sea interaction at the equator and the eastern edge of the Warm Pool. In addition to conventional shipborne measurements, UAVs will be deployed. A moored buoy will be deployed. An arrangement is being discussed to have this moored buoy to be recovered by NOAA cruise in later 2025 or early 2026. This project will provide similar observations as TEPEX-C is planning to make, but in an earlier year, thus extending the duration of the experiment.
- Global Precipitation Experiment (GPEX) is a World Climate Research Programme (WCRP) initiative centralized around the WCRP Years of Precipitation (YoP). GPEX is motivated by the recognition that, despite some progress over the past few decades, the required improvement of precipitation predictions has been hampered by major gaps in observing, understanding, and modeling precipitation. GPEX provides an opportunity to foster progress in filling gaps in observing and understanding phenomena and processes critical to precipitation and to accelerate progress in improving precipitation prediction and its applications for resilient and sustainable development by leveraging existing WCRP programs and community capabilities in satellite and ground observations, modeling and research, and conducting new and focused activities. The GPEX/YoP will include coordinated global field campaigns to cover all types of precipitation. The ocean-atmosphere coupled processes at the EEWP that are the focus of TEPEX-C are especially relevant to GPEX as they are associated with four types of precipitating systems identified as needing further study: MCSs, tropical cyclones, atmospheric rivers, and global monsoons. The EEWP is

a region of tropical MCS formation that can lead to tropical cyclone development, while the enormous latent heat release through precipitation formation initiates teleconnections that affect monsoon onset and break periods and atmospheric river events.

- The NOAA Precipitation Prediction Grand Challenge (PPGC) Initiative aims at providing more accurate, reliable, and timely precipitation forecasts across timescales from weather to subseasonal-to-seasonal (S2S) to seasonal-to-decadal (S2D) through the development and application of a fully coupled Earth system prediction model.
- TEPEX emerged from the TPOS 2020 redesign as needed to inform the next design phase of the TPOS arrays. Elements that will be piloted here include shallow point current meters for relative wind and mixed layer velocity, extra moorings at 1˚S and 1˚N (proposed here along 140W).

11. RELATIONSHIPS WITH PRIOR FIELD CAMPAIGNS AND EXISTING OBSERVATIONAL DATASETS

11.1 Past Field Campaigns

GATE (Global Atmospheric Research Program Atlantic Experiment) - It took place in 1972 over the eastern tropical Atlantic Ocean. Its main objective was to understand atmospheric convection and its interaction with the circulation at various scales. GATE was originally proposed to be over the equatorial central Pacific but was moved to the Atlantic for a political reason (Zhang et al. 2022). The proposed location for TEPEX-C is where GATE was first envisioned but has never been observed by any air-sea coupled field campaign. The equatorial cold tongues are common features for GATE and TEPEX-E, even though their objectives and observing strategies are very different. The main difference is that ocean mixing was not a main target of GATE, but it is for TEPEX.

TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment) - It took place during November 1992 - February 1993 over the Warm Pool (Webster and Lukas 1992, Anderson et al. 1996, Cronin et al. 1997). Its main goal was to describe and understand the key processes (e.g., atmospheric organized convection, buoyancy and wind-stress forcing of the ocean and their oceanic responses, multi-scale interaction) that are responsible for air-sea coupling and their role in the maintenance of the Warm Pool. The main outcomes from TOGA COARE (e.g., enhanced understanding of air-sea fluxes, the upper-ocean stratification related to atmospheric forcing, and the role of the MJO in air-sea interaction) laid the foundation for TEPEX-C to address the issue of zonal movement of the Warm Pool, which TOGA COARE did not cover.

TIWE (Tropical Instability Wave Experiment) - This Nov-Dec 1991 ship-based campaign focused on ocean mixing, air-sea interaction, and clouds in the presence of TIWs with ships at 140°W, 0°N (Moum et al. 1995, Chertock et al. 1993, Inoue et al. 2012). Mixing measurements had been taken here in several prior campaigns in the 1980s (Lien et al. 1995), and it took all these cruises from the 1980s to the 1990s combined to get a better idea of the seasonal variability of the processes and the potential role of TIWs in modifying and organizing shear, stratification, turbulence, air-sea exchange, SST, cloudiness, cloud-radiative feedbacks, and lower tropospheric moisture and temperature. The seasonal and interannual (ENSO-related) variability in these physics proved larger than expected, and more coupled between ocean and atmosphere than previously understood, which motivates a longer duration and more comprehensive air-sea campaign during TEPEX.

EPIC (Eastern Pacific Investigation of Climate) - It took place in September - October 2001 over the eastern tropical Pacific, mainly along 95˚W, between 0 - 12˚N (Raymond et al., 2004). Its main objective was to observe and document physical processes that are key to improving model simulations of climate in the tropical east Pacific, including atmosphere deep convection, the vertical structure of the atmospheric boundary layer, ocean mixed layer dynamics, and upper-ocean processes that affect the structure and evolution of the shallow thermocline. TEPEX-E will complement the outcomes from EPIC by focusing on air-sea interactions and ocean mixing in a region with a deeper thermocline and stronger current shear.

DYNAMO (Dynamics of the MJO) - It took place during October 2011 - March 2012 over the tropical central Indian Ocean (Yoneyama et al. 2013). Its main goal was to understand the mechanisms for MJO initiation. The DYNAMO observing technologies and strategies (e.g., observations from ships, aircraft and land stations) have advanced our understanding of key processes (e.g., wind and freshwater forcing to the ocean, structure and mixing processes of the upper ocean responses and feedback) in air-sea interactions related to the MJO. They will be applied to TEPEX-C to observe the role of similar processes in the very different environment of the EEWP. The DYNAMO Legacy Data user interface is an example of how the TEPEX data user interface can be built.

SPURS-2 (Salinity Processes Upper Ocean Regional Study 2) - This air-sea interaction and full-depth ocean and atmosphere experiment occurred at and around 10N, 125W in 2016-2017, the heart of the summertime East Pacific fresh pool created by the northward extent of the ITCZ. A full-depth research quality mooring was at this central location, two additional Prawler moorings were located +/- 1˚N/S, and surface drifters, Wave Gliders, Seagliders, and an instrumented sailboat covered the area and +/- 20˚ longitude and +/- 5˚ latitude throughout a 15-month total period. Ship cruises went to and from San Diego and Hawaii in August 2016 and October 2017 to set the fixed and autonomous observing array, which documented some of the meridional gradients in the ASTZ of the summertime east Pacific ITCZ. Focus was applied to the coupled hydrologic cycle, ocean stability and turbulence in the presence of rainfall, and ASTZ observing in the E. Pacific ITCZ. See special issue (TOS, June 2019, and introduction article Lindstrom et al. 2019).

PISTON (Propagation of Intra-Seasonal Tropical Oscillations) and *CAMP^{2}EX* (Cloud, Aerosol and Monsoon Processes Philippines Experiment) - This experiment was originally planned for the territorial waters of the Philippines but ended up taking place between Taiwan and Palau in the far western tropical Pacific during 2018 and 2019 summertime ship cruises (Sobel et al. 2019), plus 2 full depth subsurface moorings and an array of profiling floats in the time between (Johnston et al. 2020, 2021). Progress was made in understanding small scale ASTZ coupled physics and the evolution of typhoons and the MJO/BSISO (Boreal Summer Intraseasonal Summer Oscillation) just downstream of the Maritime Continent. Coordination occurred between the 2019 ship cruise for PISTON and the aircraft campaign of CAMP^{2}EX (Reid et al. 2023). The aircraft of the latter was based out of the Philippines, and visited the ship from PISTON several times, providing for some joint platform ASTZ sampling. Whereas PISTON's focus was on air-sea coupled physics and its role in intraseasonal weather and climate patterns, CAMP^{2}EX had a stronger focus on atmospheric chemistry and atmospheric convection including cold pools.

YMC (Years of the Maritime Continent) - This multi-year international program under which teams from different countries design and conduct their own field observations in the region of the Indo-Pacific Maritime Continent (MC). It started in 2017, and its last field cruise is still pending. Its overarching goal is to expedite the progress toward improving understanding and prediction of the local oceanic and atmospheric multiscale variability of the MC and its global impacts (Yoneyama and Zhang 2020). Some of the participants of YMC are also potential participants of TEPEX.

EquatorMix - took place on and around the Equator at 140°W between October 6 and November 3, 2012, while a tropical instability wave front was passing through. It aimed to determine the role of night-time buoyancy-driven convection and shear instabilities in forcing high-frequency internal waves. It observed the upper ocean and atmosphere boundary layers with Fast-CTD profiles, Hydrographic Doppler Sonar System (HDSS) current profilers, High-Resolution Phased Array Doppler Sonar (HiPADS), and extended meteorological sensors including from a Leosphere WindCube and unmanned aerial vehicles (UAVs). EquatorMix produced meter- and minute-scale depth and time sampling of buoyancy frequency and shear between 30 m and 250 m, observing many interleaved layers with strongly varying Richardson number (Pinkel et al., 2023). EquatorMix helps demonstrate what components of the TEPEX study could look like, and the usefulness of observations like EquatorMix for testing TEPEX hypotheses.

ARM Tropical Pacific Sites - The Department of Energy ARM (Atmospheric Radiation Measurement) research facilities were deployed on two tropical Pacific sites: Nauru (January 1998 - September 2013) and Manus (October 1996 - September 2013). Their long-term observations of more than a decade provide data needed to evaluate tropical cloud systems in models, measurements of tropical clouds, the environment in which they reside, and their impact on the radiation and water budgets (Long et al. 2013). In addition, there were Nauru99 intensive field observations with two research vessels deployed next to Nauru during June and July 1999 (Post and Fairall 2000; Yoneyama 2000). The main objective of Nauru99 was to compare radiation measurements from land and ships. The knowledge and experience gained from the deployment at the Nauru site are invaluable to TEPEX-C island measurement on Tarawa or Nauru. The advanced observing technologies (e.g., aircraft, uncrewed systems) to be deployed by TEPEX-C will make observations that were impossible in the past, and connect the single-point time series to related spatial gradients and variability.

11.2 Existing Observations

TAO (Tropical Atmosphere Ocean) Moored Buoy Array, now referred to as TPOS (Tropical Pacific Observing System) - Building on the persistent efforts by many, the TAO moored buoy array was completed in 1993 (McPhaden 1995). While its data flow has gone through fluctuations through the years, its observations, when taken, have been available in real time for environmental prediction worldwide. TAO data have been used to help formulate the hypotheses, scientific questions, and observing strategy of TEPEX. Its newly upgraded observing capabilities (Fig. 6) will play a central role in TEPEX-E. Select TAO moorings at 140°W and 110°W and the Equator have at times hosted in-situ turbulence sensors at 20m vertical spacing. The turbulence time series at 140°W spans more than a decade from 2005, although it has gaps in 2012 and 2013. These rare direct observations of ocean mixing shaped our physical understanding of the Cold Tongue and motivated TEPEX-E.

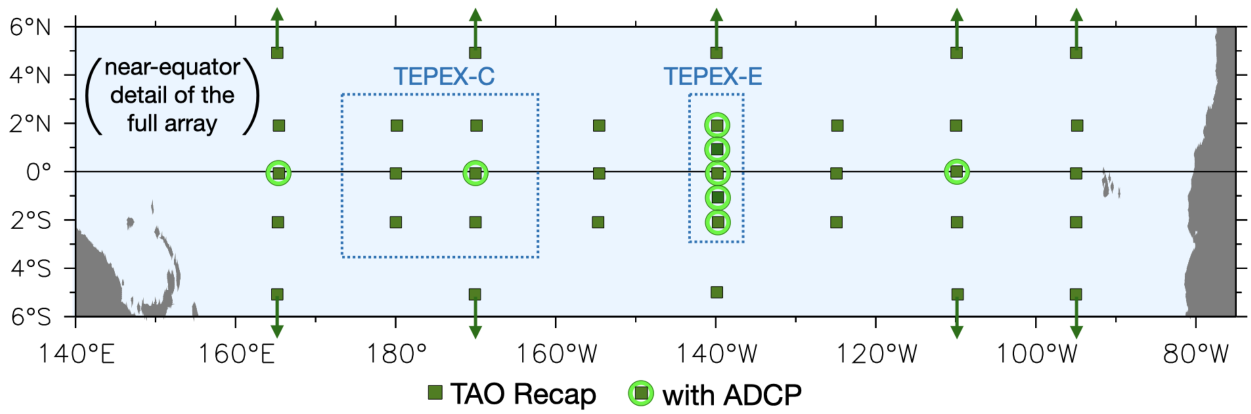

Figure 6. Near-equatorial detail showing the TAO moorings likely to be available for TEPEX fieldwork. Green arrows at the edges of the map show where mooring lines extend further north and south. Blue-dashed boxes show the approximate regions of fieldwork for the two elements of TEPEX.

Argo - The Argo float network has revolutionized the way we observe the ocean. Argo data have been used to document upper-ocean structures, including the barrier layer, of the world ocean covered by the network (Drushka et al. 2014; Hu et al. 2020; Katsura et al. 2023), and increasingly include biogeochemical sensors (BGC-Argo). Argo data will continue to provide needed background information for TEPEX. Because of their relatively coarse horizontal and temporal coverage and their lack of a counterpart of simultaneous and collocated atmospheric measurement, however, Argo data are insufficient to resolve the transient nature and constant interactions between the ocean and atmosphere. Argo data near the TEPEX observing domains will be used to expand the TEPEX spatial coverage of the ocean observations and, when feasible, to compare with new uncrewed observing technologies (e.g., USVs) to enhance confidence in the data accuracy.

Surface Drifters - satellite-tracked drifting buoys are an inexpensive platform to directly measure 15m ocean currents and SSTs at hourly resolution, and can house additional sensors such as the barrier-layer-resolving salinity profile drifters deployed in ATOMIC. They can also measure a limited suite of atmospheric properties (surface pressure, winds). However, they provide inhomogeneous measurements in space and time that must be complemented with other platforms, and they tend to leave regions of strong surface divergence relatively quickly.

Satellites - Satellite data provide detailed spatial coverage of the ocean surface and the atmosphere that no in-situ platform can match. However, certain satellite-observed variables have known biases or deficiencies: (1) temperature and humidity are not well retrieved or constrained in the boundary layer or near the sea surface; (2) sub-pixel or sub-time step scale rainfall is missed; (3) non-precipitating layered clouds are not well constrained by IR or visible measurements; (4) waves and currents rely heavily on retrievals and assumptions; (5) MABL height retrievals need observational constraints; (6) SST at high resolution (< 25 km) is missing during rainfall or persistent clouds, when IR retrievals of the surface are not possible and passive microwave must be used instead; (7) SSS cannot be retrieved during rainfall. In these conditions, key ASTZ variables are not sufficiently observed for accurately quantifying or studying air-sea interactions. Surface chlorophyll retrievals are also impacted by cloudiness, and require in-situ validation. TEPEX observations will provide "surface truth" to validate satellite observations. Once validated, satellite data will provide large-scale information for the TEPEX observations. Equally important, satellite data that are available in real time will provide nowcasting information to guide certain operations during the TEPEX field campaign (e.g., aircraft operations).

12. Ethics Statement

Built upon the experience from past field studies (Zhang and Moore 2023), TEPEX will promote diversity, equity, accessibility and inclusion. All TEPEX participants must be equally respected regardless of their ethnic and national backgrounds, gender, education, positions, or roles in the project. TEPEX welcomes participants at all career stages and particularly will actively recruit and support participants who are of early career and from underrepresented groups in geoscience to help build and promote a more representative future workforce. For the land-based observations, TEPEX will try everything possible to leave a long-lasting positive legacy to benefit the hosting communities. Safety is the number one priority of the TEPEX field campaign with zero tolerance to any type of physical or mental abuse or harassment. TEPEX participants must go through ethics training to be fully aware of how to prevent, report, and manage safety incidents and violations.

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APPENDIX A
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APPENDIX B
POTENTIAL FIELD OBSERVING FACILITIES
(non-exclusive)

- Research vessels (e.g., NOAA, UNOLS, NTU). They provide comprehensive observations of the ASTZ and beyond (e.g., the tropospheric profiles).
- Aircraft (e.g., NOAA, NCAR). They cover a broad spatial range to measure large-scale gradients of both the atmosphere (dropsondes and flight level instruments) and the ocean (AXBT and other airborne floats).
- Moored buoys. They provide long-term continuous time series of the upper ocean and air-sea interface.
- UxS. They are capable of being launched and recovered from both land and ships, and can measure the atmosphere, air-sea interface, and the upper ocean. Atmospheric measurements include aerosol and cloud properties relevant to aerosol direct and indirect forcing in the marine atmosphere (Quinn et al., 2024) as well as other variables (temperature, humidity, pressure, wind, radiation). These systems can also measure atmospheric turbulence to allow for eddy covariance calculations of fluxes of heat and momentum (de Boer et al., 2024). Upper-oceanic measurements include profiles of currents, temperature and salinity, etc. At the air-sea interface, they measure all state variables needed to estimate air-sea fluxes of energy, momentum, and mass (e.g., CO2).
- Autonomous devices (drifters, floats). They provide spatial coverages of the air-sea interface and the upper ocean.
- Land-based facilities (e.g., NCAR, DOE ARM). They provide comprehensive continuous time series of the surface, MABL and atmospheric profiles.
- Satellites. They provide broad spatial coverages of the ocean surface (SST, salinity, color, etc.) and atmosphere (surface wind, precipitation, clouds, radiation, etc.)

APPENDIX C
TABLE OF ACRONYMS

AGCM	Atmospheric General Circulation Model
AGU	American Geological Union
AMS	American Meteorological Society
DOE ARM	Department of Energy Atmospheric Radiation Measurement
ASTZ	air-sea transition zone
AXBT	Airborne EXpendable BathyThermograph
BSISO	Boreal Summer Intraseasonal Summer Oscillation
CAMP^{2}EX	Cloud, Aerosol and Monsoon Processes Philippines Experiment
CCN	cloud condensation nuclei

CRM	Cloud Resolving Model
CSM	Cloud System Model
DA	Data Assimilation
DNS	Direct Numerical Simulation
DYNAMO	Dynamics of the Madden-Julian Oscillation
EEWP	Eastern Edge of the Warm Pool
ENSO	El Niño - Southern Oscillation
EPIC	Eastern Pacific Investigation of Climate Processes
EUC	Equatorial UnderCurrent
GATE	Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment
GPEX	Global Precipitation Experiment
ITCZ	Intratropical convergence zone
LES	Large Eddy Simulation
MABL	Marine atmospheric boundary layer
MC	Maritime Continent
MIMOC	Monthly Isopycnal / Mixed-layer Ocean Climatology
MJO	Madden-Julian Oscillation
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NTU	National Taiwan University
PISTON	Propagation of Intra-Seasonal Tropical Oscillations
PPGC	Precipitation Prediction Grand Challenge
OGCM	Oceanic General Circulation Model
S2D	seasonal to decadal

S2S	subseasonal to seasonal
SPURS	Salinity Processes in the Upper Ocean Regional Study
SSS	sea surface salinity
SST	sea surface temperature
TAO	Tropical Atmosphere Ocean
TDAC	TEPEX Data Archive Center
TEPEX	TPOS Equatorial Pacific Experiment
TEPEX-C	TEPEX Central Pacific
TEPEX-E	TEPEX Eastern Pacific
TKE	turbulent kinetic energy
TOGA COARE	Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment
TPOS	Tropical Pacific Observing System
TWE	Tropical Instability Wave Experiment
UNOLS	University-National Oceanographic Laboratory System
UxS	Uncrewed systems
WCRP	World Climate Research Programme
WMO	World Meteorological Organizaion
WWE	westerly wind event
YMC	Years of the Maritime Continent
YoP	Years of Precipitation