A New Paradigm for Observing and Modeling of Air-Sea Interactions to Advance Earth System Prediction

A US CLIVAR Report
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COVER IMAGE:

Clouds over the Atlantic Ocean. Image credit: Tiago Fioreze. Source: https://en.wikipedia.org/wiki/File:Clouds_over_the_Atlantic_Ocean.jpg

BACK COVER IMAGE:

Waves breaking. Image credit: Anne Manning. Source: https://source.colostate.edu/salty-sea-spray-affects-the-lifetimes-of-clouds-researcher-finds/

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Executive Summary

The protection of people, property, and environmental resources from extreme weather, seasonal patterns, and climate change drives the need for predictions of weather, ocean, and climate patterns that have skill and value at timescales longer than traditional 1-10-day forecasts, including outlooks spanning weeks to decades. Advancing Earth System Prediction (ESP) skill at this range of timescales requires improved observations, understanding, and modeling of the processes in the ocean boundary layer, the atmospheric boundary layer, and their interface. A new way of referring to this coupled system is the Air-Sea Transition Zone (ASTZ). The report that follows is framed by the paradigm that the ASTZ is a single entity that regulates the flow of energy and matter between the ocean and the atmosphere. The ASTZ is thus the medium through which the ocean and atmosphere respond to and influence one another across their often disparate scales of variability. ASTZ modeling, observing, and understanding needs are particularly acute because very few measurements exist over oceans, and even fewer span the entire ASTZ, even though oceans cover 70% of Earth's surface and are the source of most of the rain and snow that falls on both the land and the oceans.

The research and forecast communities have called for enhanced observations of the ASTZ to fill gaps in our understanding and modeling of ocean-atmosphere feedback in ESP models to benefit society. This call is motivated by recent advances on several fronts: a large body of work has advanced our understanding of how ocean states throughout the globe regulate extreme weather and climate; the technological development of autonomous observing systems and sensors that hold promise for collecting ASTZ observations in regions not covered by, or in conditions not possible with, current observing systems; and advances in computing power and data assimilation methods that offer a pathway for extracting the full value of existing and new ASTZ observations for the improvement of ESP.

In response to this community-wide call for action, a US interagency group consisting of program managers from NASA, NOAA, NSF, ONR, and DOE sponsored an ASTZ Study Group to develop a "well-defined strategy to advance observing and modeling capabilities and understanding of air-sea interaction at all required scales for ESP." The Study Group's expertise covers oceanography, atmospheric science, air-sea interaction, in situ measurements, remote sensing, process understanding, parameterizations, coupled modeling, and data assimilation. It is charged with identifying current capabilities and key gaps in observing, understanding, and modeling ASTZ processes; assessing their relative importance to ESP; and developing a strategy to incorporate recent and potential future sensor and platform advances to recommend a new ASTZ observing system that harmonizes with evolving data science and data assimilation methods for advancing ESP.

Processes, scales, regions, and extremes that help define ASTZ observing and modeling needs are reviewed in Chapter 2. Current research has highlighted the role that the coupled boundary layers play in predictions while also providing insight into the gaps remaining in our observations and modeling of these turbulent systems. In Chapter 2 the key processes, scales, regions, and extremes which are affected by the ASTZ and areas where questions remain are outlined, and observational and associated modeling needs are presented. For example, enhanced observations of the ocean mixed layer (OML), marine atmospheric boundary layer (MABL), and direct flux measurements in a wider variety of regimes in combination with observations of waves and the very near-surface ocean are needed to improve bulk surface flux parameterizations, turbulence models of the near-surface ocean and atmosphere, and satellite retrievals of ASTZ state variables. These measurements are needed for improving our basic understanding of ocean-atmosphere coupled processes, for improving the initialization of coupled forecast models, and for improving predictions of the influences of ocean processes on weather and climate across timescales.

Enhanced vertically and horizontally resolved, colocated observations of ASTZ variables are needed in many under-observed regimes. Measurements of MABL temperature and humidity, surface waves, winds, and currents are needed in regimes such as ocean mesoscale and submesoscale eddy-rich regions, including western boundary currents, to understand these features and how they influence storm paths in the atmospheric synoptic scale. This is especially true in data-sparse but climate-sensitive regions and in extreme environments such as the high wind regime of the Southern Ocean, regions with sea ice, and in tropical cyclones. At the global scale, there is a clear need for globally distributed in situ measurements of MABL thermodynamic properties to better constrain global surface flux estimates, improve the initialization of forecast models, and provide ground truth information for satellite retrievals of ASTZ variables. The height or depth of the MABL, OML, and the critical sublayers within, are also greatly needed quantities.

Existing observing and modeling capabilities and advancements needed for improved ESP are assessed in Chapter 3. Instruments and platforms necessary to fulfill many of the observing needs identified in Chapter 2 already exist, but their broader deployment has been limited by operating costs, power needs, and maintenance requirements. Some observing needs, such as for more eddy covariance (e.g., direct) measurements of surface fluxes in under-sampled ASTZ conditions, could be met today by deploying existing technology to additional key locations. Other gains can be made by adding additional sensors to existing ocean platforms, including both stationary and drifting platforms. Technological advances that reduce the cost, size, weight, power needs, and improve the autonomy of in situ and remote sensing instruments and their platforms are needed to meet the objective of sustained ASTZ sampling to improve understanding of ocean-atmosphere scale interactions and to characterize statistical relationships among ASTZ variables that are needed for coupled data assimilation (CDA) across a variety of time scales. Recent advances in remotely operated unattended vehicles, possibly paired with large, fixed platforms developed by offshore commercial enterprises, offer exciting prospects for meeting this need. Finally, to maximize the usefulness of the above-described ASTZ measurements, it is essential that needs identified by communities in process understanding, model development, and data assimilation communities be incorporated into the design of any new observing system.

This report culminates with a set of recommendations and roadmaps for their implementation in Chapter 4. The Study Group identified four strategies that answer our charge of producing a "well-defined strategy to advance observing and modeling capabilities and understanding of air-sea interaction at all required scales for ESP." The four strategies are:

- **Develop observational and modeling technology for coupled ocean-atmosphere prediction.** *Advances in instrumentation, platforms, and parameterizations, as well as the collection, distribution, assimilation, and management of data, are all components of this strategy. These advances will permeate through each of the following strategies.*
- **Observe the ASTZ in strategic regions.** *Measurements of the atmospheric, oceanic, and interfacial components of the ASTZ that are coincident in time and colocated within a given sampling space will address the needs for improved understanding of ocean-atmosphere scale interactions, parameterization development, model physics for ESP, and statistical information needed for CDA.*
- **Expand observations of extremes and other challenging regimes.** *This strategy will require new ways of collecting ASTZ variables using technologies that can be quickly deployed in rapidly developing situations and the development of assets that can be positioned in climatologically important regimes that are challenging to sample at all or challenging to do so for a long time. This strategy will meet the need for societally relevant ESP on scales ranging from landfalling atmospheric rivers (ARs) or tropical cyclones to centuries-long global climate changes.*
- **Develop a global observing network to monitor key air-sea coupling variables.** *This strategy focuses on ASTZ variables associated with air-sea surface fluxes and emphasizes the importance of collecting these measurements across the global oceans, while still adhering to the "same time, same place" guidelines outlined above. This strategy can be achieved with both in situ and remote measurements and will address the needs of constraining global surface flux estimates and improving the initialization of coupled forecast models.*

The recommended roadmaps for implementing these strategies are intended to be sequential, wherein longer-term action items follow the completion of shorter-term action items. While there is some overlap between the four strategies, each could be pursued individually or could be initiated at differing times. The Study Group recommends engaging the larger research and forecasting communities, including international partners, as well as funding agencies to put these strategies into action.

1 Introduction

The societal relevance of weather, ocean, and climate predictions and climate projections (hereafter called Earth system prediction; ESP) is well-established. Evidenced by the proliferation of their use, ESP is used to move populations out of the path of a hurricane, establish architectural building codes, construct commercial flight plans, inform shipping lanes, build expectations of future water resources, and prepare the electrical grid for impending extreme weather. Time and again, ESP has been used to save lives, protect property, and inform decisions. Expectations of future weather and climate conditions shape many decisions that are a part of daily life.

The societal relevance of ESP is growing due to the need for increased capacity in human-serving systems (e.g., additional freshwater, crop yields, energy, as well as safer public and commercial transportation). Additionally, the ongoing changes within the Earth system in response to human-induced climate change further increase the vulnerability of human systems and biodiversity to the physical states of the ocean and the atmosphere. Scenarios for immediate climate change mitigation (i.e., greenhouse gas emissions reductions and negative emissions) require superior prediction tools that represent the complexity of the interacting Earth system and the potential "tipping points" contained therein (Armstrong McKay et al. 2022). Given the increasing global population and acceleration of climate change, the need for additional capacity makes human systems more sensitive to weather and climate variability; thus, the value of ESP is growing.

The societal need for improved ESP from the scientific community is clear. The scientific community, in a collaboration between the public and private sectors, must deliver predictions that meet societal needs. Community-driven improvements in ESP are accomplished by:

1. improving observational systems (e.g., greater accuracy, greater resolution, expanded variables, new regions, new concepts that leverage technological advances, and extending time series) that provide better initial conditions, better ESP evaluation and improvement benchmarks, and improved understanding of the underlying physical processes that influence the phenomenon of interest.
2. advancing computational capabilities by developing faster computers, leveraging new hardware and high-performance computing architectures, streamlining code, developing new languages, leveraging artificial intelligence (AI), and improving data storage and telemetry from remote ocean locations.
3. advancing modeling frameworks and parameterization by improving data assimilation techniques, developing assimilation techniques for new parameters, improving the representation of sub-grid scale physics, utilizing more unified model physics across time and space scales, and developing more realistic ocean-atmosphere-land-ice coupling mechanisms.

Given the societal need to harness predictability to improve ESP, the scientific community must continually assess and reassess our observing systems, modeling approaches, and computational capabilities to identify and resolve challenges that limit our ability to advance scientific understanding and address societal needs. Vitally, recent advances in these three sectors listed above warrant a collective and dedicated effort to take advantage of new opportunities across the entire ESP arena (Gettelman et al. 2022).

The science community has identified the need to better understand, observe, and model air-sea interactions across scales and across the globe to advance ESP. For example, the exchanges of heat, moisture, momentum, and gases encompassed within air-sea interaction influence ESP by impacting the flow and cycles of energy, water, and biogeochemistry as well as the frequency of water cycle extremes (e.g., droughts, drought-related wildfire, atmospheric rivers, floods, tropical cyclones, and winter storms). Furthermore, substantial uncertainties are found in ESP of critical phenomena at and across the air-sea interface including oceanic and atmospheric boundary layer turbulence, ocean surface waves, mesoscale and sub-mesoscale ocean eddies, fluxes, sea spray under high winds, freshwater lenses, precipitation, atmospheric boundary layer clouds, cloud-radiative effects, cloud-aerosol effects, sea ice processes, and diurnal effects including but not limited to surface warm layers. Our understanding, ability to observe, and ability to model air-sea interactions have been identified as fundamental limitations to our ability to sufficiently harness predictability to meet societal needs.

"Our understanding, ability to observe, and ability to model air-sea interactions have been identified as fundamental limitations to our ability to sufficiently harness predictability to meet societal needs."

1.1 Why Now?

We sit on the cusp of a technological explosion. The rapidly advancing capabilities of autonomous platforms (i.e., aerial, surface, and submersible) have the potential to unlock observing strategies. These and other engineering feats open many opportunities to collect and use observations in challenging weather and ocean conditions that were previously inaccessible. Advances in machine learning and data science methods that allow a more effective combining of measurements from disparate sources (e.g., moorings, drifters, satellites, and ships of opportunity) are enabling more comprehensive descriptions of the evolving states of the ocean and atmosphere. The deployment of deep learning techniques for climate and weather models (e.g., recently released ClimaX (Nguyen et al. 2023), the first foundation model, and Bi et al. (2023)) is poised to revolutionize how we do ESP. Computational advances are also leading to refinements in the resolution of coupled forecast models, meaning they will resolve processes on scales at and below the capability of current observations. Coupled data assimilation (CDA) shows the promise of producing superior results if observations are expanded to capture temporal and spatial decorrelation scales of air-sea interaction variables. Such data assimilation (DA) advancements are possible and needed to mitigate the negative impacts of initialization shock on coupled model forecasts.

In addition, new and planned satellites, as well as entirely new satellite mission concepts, are now focusing on studying the ocean and air-sea interaction (e.g., Surface Water and Ocean Topography (SWOT), Investigation of Convection Updrafts (INCUS), Harmony, Butterfly, and Ocean Dynamics and Surface Exchanges with the Atmosphere (ODYSEA)). NASA's recently launched SWOT mission is providing a global survey of Earth's water with observations of sea surface topography at scales down to ~20 km which will advance the understanding of oceanic meso-to-submesoscale dynamics and coastal processes. The Plankton, Aerosol, Cloud, ocean Ecosystem experiment (PACE), which is expected to launch in January 2024, will provide polarimetric measurements to understand the links between ocean ecosystems and atmospheric aerosol and clouds. EarthCARE, which is expected to launch in 2024, provides measurements to advance our understanding of the role of clouds and aerosols in the surface radiation budget. The INCUS mission, which is expected to launch in 2026, will advance our understanding of convection over the globe using an innovative radar system aboard two SmallSat platforms. Harmony, which is expected to launch in 2029, is a two-satellite constellation of synthetic aperture radars to monitor ocean surface conditions including winds, currents, and temperature. NASA's Atmosphere Observing System (AOS), which is expected to launch in 2029 and 2031, represents the next-generation observatory to advance the understanding of aerosol, clouds, and convective processes critical to air-sea interaction science. Two other satellite concepts, Butterfly and ODYSEA, are being developed or proposed as Earth Venture and Earth System Explorers missions, respectively. Butterfly would be the first satellite mission designed to provide simultaneous, high-resolution measurements of near-surface air temperature, humidity, winds, and sea surface temperature required for calculating the air-sea turbulent heat and moisture fluxes globally, and ODYSEA proposes first-ever measurements of total surface currents with simultaneous measurements of ocean surface vector winds. These exciting next-generation satellite observations for studying a range of processes relevant to air-sea interactions would benefit from a complementary next-generation surface observation system for validation and combined analysis.

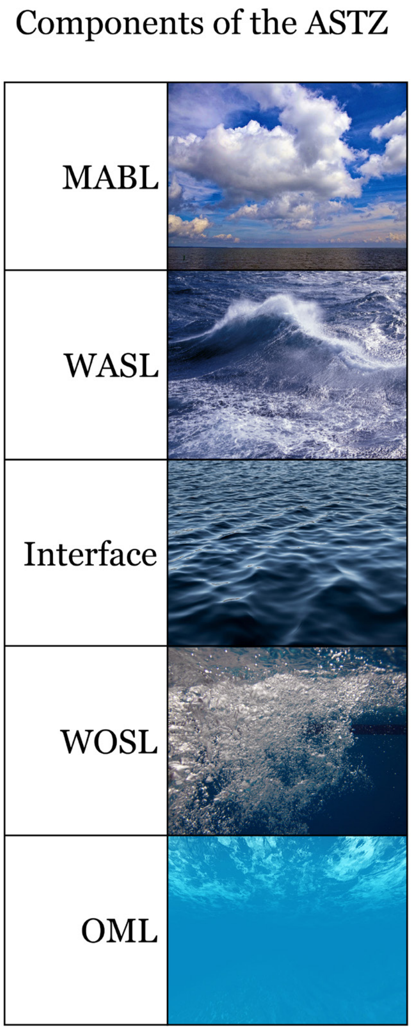

Figure 1. The components of the Air Sea Transition Zone (ASTZ) including the Marine Atmospheric Boundary Layer (MABL), the Wave-influenced Atmospheric Surface Layer (WASL), the Interface, the Wave-influenced Oceanic Surface Layer (WOSL), and the Ocean Mixed Layer (OML).

The need to establish a new air-sea observing strategy has been recognized at the international level, and work is underway, as outlined in the UN Decade of Ocean Sciences for Sustainable Development (Cronin et al. 2023). By acting now, the U.S. can amplify its return on investment to society through partnerships with international bodies with the shared goals of advancing understanding, ensuring public safety, and supporting economic activity through improved air-sea interactions in ESP. Thus, now is the time to leverage international partnerships in designing and implementing a new observing system to advance air-sea interaction understanding, observing, and modeling in ESP.

Lastly, a recent conceptual advance has transformed, energized, and unified the field of air-sea interactions. This new conceptual picture, named the air-sea transition zone (ASTZ), considers the region from the upper ocean mixed layer (OML) through the top of the marine atmospheric boundary layer (MABL) as a single system, instead of separate systems coupled by an interface (Figure 1). The ASTZ regulates the flow of energy and matter between the ocean and the atmosphere and is the medium through which the ocean and atmosphere respond to and influence one another across their often disparate scales of variability. This intellectual and community advance points to new requirements and constraints on the observing system, opens the door to creativity across disciplines, and presents a new opportunity to design an observing and modeling system that can advance ESP. The definition of the ASTZ constitutes a paradigm shift and, as with previous paradigm shifts, that suggests we are poised to accelerate scientific progress.

Against this backdrop, the ASTZ Study Group, composed of 17 U.S. scientists with expertise in observing and modeling within the ASTZ, was established and charged by the US Climate Variability and Predictability Program (US CLIVAR) in 2022 to develop a strategy to advance observing, modeling capabilities, and understanding of the air-sea interactions required to harness predictability to improve ESP (Appendix B). This strategy is anchored on observing the ASTZ to improve understanding, CDA, and air-sea interaction modeling. In developing this strategy, the Study Group has assessed the observing needs, modeling requirements, and technological advancements that will address critical gaps in our knowledge and capabilities of ESP.

Over the course of 18 months, the Study Group has (1) identified current capabilities, key gaps, lessons learned from the past, and best practices in data, technologies, understanding, and modeling requirements; (2) assessed the relative importance to ESP of resolving various space and time scales, interactions among different scale processes, and addressing model biases; and (3) explored possibilities of using modern statistical and modeling tools and co-designing air-sea observing and DA systems to optimally use available data, fill observational blind spots, and minimize cost while harnessing predictability and providing broader societal benefits.

The strategy communicated herein is not formally related to the Observing Air-Sea Interactions Strategy (OASIS) or the Surface Ocean-Lower Atmosphere Study (SOLAS), but we all support each other. The key differences are that this ASTZ Study Group has focused on physical aspects of the ASTZ, while OASIS and SOLAS include the physics as well as biogeochemistry. The Study Group recognizes the strong connection of physical ASTZ processes to atmospheric chemistry and biogeochemical oceanography but does not focus on them in this report. Biogeochemical understanding of the ASTZ will benefit from the systems approach delineated and embraced in this report.

1.2 Observing System Use Cases

A critical part of developing the strategy described herein was for the Study Group to consider the many scientific areas that could benefit from a new ASTZ observing system and understand how these observations would be used. Here we provide several examples demonstrating potential uses for the new observing system to understand ocean-atmosphere coupled processes that affect (1) the large-scale circulations of the atmosphere and ocean, (2) tropical cyclones, and (3) coastal sea level. These use cases are not intended to be exhaustive.

Ocean-atmosphere coupled processes influence atmospheric dynamics and climate change across many regions of the globe. Enhanced and simultaneous observations of the ASTZ open the door to new scientific analysis and questions. Processes occurring within the ASTZ influence the strength and propagation of the Madden Julian Oscillation (MJO) and its effect on North American weather (e.g., atmospheric rivers, drought, tropical cyclones, and coastal inundation) on subseasonal to seasonal (S2S) time scales (Wang et al. 2019). New observations of the atmospheric boundary layer thermodynamic and dynamic vertical structure, surface winds, and turbulent fluxes will provide refined boundary conditions to assess MJO predictability and a deeper understanding of the processes contributing to the free tropospheric moistening (Wolding et al. 2022). In the Arctic, monitoring of the seasonal evolution of the ASTZ and measuring surface turbulent and radiative fluxes in sea ice retreat regions can be used to constrain Arctic climate change projections and model-based assessments of the response to sea ice loss, including displacement of the polar front jet, warm mid-latitude moisture intrusions, cold-air outbreaks, and impact on the ocean circulation (Taylor et al. 2022). In the mid-latitudes, new observations of the evolution of sub-mesoscale eddies will advance ESP through a better understanding of the ocean-atmosphere heat exchanges in the vicinity of western boundary currents and their influence on jet stream position and variability (Seo et al. 2023).

The new ASTZ observing system will also advance our understanding of ocean-atmosphere coupling within tropical cyclones. Tropical cyclone intensity is influenced by anomalous ocean heat content (OHC), such as the OHC in the Loop Current and associated eddies in the Gulf of Mexico, and perhaps through barrier layers generated by rainfall and river outflow, which inhibit the upward mixing of sub-thermocline waters (Wu et al. 2007, Balaguru et al. 2012). Downward mixing of momentum into the ocean and the ocean-to-atmosphere transfer of latent and sensible heat are thought to be strongly affected by the ocean surface wave state, surface currents, near-surface wind-wave alignment, surface bubbles, foam, and sea spray (D’Asaro 2014). Routine and intensive measurements of these quantities will enable an improved understanding of the factors influencing a cyclone’s intensity and track over time.

The Study Group also envisions that the new ASTZ observing system will be leveraged by researchers to advance understanding of the factors affecting coastal sea level. For instance, sea level along the U.S. East Coast is strongly influenced by the strength of the Gulf Stream (Ezer et al. 2013). The recommended routine measurements and intensive observing campaigns will advance understanding of the variations in the Gulf Stream intensity including the influence of winds and mesoscale eddies and how these interactions impact coastal sea level. Gulf Stream intensity is also impacted by hurricanes and storms that influence the temperature difference across the interface (Seo et al. 2023). The observing system will also enable understanding of the interactions between coastal sea level rise influenced by climate change processes (e.g., glacial melt) and coastal sea level rise affected by variability in the Atlantic Meridional Overturning Circulation (Frajka-Williams et al.

2019). Overall, the proposed ASTZ observing strategy will support studies of the predictability of coastal sea level while also supporting new endeavors in harnessing coastal wind energy.

Many of the processes described above are central to the near-term thresholds of climate tipping points which are all centered in the oceans: Pacific tropical coral loss, Arctic ice loss, and Atlantic circulation collapse (Armstrong McKay et al. 2022). Overall, the new ASTZ observing system will be used in many ways to improve weather and climate prediction capabilities, serving to inform climate action and improve predictions of extreme precipitation and temperature.

1.3 Current capabilities and limitations

While the current observing capabilities available for the ASTZ are numerous (Figure 2), there are several limitations, namely, missing key variables, missing concurrent/simultaneous measurements of coupled variables, lack of spatial coverage, and key unobserved regions.

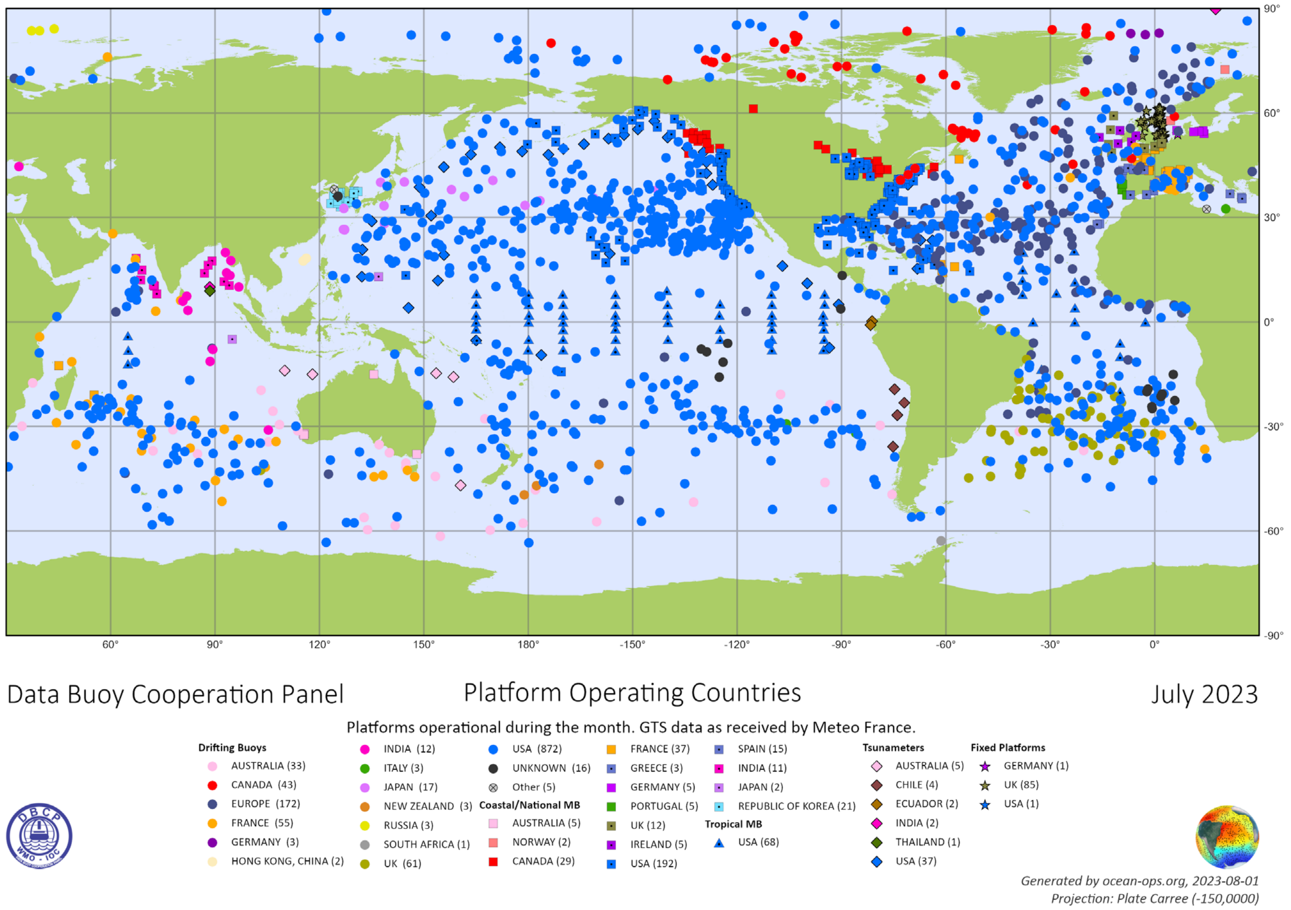

Figure 2. A map of in situ ocean and air-sea observing systems coordinated by the OceanOps program.

Long-term buoy measurements provide critical information for understanding the ASTZ but for a limited number of variables. Meteorological buoys that measure key state variables – sea surface temperature (SST), air temperature and humidity, wind, and currents – are capable of estimating atmosphere-ocean turbulent momentum, sensible, and evaporative heat fluxes using bulk algorithms. Long-term buoy measurements rarely contain direct turbulent flux measurements of buoyancy, sensible heat, or momentum, and none directly measure latent heat flux long-term; not all buoys measure precipitation; and radiation fluxes are also not commonly measured. Significant quality control issues exist with many of the near-surface and surface observations from operational buoys, limiting their usefulness and interoperability as a single set of global buoy observations. Mid- and high-latitudes have much poorer data coverage than the tropics, reducing the variability of distributions of observations and biasing satellite retrieval algorithms to tropical conditions. Global ocean drifters measure SST, and sometimes pressure, wind, or waves, but these are not sufficient to estimate surface fluxes. In situ measurements of temperature and salinity profiles from (Argo) profiling ocean floats routinely provide OML depth, barrier layer strength, and thermocline stability, but they do not measure air properties and do not always measure up to the ocean surface. MABL height is not operationally measured from the surface looking up but is sometimes measured in process studies from ships and coasts by radiosondes or remote ranging of inversion or cloud heights.

Satellite remote sensing has played a crucial role in air-sea interaction studies. However, satellite observations are unable to provide accurate information under certain conditions (e.g., under heavy rain or near coastlines). Near-surface retrievals for air temperature and humidity, clouds, and precipitation are particularly challenging. Satellites do not have sufficient spatial or temporal resolution to answer all ASTZ questions. Satellite observations also provide no information about the vertical structure in the ocean. Not only are satellite-derived near-surface air temperature and humidity subject to large errors, but they are also not colocated with each other or with wind or SST retrievals that are needed for flux calculations. These issues are major contributors to the uncertainties of the resultant air-sea heat and moisture flux estimates, along with insufficient in-situ measurements for constraining satellite-derived estimates. Considering the evaluation of long-term trends, the winds and SSTs used in the global flux products cause as much uncertainty as the air temperature and humidity. Satellite measurements of the MABL are limited and coarse (Teixeira et al. 2021) restricting their capabilities in characterizing mesoscale and submesoscale air-sea interactions.

Clouds represent a particular challenge for measuring the ASTZ. Observing the vertical structure, occurrence, and rainfall of boundary layer clouds is currently difficult. Satellite observations of clouds and precipitation in the ASTZ are often missed entirely or underestimated by several known sampling issues in the passive microwave, infrared, and even radar. Cloud base height is critical to constraining the downwelling longwave radiative flux through the ASTZ and can only be reliably detected from the surface. Satellite observations of clouds, particularly thin MABL clouds, are challenging, due to cloud top temperatures being close to that of the sea surface, so infrared radiation (IR) retrievals struggle to detect the clouds. This is particularly a problem in the tropics and Arctic where there is little to no ice scattering signal in shallow MABL clouds to trigger retrieval by certain microwave wavelengths, and there frequently is not sufficient liquid water content to detect the clouds with other passive microwave sensors. Precipitation in regions like tropical oceans is frequent but often too spatially limited to be captured by satellite sensors. The lowest clutter-free bin of most precipitating and non-precipitating satellite cloud products is well above the MABL, and MABL clouds and the associated precipitation is missed entirely in many regions.

1.4 The Report Below

In the following chapters, the Study Group outlines key areas for additional observational and modeling capabilities as well as technological advancements that must underpin a future ASTZ observing system that enables the full harnessing predictability to improve ESP. Chapter 2 presents key processes, scales, regions, and extremes for which improved observing and modeling of the ASTZ will have significant impact on ESP, identifying specific observing needs for each. Chapter 3 distills these specific needs into three overarching needs and assesses the existing observing and modeling capabilities and advancements needed to address them. Informed by the prior needs and capabilities assessments, Chapter 4 outlines four implementation strategies and provides a roadmap of sequential actions to undertake in order to fulfill each strategy. The Study Group has the vision that, with the implementation of the strategies described herein, the scientific community will be poised to make rapid advances in our understanding of air-sea interactions and their role in ESP to provide society with the actionable predictions needed to maximize the capacity of human systems.

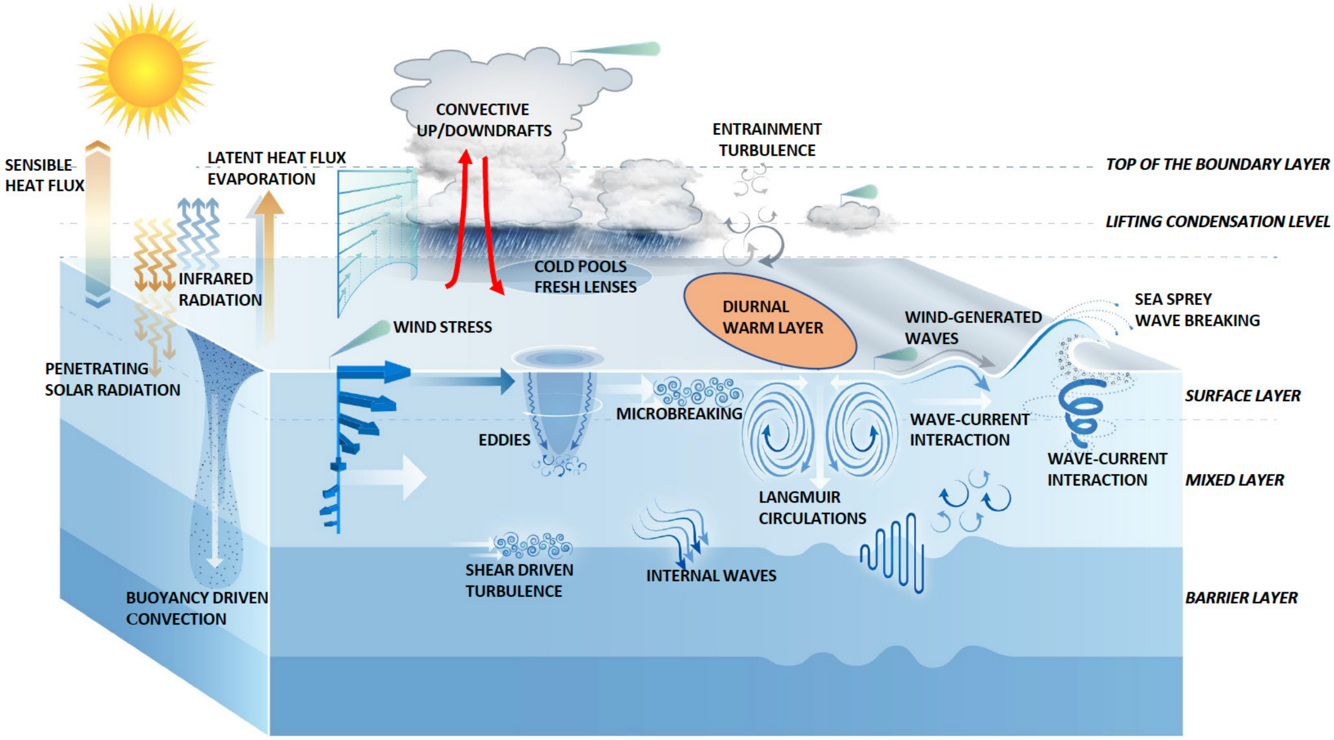

Figure 3. Some of the key processes that govern the transfer of heat, moisture, and momentum within the non-polar ASTZ. Courtesy of Chidong Zhang.

2

Observations and Modeling Needed to Improve ASTZ Representation in Predictions

Predictive capabilities have increased over the past decades, but so have the societal needs for these predictions. Here, we discuss the aspects of the ASTZ that are both most in need of improved understanding and modeling and those that have the largest impact on ESP. We view these aspects through multiple lenses, including (1) processes, (2) extreme events, (3) scales, and (4) regions. Each lens provides a unique perspective on the required physical observables and associated qualities of the future ASTZ observing system. Current capabilities for measuring or modeling ASTZ observables and needed improvements to address these issues will be discussed in the subsequent chapter.

2.1 Processes

Many processes and phenomena occur in the ASTZ and influence its evolution. Climate and weather models remain, in many ways, unable to realistically represent atmospheric and oceanic boundary layer structure and evolution despite recent progress in parameterizations that represent the range of MABL turbulence, moist convection, and clouds and their interactions with the underlying surface and ocean boundary layer (Teixeira et al. 2021; Boisvert et al. 2022). A crucial dearth of observations of the coupled system significantly impacts our ability to improve parameterizations. The variety of processes linking together the ocean and atmospheric boundary layers through their interface are highlighted in Figure 3. Processes ubiquitous to the global ASTZ, which are crucial to an improved model capability for precipitation and other predictions, include turbulent processes within both boundary layers, particularly under stably stratified conditions; ocean surface waves and their impacts on the atmosphere, ocean surface layers, and surface exchange processes; and clouds, convection, and precipitation processes.

2.1.1 Turbulence and mixing of the atmospheric and oceanic boundary layers

Turbulence and mixing within the atmospheric and ocean boundary layers obey similar physical laws but also have distinct behaviors associated with differences in their absorption of radiation, the effects of surface waves, and the effects of boundary layer clouds. In both boundary layers, the interactions between turbulence and mean thermodynamics (density from temperature and humidity in the atmosphere and temperature and salinity in the ocean) and kinematic structure (waves or currents) are key for the evolution of the boundary layers.

In both fluids, convective boundary layers tend to be more accurately modeled and more often observed than stably stratified boundary layers. This is due to the small vertical scale of stable boundary layers. Stable boundary layers in the atmosphere can be less than 100 m deep, whereas convective boundary layers can reach over 1000 m. In the ocean, highly stable diurnal or rain-induced layers can be less than 1 m, while convective mixed layers can reach 100 m or more. Models typically have vertical resolutions incapable of adequately resolving the boundary and surface layers under shallow stable conditions, and observations also rarely capture these scales. In calm, tropical or mid-latitude conditions, the interplay between the daytime deep convective MABL and shallow stable OML to the nighttime shallow stable MABL and the deep convective OML is key to the vertical transfer of constituents between the ocean and atmosphere, and out of the boundary layers. This cycle is less pronounced in the MABL than over land, but it is more temporally and spatially variable because it depends on the stratification of the upper ocean.

Organized structures within both the MABL and the OML also remain relatively undersampled. In the MABL, structures such as roll vortices and wave-driven organized structures in the WASL contribute to variability in MABL turbulence and surface fluxes (Etling and Brown 1993; Young et al. 2002; Sullivan et al. 2014; Zippel et al. 2022, 2023) and cloud development (LeMone and Pennell 1976). Clouds and other moist processes are relatively under-observed and add additional complexity to MABL turbulence discussed below. Non-local mixing schemes and scale-dependent parameterizations will be of importance for improved representations of these and other types of boundary layer mixing (NASEM 2018b). In the OML, Langmuir circulations are important for mixing and dispersion characteristics. Langmuir circulation has inspired many model parameterizations used in various flavors of ocean models (e.g., Fox-Kemper et al. 2019).

Observations in the MABL are sparse outside of the very near-surface region, which is typically sampled at only one height between 2-20 m, particularly over the open ocean. As a result, no observationally based climatology of the fundamental parameter of MABL height exists. Even fewer profiles of the mean thermodynamic and kinematic variables are available, limited to a few island sites or field campaigns (Teixeira et al. 2021). In combination with the mean parameters, the vertical structure of fluxes within the MABL is a first-order observation for improving the representation of turbulent processes (NASEM 2018b). Observations of MABL turbulence and contemporaneous profiles of the mean variables throughout the ASTZ are only available from occasional field campaigns.

The lower ~10% of the MABL is typically described by Monin-Obukhov Similarity Theory (MOST). Assuming horizontal homogeneity, MOST uses stability to define the structure of turbulent fluxes. MOST is not valid in the very near-surface WASL where wave-induced motions begin to support momentum exchange (e.g., Edson et al. 2013; Ayet and Chapron 2022) and for horizontally inhomogeneous and highly stratified flows, which create weak and intermittent turbulence. Measurements throughout the lower MABL are particularly needed over waves during weak winds and during stable stratification.

Compared to the MABL, there are more mean thermodynamic profiles in the OML due to ocean buoy datasets from OceanSITES, other buoy datasets, and the Argo program. These have allowed climatologies of diagnostic variables such as OML and barrier layer depths to be developed. As in the MABL, profiles of ocean mixing are rarely available, and they are limited to dissipation estimates. Turbulence in the upper OML is normally inferred by relatively coarse and/or infrequent observations of mean variables and their change over time (e.g., temperature or salinity profiles from Argo floats or moorings), which necessitates an assumption of ergodicity. These profiles do not have sufficient vertical resolution near the surface to diagnose surface inputs to ocean turbulence and density structure (e.g., rain, heating, river outflow, radiation, winds, and waves), nor to diagnose important subsurface features and their day-to-day changes (e.g., barrier layers and OML depth). Ocean mixing estimates are needed at more locations where turbulence is responsible for high-impact changes in the ocean and atmosphere. Observations of temperature and salinity at a higher vertical resolution near the surface, particularly in the tropics and/or where the wind is weak, are needed to infer mixing and change near the ocean surface. This is also true in complex environments like the marginal ice zone, near ice shelves, regions with freshwater precipitation and river outflows to the open ocean (i.e., where barrier layers typically form), locations where upwelling and/or vertical shear is strong, and locations where strong variability on short time scales (***O***(days)) is known to occur in the OML and/or the pycnocline.

Needed observations

- Localized direct covariance flux measurements, including pressure, within the lower MABL under a range of stable stability conditions as well as wind-wave states that are contemporaneous with dissipation measurements in the OML
- Profiles of horizontal and vertical wind speed, temperature, and humidity through the MABL at ~100 m vertical resolution and a higher resolution of ~1-10 m nearer to the surface, particularly for stable conditions
- Flux profiles of heat, moisture, and momentum through the MABL, particularly nearer the surface
- Ocean mixing estimates, contemporaneous with thermodynamic and dynamic profiles at high spatial resolution to within ~0.1 m of the surface to resolve diurnal and rain-induced stable layers and temporal resolution of ~1 hour to resolve rain events and diurnal variability
- Temperature, salinity, and velocity measurements at 1-2 m intervals, particularly where internal waves propagate and affect SST (e.g., at the upper thermocline or near the base of the OML)
- Wave characteristics, including directional wave spectra and direct pressure measurements over waves, turbulent flux, and radiative flux measurements requiring a combination of wave-following and fixed-height platforms.

2.1.2 Sea surface state

Defining and quantifying how sea state, including swell and wind waves, affects air-sea fluxes, turbulence in both boundary layers, sea spray, and bubble formation is a lingering challenge in the ASTZ. The effect of the sea state on remote sensing measurements also needs to be characterized. Observations of patterns in sea state can provide information on storms, currents, and other oceanographic phenomena. The impact of sea state information on coastal communities and safety at sea is outlined by Ardhuin et al. (2019).

Surface waves play an important role in modulating air-sea fluxes. Existing parameterizations that explicitly use the wave state for their calculation of the exchange coefficients are not well-constrained and have larger errors than state-of-the-art formulations using only wind speed under certain wind speed and wave age regimes. The wind-speed-based bulk parameterizations become less accurate in wind-wave-current misalignment conditions, swell-dominated regimes, very low or very high wind conditions, strongly stable conditions, and under regions of significant surface heterogeneity. High-impact weather events demonstrate the need for improved formulations including wave and current information to improve forecast accuracy (Pullen et al. 2017; Iyer et al. 2022; Sauvage et al. 2023).

Wave processes also affect turbulence throughout the ASTZ. Modeling demonstrates that some parameterizations of wave-induced turbulence affect OML depth and upper ocean heat content. In the atmosphere, wave breaking, bubble ejection, and sea spray alter the kinematic and thermodynamic structure of the MABL (e.g., Deskos et al. 2021), and microlayer processes impact boundary layer cloud development (e.g., Sellegri et al. 2023). Waves drive low-level wind jets and variability in turbulence in the MABL, especially in low-wind conditions. Wave breaking increases mixing in the OML to a depth of roughly one significant wave height (Sullivan et al. 2004). Waves are key to Langmuir circulation. Mixing due to Langmuir turbulence has been studied mainly through modeling and laboratory studies, but it has not been comprehensively validated against field observations (Savelyev et al. 2020).

A new understanding of the heterogeneity of surface waves shows that they are much less spatially uniform than previously thought. Sea state gradients at ocean meso- and submesocales are driven by current gradients (Ardhuin et. al. 2017; Quilfen et al. 2018; Villas Bôas et. al. 2019, 2020), and result in variations to the MABL (e.g., Ardhuin et al. 2019) which highlights the need for high-resolution measurements of sea state gradients – especially of stress, waves, and currents – to capture the coupling between the atmosphere and ocean through the wave field. Heterogeneity requires further observational and modeling insight, as it violates Taylor's fundamental hypothesis that allows for the estimation of fluxes from both direct covariance and bulk aerodynamic algorithms.

Needed observations

- Direct heat, moisture, and momentum flux measurements, wave properties, surface currents, and skin SST in combination with surface radiation fluxes across a wide range of the sea state and wind speed parameter space (Ample measurements are needed in regions with typical wind-wave-current misalignment, such as low latitude regions where swell dominates (e.g., tropical eastern Pacific), under rapidly translating storms and atmospheric fronts, in strong SST and vorticity gradient regions like western boundary currents, coastal regions, or extreme conditions, and in regions where strong model biases are observed.)
- Coincident high wavenumber directional wave spectra for flux parameterizations and process studies (10-1000 rad/m)
- Spatial distribution of direct flux measurements, wave properties, surface currents, radiation fluxes, and skin SST for heterogeneity questions
- Vertically, well-resolved measurements of the MABL kinematic and thermodynamic profiles, coincident with measurements of processes in the lower MABL, WASL (including measurements of sea spray and aerosols), and the OML

2.1.3 Clouds, convection, and precipitation

Feedbacks between the atmospheric and oceanic boundary layers and clouds, convection, and precipitation are significant drivers of uncertainty in weather and climate predictions. A unified atmospheric boundary layer turbulence theory that includes turbulence, convection, and clouds is key to improving this uncertainty (Teixeira et al. 2021). The coupling of clouds to the ocean surface, and the impact of key mesoscale cloud-driven events such as cold pools and freshwater lenses on the ocean surface and the fluxes, remains an ongoing area of model improvement. Understanding how the thermodynamic structure and turbulent dynamics of the MABL play a role in mesoscale circulations and shallow convective cloud organization is at the heart of these feedbacks. Clouds transport momentum, heat, and moisture between the surface and the free troposphere through the MABL, and greatly impact the sea surface and OML.

Observations of clouds, the MABL, and surface and OML processes connected to the MABL are rarely captured together. Measurements of the MABL and the surface turbulent, radiative energy, and freshwater fluxes, along with surface characteristics, are sparse particularly in regions of persistent cloudiness. Longstanding model deficiencies and uncertainties surrounding the cloudy MABL have had limited improvements due to the current state of observations and modeling. However, better predictions of clouds and cloud coverage can make large impacts on model fidelity, given the potential for local and remote impacts of model errors. In stratocumulus regions, for example, too little cloud cover is compensated by too strong turbulent fluxes (de Szoeke et al. 2010, 2012; Zuidema et al. 2016), emphasizing the coupling between the surface, MABL, and the MABL clouds. In addition, excessive cloud cover in the eastern tropical Pacific results in inaccurate simulation of the East-West temperature gradient across the Pacific and therefore the entire tropical circulation.

For shallow cloud fields with less persistent cover such as trade-wind cumulus, mesoscale circulations must also be considered (George et al. 2023). Clouds are often the energy-containing scales for driving turbulence in the MABL. For example, precipitation-induced cold pools inject momentum and relatively cold, dry air into the MABL (de Szoeke et al. 2017), encouraging radically-different cloud distributions from those characterizing more quiescent conditions (Zuidema et al. 2012). Clouds also affect the upper ocean by blocking downward shortwave radiation, emitting infrared radiation, and depositing freshwater lenses when precipitating. Above the MABL, clouds help set the vertical gradients of vapor and temperature that can be entrained by the MABL. The MABL is the source of moist static energy, enthalpy, and water vapor for convective cloud updrafts, influencing the horizontal organization and vertical structure of cloud populations.
The impacts of moist processes on the MABL, from evaporation at the ocean surface to entrainment and convective downdrafts (i.e., cold pools) at the top of the MABL, are relatively under-observed. Small-scale gustiness is also a result of convective processes and affects observations of air-sea fluxes from both in situ and satellite measurements. Model representation of these MABL moistening and convective response processes are thus poorly constrained, contributing to uncertainty in how these processes influence cloud development and teleconnections that shape global weather patterns. MABL observations in the tropics, particularly in the regions of deep convection and cold pool boundary layers, over the MJO cycle can lead to S2S model improvements (NASEM 2018a).

Needed observations

- Localized direct covariance flux measurements
- Mesoscale SST, wind, and state variables to compute turbulent fluxes
- Radiative fluxes
- Profiles of horizontal and vertical wind speed, temperature, and humidity through the MABL at ~100 m vertical resolution with a higher resolution of ~1-10m nearer to the surface, particularly for stable conditions
- Profiles within the MABL of heat, radiative, moisture, and momentum fluxes
- Observations of cloud fields at hourly resolution including cloud fraction, base height, optical depth, and precipitation

2.2 Extremes

All the challenges described above are exacerbated in the case of extreme events. Extreme events are generally more poorly sampled than other regimes, due to their transient nature, low frequency of occurrence, and often particularly challenging conditions, such as high winds and large breaking waves. Here we highlight three of these extremes which are impacted by the ASTZ: marine heat waves, tropical/extratropical cyclones, and atmospheric rivers. Other types of extremes associated with particular regions (e.g., coastal cold air outbreaks (CAOs)) are discussed in the associated Regions section. Our understanding of these events, including their predictability and evolution, continues to evolve, and any observational system developed to address these extreme events or others will require flexibility and continued updating.

2.2.1 Marine Heat Waves

Marine Heat Waves (MHWs), a relatively newly identified phenomenon (the first major MHW was documented in 2003), have been strongly linked to mesoscale and regional ocean and atmospheric phenomena, in particular, variability in precipitation in the Pacific and U.S. West Coast. Regional interannual variability such as El Niño-Southern Oscillation (ENSO) can play a role in the timing and location of MHWs (Holbrook et al. 2019; Capotondi et al. 2022). Downstream of the MHWs, precipitation can be affected over land (e.g., Beaudin et al. 2023), with a potential impact on drought conditions. The mechanisms driving MHWs are poorly understood, and their variability in terms of development, persistence, frequency, and other characteristics is still under study. There is some indication that MHW frequency is likely more sensitive to greenhouse gas forcing (Frölicher and Laufkötter 2018), and as such, their prevalence may be more sensitive to climatic change as opposed to terrestrial heat waves. In our changing climate, the need to understand and forecast these events and their impacts on downstream precipitation becomes more acute. For many MHW events, there are very few direct observations of the ASTZ. Several ASTZ variables have been identified as important in influencing the formation and evolution of MHWs. These include upper ocean stratification, anomalous surface freshwater flux, and changes in surface winds (e.g., Gao et al. 2020; Lee et al. 2023). The instantaneous surface heat flux, perhaps triggered by atmospheric heat waves, is likely the proximate cause, but preconditioning of the upper ocean through the OML depth appears to be an important component (Amaya et al. 2021). Connections between the evolution of the MHWs and the overlying atmospheric variability including storms are still tenuous, and much more work is needed to improve our predictions and understanding of these events.

Needed observations

- Direct, reliable, contemporaneous, and colocated measurements of interfacial flux (primarily momentum, heat, and moisture), atmospheric, and oceanic bulk parameters, including sea state, near the interface
- Colocated measurements of the ocean and atmosphere boundary layers' kinematic, thermodynamic, cloud, and precipitation parameters specified above
- Long-term and more extensive ocean monitoring, focused on temperature, wind, and stratification to realize predictability.

2.2.2 Tropical and extratropical cyclones

Tropical and extratropical storms impact safety, security, and the economy on a massive scale, disproportionately affecting socioeconomically marginalized countries, regions, and communities. Rapid intensification of tropical/extratropical cyclones, for example, remains very challenging to forecast (Trabing and Bell 2020). Observations during tropical cyclones are sparse due to the limited time and spatial scale of the storms as well as the challenge of making observations under these conditions. More timely and extensive in situ observations preceding landfall could greatly improve near-field prediction of a storm's track and intensity, which informs decision-makers and stakeholders. Most fundamentally, we lack a well-defined framework to conceptualize the ASTZ within the storm itself due to the mixed-phase environment of water, bubbles, foam, spray, and air that cannot be physically described using available theory and models. This hinders model fidelity during these events, as well as available empirical approaches to directly measure critical parameters such as momentum and heat flux, which are crucial sources and sinks of storm energy. Increasing model resolution, though helpful for resolving the small spatial scales (~ 1-10 km) of tropical cyclone eyes and eyewalls, cannot overcome basic problems with model physics and parameterizations. Rather, forecast uncertainty must be reduced by improving our fundamental understanding of the physics of the system and implementing this understanding in model parameterizations, initialization, and data assimilation.

Significant debate lingers on the role of sea spray and bubbles in mediating fluxes across the ASTZ (Veron 2015). A comparison of previous model parameterizations to lab-observed spray generation at the interface demonstrates a difference of 1 - 3 orders of magnitude (e.g., Ortiz-Suslow et al. 2016). Given the varying atmospheric and surface properties across all quadrants of a storm, parameterizations need to be developed for appropriate locations within the storms themselves. Synthesis and comparison of models and observations is a valid path forward for difficult and dangerous high-wind regimes such as tropical cyclones. For example, transfer coefficients at high wind speeds inferred by a storm-wave-ocean model (Barr et al. 2022) agree with transfer coefficients evaluated from recent observations and those reevaluated from past observations (Edson 2019; Curcic and Haus 2020). This success, however, reveals the fragility of current parameterizations.

A better understanding of mixing and wave/current generation within the OML during storm conditions is also needed. This requires an analysis of momentum flux partitioning and the magnitude of the components with height in the WOSL. Interactions between upper-ocean temperature and salinity stratification, upwelling, mixing, and storm-induced SST cooling, and its feedback to storm intensity, are not well understood despite numerous recent attempts (D'Asaro et al. 2011; Sanabia and Jayne 2020). This is especially true for large and/or slow-moving storms and in the near-coastal region, where shallow, sloping bathymetry can generate coastal upwelling or downwelling and onshore winds can drive strong vertical current shear and mixing (Glenn et al. 2016; Gramer et al. 2022). The impacts of tropical and extratropical cyclones on OHC and transport, through downward mixing and sequestration of warm near-surface water in the permanent thermocline, are poorly constrained but are potentially an important source of seasonal, interannual, and possibly longer timescale variability (Gutierrez Brizuela et al. 2023). Coincident with the need for improvement of the OML mixing is a better understanding of the MABL response to tropical cyclone-induced heat, moisture, and momentum fluxes, as well as recovery and heating following downdrafts and the impacts of other boundary layer structures (e.g., roll vortices and eyewall vortices) on the surface coupling.

Needed observations

- More comprehensive and frequent measurements of ocean temperature, salinity, current profiles (0-300 m, vertical resolution of ≤ 5 m in upper 150 m and ≤ 10 m between 150 and 300 m), surface waves (including 2-dimensional directional spectra), vertical turbulent mixing (vertical profiles of turbulent dissipation with resolution of ≤ 5 m in upper 150 m) ahead of, during, and after tropical cyclones
- Improved quantification of air-sea heat, moisture, and momentum fluxes in tropical and extratropical storms
- Direct measurement of interfacial fluxes of momentum, heat, and moisture that are reliable, contemporaneous, and colocated with measurements of atmospheric and oceanic bulk parameters, including sea state, from hardy platforms that can communicate real-time data to shore
- Colocated, simultaneous measurements of wave height, period, direction, age, sea spray, air bubbles, and foam in each storm quadrant (A key target is distributed measurements within each quadrant of the storm.)

2.2.3 Atmospheric Rivers

The horizontal and vertical transports of water vapor play an important role in the global energy and water cycle and they affect the general circulation of the atmosphere (Peixoto and Oort 1992). The main source of water vapor for the extratropics is ocean evaporation associated with the regions of large subtropical maritime highs. These moisture source regions typically have shallow MABLs whose vertical extent is limited by the dry air subsidence aloft.

There exist a wide variety of transient tropical-extratropical teleconnections, some resulting in Tropical Moisture Export (TME) events. Transient circulation patterns can cause conditions whereby the moist, tropical MABL air is directly transported to the mid-latitudes, causing heavy precipitation and strong winds and sometimes leading to explosive cyclogenesis (Knippertz and Wernli 2010).

A similar event, in which a long and narrow "river" of water vapor that is often associated with a low-level jet stream ahead of the cold front of an extratropical cyclone, is called an Atmospheric River (AR). The exact relationship between TMEs, ARs, and other similar processes like warm conveyor belts is an active area of research, as these events can occur independently of each other but also can occur in tandem (Ralph et al. 2018). ARs gain their water vapor from tropical or extratropical moisture sources and are affected by intraseasonal variability from the MJO (Mundhenk et al. 2016), interannual variability such as ENSO (Payne and Magnusdottir 2014), and even the submesoscale structure of western boundary currents (Liu et al. 2021).

ARs are the dominant source of flood damage in the Western U.S. (Corringham et al. 2019). The economic impacts attending these events; which are growing in frequency, duration, and magnitude; represent over $1B a year in damages. These events continue to deliver escalating and compounding impacts to the western U.S.. Copious rainfall from ARs has been shown to affect the surface buoyancy forcing over the open ocean (e.g., Edholm et al. 2022) and over nutrient-rich upwelling regimes of eastern boundary currents (e.g., Hoffman et al. 2022). Observational estimates indicate that latent heat flux is typically increased before the AR landfall in the broad nearshore regions, and this upward latent heat flux is further enhanced during El Niño events (Bartusek et al. 2021). Recent modeling work indicates that the method of coupling between the ocean and atmosphere can make a distinct difference in the forecasted AR and associated rainfall, with more realistic boundary conditions and evolving boundary layers in coupled models driving a demonstrable improvement (Sun et al. 2021). However, several open questions remain related to the relationship of the atmospheric and ocean boundary layer and the fluxes between them to the formation and development of ARs, and of the impact of the ARs, particularly the changes in rainfall and winds, on the OML and MABL.

Needed observations

- Measurements defining the vertical and horizontal structure of the MABL and OML in the source region of an AR as well as the boundary layer regions affected by the enhanced precipitation, storms, and winds
- Moisture of moisture flux from the ocean to the atmosphere along the AR path from the source region in the tropics to the landfalling region in the coastal oceans

Enhanced modeling capabilities of ARs may further dictate other observations that are needed as our understanding of ARs and their relationships to the ASTZ evolve.

2.3 Scales

Coupling between the ocean and atmosphere occurs across a wide variety of time and space scales (Figure 4). It is also clear that coupling between the MABL and the OML through the interface is fundamentally different at different scales (e.g., Gentemann et al. 2020; Seo et al. 2023). On the shorter and smaller time scales, diurnal changes, individual rain events, and mesoscale features like convectively driven cold pools and ocean submesoscale eddies have been shown to impact not just coupling at the scale of the phenomena itself, but also coupling and fluxes at larger scales. However, few observations at these smaller and shorter time scales exist across the globe. Measurements of the ASTZ need to sample the horizontal heterogeneity due to ocean mesoscale and smaller scale variability to validate or improve model simulations. Model simulations have continued to increase their horizontal resolutions with no corresponding observations. In general, the MABL must be observed at these same scales to understand the response of the MABL thermodynamic and dynamic structure to this surface inhomogeneity.

2.3.1 Mesoscale, sub-daily, and smaller scales

In the tropics, diurnal variability of the MABL and OML, and the fluxes between them, can impact longer-scale means and variability around the mean (Seo et al. 2014), but many operational products do not yet capture this variability. Diurnal variability outside the tropics has also been observed, driven perhaps by other aspects of the coupled system, including atmospheric and oceanic advection and turbulence (Minobe et al. 2015). Currently, the best operational observations that capture more than the SST at hourly or semi-hourly resolutions are from oceanic buoys, which have a limited vertical resolution in the OML and sample the MABL only within the lowest meters. Some variability at the diurnal scale can be extracted from drifters and Argo floats, which is useful

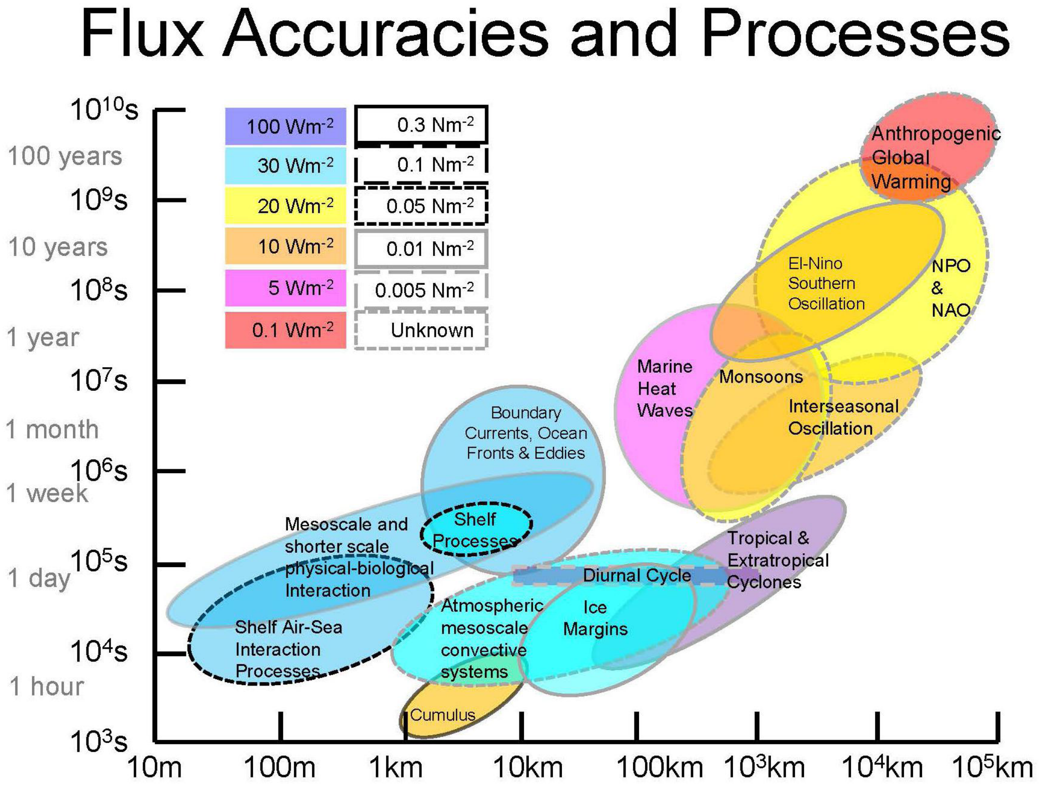

Figure 4. The scales and flux accuracy that are needed to capture various ASTZ-influenced processes. From Cronin et al. (2019).

for understanding diurnal scales of variability but not for understanding the individual processes contributing to this variability. Operational radiosondes from island stations typically occur twice daily only, but, more importantly, these observations are not able to capture the nearby, undisturbed surface or the near-surface layer due to island-caused perturbations to the MABL. Satellite observations of parameters other than SST are at coarse temporal, vertical, and horizontal resolution. Precipitation events lead to the formation of fresh lenses, which act to stabilize the upper ocean and at least initially tend to have the same horizontal spatial scale as the precipitation.

Large-scale air-sea coupling from the ocean mesoscale occurs through the MABL thermal disequilibrium and air-sea flux responses to the ocean mesoscale, influencing the circulation dynamics, energetics, and stratification of the atmosphere (Figure 5). These interactions in turn help set the large-scale SST and upper OHC that further modulates the atmosphere. More locally, semi-permanent SST and vorticity fronts and transient mesoscale and filamentary eddies perturb surface fluxes and convergence/divergence patterns in the MABL winds, driving kinematic and thermodynamic responses of the MABL. Over ocean fronts, such as the western boundary currents and the Southern Ocean, the open ocean mesoscale monthly averaged and high pass filtered wind response is estimated to be ~0.3-0.4 m/s/K. At this scale, microwave satellite

> *"Currently, the best operational observations that capture more than the SST at hourly or semi-hourly resolutions are from oceanic buoys, which have a limited vertical resolution in the OML and sample the MABL only within the lowest meters."*

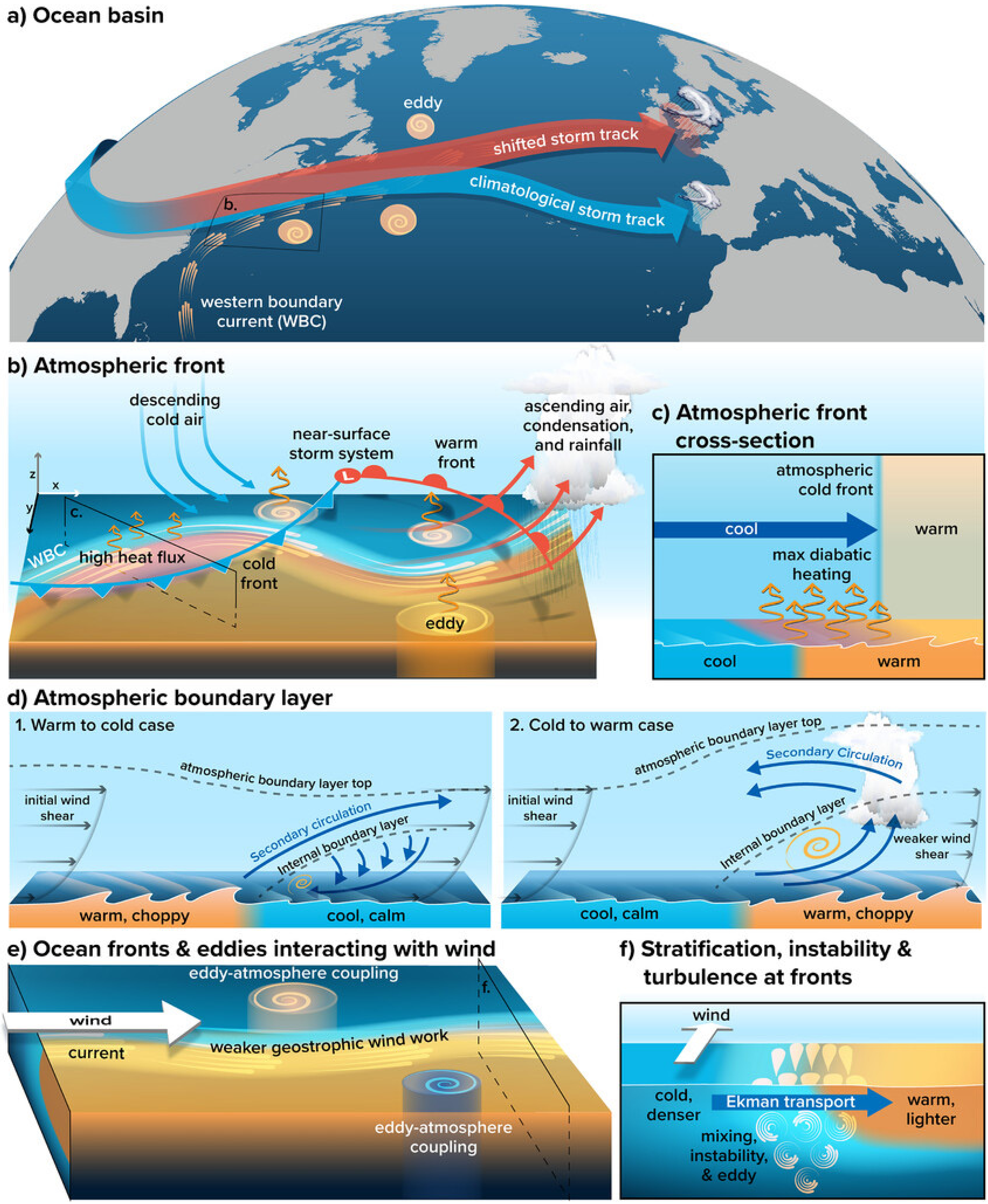

Figure 5. These schematics depict the influence of mesoscale ocean features on the atmosphere and ocean boundary layers. From Seo et al. (2023).

measurements give SST anomalies of ± 2-4 °C (O'Neill et al. 2012). At shorter scales, the anomalies are greater (Strobach et al. 2020). The MABL and air-sea flux responses are communicated to the free troposphere in the baroclinically unstable atmosphere over the western boundary currents, modifying the intensity and path of synoptic storms (Czaja et al. 2019; Seo et al. 2023), which impacts both numerical weather predictions and S2S-scale prediction (e.g., Siqueira et al. 2021).

Questions related to mesoscale, sub-daily, and finer air-sea interactions have been studied intensely over the past decade, yet there are still open questions related to the observations needed to understand and better model these phenomena. It is not yet clear what the optimal length scales of the ocean and atmosphere are that need to be measured. In the tropics and western boundary current regions, the impacts of the ocean mesoscale on the deeper atmosphere appear to be the strongest, but it is not clear which oceanic scales are most impactful on the atmosphere elsewhere. Furthermore, the depth of the interaction across the ASTZ at these scales is still unknown, and work needs to continue to determine the needed vertical resolutions and depths of thermodynamic and dynamic profiles for optimal understanding and assimilation. While the optimal temporal and spatial resolution of the measurements required is unclear, it is clear that to resolve this challenge, technological advances that provide observations at fine temporal and spatial resolution are needed to assess the effects of small-scale phenomena to ocean-atmosphere coupling.

Needed observations

- Multi-platform, coordinated measurements for a sustained ASTZ observing system at air-sea interaction "hot spots" (e.g., western boundary currents and the Southern Ocean; Todd et al. 2019), where resolving the coupling has significant impacts on the simulation of extreme weather and precipitation
- Colocated, small-scale state variables, including parameters to estimate bulk and radiative fluxes, at 10-25 km scales (i.e., cross-frontal scales of atmospheric and ocean fronts), especially over western boundary currents with strong storm-ocean front interactions. Specifically, observations are needed at fine spatial scales (< 10 km) across the fronts with contemporaneous measurements at multiple locations across the frontal regions.
- More direct covariance surface turbulence and flux estimates, including direct covariance flux systems (DCFS), along with measurements of bulk meteorology and surface waves over a range of wind and wave regimes to identify and improve areas of differences from the modern bulk formula and provide insight into the estimation of turbulence and fluxes across inhomogeneous surfaces (e.g., Pezzi et al. 2021) and over mixed sea states (e.g., Sauvage et al. 2023)
- Vertical profiles across the MABL and OML of thermodynamic and dynamic quantities, with high resolution (~0.1 m in the upper ocean and ~1-10 m in the lower atmosphere)

2.3.2 *Subseasonal to seasonal scales*

The advancement of prediction skill on S2S scales was highlighted by the ESAS Decadal Survey (2018) as one of the most important challenges of the coming decade, and recent advances in skill have increased the demand for forecasts at these lead times. Improved understanding and modeling of the ASTZ is essential to atmospheric prediction as well as disaster mitigation, marine ecosystems management, and coastal management (Subramanian et al. 2019).

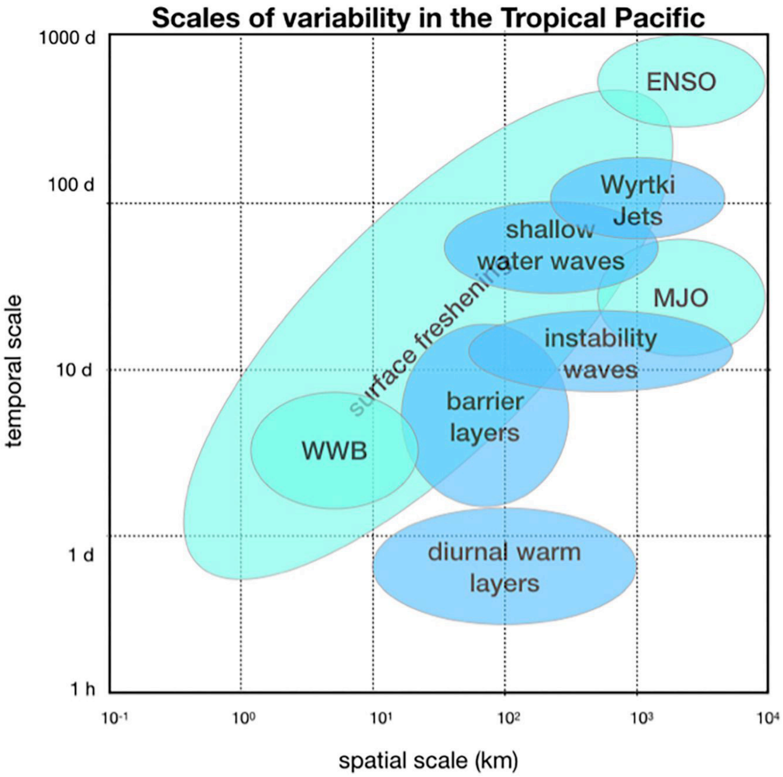

Figure 6. Schematic depicting some of the key oceanic (blue) and atmospheric (green) processes that govern variability in the Tropical Pacific. From Subramanian et al. (2019).

In the tropics, S2S variability is associated with intraseasonal variability such as the MJO and other atmospheric modes (e.g., monsoon intraseasonal variability and convectively coupled equatorial Rossby and Kelvin waves). Via tropical-extratropical teleconnections, this variability regulates the frequency of extreme weather events and other phenomena across the globe, such as coastal sea level, sea ice concentrations, and severe storms. The teleconnection patterns are initiated by latent heat released during precipitation formation. The maintenance and propagation of tropical S2S convection are affected by heat, momentum, and freshwater exchanges across the air-sea interface. Ocean and atmospheric variability on a variety of timescales can amplify or dampen the ocean-atmosphere coupling and so affect the intensity and propagation of the MJO. These time scales and processes are shown in Figure 6 (Figure 1 in Subramanian et al. 2019). Some of the processes at the shorter or smaller scales have been discussed previously and observations to improve their representation have also been described.

Progress in understanding ASTZ processes is needed to improve our understanding of the MJO. MJO maintenance and propagation hinges upon the interaction of the atmospheric boundary layer with convection and lower tropospheric moisture on diurnal-to-S2S timescales. No two MJO events are alike, and some MJO events appear to be more strongly coupled to the ocean than others (Gottschalk et al. 2013; Fu et al. 2015). Key aspects of the ASTZ related to MJO maintenance and propagation that need further observations and understanding include the effect on the growth of tropical convection due to the MABL thermodynamic state compared to that just above the boundary layer and determining the scales at which the role of ocean stratification is important for suppression, initiation, maintenance, and organization of tropical convection. Furthermore, a better understanding of how the relatively fast ocean-atmosphere coupling imprints on the seasonal spatial distribution of lower-atmosphere moisture and cloudiness is required.

Constraining key parameterized processes in models (e.g., convection, surface fluxes, and ocean mixing) requires coincident observations of the ASTZ that are temporally, horizontally, and vertically well-resolved. These observations should be collected at several key locations to sample the known changes in the spatial scale and vertical structure of the MJO as the disturbance evolves during its transit from the Indian Ocean to the western and eastern Pacific Ocean.

Previous experiments have provided valuable observations for understanding the MJO (such as the Tropical Ocean Global Atmospheres/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE) and Dynamics of the Madden-Julian Oscillation field campaign (DYNAMO)), but it is essential to collect the aforementioned, well-resolved ASTZ measurements over long periods to adequately describe the range of coupled feedbacks that are possible across the spectrum of low-frequency background states. While previous and current sustained observing systems (e.g., Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA), Tropical Atmosphere Ocean (TAO), Atmospheric Radiation Measurement Tropical West Pacific (ARM TWP)) have proven to be of tremendous value for advancing process understanding on multiple time and scales, they were not designed to provide the type of information most needed to improve prediction skill of precipitation events associated with MJO teleconnection patterns. Specifically, observations are needed that provide vertically, horizontally, and temporally well-resolved measurements of the upper ocean and lower atmosphere needed to compute ocean-atmosphere covariance statistics which will help to improve parameterizations, DA, and coupled forecast model initialization. Intraseasonal timescale tropical variability such as MJO has been connected to the predictability of the Arctic Oscillation at S2S scales (Zhou et. al. 2021; Henderson et al. 2021). A better understanding of the ASTZ in the tropics and the links to the Arctic will improve S2S predictions of Arctic circulation variability. Improvements in forecasts at S2S scales will improve storm location variability because the phase of the Arctic Oscillation impacts the meridional location of the mid-latitude jet stream and resulting storm tracks.

ASTZ measurements, including surface-to-atmosphere turbulent fluxes, in the high-latitudes will advance understanding and improve representations of atmosphere surface energy exchanges and OML processes that are critical to seasonal energy exchange (Taylor et. al. 2022). An advanced measurement system of the ASTZ therefore can improve the forecast of sea ice at seasonal scales. Seasonal characteristics of sea ice have been tied to the structure and occurrence of Arctic ARs. In the Antarctic, sea ice variations impact the meridional location of the storm track and jet stream over the Southern Hemisphere (Hobbs et al. 2016). Better S2S predictions of sea ice is therefore important for improving knowledge and prediction of Arctic ARs. These mechanisms also operate on longer time scales and influence Arctic amplification.

Needed observations

- Sustained and synchronous sampling of ocean surface properties (e.g., wave state) and vertical profiles of the tropical upper ocean and lower atmosphere, including clouds, at finer vertical and temporal resolution than is currently available
- Sampling of the diurnal cycle of air-sea coupling and MABL and OML structure

The main emphasis of these efforts should be on regions with known sources of S2S predictability, including key regions in the tropics and polar regions as global coverage is neither feasible nor strictly necessary.

2.3.3 Interannual and longer time scales

At time scales longer than one year, variability in the climate system is driven by atmosphere-ocean oscillations on the large scale, such as ENSO, the North Pacific Oscillation (NPO), the Interdecadal Pacific Oscillation (IPO), the Atlantic Multidecadal Oscillation (AMO), and the North Atlantic Oscillation (NAO). Efforts to predict ENSO provide an example of the need for improved measurements across the ASTZ. Despite the vast success of the TAO/TOGA observing frameworks, the potential predictability of the ENSO-ISO system was not realized by initializations from the present observing system. Although the TAO array samples across the basin, and satellite sea surface salinity (SSS) provides some improvement in initial conditions (e.g., Hackert et al. 2020), it appears that more resolution is needed to capture thermocline wave processes. The recent development of CDA prompts for enhancing the observing system to improve observations of the ASTZ (e.g., Penny et al. 2019).

At longer time scales (e.g., trends in climate variability), OHC is a key parameter. To assess trends in climate variability, measurements of OHC require at least annual sampling of T, S profiles to below 700 m. Budget-based estimates are more accurate than climate-scale flux-based estimates (IPCC AR6). Trends in key climate indicators such as global ocean evaporation remain uncertain even with several decades of buoys and satellite observations, with nearly all components of the parameters for flux estimation differing amongst observations and models (e.g., Robertson et al. 2020). No systematic, published synthesis of requirements specific to climate variability exists, but there are some community efforts describing the requirements for improving the ASTZ observations relevant to climate variability (Kessler et al. 2021; Cronin et al. 2019; 2022 GCOS Implementation Plan).

Needed observations

- Sampling of the tropical waveguide in the troposphere and upper ocean including sea surface height, thermocline depth, wind stress, air-sea heat fluxes, SST, salinity, currents, atmospheric pressure, precipitation, water vapor, and clouds (The Tropical Pacific Observing System (TPOS) plans for updating the tropical Pacific array with additional ASTZ parameters are an important component, as is keeping the PIRATA and RAMA observational systems.)
- More global coverage of key foundational ASTZ parameters, including the air-sea fluxes of heat, moisture, and momentum, as well as information about the OHC, and variability in the OML depth and MABL height
- Maintaining the current methods of observing these parameters, including OceanSites and Argo

2.3.4 Global observations

Energy and water cycles are essential for understanding and modeling the Earth as a physical system. The cycling of water within the Earth system and the impacts of this cycling on life, both in the ocean and on land, mean that understanding regional and global changes over time scales from storms to climate trends remains key to predictability across a wide variety of phenomena. The coupled energy and water cycles together help provide information on the energetics of the system, which remains a physical basis for our understanding of the evolution and consequences of climate variability across many temporal and spatial scales. Water vapor and cloud radiative feedback, aerosol-cloud radiative forcing, and precipitation are essentially a function of the water and energy flows across the Earth system.

The exchange of heat, moisture, and momentum, as well as greenhouse gases such as carbon dioxide, helps drive moist processes and atmospheric convection, which, when coupled to atmospheric circulation, influences precipitation patterns across the globe. Given the fundamentally different coupling across the ASTZ at different scales, observations of these surface fluxes across the globe require further investigation. Progress has been made in satellite-based observations of the surface fluxes, but much remains to be done in this respect (e.g., Robertson et al. 2020). Trends, global means, and budgets remain somewhat inconsistent between data products, and reanalysis and climate model datasets are even less similar to each other than the sparse in situ observational data sets.

A further need that will improve our understanding of the impacts of the ASTZ on weather and climate are global profiles of mean dynamic and thermodynamic properties of the MABL and OML. Argo remains key to the global dataset of barrier layer and OML depth to at least subseasonal variability; OceanSITES and other buoy datasets provide higher temporal variability in locations where they are available. However, the MABL remains severely data constrained on any kind of an operational basis. Understanding how the MABL mixes with the free atmosphere has been shown to be a constraint on understanding climate sensitivity, mainly through the influence of these turbulent processes on low cloud feedback (Sherwood et al. 2015). Resolving the height of the PBL and the cloud and thermodynamic structure across many oceanic regimes is another key challenge. We need concurrent observations of the ASTZ to address many of these questions.

While global coverage is important for budgets and other aspects of air-sea interactions, there is also a need for additional in situ air-sea flux measurement sites (e.g., Cronin et al. 2019). Currently, in situ flux measurement sites are very heavily weighted towards the tropics; other important regions identified above such as western boundary currents and other mid- and high-latitude locations remain almost completely unsampled. The needs of specific regions not thoroughly discussed previously are highlighted in the next section.

Related to this, a global site comparison of climate-related fields has revealed a distinct gap in CMIP and atmospheric reanalyses (e.g., ERA5, NCEP-2, and MERRA-2) outputs in matching observed heat flux (Weller et al. 2022; Boisvert et al. 2022). More distributed sites for long-term Ocean Reference Stations are warranted.

Needed observations

- Observations of key parameters for estimating the surface turbulent fluxes from bulk parameters, surface radiative fluxes, and precipitation (Spatial and temporal scales that are needed for resolution are discussed above but include diurnal and at least ocean mesoscale (i.e., 10-25 km) variability.)
- In situ direct measurements of the turbulent fluxes, radiative fluxes, and precipitation, as well as the bulk parameters needed to calculate bulk fluxes (i.e., surface and near-surface temperature, humidity, and winds), distributed across more of the mid- and high-latitudes, at least for calibration and validation purposes
- Additional sites in the mid- and high-latitudes for these key measurements and for providing additional validation sites for satellite observations

2.4 Regions

There are a few regions that have been shown to have a high impact on weather and climate, and where larger deficiencies in data, understanding, and modeling currently exist. Here we prioritize these regions for expanded observational needs or specific types of observations related to these regions particularly. Some of these regions have been highlighted above due to their prominence in the processes and scales that are key science questions, including the tropical Indo-Pacific warm pool, the eastern tropical oceans, western boundary current regions, and coastal areas. In addition, the high-latitude regions have other challenges, particularly related to the presence of ice and the marginal ice zones, as well as the unique characteristics of the Southern Ocean.

2.4.1 Coastal and Boundary Current regions

Coasts uniquely host littoral and estuarine ecosystems, and human populations and infrastructure, enabling activities such as fisheries, agriculture, and commerce, and exposing human systems to risks. The atmospheric boundary layer transitions as it flows from ocean to land and back, and land-sea contrasts and orography generate unique coastal atmospheric circulations. The continental shelf, river outflows, and boundaries lead to uniquely coastal ocean boundary currents and mesoscale eddies that have surface expressions felt by the atmosphere, and implications for basin-scale ocean circulations. Sea level rise is impacted by a multitude of processes including changes in ocean currents over both short and long time periods and the effects of storms and associated wave variability. CAOs bring cold, dry air from the land over the ocean and can play a major role in air-sea heat exchange and storm evolution. The near-coastal, upper-ocean density structure and atmospheric stability can strongly impact tropical cyclone intensity before and during landfall. The time and space scales of coastal ASTZ processes are often shorter and smaller than in other regions of the ocean. Recent recommendations for observations of the coastal ocean highlight these features by promoting the sustained use of autonomous platforms for high-resolution and broad-scale monitoring, as well as the use of moored platforms to measure high-frequency variability (Todd et al. 2019). The mesoscale processes described above are particularly acute along the western boundary currents with their strong SST gradients and associated eddy-rich systems. In these regions, the SST gradients can affect the MABL to the extent of fueling coastal storms and influencing mid-latitude storm tracks, and then impacting regional climate (e.g., Seo et al. 2023). The intense SST gradients are sufficiently localized that they are not well-captured by the coarser resolution of leading reanalyses

(Seethala et al. 2021). The world's eastern boundary currents are unevenly observed, and the Benguela upwelling region in the South Atlantic in particular remains poorly characterized.

Relevant phenomena and scales: 2.2 Extreme Events, 2.3.1 Mesoscale and smaller, and 2.3.2 Subseasonal to seasonal scales

2.4.2 Tropical

Large-scale tropical coupled modes of interannual (e.g., ENSO) and S2S (e.g., MJO) variability propagate about the tropics with its equatorial oceanic and atmospheric waveguides Indo-Pacific and Atlantic Warm pools, and moist convective atmosphere. The modes have important teleconnections through atmospheric Rossby waves to weather in mid-latitudes. These teleconnections influence extratropical weather, storm tracks, and extremes such as ARs and MHWs. Thus, these regions are of specific importance to variability at subseasonal and longer time scales. The life cycle of tropical moist atmospheric convection and its coupling with turbulence and moist static energy in the MABL and OML is particularly important for accurate forecasting. Capturing the entrainment at both the top of the MABL and the bottom of the OML to understand how changes in the ASTZ play a role in larger atmospheric and oceanic circulation and variability is also of key importance in this region. Current tropical observing plans (i.e., TPOS, the Indian Ocean Observing System, the Tropical Atlantic Observing System, Argo, and the island stations) remain important, but in general, additional variables need to be observed and on higher spatial resolutions than are available from these observational networks, and the coupled nature of the ASTZ emphasizes the critical need for colocated and contemporaneous measurements of both the boundary layers.

Relevant phenomena and scales: 2.2 Extreme Events, 2.3.2 Subseasonal to seasonal scales, and 2.3.3 Interannual and longer time scales

2.4.3 Mid-latitude

The mid-latitude ASTZ experiences strong seasonality in the upper ocean and land-sea temperature contrast. The mid-latitude ocean integrates the effect of westerly wind stresses. Especially in winter, mid-latitude storms are influenced by their interactions with the ocean, impacting regional weather, affecting human systems, and modulating ocean surface wind stresses, waves, surface heat fluxes, and ocean mixing to extremes. The ocean integrates and lengthens the time scales of weather and climate variability (e.g., NPO) in mid-latitudes. In particular, the ASTZ in boundary current regions is tightly coupled and appears to strongly influence much of the weather and climate variability across the mid-latitudes, but these regions also pose difficult conditions for long-term stationary monitoring systems due to the significant wind, currents, and wave actions.

Relevant phenomena and scales: 2.2 Extreme Events, 2.3.1 Mesoscale and smaller, 2.3.2 Subseasonal to seasonal scales, and 2.3.3 Interannual and longer time scales

2.4.4 High-latitude

The high-latitudes of the planet represent unique atmospheric, ocean, and surface conditions, and these conditions have changed much faster than most other regions of the planet. Weather predictions and climate projections in these regions carry large uncertainties. In high-latitude regions, understanding the ASTZ evolution is critical for producing high-fidelity models capable of informing society (e.g., Screen and Simmonds 2010; Boeke and Taylor 2018). The value of high-latitude projections and predictions is increasing, but uncertainties in our understanding of the ocean-sea ice-atmosphere system limit the realized value of these predictions. Thus, better observations of the ASTZ at high-latitudes are critical to inform projections of global sea level rise and changes to oceanic and coastal circulation, the global energy and water budgets, the seasonality and magnitude of Arctic amplification, and the carbon cycle.

The unique aspects of high-latitude regions drive the observational strategies. The high-latitude regions and the ice margins are characterized by sparse in situ and satellite observations of the ASTZ. Geostationary satellite orbits do not cover high latitudes and persistent clouds limit the use of infrared sensors to sample the ASTZ. Argo observations are not available when seasonal sea ice is present, and virtually no long-term datasets exist (Penny et al. 2019). The primary source of ASTZ measurements is ship-based field campaigns, which occur for short times and in narrow spatial regions (e.g., SHEBA, MOSAIC, Thomson et al. 2018). Reanalysis produces the incorrect sign of the sensible and latent heat fluxes at high-latitudes, so it is not adequate for estimating the surface energy budget, and satellite climatologies have significant disagreements amongst themselves and in comparison to model outputs (Gille et al. 2010). Climate models also struggle to produce observed stable air-surface temperature gradients (Boisvert et al. 2022). Surface flux schemes used in these models may not be appropriate for high-latitudes. In addition, present observations are inadequate for determining the surface radiative fluxes at high latitudes, which adds to further uncertainty of the net surface energy budget.

ASTZ processes over ice and near-ice margins are not expected to be governed by the same air-sea flux parameterizations developed for ice-free zones (Andreas et al. 2010). Complicating issues for the marginal ice region include sea ice thickness, surface type and its inhomogeneity, fractional coverage, wave-ice edge interactions, and the dynamics of the sea ice itself.

The Southern Ocean presents unique current and wave characteristics. Due to its nearly unlimited fetches, the Southern Ocean produces the largest waves on the planet (Young et al. 2020) and complex mixed sea states, which significantly influence the turbulent fluxes through modulation of the surface roughness breaking waves or sea spray generation (Babanin 2023). However, to date, there are very limited direct covariance flux measurements of turbulent air-sea fluxes in the Southern Ocean. Direct flux measurements from one Ocean Observatories Initiative (OOI) deployment in the Southern Ocean for one year demonstrate the differences in wave fields in this long-fetch region and their relationship to the drag and transfer coefficients (Edson et al. 2022). More direct covariance flux measurements will help improve the representation of the effects of surface waves and sea state in the wind stress and turbulent heat fluxes as well as ocean-side turbulent stresses in numerical models.

Needed observations

- Coincident measurements of ASTZ relevant properties and their evolution including surface temperature, lower troposphere temperature and humidity profiles, OML temperature and salinity, sea ice properties (e.g., cover, thickness, floe size distribution, snow cover), conductive heat flux, radiative fluxes, turbulent fluxes of heat, moisture, and momentum, wave state variables, and cloud properties

Measurements at turbulence time scales are needed for intensive observation periods, while measurements at daily time scales are needed to understand the synoptic and longer time scale impacts on the atmospheric thermodynamics and dynamics, clouds, surface energy budget, and sea ice. These observations need to continue for long enough to make progress on understanding seasonality, which becomes more important as sea ice is retreating, and ASTZ evolution under different atmosphere regimes (e.g., on-ice and off-ice flow). Shorter-term observations should be aimed at understanding several key mechanisms including the seasonality of upper Arctic Ocean heat content and OML depth, the interactions with sea ice, atmosphere, and energy flows, and the influence of sea ice floe characteristics and marginal ice zone atmosphere-sea ice-ocean coupling on ASTZ evolution.

2.5 Modeling and observational aspects

Our current understanding of the role of the ASTZ for predictability is from modeling experiments. Yet, these are often performed with little to no observations to either inform the simulations or evaluate processes, feedbacks, or predictions. Examples of the modeling leading the observations are in the investigations of the impacts of the western boundary currents on storms, storm tracks, and atmospheric circulation (see Section 2.3.1). Modeling resolutions are far outstripping the observational network, as there are no current arrays of in situ measurements across the western boundary currents at submesoscale to mesoscale resolution, nor are most of the surface flux parameters, OML depth, or MABL height available at the needed resolutions from satellite or suborbital assets. Thus, it is hard to either characterize or contradict the impact of the modeled ASTZ processes on the forecasts. This is only one example in which increasing model resolution demonstrates the need for observations at a higher resolution (i.e., mesoscale or finer) to provide information on the role of the ASTZ on predictability.

Models need to accurately simulate scale interactions between turbulence and the next larger scales. Convective clouds in the atmosphere and submesoscale diapycnal mixing in the ocean are at gray scales – too small to be well resolved by the model grid, yet too large to be treated as a statistical ensemble within that grid. Similar challenges exist for the marginal ice zone. Observational guidance is also needed to determine the complexity required of wave models to capture the important effects for forecasts. Superparameterization, stochastic parameterization, and scale-aware parameterizations are under development for gray scales in the ocean and atmosphere, and evaluation of all of these will need a much larger number of observations of more variety and at higher spatial and temporal resolutions than are currently available.

Modeling can also help provide information on aspects of the observational system that appear to be particularly acute for addressing questions of predictability and predictions. Our ability to observe transient events with in situ, suborbital remote, or ground-based remote platforms and sensors will in part depend on the forecast ability of the modeling system to predict key regions where enhanced observations would improve model forecast quality. Inferences made from turbulence observations rely on conditions, such as Taylor's hypothesis, that may not be appropriate in regions with strong horizontal inhomogeneities, such as those realized in high-resolution models. This argues both for the need for frequent turbulence measurements for resolving turbulent fluxes throughout the ASTZ and for new methods for combining the modeling and observations at finer scales to guide how to appropriately use the turbulence measurements within a coupled system.

In the following chapter, we outline the current observational and modeling capabilities concerning the needs we have highlighted above. We then discuss the advancements in both observations and modeling that are needed to address various aspects of the ASTZ and its role in predictability across the globe and across multiple time scales.

3 Current Capabilities and Needed Advancements

In Chapter 2, we identified observing and modeling needs for improved ESP through a variety of lenses. Through this exercise, several cross-cutting or overarching observational and modeling needs emerged. These needs can be broadly classified into three groups:

1. the need for a 3D column approach (i.e., coincident MABL, sea surface, and OML measurements, including across local, horizontal gradients) to ASTZ sampling in inhomogeneous surface conditions as well as across/along ocean surface fronts (e.g., sharp gradients of SST, SSS, surface currents, sea states or sea ice concentration) with sampling priorities that target where or when ocean-atmosphere coupled processes are poorly understood, significantly impactful on predictions, and/or poorly represented in the state-of-the-art ESP models;
2. the need for coincident measurements of surface state variables across the globe to better constrain surface flux estimates over the global oceans because of the pivotal role surface fluxes play in modulating weather and climate; and
3. the need for closer collaborations among observers, process experts, model developers, forecasters, and DA experts to coordinate observations with ongoing efforts to evaluate and improve models, make decisions about needed simulations or assimilations, develop new parameterizations, and advance coupled data assimilation.

The purpose of this chapter is to assess the current observing and modeling capabilities for addressing these needs and to identify key limitations or gaps that hinder advances in ESP. This information provides a basis for recommendations put forth in Chapter 4. Current capabilities and needed advancements are summarized in the sections below and vary according to the process, scale, and location within the ASTZ. A high-level summary of the findings is given below.

- ASTZ sampling at select locations can be improved today by equipping existing platforms with proven instruments.
- Sustained ASTZ sampling across locations representative of various circulation regimes, including challenging environments that feature sea ice and/or high winds, will require technology development for fixed platforms, including their ability to "host" or temporarily dock smaller uncrewed platforms, such as uncrewed underwater vehicles (UUVs), uncrewed surface vehicles (USVs), and uncrewed aerial vehicles (UAVs).
- For uncrewed platforms to advance, the size, weight, and power requirements of in situ oceanic and atmospheric sensors need to be reduced to enable longer ranges.
- There is a critical need for more surface-based and suborbital observations of the MABL across the globe to constrain global surface flux estimates, provide ground-truth measurements for satellite retrievals, advance CDA, and improve initializations of forecast models.
- Bulk surface flux algorithms need improvement through better understanding and representation of the effects of surface waves, currents, and atmospheric stability on the flux,

especially in regions where waves are not in equilibrium with winds, including swell, and in regions of high surface inhomogeneity.

- New strategies are needed to collect surface-based and suborbital measurements of rapidly developing extreme events (e.g., MHWs, ARs, and tropical cyclones) which often account for large fractions of total variability or seasonal mean rainfall.
- Observations are needed to advance parameterizations, including their scale dependencies, of ocean mixing, the MABL, and atmospheric convection.

3.1 Thermodynamic, kinematic, and flux profiles of the ASTZ

The need for the colocated, coincident, and sustained sampling of the ASTZ has been well-articulated by process-oriented and DA communities. For process understanding, this objective is rooted in the need for improved observations of how high-frequency ocean-atmosphere coupled processes (e.g., diurnal cycles of SST and cloudiness) are regulated by forcing on longer or larger scales (e.g., ocean eddies and subsurface currents and mid-latitude jet stream variations). For DA, this objective stems from the need to characterize error covariances and decorrelation time and space scales for ASTZ variables and to provide uncertainty estimates for assimilation records. These needs strongly motivate three flavors of a column-sampling approach of the ASTZ: (1) at a series of carefully chosen fixed locations spanning a range of dynamic regimes and environmental conditions; (2) horizontal transects across marginal ice zones and ocean surface fronts, such as those associated with western boundary currents and ocean eddying regions; and (3) targeted deployment of measuring assets for sampling short-duration extreme events that vary rapidly in space and time.

In the summaries below, sampling capabilities are assessed for different ASTZ sublayers: the MABL, the wave-influenced atmospheric surface layer (WASL), the air-sea interface, the wave-influenced ocean surface layer (WOSL), and the OML (Figure 1). Our reason for this approach is that each sublayer poses distinct observational challenges requiring sublayer-specific instrumentation, platforms, and data blending approaches. Furthermore, understanding ASTZ multiscale relationships rests on our ability to monitor variables on the fastest scales possible for long periods. The precise definition of the fastest needed scale will vary according to the process of interest, proximity to the air-sea interface, and geographic location.

3.1.1 Thermodynamic and kinematic profiling of the MABL

The need for vertically resolved measurements of the MABL was identified for multiple processes, scales, and locations in the previous chapter. Technology for in situ balloon-based measurements of MABL profiles of temperature, moisture, and winds is well-developed, as are land-based methods for remote sensing of wind profiles. Ongoing development of upward-pointing remote sensing of atmospheric temperature and moisture profiles up to 1-3 km show promise (Weckwerth et al. 2016). For land-based in situ and remote measurements, sites for stable, repeatable, and maintainable sampling are plentiful. The same cannot be said for the MABL. In the ocean domain, the practical challenges to making long-term MABL profiling measurements can easily overwhelm experimental objectives, platform capabilities, and budgets. This drives the need for remotely operated, autonomous, reusable, and/or highly durable instruments and platforms.

In the following subsections, we first focus on in situ and near-surface remote sensing MABL observations and then turn our attention to satellite retrievals of the MABL.

In situ and surface-based remote observations of MABL profiles

Given the mature state of in situ MABL profiling instrumentation, and the ongoing development of surface-based remote temperature and humidity profiling instruments, the remaining gaps for sustained in situ and surface-based remote MABL profiling are driven by the need for stable platforms, strategies to reliably ensure remotely controlled sampling, and technological advances to reduce the power demands and extend the usable lifetimes of in situ and remote sensing instruments.

Sustained fixed-site ASTZ observations require a fixed platform. Large, stable, fixed platforms are already being used by energy providers in the form of offshore barges for wind-energy and ocean drilling platforms. Such platforms could host a variety of profiling capabilities including automated radiosondes, towers, tethered balloons, upward-looking Doppler lidars, passive radiometers, and GPS receivers. They could also serve as a "home base" where remotely controlled vertically profiling UAVs and USVs could charge and then be strategically deployed to collect MABL profiles across nearby SST gradients and high wind and wave conditions, as well as a host of other instruments for sampling the full vertical extent of the ASTZ.

To sample across SST gradients, strong currents, and extreme winds and waves, observations of MABL variability require multiple platforms that can survive the conditions and house sensors to vertically profile the ASTZ. The ability of USVs to reliably collect in situ, near-surface ASTZ variables across offshore and open ocean SST fronts spanning many months has been demonstrated through multiple pilot studies over the past several years. The reliability of USVs to return continuous high-quality near-surface data in strong currents and extreme winds continues to develop. Reducing the size, weight, and power requirements of instruments raises the prospect of in situ MABL profiling from buoys, drifters, barges, and remotely controlled USVs, including profiling platforms such as balloons and UAVs.

Remote sensing lidar instruments have successfully retrieved winds from buoys (i.e., DOE lidar buoys; Shaw et al. 2020). The technological challenges to long-duration remote sensing are power consumption, range, and motion stabilization. Solving these would enable more remote sensing by Doppler, aerosol, temperature, and moisture lidars; cloud ceilometers; microwave and infrared radiometers; global navigation satellite system (GNSS) water vapor path; and cloud, rain, and wind radars from uncrewed mobile platforms. Phased-array radar profilers retrieve wind and refractive index gradients associated with inversions at the MABL top.

Direct measurement of turbulent fluxes

The technology for direct, in situ measurement of surface turbulent, radiative, momentum, and freshwater fluxes is mature. Furthermore, instrument systems used to collect these measurements have been successfully deployed on a variety of platforms. The greatest need for improving surface flux observations for ESP is to increase the number of locations where covariance flux measurements are made, including on and near sea ice, to better constrain bulk flux algorithms in conditions not comprehensively observed (e.g., over a range of wave and stability regimes and for heterogeneous surface conditions). Locations like the Southern Ocean have had only one long-term buoy with direct covariance flux measurements for one year, for instance. OOI buoys are currently the only buoys to make continuous direct turbulence momentum and sensible heat fluxes for multi-year time scales, and only at three locations. For example, collecting these observations across surface ocean fronts or broken sea ice will require instruments mounted on mobile platforms capable of quickly crossing surface heterogeneity plus downstream and upstream conditions at speeds high enough so that diurnal variations do not imprint on the cross-frontal measurements. Platforms capable of doing this in a sufficiently short amount of time before the surface and near-surface features change include UAVs and aircraft. Reductions in instrument weight, size, and power will aid these efforts. New instrument-platform combinations should also be tested carefully against current and more vetted buoy, ship, and off-shore tower arrangements. Below, we give a summary of current capabilities and needs for flux measurements.

Direct flux measurement technology has been successfully deployed on a variety of platforms, including ships, moorings, USVs, drifters, and aircraft. Despite their proven capabilities, marine surface flux measurements with direct flux systems are most commonly collected on research-quality moorings, and during process studies where ship-induced flow distortion can reduce measurement accuracy. Tested platforms for direct flux measurements with the least flow distortion include buoys (moored and drifting) and towers. Flow distortion on ships can be minimized by locating the sensors on the bow as far forward and high up as possible. Even with this careful placement, quality observations can only occur when the bow is pointed roughly into the wind (Bradley and Fairall 2006). UAVs have been shown to provide robust direct measurements of turbulent fluxes (Reineman et al. 2013, 2016; Zappa et al. 2020). Deployments of UAVs in high-wind conditions are starting to emerge, though the technology remains in the nascent stage (Cione et al. 2020).

Satellite retrievals of MABL profiles and lower atmosphere state variables

Satellite retrievals of MABL properties (i.e., MABL depth, temperature, humidity, and vertical structure) are operational and have the advantage of covering a broad spatial area. Their chief limitation is their coarse vertical resolution and accuracy, particularly of humidity. For example, the near-surface vertical resolution of temperature and humidity profiles from infrared sounders, such as the Atmospheric Infrared Sounder (AIRS), microwave sounders, such as the Advanced Technology Microwave Sounder (ATMS), and wind profile retrievals from spaceborne Aeolus Doppler wind Lidar are on the order of the convective MABL depth itself. Retrievals from GNSS-radio occultation (RO) can also be useful for planetary boundary layer studies, as the vertical resolution is higher. However, there are still issues in getting profiles under many conditions closer than 1 km to the surface. Aerosol and cloud vertical distribution information can be determined from space-based lidar observations (Teixeira et al. 2021). Space-based retrievals of MABL profiles could be enhanced by configuring radiometer payloads to optimize the vertical resolution of the MABL and improving the humidity retrieval, although such retrievals may remain challenging in regions with strong temperature inversions, such as marine stratocumulus regions.

From the perspective of "fixed location" ASTZ profiling needs, the revisit time of polar orbiting satellites, from which MABL retrievals are based, is on the order of days rather than what is needed (i.e., hours). Temporal sampling could be improved by flying multiple satellites to reduce revisit times. From the perspective of SST cross-gradient sampling, satellite retrievals of MABL profiles may be reliably collected over the span of several days, falling short of sub-daily sampling, for spatially large SST gradients, such as those associated with western boundary currents. Microwave footprints are typically too large to resolve smaller SST features like those associated with ocean eddies, especially in cases where the field is contaminated by clouds or rainfall.

Observations of near-surface temperature and humidity from satellites that are needed for bulk flux parameterizations are more difficult to obtain. Multiple techniques have been used for estimating near-surface humidity from microwave sensors since the Scanning Multichannel Microwave Radiometer (SMMR) launched in 1978. Often, a 3, 5, or 10 m value is estimated, and MOST is used to translate its position if a higher or lower measurement is needed. Global products began with the advent of the Special Sensor Microwave/Imager (SSM/I) series of satellites in mid-1987, and as additional microwave imagers and sounders have been added to the constellation they have been included in various configurations. These satellites were not designed for near-surface measurements of temperature or humidity, and, as such, regression algorithms of various kinds are used to determine their values as compared to buoys and/or ships. Near-surface air temperature is most commonly determined solely from reanalysis data, although some neural network techniques have been used to make this estimation. Similar regression techniques can be used with these same sensors to determine near-surface wind speed. Polarimetric capability allows for the determination of wind direction as well. A common horizontal resolution of the microwave estimations is 25 km, and due to side-lobe contamination generally values closer than 50 km to land or ice edges are masked out. Satellite microwave scatterometers retrieve neutral surface wind vectors, which are closely related to wind stress. Scatterometry has not been transitioned to regular operational management for weather prediction.

3.1.2 The wave-influenced atmospheric surface layer (WASL)

The WASL is a region of emerging study. This ASTZ sublayer is recognized as a region where MOST and its scaling assumptions break down due to the direct impacts of the wavy surface that were not addressable by the original theory nor present in the observations used to develop the stability functions. This includes the wave-driven partition of surface stress, wave impacts on atmospheric turbulence structure, and wave breaking. We currently lack a clear theoretical framework or comprehensive set of measurements to address these wave impacts. Our ability to measure these impacts directly using conventional techniques is limited. The impact of waves on state properties at the conventional MABL reference height of 10 meters is ill-defined and varies by wave state.

Compared to the ocean-side, observing requirements in WASL are more stringent (i.e., 10-20 Hz sampling). Since this layer can be as shallow as a few meters to as deep as tens of meters, a 1-5 m vertical resolution up to about 20 m altitude is needed. The best measurement height and the number of measurements needed is up for debate and depends on the wave state and whether the platform is surface following or fixed height with waves blowing over the top of it. It is more likely that the community will embrace any height that is feasible on multiple long-duration platforms once the turbulence and its wave-effects at that feasible level are better understood. While the same instruments and maturity levels described in Section 3.1.1 above also apply to the WASL, more stringent vertical and temporal resolution requirements can sometimes exceed the remote sensing capabilities of pulsed lidar.

In situ observations of WASL profiles

For fixed-location sampling, the WASL could be well sampled with in situ instruments mounted on a tower or mast that is fixed to a stationary or quasi-stationary platform. The ideal platform for this would be akin to the R/P FLIP, but conventional ship- or buoy-based solutions could be devised (e.g., drifting X-Spar). In certain regimes, a moored barge-like platform could be a suitable base for a mast, although flow distortion could complicate measurements. Alternatively, it is exciting to explore the possibility of profiling the WASL with UAVs. These platforms provide distinct advantages including: adaptive vertical sampling, continuous sampling with a single measurement package reducing instrument biases, and minimal infrastructure to distort the ambient conditions. Sampling by UAVs would facilitate separate estimates of the wave-induced and surface turbulent momentum fluxes. However, the unique challenges to making measurements from these platforms (i.e., battery limits and blade distortion) need to be addressed. The greatest need for WASL sampling, however, is that these measurements be collected across a variety of stability and sea state regimes, including over sea ice, implying the need for sustained measurements collected at multiple locations.

WASL profiles could also be collected as part of transects across surface ocean fronts using instruments mounted on USVs and/or UAVs. This approach could enable measurements in a wide range of conditions, including extreme wind and wave regimes, although significant technological advancement and testing would be needed.

Sea spray within the WASL

Marine aerosol and spray (MAS) production is a direct consequence of surface wave breaking. Wave breaking mechanically disrupts the ASTZ and creates a multi-phase medium through the ejection and entrainment of water droplets. The impact this has on the ASTZ, especially the flux of heat, moisture, and momentum, is a very active field of investigation and discovery. This is in part because of the distinct challenges of measuring MAS near the source in the conditions where the production volume is high enough to impact the ASTZ (i.e., very high to extreme winds at the base of tropical and extratropical cyclones). Empirical developments are largely limited to laboratory studies or aircraft measurements made in the upper MABL. Current techniques rely on direct spray imaging systems (in the lab) or light scattering techniques to count and size droplets. A miniaturized version of the latter is in discussion for mounting on USVs. Recent developments in Large Eddy Simulation (LES) modeling coupled with Lagrangian droplet models have been used to fill in for the empirical shortcomings. While this is a promising approach, these model studies lack validation given the dearth of oceanic measurements.

3.1.3 The air-sea interface

The air-sea interface is the nexus of ocean-atmosphere coupled processes. Fluxes of turbulent and radiant heat, moisture, and momentum that couple the ocean and atmosphere can be strongly affected by ocean surface temperature, freshness, and roughness as well as the overlying atmospheric stability and the vertical gradients of temperature and humidity. Consequently, to faithfully simulate ocean-atmosphere coupling using ESP models and advance process understanding and model representation of their interactions, there is a need for direct measurements of surface stress, radiation, surface heat fluxes, and surface moisture fluxes as well as direct measurement and remote estimates of atmospheric wind, humidity, temperature, ocean SST, SSS, sea surface height (SSH), total ocean surface currents (geostrophic+ageostrophic), and directional surface wave spectra. Measurements of surface turbulent fluxes, which are ideally made above the air-sea interface and WASL, are discussed in Section 4.1.2, above.

Radiative and freshwater fluxes

Surface radiative fluxes are an important component of the net surface energy budget, which drives upper ocean heating and stratification. In situ measurements of downward shortwave and IR radiative fluxes from moorings, ships, and USVs are typically collected with pyranometers and pyrgeometers, respectively, both of which are proven technologies. The need to calibrate, clean, and heat these instruments during prolonged deployments in remote environments remains a challenge. Net surface IR fluxes are estimated from SST and the downwelling IR flux. These measurements are routinely collected on only a small number of moorings but are aimed to be expanded by the TPOS and the International Arctic Buoy Programme (IABP) in the coming decade.

Rainfall is an important component of ocean-atmosphere coupling: it freshens and, when greater than evaporation, can stabilize the upper ocean, which can modulate MABL turbulence and cloudiness. Optical rain gauges and subsurface hydrophones (Passive Aquatic Listeners, or PALs; Yang et al. 2015, Bytheway et al. 2023) are the instruments of choice for rainfall measurement for their superior dynamic range and sensitivity. PALs are also sensitive to rainfall over a ~5 km diameter footprint, similar to that of satellites. However, optical rain gauges and PALs are not routinely used for sustained monitoring or even during all process studies. Instead, research-quality moorings and ship-based in situ rainfall measurements are more typically collected with less-sensitive capacitance or self-siphoning gauges. Many platforms still lack rain gauges of any type (e.g., many buoys and USVs).

Measurements of sea-surface state variables

Measurements of the sea state are crucial for understanding ocean-atmosphere coupling: SST and SSS affect buoyancy and surface fluxes throughout the ASTZ; SSH is necessary for studying ocean circulation; and ocean surface waves are the physical action that injects momentum to the ocean that affects the entire ASTZ by altering surface stress. Technologies for measuring SST, SSS, SSH, and directional surface wave spectra are mature but are platform-limited for some variables. Near-surface ocean temperature, often considered a proxy for SST, is routinely measured by in situ sensors but at depths below the ocean surface. A bulk flux diurnal warming/cool-skin algorithm is recommended for estimating the skin SST used in flux calculations. Skin SST can also be measured with downward-looking IR radiometers if properly calibrated and if they properly correct for emission from the sky and surface (Donlon et al. 2014). In situ temperature sensors are routinely mounted on buoys, USVs, and fixed platforms, but are susceptible to flow distortion. IR radiometers can be mounted on buoys, ships, USVs, UAVs, and fixed, suborbital, and space-borne platforms.

Skin SST products require no adjustments for use in bulk flux parameterizations; many products create a foundation temperature (i.e., the temperature that should exist below the diurnal warm layer). Depending on the revisit time of the satellite, the use of these foundation products requires the additional use of a diurnal warm layer and a cool skin layer model. Microwave SST measurements are at roughly 25 km spatial resolution, which is insufficient to fully characterize SST gradients across westerm boundary currents, fronts, mesoscale eddies, or anything smaller scale. IR SST measurements are at a much higher spatial resolution (i.e., < 5 km) but are unretrievable under clouds.

In situ observations of near-surface salinity, often considered as a proxy for SSS, are typically made using Conductivity-Temperature-Depth (CTD) sensors (e.g., on profiling floats, moorings, or USVs) or with ship thermosalinograph sensors. Skin SSS has been measured from space using L-band microwave sensors since the 2010s but with low revisit times. Land-based radio frequency noise limits L-band radiometers from retrieving SSS at or near coastlines where significant freshwater discharge and human impacts occur.

Shipboard or moored Acoustic Doppler Current Profilers (ADCPs) and current meters have been used to measure horizontal currents. Mooring and ship measurements are sparse. Measurements from thousands of drogued surface drifters in the Global Drifter Array have helped fill this gap by estimating near-surface currents from the drifters' positions. USVs can also provide measurements of horizontal currents at shallower depths using downward-looking ADCPs. Coastal high-frequency radars (HFR) can infer total surface currents but are limited to very few coastal regions. Remote sensing technologies based on Doppler scatterometry, optical imagery, and Synthetic Aperture Radar (SAR) are being applied to satellite mission concepts to measure total surface currents. The geostrophic component of surface currents is also derived from SSH estimates, but at a very low revisit time of ~ 9 days, so does not adequately capture mesoscale or submesoscale ocean variability or scale air-sea interaction adjustments. SWOT improves the spatial imaging capability of this small-scale variability but with a 21 day revisit time.

SSH refers to departures of the height of the ocean surface from a long-term reference height. SSH can be measured by tide gauges near the coasts, GPS-equipped surface platforms (e.g., GPS buoys), or inferred from in situ subsurface pressure sensors. SSH anomalies, referenced to the geoid, at scales larger than oceanic mesoscale, > 150 km, have been measured by satellite altimeters since 1992.

Surface gravity waves coupled with winds and currents can modify roughness elements, and thus surface fluxes of momentum and to a smaller extent sensible and latent heat. Measurements of the full directional wave spectra have great potential to advance process understanding and surface flux parameterizations but are not easily collected from all platforms. The full directional wave spectrum includes measurements of wave energy as a function of direction and wavelength. From the full directional spectra, the bulk wave quantities can be derived, such as significant wave height, peak and mean direction, peak and mean period, and characteristics of coexisting or multiple wave modes. The wave spectra and these bulk parameters are needed to better understand and parameterize the relationship of waves to turbulence in the atmosphere and ocean. Directional wave spectra can be obtained from ADCPs and accelerometers mounted on drifters or moored buoys (known as directional wave buoys) from lidars mounted on fixed platforms (e.g., the Air-Sea Interaction Tower) or aircraft, stereo and polarimetric imaging systems on fixed platforms (Zappa et al. 2008), and aircraft-mounted remote sensing Wide Swath Radar Altimeters (WSRAs). Wave-capable drifters are deployed both operationally and in research settings by private companies or deployed for research projects by a few universities and labs across the country. Ocean bottom-mounted pressure sensors are also used to measure waves but only capture the wave frequency spectrum.

While the technology to measure directional spectra at a fixed location is well-developed, wave buoys have limited spectral resolution based on the platform response characteristics and dynamic range, plus most wave sensing platforms are limited to areas near coasts, particularly along or near the U.S. coast. Thus, directional wave spectra are poorly observed in a comprehensive set of wave regimes, including open ocean conditions. Wave spectra measurements are needed in areas with strong winds, swell, mixed seas (i.e., multiple wave modes present), varying fetch, sea ice, strong currents, and in the presence of submesoscale and mesoscale current and SST fronts. Variations in sea state on small scales (i.e., ocean meso-to-submesoscale) can impact the ASTZ, which drives the need for spatially resolved wave spectrum measurements. For smaller, regional domains of interest, spatial measurements of wave spectra can be obtained from slow-moving USVs with potentially improved frequency and directional resolution compared to that available from wave buoys, drifters, or from airborne lidar, which is currently the only sensor-platform combination capable of measuring the full directional spectrum. Satellite altimeters have been providing global measurements of significant wave heights but cannot resolve the full wave spectrum and have a limited spatial resolution of > 30 km. USVs can also measure significant wave height but do not capture the full directional spectra. To advance our understanding of how the spatial variability of surface waves regulates processes within the WASL and WOSL, we need simultaneous measurements of directional waves, winds, and currents, along with other ASTZ state variables discussed herein, over a broad range of environmental and sea state conditions.

3.1.4 The wave-influenced ocean surface layer (WOSL)

The surface fluxes and WOSL are modified by the presence of surface ocean waves. However, bulk flux parameterizations and particularly their transfer coefficients are not comprehensively constrained or fully understood at high winds, > 30 m/s, or in the presence of complex wave fields containing both swell and wind waves, wave-current interactions, winds not aligned with the mean wind, and the presence of multiple wave modes. More direct flux observations are needed in these conditions. These uncertainties in observations and models limit our ability to predict or fully characterize the momentum budget of the WOSL, and therefore its influence on surface fluxes, the ocean below, and the rest of the ASTZ.

Surface waves have a mean Lagrangian transport associated with their propagation known as the Stokes drift. The Stokes drift plays an important role in the transport of physical and biochemical tracers, as well as flotsam, oil, and plastics. Although the technology to directly measure Stokes drift is not presently available, Stokes drift can be estimated from the directional wave spectrum. The interaction between current gradients and the Stokes drift leads to Stokes forces that can modify currents. These interactions also give rise to Langmuir turbulence, which enhances mixing in the upper ocean impacting the OML depth and upper-ocean budgets. Recent numerical modeling efforts suggest that parametrizing Langmuir turbulence in climate models has the potential to reduce persistent biases in modeled OML depth and improve estimations of upper OHC. However, a lack of simultaneous observations of winds, waves, and upper ocean properties hinders our ability to assess the validity of such parametrizations and better constrain the parameter space for developing improved parameterizations of surface wave interactions with fluxes and other ASTZ processes.

Vertical profiles of temperature, salinity, and currents in the WOSL do not have sufficiently fine vertical resolution near the ocean surface to comprehensively characterize the full surface budgets of near-surface ocean turbulence and buoyancy from wind, waves, wind-wave-current interactions, rain, solar heating, cooling by radiative and turbulent fluxes, and river outflow. Currently, the near-surface layer is approximated by rather rudimentary parameterizations of a “laminar sublayer.”

3.1.5 The ocean mixed layer (OML)

The amplitudes of upper ocean temperature, salinity, and momentum tendencies driven by surface fluxes are regulated by OML depth. For a given flux, a shallower OML will yield a larger tendency than a deeper OML. These tendencies affect important climatological variables such as SST, SSS, and surface currents, as well as OHC, freshwater content, and deeper ocean circulations. OML depth is the depth at which upper ocean stabilizing processes (i.e., surface heating and freshwater input) are balanced by destabilizing processes (i.e., vertical mixing driven by surface cooling, winds, waves, current shear, and subsurface turbulence as well as vertical diffusion). The processes that regulate OML depth can operate on very short timescales, seconds to hours, and can lead to similarly fast adjustments of OML depth on the order of OML depth itself.

Observational needs for the OML can be grouped into two categories: those capable of describing the OML state and those capable of resolving the processes that regulate OML depth. The former are needed for initializing coupled forecast models, generating ocean reanalysis products, and diagnosing coupled simulations. The latter are needed to advance process understanding and help validate and improve parameterizations of ocean mixing. The variables required for each type of observation are the same – vertical profiles of temperature, salinity, currents, and turbulence – and differ only in their vertical resolution requirements.

We first discuss observing capabilities for characterizing the OML state. Currently, profiles of OML temperature and salinity, and sometimes currents, are routinely collected by profiling Argo floats and at sustained mooring locations (see Figure 2). Temporal sampling at mooring locations is quite good, with hourly or 10-min data provided at some locations. The vertical resolution of profiles of the OML from these platforms, however, can be coarse, with a measurement at 1 m and then only ~10 m vertical resolution below, or a few to ten samples collected within the OML for most locations. Argo has higher vertical resolution, but, up until the last few years, Argo floats did not retain data at depths within 10 m of the surface due to sensor issues; they now report data up to 2-3 m below the surface. The planned redesign of the TPOS (i.e., Figure 3 in Kessler et al. 2021) will greatly improve vertical sampling of the OML (i.e., every 5 m), at least for the equatorial Pacific. These improvements still limit sampling of most near-surface fresh layers, jets, or diurnal warm layers. The Argo network aims for 1 vertical profile per month per 3° x 3° area. Each float collects one vertical profile approximately every 9 days in between periods of drifting with currents at a depth of 1 km and then surfacing to telemeter data. The result is approximately 4000 non-synchronized profiles of temperature and salinity profiles across most of the global oceans. Additionally, floats must be consistently reseeded in equatorial regions to maintain coverage there due to consistent current divergence in the region. Argo floats and mooring data are thus unable to resolve mesoscale and even some larger basin-scale OML spatial or temporal variations.

Profiling drifters and UUVs can help fill some of these gaps in OML observing, as they can be deployed for relatively long periods (i.e., months to years for drifters and weeks to months for UUVs). A global, spatially dense, and vertically and temporally well-resolved OML observation system is currently not feasible. A compromise approach to collecting OML observations with high temporal and fine vertical resolutions follows previous recommendations for Super Sites stationed across a number of representative circulation regimes that can host stationary fixed-location instruments and serve as a hub for recharging mobile platforms (Clayson et al. 2021; Hagos et al. 2020).

Diagnosing processes that shoal and deepen the OML requires sampling at a vertical resolution of ~1 m or less and sampling up to the surface where inputs are large in magnitude and highly variable. At a minimum, finely resolved measurements of horizontal currents are needed to compute turbulent mixing rates, while similarly dense and vertically resolved measurements of temperature, salinity, and currents are needed to estimate eddy covariance vertical fluxes of these fields. These measurements have been obtained with instruments towed from ships and fixed to the seafloor or ice.

3.2 Measurements of surface state variables across the global oceans

Surface turbulent fluxes play an important role in ocean-atmosphere coupling. The critical need for surface flux observations across the global oceans has led to the development of several global surface flux products in sea ice-free regions. These products employ bulk surface flux algorithms to estimate fluxes from inputs of surface wind from satellites and inputs of SST and near-surface temperature and humidity using varying combinations of satellite retrievals, in situ observations, or reanalysis products. While these global products all use the COARE bulk flux algorithm (Fairall et al. 1996a,b, 2003; Edson et al. 2013), or something similar, marine flux climatologies differ by more than 20 W/m2 globally and over 35 W/m2 locally (Yu 2019; Robertson et al. 2020).

These discrepancies can be traced to differences in all the state variables across the different products, how much and which reanalysis data is used, uncertainties, and time/space mismatches in non-colocated, non-coincident surface winds and near-surface temperature and humidity retrievals. Cronin et al. (2019) provide a recent summary of the state of satellite-based bulk surface flux inputs. Sources of uncertainty for surface flux inputs from satellites include insufficient sampling and/or resolution inconsistencies, especially for surface winds, currents, and SST but also for other variables, and satellite retrieval algorithms, particularly for air temperature and humidity, surface radiation, and SST. Additional sources of uncertainty are introduced when interpolating and/or coarsening inputs from disparate sources and resolutions to a common spatial grid and temporal resolution to compute the flux, which sometimes results in a single daily flux estimate from various retrievals made throughout that day but not colocated or coincident. This usage of multiple products of various resolutions, separated in space, and mismatched footprints leads to effective resolutions of much less than the microwave footprint, which can lead to significant errors (Gentemann et al. 2020).

There is a clear need for colocated in time and space, higher-resolution, satellite observations that have been optimized to retrieve the state variables to reduce uncertainties in global surface flux estimates. In addition, in situ measurements of surface state variables (i.e., SST, wind, temperature, humidity, rain rate, and sea level pressure (SLP)) across the global oceans are needed both for calibration/validation of satellite products and for inclusion in global flux products. The very few numbers of high-quality buoys for these comparisons outside of the tropics are particularly needed for winds and air temperature and humidity. Other surface variables are already widely measured with in situ sensors. The NOAA-managed Global Drifter Program (GDP) currently measures SST and surface currents, and sometimes SLP and salinity from roughly 1300 drogued and undrogued drifters distributed across the global oceans. Data are processed onboard and transmitted to satellites for near real-time distribution to modeling centers. Ships of opportunity have been used to collect the state variables and research ships collect observations of state variables during process studies or other transits.

The ability to collect colocated measurements of state variables has been demonstrated with a limited number of well-instrumented research-based drifters (e.g., ASIS, SWIFT drifters, Spar and X-Spar buoys, low-profile drifters, and "mini" buoys) and USVs. Building upon the success of these demonstrations will require new approaches for combining instruments and mobile platforms including reducing the size, weight, and/or power requirements of instruments; minimizing flow distortion between closely spaced sensors; and advancing battery technology. The success of the GDP, with its relatively low-cost payloads and broad international participation, and the recent profusion of USV technology raise exciting prospects for an affordable, durable, scientifically robust, and comprehensive ASTZ measurement array for colocated measurement of all flux-related surface variables. A global surface state observing system would dramatically increase the density of near-surface measurements available for initializing forecast models, while also providing much-needed ground-truth data for improved process-level understanding and satellite retrievals, especially in regions with large flux uncertainties and few observations. This would include nearly all regions outside the tropics; providing the current buoy systems of TAO, RAMA, PIRATA (PredIction and Research moored Array in the Tropical Atlantic), and other research buoys are maintained; where there are relatively few observations.

"A global surface state observing system would dramatically increase the density of near-surface measurements available for initializing forecast models, while also providing much-needed ground-truth data for improved process-level understanding and satellite retrievals, especially in regions with large flux uncertainties and few observations."

Consideration of the ASTZ also requires that we include not only the surface state but the MABL height and the OML depth as ASTZ key state variables. Global radiosonde observation networks (GTS and GCOS Reference Upper-Air Network (GRUAN)) profile the boundary layer over land but do not measure routinely over the ocean. Nevertheless, high-resolution radiosondes from ships and small islands help profile the MABL and determine its height in a few locations. Argo profilers are key for measuring OML depth as well as temperature and salinity structure at the base of the OML.

3.3 Modeling: parameterization, data assimilation, and experiments

In this section, we briefly summarize areas of needed model improvement for ESP. We then provide an overview of model capabilities and limitations as a function of model resolution and scale, and how these models have been applied to ASTZ science and prediction problems. For each type of modeling system, we consider what observations may be needed to address known model limitations. Finally, we review model experiments that should be incorporated during observing system design.

3.3.1 ESP limitations for the ASTZ

ESP inherently involves scales spanning many orders of magnitude. Even with ongoing advances in computing architecture, ESP relies on parameterizations to represent many fundamental processes that operate on unresolved scales. The principal model limitations for ESP identified in Chapter 2 include parameterizations of clouds, cloud microphysics, the MABL including turbulent mixing, surface fluxes (particularly under stable conditions and heterogeneous surfaces), waves, ocean submesoscale processes, and OML turbulent mixing.

Clouds and their precipitation, both within and above the MABL, affect nearly all aspects of the ASTZ through their regulation of radiative, freshwater, thermal, and momentum fluxes. Clouds are challenging to parameterize because their forms are highly variable and the processes that regulate their larger-scale organization, which further influences their effects on the ASTZ, are poorly measured and poorly understood. Clouds and cloud processes at high-latitudes are particularly challenging due to the presence of mixed-phase clouds and the vertical distribution of the condensate phase.

Turbulent fluxes of heat, moisture, momentum, and gases across the air-sea interface are driven by small-scale vertical gradients of temperature, humidity, wind, vapor pressure, and gas concentration, and thus must be parameterized in ESP models. A variety of bulk flux algorithms are used in models, and they vary substantially in the stability functions they use, in the behavior under high wind conditions, in their treatment of surface waves and wave breaking, and in their treatment of the air-sea laminar sublayer. Many bulk flux algorithms do not yet comprehensively treat wave states. Efforts to improve understanding of how fluxes are regulated by the MABL stability, how wind-wave-current interactions modify the momentum flux, and how to estimate fluxes in regions of significant surface inhomogeneity, are still areas of active research, the findings of which are needed to develop and improve bulk flux algorithms used operationally and in research settings.

Recent high-resolution coupled models suggest that the dynamic coupling between mesoscale or submesoscale currents and winds can impact the MABL directly by influencing atmospheric vertical motion and substantially impacting the magnitude of surface fluxes. It can also affect the position and strength of major ocean currents (e.g, the Gulf Stream and the subtropical gyre), which influence SST gradients and thus air-sea heat and moisture fluxes, with cascading impacts on weather, climate variability, and ocean productivity. How to represent the effects of such dynamic coupling in coarse-resolution ESP models is an open area of research that requires improved observations of mesoscale and submesoscale ocean features and their ASTZ physics.

Ocean turbulent mixing is another important subgrid scale process that needs improvement in ESP models. In open ocean areas, turbulent mixing within the surface OML is dominated by vertical fluxes. These fluxes are responsible for communicating atmospheric properties into the interior, and thus their accurate representation is critical for ESP models. Parameterizations with varying degrees of complexity have been developed to represent vertical turbulent fluxes in the ocean, including bulk boundary layer models, turbulence kinetic energy (TKE) closure, and the K-profile parameterization. However, along major oceanic fronts in western boundary current regions, vertical fluxes associated with submesoscale, horizontal scales between 100 m and 10 km, turbulence can contribute significantly to vertical fluxes and OML processes as the byproduct of the dynamical interplay between lateral density gradients and atmospheric forcing. Although many recent advances have been made in understanding and parameterizing submesoscale turbulence using high-resolution numerical simulations, only a few comprehensive sets of ASTZ observations exist for these features, making it difficult to validate the modeling results for these cases.

It is important to collect observations that allow rigorous testing and evaluation of ocean turbulent mixing parameterizations. Such observations generally require detailed and highly resolved measurements, such as those collected during field campaigns, but also include time series of measurements spanning many months or years. Collaboration among observers, parameterization developers, and data assimilation experts is needed to design observing strategies that maximize the usability and value of the observations.

Parameterization of ocean cross-isopycnal mixing is employed when the model is run using a grid spacing at which these processes are not explicitly resolved (e.g., at ~50 km and coarser). At eddy-permitting resolutions, there is no need for this parameterization, but many global models used for seasonal prediction run at resolutions where the cross-isopycnal mixing is partially resolved. This motivates the need for a "scale-aware" parameterization that allows for the appropriate level of parameterized mixing.

3.3.2 Current capabilities in modeling

This section gives an overview of the types of models used to study the ASTZ, and how models are used to transform sparse atmospheric and ocean observations into gridded state estimates for the atmosphere and ocean.

Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) models

Modeling the fine scales and small-scale physical processes of the ASTZ requires fine-resolution models that resolve most or all scales of turbulence, such as LES and direct numerical simulation (DNS), respectively. With DNS, the Navier-Stokes equations are solved directly by resolving a wide range of time and length scales, and for coupled air-sea simulations, this requires the use of interface-tracking or other multiphase methods. LES is similar but resolves only the largest eddies, which accomplish most of the vertical transport within a layer. A subgrid-scale parameterization is included to model the turbulent transfer to scales not resolved in LES. The idea behind LES modeling is that the effects of turbulence on larger scales can be understood and incorporated by explicitly resolving the dominant scales of turbulent motion. The use of LES output to develop parameterizations for use in coarser resolution models has been extensive for scaling the different terms in atmospheric turbulence parameterizations. For example, LES and DNS have been used to study the dynamics of marine stratocumulus and trade wind cumulus clouds, entrainment within the uppermost layer of marine stratocumulus cloud decks, and a range of near-surface processes, including capillary wave-Langmuir circulation interactions, and convective deepening of the OML.

LES and DNS simulations are widely used for ASTZ process understanding and parameterization development. For the atmosphere, LES grid spacing typically spans ***O***(10-100 m). Ocean resolutions range from ***O***(1 cm) for DNS and up to ***O***(10 m) for LES. Simulations capturing the full air-water coupling, including wave growth/breaking and bubble/droplet production, are becoming more common, but are limited in spatial extent due to computational requirements and are thus typically only run in idealized configurations (Wu et al. 2022). Because DNS and LES are computationally expensive, these models are typically integrated only long enough to span a few cycles of the equilibrated system to generate statistics of the resolved transports and with small spatial domains that represent only a subsample of the larger circulation regime. This implies that the simulated scales are well-separated from the forcing scale.

Models that run at cloud and eddy-permitting or -resolving resolutions

Models that run at resolutions that begin to resolve processes that must otherwise be parameterized at coarser resolution are referred to as scale-permitting or scale-resolving simulations, where the scale resolved typically refers to convective clouds for the atmosphere, and ocean mesoscale and submesoscale eddies for the ocean. Global scale-permitting models with resolutions of ***O***(3-10 km) for the atmosphere and ***O***(2-5 km) for the ocean exist, for example, some of the Dynamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) Phase II simulations are coupled, but their widespread use for understanding climate dynamics is limited by their short integration period, ***O***(months to one year), current processor speeds, and most importantly data storage and sharing technologies. Scale-resolving models with resolutions of ***O***(1 km) for the atmosphere and ***O***(10 m to 1 km) for the ocean are most commonly either global or regional in scope and are either atmosphere- or ocean-only, or coupled models that are regional in spatial extent.

Regional models and global models with regional grid refinement capabilities are useful tools for studying coupled feedbacks over larger spatial domains and longer integration periods than possible with DNS and LES but with short enough integration periods such that model drift from energy imbalances and limitations due to lateral boundary conditions is not a large concern. They are useful tools for advancing process understanding, as they provide a flexible testbed for hypothesis testing, such as "mechanism denial" experiments where certain feedbacks are inhibited to reveal their effect on, for example, cloudiness or ocean stratification and mixing. Regional scale-permitting or -resolving models have the advantage of generating less data than global scale-permitting models.

Two caveats for regional models warrant discussion. First, unlike DNS and LES simulations, limited domain simulations often intentionally span periods with evolving large-scale forcing. For these cases, the large-scale forcing for the atmosphere and ocean is applied at the domain boundaries and can substantially constrain model solutions, even during mechanism denial experiments. Idealized simulations are a less-constrained approach that avoid this complication, albeit at reduced realism, wherein the atmosphere and ocean are initialized at rest, or with constant weak forcing and integrated with cyclic boundary conditions to allow a greater degree of freedom for the model solution.

The second caveat is that balancing the requirements for domain size, integration period, and computational resources can lead to model resolutions that operate in the "gray zone." The gray zone refers to resolutions where the assumption of the separation between resolved and unresolved processes is not well justified, yet the resolution remains too coarse to be considered scale-permitting or -resolving. Despite this challenge, gray-zone resolutions have been used to study a variety of problems, such as feedbacks between the annual cycle of the Indian Ocean Wyrtki jet and the Indian Ocean dipole, the impact of the seasonal evolution of western boundary currents on mid-latitude jet stream dynamics, and the feedback between evolving Arctic cold-air outbreak clouds and the underlying ocean (Field et al. 2017; Duscha et al. 2022).

Earth system models

Here, we define Earth system models (ESMs) as global models that simulate and couple various components of the Earth system – including the atmosphere, ocean, land, and ice – at resolutions requiring parameterizations of many key processes, such as atmospheric convection, surface turbulent fluxes, ocean and atmospheric mixing, vegetation and groundwater, atmospheric aerosols and gases, and ocean biogeochemistry. ESMs are the tool of choice for studying scale interactions involving modes of low-frequency variability, such as ENSO, and for assessing changes to Earth's climate under atmospheric CO2 forcing. Global numerical weather prediction (NWP) models are a subset of ESMs and are typically run with finer spatial resolution and fewer interactive components (e.g., vegetation, biogeochemistry, and even the ocean) and for shorter durations than ESMs used for multi-year integrations.

Coupled data assimilation (CDA)

DA uses sparse observations, statistical methods, and forecast models to produce spatially-resolved state estimates of the atmosphere and ocean. DA can be applied to historical observations to generate reanalysis products or to near-real-time observations to generate initial conditions (i.e., the "analysis") for NWP and seasonal or decadal prediction models. Uncoupled DA assimilates atmospheric observations with an atmospheric model, or ocean observations with an ocean model, to produce an atmospheric or ocean (re)analysis product, respectively. For coupled models, this can lead to dynamically imbalanced coupled states and give rise to "initialization shock" in model forecasts, wherein the imbalance leads to erroneously large surface fluxes and precipitation in the first few time steps. These initialization shocks can be large enough to project onto forecast solutions and are known to degrade model prediction skill (Meehl et al. 2021).

CDA utilizes coupled atmosphere/ocean models to assimilate atmospheric and ocean observations to produce a coupled (re)analysis. CDA can be done using a "weakly" coupled approach (WCDA) or a "strongly" coupled approach (SCDA). With WCDA, a coupled model is used throughout, both to provide background or first guess fields to the data assimilation conducted independently for each fluid, to ensure the dynamical balance of the Earth system as a whole, and to indirectly allow the assimilation of one fluid to affect the other. The data assimilation, however, in WCDA uses the observations and error statistics relevant for each fluid independently. With SCDA, the assimilation of observations is done by considering all available observations and making use of error covariance statistics that span the atmosphere-ocean boundary.

WCDA is not commonly used at operational forecast centers, although most centers are developing these data assimilation schemes. It has the advantage of allowing for asynchronous assimilation across model components, driven by longer latencies of many ocean observations compared to atmospheric observations, for example. The rapid assimilation cycle for atmospheric observations combined with a less-frequent assimilation cycle for ocean observations is important for S2S, where initial conditions in the atmosphere, as well as low-frequency variability of the ocean, are important for predictions on this timescale (NASEM 2016). A key limitation of WCDA is that an observation assimilated with one component model is unable to directly affect the state determined by another component model and must rely on the coupled model to communicate that information. For example, assimilation of near-surface atmospheric temperature may affect the stability of the MABL, and thus the surface sensible heat flux, but this effect will not be communicated to the ocean directly since the ocean model only assimilates ocean variables.

SCDA brings additional challenges that have so far limited its development and use in operational settings. First, assimilating all observations with a coupled model requires synchronous, or near-synchronous, availability of observations for all component models. Many subsurface ocean measurements are not validated by quality-control measures within the time constraints needed for SCDA. Second, SCDA requires information on the cross-fluid error covariances of ocean-atmosphere variables to constrain the assimilation, and this information does not exist over many parts of the globe (NASEM 2016).

Experiments to inform observing system design

Two types of modeling and assimilation experiment frameworks have been developed for aiding in the design of and evaluation of the effectiveness of observing strategies: observing system experiments (OSEs) and observing system simulation experiments (OSSEs).

OSEs have been and remain a critical set of modeling and assimilation experiments for evaluating the impact of individual observations on assimilation fidelity and forecast skill and elucidating the relevant processes that are affected. An OSE is in essence a "data denial" experiment, wherein selected observational data are withheld from an assimilation for an experiment of some appropriate length, and forecasts initialized from this assimilation are compared with forecasts initialized from an assimilation that used all available observations. OSEs have been performed for both the atmosphere and the ocean (e.g., Fujii et al. 2019) and both weather and seasonal forecast skill evaluation. These experiments directly evaluate the impact of particular observations on forecast skill and have been used to provide detailed evaluations of the physical mechanisms by which forecast skill is improved. This strategy is critical for motivating and prioritizing the benefits of an ASTZ-resolving operational observing system. Although OSEs do not directly evaluate the potential gains in skill from proposed new observations, they provide clear metrics for improvements in skill brought by assimilating existing, but not currently assimilated, observations, and they may suggest the usefulness of additional observations of a similar nature.

Although OSSEs have not traditionally been used as part of the design of new observing systems or instruments, they provide the potential to do so. OSSEs are constructed to evaluate the potential impact of proposed new observations on assimilation and forecast skill and can contribute to the design of an instrument and/or its deployment. The OSSE system includes a data assimilation system with a model and a free-running model simulation termed the nature run, usually conducted at substantially higher spatial resolution and with a slightly different model. Synthetic observations are generated from the nature run, with some error added based on the sampling and error characteristics of the suite of existing observing systems and are expanded to include sampling from the proposed observing system. Assimilation experiments with and without the synthetic proposed observations are used to examine the fidelity of the assimilation, where the nature run is the "truth", and initialized forecasts. This provides promise for "testing" ASTZ observing system datasets for use in forecasts. As for OSEs, the comparisons of forecasts that feel the influence of the additional observations and those that do not can reveal the impact on skill as well as elucidate the physical mechanisms that contribute to the difference. OSSEs have historically been conducted generally after the new instrument is designed and have been conducted using atmosphere-only or ocean-only assimilation systems and nature runs.

OSSEs can also be leveraged for designing sampling strategies for process studies. Synthetic observations can be drawn from the nature run according to planned sampling strategies in the field. The combination of synthetic observations with measurement uncertainties from deployed instruments provides information needed to determine required sensor spacing, sampling frequency, and trajectories for unpiloted platforms to achieve acceptable uncertainty limits for quantifying state variables, their tendencies, and budget terms. For ASTZ-specific process studies, OSSEs could help determine how many UAVs, USVs, or UUVs are needed to measure variables for computing MABL and OML heat budget terms, for example.

3.3.3 Modeling and model-informed needs

Modeling needs

Parameterization of subgrid-scale processes is needed for all models used for ESP and for studying the ASTZ, regardless of resolution. In LES models of the atmosphere, cloud microphysics and small-scale turbulent mixing are still parameterized. Microphysical processes are tightly coupled to cloud dynamics and radiative heating so the details of their parameterization can influence the dynamics of LES results for the cloudy MABL. This points to the need for continued development of microphysical parameterizations and simulators for comparing modeled cloud properties to those deduced from available observations (Morrison 2020).

For gray zone resolutions, there is a need for the development and tuning of flexible scale-aware parameterizations for the processes that occur just below the resolved scale, which is nominally four times the grid resolution. These processes include atmospheric convection and ocean cross-isopycnal mixing. These scale-aware parameterizations are generally developed as add-ons to existing parameterizations to include the ability to "turn off" the parameterized process gradually as increased grid spacing allows for the process to be resolved. The community has also called for scale-aware flux parameterizations to account in part for the "mesoscale enhancement" of fluxes that are not resolved at coarse resolutions. This is an expression of a need for an entirely new class of parameterization.

An ongoing modeling issue is related to model shortcomings that are unrelated to missing or inaccurate parameterization. These shortcomings are typically addressed with ad-hoc model tuning. One such tuning, designed to optimize the NWP forecast skill score (e.g., anomaly correlation of 500 hPa height), is the artificial increase of mixing or diffusion, particularly near the surface. This increases forecast skill at the expense of structure within the atmospheric boundary layer. These types of issues need attention but are difficult to address without a coordinated effort across modeling centers.

Coupled data assimilation needs

CDA has the potential to reduce the negative impacts of initialization shock on prediction skill. A major limitation of CDA for NWP and seasonal prediction is the poor continuity of available ocean data. For example, the European Environment Agency State of Play Report (European Environmental Agency 2017) points to the lack of sustained funding for ocean observations such that ~70% of ocean data in the Global Ocean Observing System (GOOS; Moltmann et al. 2019) is funded by time-limited research projects. Additionally, many ocean observations are not used to initialize NWP or seasonal prediction models as they are not available in time for assimilation (Penny et al. 2017). There is a critical need for this data latency barrier to be reduced through improved infrastructure to reduce real-time data transmission and quality control of that data, the latter of which could potentially be accelerated with machine learning strategies.

New observing technologies that exist, including those used in instruments on SWOT, VIIRS, Sentinel A, and B, provide observations at spatial resolutions that are higher than the resolutions used in operational, global, coupled models and data assimilation systems. This points to the need for either increased resolution in the models, which is computationally expensive and perhaps beyond current capabilities, or the need for advanced data assimilation methods to take advantage of the higher resolution observations in the coarser resolution assimilation systems (Penny et al. 2019).

Finally, CDA, particularly SCDA, requires improved characterization of flow-dependent error statistics, and SCDA requires covariances of ocean-atmosphere state variables. These statistics require colocated observations throughout the ASTZ, from the top of the MABL through the depth of the OML.

OSE and OSSE needs

The ongoing efforts in many centers to develop CDA systems, along with the current availability of coupled nature runs, opens the door for coupled OSE and OSSE experiments which are needed to properly assess the impact of new and existing observing systems on the understanding and prediction of processes that occur in the ASTZ. The fundamental technology for coupled OSSEs does not exist yet, and although it is being called for in the community to assess the impact of any proposed instrumentation on S2S prediction, there is no active effort to develop such a framework at the time this report is being drafted. The initial steps toward such a capability would be the use of coupled nature runs in atmosphere- or ocean-only OSSEs.

There is also a need, once a coupled OSSE infrastructure exists, to include the OSSE experiments as part of the instrument and/or platform design. This would allow for adjustment of the sampling, accuracy, or even orbit of the proposed instrument to ensure the maximum benefit of new missions for the understanding and prediction of the ASTZ.

Programmatic needs

Climate process teams (CPTs) have been proven effective for leveraging LES and DNS, observations from process studies, and scale-permitting models to improve parameterizations. There is a continued need for such activities focused on ASTZ processes. One example of where a CPT-level activity could be particularly beneficial for ESP is the evaluation and improvement of bulk surface flux algorithms used in climate and forecast models.

CPTs for the ASTZ require members with expertise that spans ocean and atmosphere physics and dynamics as well as the diagnosis and development of coupled models. Presently, however, “vertically integrated” ASTZ expertise tends to be limited to a few subfields of interest. Similarly, coupled regional scale-permitting models are not widely used throughout the community. This is likely a reflection of the long-standing separation of atmospheric and oceanic scientific and modeling communities, which may give rise to the lack of widely available coupled models and user support infrastructure to reduce barriers to their use. With growing interest and awareness from the ESP community of the importance of ocean-atmosphere coupled processes, there is a clear need for a transition from “in-house” to community-supported regional coupled modeling efforts.

ESMs are particularly well-suited for studying scale interactions within and between different Earth system components, but daily ocean model output needs to be saved during more simulations and made more easily available to the public to advance understanding and to facilitate model diagnosis and development. Some of the higher temporal resolution output is available from atmospheric weather models. High temporal resolution output is also important to retain for the ocean. The ocean can vary on submonthly timescales in ways that are important for overlying atmospheric processes. Examples of submonthly ocean variability that can affect the atmosphere include the excitation of ocean equatorial Kelvin and Rossby waves; tropical-Pacific surface current variations induced by westerly wind bursts that affect ENSO development; the transit and evolution of mesoscale ocean eddies, fronts, and boundary currents; the formation of ocean barrier layers caused by winds and precipitation; OHC depletion by tropical cyclones; and ocean stratification by large-scale rain events. Cross-scale interactions can span the full depths of the ocean and atmosphere and include both upscale and downscale interactions. Deducing the pathways of these feedbacks, and their potential impacts on ESP, is difficult or impossible without more frequent ocean output, leading to a blind spot in model assessment efforts. The more frequent output of modeled ocean temperature, salinity, and current profiles will immediately enable more meaningful comparisons to available in situ data.

The increased spatial and temporal resolution of coupled model output and analysis data needed to advance the study of the ASTZ requires a mechanism for the centers producing such data to provide it publicly. The community shift towards open science principles is consistent with this need, but currently available mechanisms are inadequate to host such large data volumes. Either local or cloud-based data access requires a stable funding mechanism to sustain access to data products.

Ready access to existing high-resolution oceanic and atmospheric reanalysis products, CDA systems, and regional coupled models will help accelerate the use of these models and the scientific advances they can enable. In essence, the atmosphere and ocean communicate with each other regularly, and their modeling and observing research communities should too.

> *" The atmosphere and ocean communicate with each other regularly, and their modeling and observing research communities should too."*

4 Strategies and a Roadmap to ASTZ Observation and Prediction

Findings from the Study Groups review of observing needs (Chapter 2) and current capabilities (Chapter 3) point to the need for four ASTZ implementation strategies toward improving ESP. These four strategies are:

1. ***Develop observational and modeling technology for coupled ocean-atmosphere prediction.***
2. ***Observe the ASTZ in strategic regions.***
3. ***Expand observations of extremes and other challenging regimes.***
4. ***Develop a global observing network to monitor key air-sea coupling variables.***

The ultimate objective of these four strategic goals is to enhance the understanding, modeling, and observing capabilities of ASTZ processes to improve predictions of societally-relevant natural events that affect the safety, health, and economic well-being of people and natural resources. Accomplishing these objectives calls for a new paradigm for the collection, dissemination, assimilation, and aggregation of ASTZ measurements, similar to those currently in place for atmospheric soundings from twice-daily radiosondes, surface pressure measurements by the GDP, and ocean profiles from the Argo array. Achieving this will require strategic investment in technology development and data management with the aim of being expandable and adaptable to future needs and technological advances. Fulfilling the outlined strategies and realizing the full potential of ASTZ measurements requires coordination at a level that transcends any individual agency and a funding commitment that extends beyond typical research funding cycles. Finally, to extract the full value of the ASTZ measurements proposed herein, the research and operational forecasting communities should fully embrace the notion that the ocean and atmospheric boundary layers are seamlessly connected, and should be taught, observed, studied, modeled, and supported as such.

These systems for the defense of human well-being and the environment require a large investment. Environmental information systems should be designed with a new paradigm of inclusive, accessible, and flexible practices that democratize access and participation among observers, weather and climate modelers, as well as the markets and people that benefit from them. Some historic private and government investments in science have accompanied the extraction of resources and conferred benefits and risks inequitably among people. To ensure they will be used as broadly and effectively as possible, present investments in weather, ocean, and climate prediction systems should in all phases of their design include non-academic experts, persons with traditional knowledge, and historically marginalized communities. The Findability, Accessibility, Interoperability, and Reuse of data (FAIR) and the Collective benefit, Authority to control, Responsibility, and Ethics (CARE) principles are necessary to encourage protocols for efficient and open reuse of scientific data by other scientists. The effective implementation of these, and other inclusive principles drafted collaboratively with historically excluded communities, must be assessed throughout the design and implementation of the observing, modeling, and data systems.

4.1 Develop observational and modeling technology for coupled ocean-atmosphere prediction.

The vision

Skillful predictions and projections of weather, ocean, and climate will provide people with information to preserve ecosystems, optimize energy, water, agriculture, and commerce, and manage risks. The oceans store thermal energy in the climate system, which they exchange with the atmosphere through the ASTZ on a range of timescales from turbulent timescales to timescales of planetary climate by thermal heating, evaporation, and radiation. These exchanges and modes of climate variability suggest that there may be predictability in the coupled climate system that climate models have yet to clearly simulate. Through better observations and physical understanding, we will build prediction technologies, including coupled ESMs, CDA, sensors and platforms, and tools to make optimal observations and use them for initializing weather, seasonal, and interannual predictions.

How this strategy fulfills needs

1. Improving our understanding of coupled processes in the ASTZ in ways that enable us to formulate them to be explicitly resolved, and either physically or statistically parameterized, in coupled models.
2. Creating new technologies for making and using observations of the ASTZ and their covariance statistics to initialize and interpret predictions in coupled models.
3. Designing observing and environmental data systems that optimally and adaptively seek and sample predictable dynamics of the weather, ocean, and climate.
4. Catalyzing activities that connect communities of experts in CDA, model development, forecasting, observations, and process studies.

What is needed to get us there

Interagency coordination is needed to spur the development of a data collection and usage pipeline from ASTZ observations to knowledge for improving ESP. The overarching goal is the collection of ASTZ measurements for improved CDA and ESP. The knowledge generated evolves across multiple branches to improve ESP encompassing process understanding, model improvement, enhanced CDA capability, and operational observation system design.

Coupled processes and phenomena on disparate time and spatial scales increase the requirements for resolution in coupled models, and new parameterizations will be needed to bridge the scales of coupling. Scale-aware and/or stochastic parameterizations will be needed to include multi-scale interactions among atmospheric convective clouds and precipitation, atmospheric mesoscale circulations, ocean meso- and submesoscale fronts and eddies, air-sea fluxes, turbulence, and waves. Observations and idealized high-resolution LES, mesoscale, and coupled model experiments are needed to explore and understand these multi-scale processes, and interface with operational ESP model frameworks. Statistics of multi-scale interactions are needed for interpreting observations in CDA.

The design of observing systems should consider the need to develop and test CDA through the coordination of experts in CDA, observations, process studies, parameterization and model development, and data management. CDA is needed to inform modelers and observation system designers about which measurements (e.g., variables, frequencies, locations) are most needed, as well as what quality control, error statistics, and data latency requirements must be met. What existing ASTZ observations are currently most easily assimilated? What are the most effective independent observations required to validate CDA results? What existing observations are rarely assimilated and what are the barriers that prevent us from using them in ESP modeling systems?

Furthermore, developing the technological infrastructure to conduct OSSEs is a catalyzing activity for improving prediction technology and observing system design. OSSEs initialize ESP models using CDA by interrogating artificial observations from long, high-resolution coupled model "nature" runs and they can show which observations are most needed to improve predictions from ESP models. Nature runs must have predictability similar to nature to be useful. The modeling and CDA tools required for this challenging activity require investment and research.

Prediction can be improved by developing, testing, and deploying sensors and platforms that measure ASTZ state variables. More observations will be made at a lower cost by developing robust sensors on networks of unattended, long-endurance platforms. Some platforms may be autonomously piloted or remotely directed by navigational models making decisions to optimize sampling for the CDA.

4.2 Observe the ASTZ in strategic regions.

The vision

This strategy envisions a collection of multi-instrumented, fixed platforms at key sites across the globe. The objective is for these platforms to enable colocated and coincident observations across ASTZ vertical and horizontal gradients at and near these sites. Measurements should include ASTZ vertical profiles of scalars, turbulence, and radiative fluxes. Long time series (i.e., decades) are needed to capture cross-scale interactions and climate change signals. Theory, modeling, and data assimilation needs should be leveraged to define required resolutions for each set of observations. One possible configuration for this vision, generally known as a Super Site, is shown in Figure 7 (Clayson et al. 2021). Another ideal option is optimized satellite missions that can measure the full, or at least an expanded, parameter space of ASTZ variables coincidently.

How this strategy fulfills needs

1. Colocated, coincident, and sustained sampling will provide observations needed to advance ASTZ process understanding, including ASTZ processes involved in coupled cross-scale interactions, and observations to support parameterization testing. This includes expanded point measurements as well as expanded vertical profiles throughout the ASTZ.
2. Colocated, coincident, and sustained sampling will support the development of CDA methods by collecting measurements to generate probability density functions of ASTZ variables and their covariances.

3. Measurements across horizontal gradients provide needed information for CDA and for satellite retrievals of ASTZ quantities (e.g., to characterize representation errors and spatial variability at sub-footprint scales).

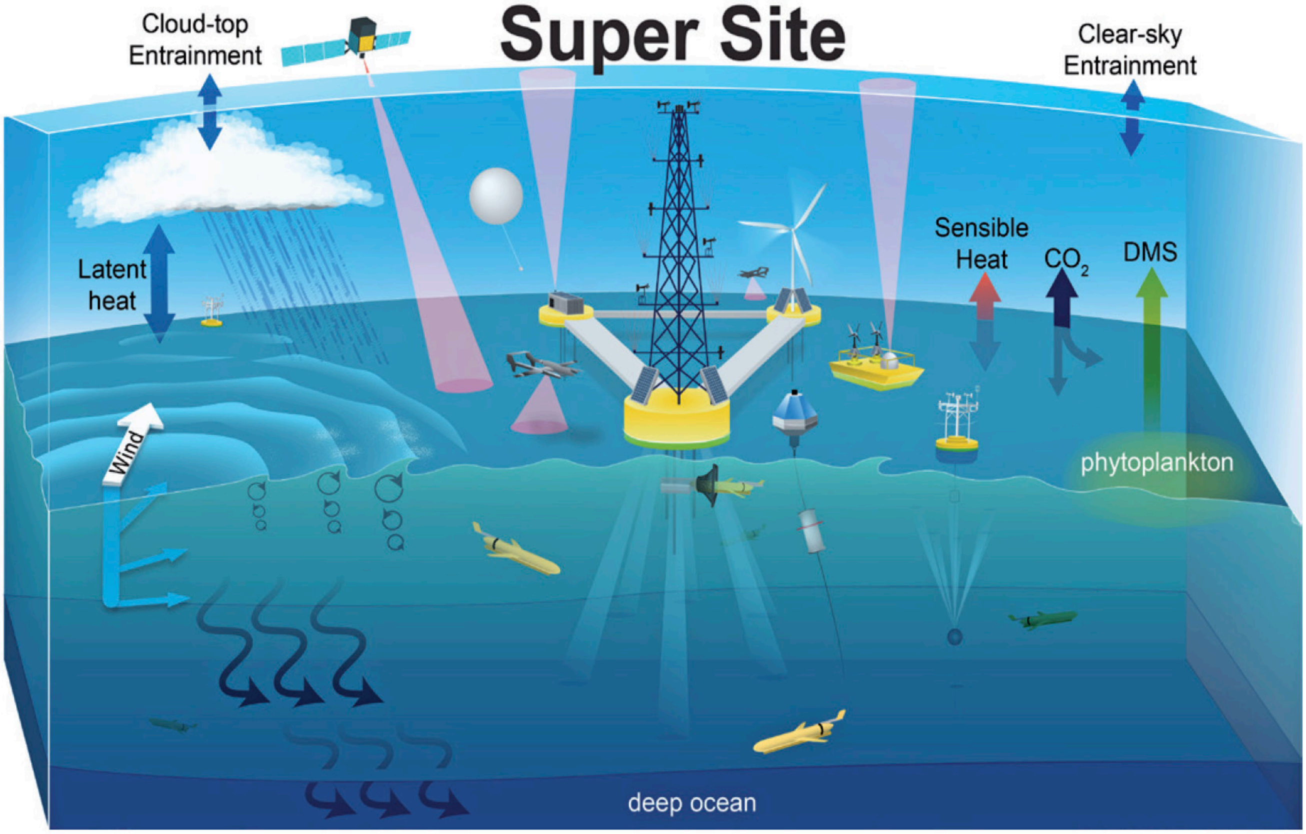

Figure 7. A schematic representing various platforms, instruments, and deployments made possible by a Super Site. This site would facilitate observations across the ASTZ with autonomous instruments that could self-dock and conduct repeat deployments in strategic locations. This schematic is for illustration and does not include the complete set of necessary measurements or variables. From Clayson et al. (2021)

What is needed to get us there

The goal of this strategy is to collect measurements to characterize the vertically resolved Eulerian evolution of the ASTZ across scales and its changes across horizontal gradients. This strategy will require improved observation of a subset of ASTZ variables that are currently difficult to measure or difficult to measure coincidently, technology development for instruments and platforms, a tiered approach for Super Site design and testing, input from multiple stakeholders for selecting Super Site locations, and satellite development.

Within the ASTZ, certain measurements are more difficult to collect, or are generally under-collected compared to others, and should be given special attention when designing Super Site measuring systems. Among these are vertically resolved state variables, turbulence, and fluxes across the sea surface and through the MABL, directional wave spectra, rainfall, clouds, and turbulence in the upper ocean. The establishment of a few Super Site platforms in key locations can support flexible measuring strategies for some ASTZ variables and processes. For example, sustained measurement of state variables at well-resolved vertical and horizontal resolutions could be paired with a more intermittent sampling of other variables, such as directional wave spectra or ocean-atmosphere turbulence profiles, during different seasons or ENSO phases. These more intensive intermittent sampling efforts could be organized as part of process studies or conducted during periodic maintenance visits to the Super Site.

Building Super Sites will require technological advances for instruments (e.g., size, weight, durability, and cleaning), platforms (e.g., stability and power generation), batteries (e.g., weight and capacity), remote operation of instruments and uncrewed vehicles, and the rapid transmission of data to modeling centers. Public-private partnerships (PPPs) with offshore energy developers should be forged to explore avenues for hosting ASTZ measuring systems on ocean-based oil or wind turbine platforms, and for leveraging platform designs for deployment in remote ocean regions. An example of one such PPP is the Gulf of Mexico Research Initiative (GoMRI). PPPs could also work toward equipping aircraft and ships tasked with transporting people and materials to offshore platforms with in situ and remote sensors to collect high-resolution ASTZ measurements. Such an approach could dramatically increase the collection of well-resolved measurements across ocean horizontal gradients.

The Study Group recommends a tiered approach to Super Site development and testing. Newly developed instruments and platforms developed for unattended long sampling periods should be tested during process studies focused on ASTZ science questions. We further recommend the establishment of one or more coastal Super Site "testbed" locations where the platform, its instruments, and any docked uncrewed vehicles can be tested for accuracy, durability, and remote operation. Such sites should be located sufficiently near shore to enable routine and as-needed visits to the site for instrument installation, repair, configuration, or retrieval. Super Site testbeds can also meet societal needs while serving as a laboratory or laboratories for instrument testing. Namely, by being in coastal locations, they can collect and transmit data that can be used for initializing and validating coastal inundation models, managing fisheries, and sampling ASTZ variables when the site is affected by extreme weather events, such as tropical cyclones, ARs, harmful algal blooms, or MHWs. The Study Group anticipates a multi-year development and testing period at Super Site testbed locations before the sites are deployed to remote locations deemed most needed for their observing capabilities.

Finally, the Study Group recommends that Super Site location(s) be selected using input from various scientific and community stakeholders. To improve ESP, sites should be selected in terms of their representation of dynamic regimes, processes, and scales most relevant to ESP spanning lead times from the subseasonal to multi-decadal. While the process understanding, model development, and CDA communities may give weight to some regimes differently from others, there is a consensus among the Study Group that regions should be selected based on their propensity for strong coupled cross-scale interactions and being poorly sampled regions that are thought to play important roles in regulating the Earth's weather, ocean, and climate fluctuations. Examples of the former include ocean eastern and western boundary currents, their respective upwelling and eddying regimes, and the equatorial Pacific Ocean. Examples of the latter include the Southern Ocean, the Arctic Ocean, the Barents Sea, the Western tropical Pacific Ocean, and marine stratocumulus and trade wind regimes. The Super Site location(s) should also be evaluated in terms of how the measurements may improve forecasts most relevant to public safety managers and the commercial sector. These considerations can help identify the Super Site location(s) that target the scales of ESP most relevant to these stakeholders. The final Super Site selection(s) should be guided by error propagation analyses and OSEs conducted in parallel with Super Site testbed research activities, with close coordination and open communication among federal agencies, researchers, forecasters, model developers, private enterprises, and indigenous and local partners.

4.3 Expand observations of extremes and other challenging regimes.

The vision

This strategy envisions the capability of rapidly deploying a targeted, coordinated set of ASTZ observations in regions of developing, high-impact, highly variable extremes. This report has highlighted several of these regimes which have a significant influence on precipitation predictions: tropical/extratropical cyclones, ARs, MHWs, and marginal ice zones. The goal is to have the technology, platforms, and operations to a technology-readiness level such that assets could be mobilized and deployed rapidly in specific regions towards an intensive campaign targeting the extreme event to augment other observations in the region. The timing, location, and types of observations should be coordinated with NWP modeling centers so that these observations can be used immediately in forecasts but also available for study and analysis after events that are spatially and temporally limited. In some cases, such as studies of the marginal ice zones, times of deployment can be determined, but changes in the spatial structure or locations will require continued changes in the deployment strategy.

How this strategy fulfills needs

The need for this approach is predicated on the idea that predictive models of synoptic-scale events can be improved by the ingestion of key variables at key times. The value of this kind of targeted observational strategy has been demonstrated by tropical cyclone campaigns, which is the closest analog to this capability that we have in our community at present.

1. The colocated and coincident sampling of extreme events is needed often in a localized source region, which can be highly variable, and often over a constricted time window to influence prediction.
2. Mechanisms driving many of these extreme events are linked to ASTZ conditions, yet relationships between the coupled boundary layers and the formation and evolution of these events are often tenuous because of the lack of observations and resulting model development.
3. Observations of coupled boundary layers for CDA and ESP are of great importance when they have been made, as evidenced by the work of the tropical cyclone community.

What is needed to get us there

A truly deployable observational program covering the full ASTZ will require substantial investment in developing new technology and systems to meet these needs, including autonomous and expendable systems for real-time data collection for forecasters and stakeholders. This effort should focus on innovations and developing synergies between existing technologies, basic research programs, and ongoing operational activities. Our ability to deploy these technologies in time to make a difference at the scale that is required will depend on many of the innovations described under the other strategies and our target observations will need to be continually evaluated as measurements under these conditions will inevitably reveal evolving needs for the observations. A key component of this is the close connection between the modeling and observational communities; a longer lead time from the models for the development of these events will improve our ability to deploy observations and the role of the observations in improving the evolving event predictions will guide future observational needs. This strategy will require sustained investment and technology demonstration programs.

Varying types of extremes will require different deployment and observational strategies. Here we discuss three distinct types of extremes, with the current status of observations and future observational aspects that will need to be developed for success. This list is not meant to be exhaustive, but rather illustrative of the types of analysis and planning that will need to be initiated for this aspect.

Tropical Cyclones

Some of the biggest gaps in TC observations are in the MABL (0-1000 m) and upper ocean (0-300 m). Hurricane reconnaissance aircraft cannot safely fly below 1000 m, so data sources are mainly dropsondes and remote sensing such as Tail Doppler Radar for 3-D winds and rainfall, Stepped Frequency Microwave Radiometer for near-surface winds, and WSRA for surface wave height and directional spectra. The remotely sensed observations from aircraft are limited to narrow swaths along the flight tracks and have larger uncertainties than in situ measurements. Dropsondes provide in situ profiles of air temperature, humidity, pressure, and winds from GPS fixes, but they are limited to single locations. Aircraft-launched floats can be deployed ahead of an approaching tropical cyclone. They can provide vertical profiles of ocean temperature, salinity, and horizontal velocity in the upper 300 m every ~2 hours, and surface wave height and spectra. Deployment opportunities for ocean floats are limited by available flight hours and storage space on the aircraft. The use of airborne expendables is usually limited by cost, so any effort to reduce their cost or miniaturize the units would advance ASTZ goals greatly.

Established and emerging uncrewed technologies can potentially fill some of the observational gaps. Underwater gliders are remotely operated and provide temperature and salinity profiles with adaptive sampling. However, they move slowly (e.g., < 0.5 m/s), so they cannot be effectively moved into the paths of approaching tropical cyclones and cannot be air-deployed into tropical cyclones. Small uncrewed aircraft systems (sUAS) are deployed from hurricane aircraft to measure the atmospheric boundary layer for hours at a time. Development of a long-range, ~24-hr duration, land-deployed sUAS is underway and could potentially open new opportunities for observations in tropical cyclones. USVs can measure the near-surface atmosphere and upper ocean in tropical cyclones. Except for gliders, which are technologically mature, sUASs and USVs are in the intermediate stages of testing: they have successfully returned data from within major hurricanes (category 4 for USV and category 5 for sUAS), but the quality of the data is under investigation and further work is required to ensure consistent performance in extreme conditions. Pursuing the advancement of all these uncrewed technologies in parallel is important because the strength and revolutionary power of these data will be multiplied when multiple vehicles can operate in the same location at once, hence measuring the full depth of the ASTZ.

To make rapid progress on some of the most challenging problems related to TC research and prediction, a significant increase in observations in the ASTZ is required. This can be achieved through a combination of approaches:

1. Enhanced observations from hurricane reconnaissance aircraft by developing cheaper and smaller air-deployed profiling floats to profile to upper ocean ahead of, during, and after a tropical cyclone and through the development of dropsondes that measure atmospheric variables and oceanic variables.
2. Continued investment and testing of uncrewed systems (i.e., USVs, sUASs, and gliders) to capture continuous, colocated observations of the ocean and atmosphere throughout a tropical cyclone.
3. Optimization of existing sustained ocean observing systems by adding ocean temperature, salinity, current, and direct covariance flux sensors to meteorological buoys in tropical cyclone prone regions.

The Arctic

The Arctic is changing rapidly and the response of the Arctic climate to anthropogenic forcing is strongly dependent on the evolution of flux exchanges within the ASTZ. The marginal sea ice zone is a specific area where higher resolution and systematic measurements are needed to advance ESPs by improving the modeled representation of ocean-sea ice-atmosphere coupling.

The measurement of ASTZ properties, characteristics, and their evolution using a rapid deployment approach would represent a substantial advance in our understanding because ASTZ evolution in the marginal ice zone during these seasonal transition events is poorly constrained as very little data exists. These data would result in a substantial increase in the available statistics on the ASTZ and would improve NWP models as well as climate simulations of Arctic Amplification as the structure of the stable boundary layer and its forced evolution is poorly represented in both cases. This approach would also benefit from a related modeling capability where NWP centers routinely produced CAO and AR metrics and visualizations to inform deployment decisions and continuous model evaluations.

There are several specific cases where a rapid deployment capability would enable key advances. This capability could be used to provide multi-day observations of air mass evolution for CAOs and moisture intrusions via Lagrangian trajectories and it would represent a new capability that would revolutionize our understanding of air mass evolution, a critical process to Arctic Amplification. A rapidly deployable ASTZ observing system could provide data to study the evolution of the ASTZ after a strong calving event in either polar region, a strong Arctic sea ice export event, or the opening of a large polynya. Arctic cyclones have strong influences on the sea ice evolution and have seasonally dependent impacts. Observing the sea ice evolution after a strong cyclone (e.g., August 2012, which drove the record low September sea ice cover) also represents an important case study or target of such a system. One could imagine an NWP system predicting a record Arctic cycle in the next week and then wanting to deploy to observe the "aftermath" and associated ASTZ evolution. The rapid deployment capability could also be used to explore the evolution of large algal blooms in the marginal seas.

Technologies that will need to be enhanced or developed include:

1. the improvement of sea ice and ocean buoy technologies to enable rapid deployment (e.g., dropping from aircraft),
2. the development of uncrewed systems to enable operation throughout the marginal ice zone ASTZ,
3. the advancement of technologies that enable high-resolution mapping (~10 meters) of snow and sea ice layer's thicknesses, and
4. the development of instrumentation to operate within the Arctic environment to avoid freezing over.

Atmospheric Rivers

As detailed in Chapter 2, much is still unknown about how ASTZ processes such as enhanced evaporation, atmospheric water vapor variability, and ocean mixing play a role. The strategy and need for rapidly deployable observations will evolve as observations are studied and models are improved.

The impact of rapidly deployed observations by some hurricane reconnaissance aircraft (i.e., Air Force and NOAA) for the surveillance of AR in the Pacific Ocean has strongly improved the forecast of landfalling events (Ralph et al. 2014; Wick et al. 2013; see also https://cw3e.ucsd.edu/arrecon_overview/). Since 2016, the number of intensive observing periods and associated dropsondes has increased by a factor of 13 and 5, respectively. Given the growing prevalence of ARs, this program should be supported at an enhanced level.

Monitoring of the entire atmospheric column, including ASTZ through the troposphere, has been vital for improving forecast skill (e.g., Ralph et al. 2014). Alternative platforms like UAVs should also be considered as part of the observing strategy, along with autonomous ocean-going vehicles and buoys that can observe oceanic variables such as temperature and sea level pressure.

In addition, the advent of coastal AR Observatories to measure Doppler wind and column-integrated water vapor along with other parameters across the ~400km wide AR structure could be extended to include offshore floating installations. This would allow for better surveillance of AR structure in advance of landfall.

The extension of monitoring systems to broader regions of the ocean is warranted given the growing risks of extreme AR under human-induced climate warming. These areas include the West Pacific, South Pacific, and South Atlantic. Additional monitoring in these locations to identify precursor conditions could yield better predictive skill further in advance and help identify the role of ARs in episodic meltwater release at the poles. The combination of enhanced global observations with significant deployed resources will be key to improving representations of these extreme events.

4.4 Develop a global observing network to monitor key air-sea coupling variables.

The vision

Distributed networks of sensors sampling ASTZ state variables are needed to estimate surface fluxes of heat, moisture, momentum, and radiation over the global oceans. Measuring these fluxes encompasses enthalpy and buoyancy fluxes, as mentioned in prior sections. These fluxes are needed to constrain coupled problems in large-scale weather, ocean, and climate. The heat fluxes regulate Earth's energy balance including heat transport and storage throughout the globe in both the atmosphere and ocean. Moisture fluxes are the primary source of water vapor into the atmosphere and sources for forming clouds and precipitation in the atmosphere. Momentum fluxes must be observed for understanding the surface forcing driving ocean circulations that affect seasonal to interannual climate variability.

The key state variables are OML depth, temperature, current vector, and salinity, and MABL temperature, humidity, wind vector, and height. The state variables of OML depth and MABL height indicate, to first order, the responsiveness of the coupled ASTZ to forces from either the ocean or the atmosphere (i.e., the depths over which mixing has occurred). These depths and heights are highly consequential because they determine, for example, whether a cloud will form or whether water from the thermocline or deeper ocean will be entrained upward into the ASTZ. For that reason, the heights and depths of the critical sublayers that are contained within and define the OML and MABL are of great interest: the atmospheric mixed layer, subcloud layer, lifting condensation level, and inversion, as well as the oceanic near-surface stable layers, barrier layers, and pycnocline. Turbulence (i.e., turbulent dissipation rate) in both the OML and MABL is also valuable to measure when and where possible to proactively measure change between these layers of the ASTZ, as opposed to simply monitoring ASTZ state variables and assuming what change or mixing might have occurred between time steps or between certain layers. Many subgrid-scale parameterizations in ESP models use modeled turbulence estimates to determine how the scheme should behave. Gaining measurements of turbulence and the ASTZ state variables it affects would help validate and improve these essential subgrid-scale ESP model components.

Though we emphasize the state variables essential to surface fluxes and between the OML base and the MABL top, observations of properties at the edge of the ASTZ may also be strategic and available. For example, the MABL may be capped by an inversion and entraining free tropospheric air from aloft, or it may alternatively be coupled to clouds with an observable fraction and base height. The OML may entrain cold water from a thermocline, or even warm dense water from a barrier layer below a pycnocline. Significant ocean memory exists in the deep ocean and thermocline so the OML's interaction with these layers must be captured. All these processes influence SST, ocean circulation, and the ocean's ability to store or provide heat and freshwater to the atmosphere through fluxes.

How this strategy fulfills needs

Key gaps of existing global observations to be addressed are MABL height, air near-surface temperature and humidity, and ocean wave and current vectors. Air surface temperature and humidity constrain the sensible and latent heat fluxes. This constrains the sources of water vapor in the atmosphere, itself an important radiative absorber, as well as being coupled to clouds and precipitation. Combined with vector winds, ocean waves and currents improve estimates of surface momentum flux and ocean circulation, which is critical for seasonal and longer climate variations. Enhanced estimates of global surface heat, moisture, and momentum fluxes by filling these two key gaps will play a crucial role in validating and improving ESP.

What is needed to get us there

Sustaining existing assets and networks of observations is the first step toward this strategy. Networks must also increase the density and improve the spatial distribution of observations to measure in under sampled, divergent places. Observations from long-term projects anticipated to end must be continued by missions coordinated among agencies. Excellent existing observing capabilities are provided by operational and research networks, including satellites, moored buoys, drifters, and profiling floats.

Existing satellites provide broad global coverage near the resolution of global circulation models with quasi-daily sampling (e.g., 10 minute to multi-day sampling repeat periods, depending on the vehicle and variable) of SST, wind speed, near-surface humidity, near-surface temperature, and various precipitation, cloud, and column integrated water vapor fields. Surface wind vectors, SSH, and salinity are also available from a handful of research missions. The ability to accomplish continuous monitoring from these missions is tenuous, as they lack a plan for coordinated succession to operations. Although the lower troposphere is responsible for much of the integrated water vapor, vertical resolution from existing microwave sounders aboard satellites is too low to resolve the MABL temperature and humidity sufficiently well to estimate surface heat and moisture fluxes.

ASTZ state estimates also rely on networks of in situ observations, some from volunteer ships, yet mostly from autonomous platforms and vehicles. Some existing moorings measure all the colocated variables needed to estimate the radiative and turbulent fluxes at one location (Cronin et al. 2019). These assets provide coherent, colocated observations in the ocean and atmosphere and are important not only to estimate fluxes observationally but to verify and improve covariance and phase relationships between the atmosphere and ocean in models.

In addition to meteorological buoys, there are drifting surface floats, profiling ocean floats, and USVs that measure ASTZ state variables. Surface wave spectra are measured from moored and drifting surface buoys but are not available on all platforms. Drifting surface floats measure SST, and often sea level pressure and wind. The nearly 4000 Argo profiling floats observe vertical profiles of ocean temperature and salinity. They are thus the essential suites of measurement for estimating the OML depth and are worthy of expansion to operational networks. At a minimum, these networks must be maintained in the future.

Proposed satellite missions would fill key gaps in existing measurements of the ASTZ state variables. The Butterfly mission proposes to simultaneously measure near-surface MABL temperature and humidity and would be the first satellite mission designed to do so; it will also simultaneously measure all other parameters needed to calculate the air-sea heat and moisture fluxes at high-resolutions. The ODYSEA mission proposes to simultaneously measure winds and ocean surface currents. These would enable frequent estimation of heat, evaporation, and momentum fluxes over broad areas of the world oceans.

Sensor suites on autonomous platforms may be extended and validated to measure more ASTZ state variables coincidently. With further sensor development, air temperature and humidity could be measured near the surface in situ by floats. Current autonomous profiling and surface floats usually measure SST, validating satellite remote SST retrievals. At times, the SST sensors on surfacing floats measure air temperature by opportunity. Despite the value of independent air temperature measurements, these measurements are not currently validated and used operationally. Another advance in technology that could be added to more measurement platforms is subsurface hydrophones, such as PALs,(Yang et al. 2015, Bytheway et al. 2023) that measure instantaneous rain rate over a surface area about five times wider than their depth. PALs can also measure wind speed when it is not raining. Engineering advances are needed to operationalize the research-grade PALs and deploy them more regularly on ocean platforms.

Outside of short intensive research campaigns, MABL height or any MABL vertical profiles are more challenging to measure with existing ocean platforms. Radio and light backscatter determine inversion heights and lidar backscatter locates gradients in aerosols, turbulence, or cloud base. Lidar can be used for moisture and 3D wind monitoring in the MABL. The infrared and passive microwave can be used for temperature and moisture profiling. The size and power consumption of these MABL remote sensing systems have usually precluded their use on unattended platforms. Investing in opportunities to harden and miniaturize such remote sensors to run for long unattended deployments, and to adapt existing or design new platforms with sufficient space, buoyancy, and power to run them, would vastly improve the possibility of measuring MABL height and vertical profiles of state variables in more locations over the oceans.

Rarely are all the key ASTZ state variables measured at the same time and location. Data analyses, using CDA and models trained to reproduce the physics and statistics observed at intensive sites with colocated observations are needed to fill gaps between the relatively sparse global observations we have currently. These analyses are needed to combine, to a consistent grid, ASTZ observations made at different times and places on satellite swaths, at fixed sites, and by drifting assets.

Robust low-cost autonomous observations, some remotely or auto-piloted, will play an increasing role in ASTZ observing networks. As an added benefit, autonomous vehicles can be piloted adaptively to target phenomena of interest. Strong ocean currents or either a lack or excess of winds sometimes steer certain uncrewed vehicles off course. Automated or manual guidance can help accomplish these adaptive sampling goals and help overcome these logistical challenges. For example, wind and current analysis from ocean density profiles, scatterometers, and altimeters could be used to direct floats to sail or dive to depths where eddies can more easily direct the platforms towards areas of interest and away from lines of convergence.

4.5 The Roadmap

In this section, we present roadmaps for steps that should be taken to fulfill each of the four ASTZ strategies. The roadmaps include short-term (0-2 years), medium-term (3-5 years), and long-term (5+ years) action items, which are intended to be sequential. In other words, short-term steps should be completed first, then medium-term, and then long-term steps.

1. ***Develop observational and modeling technology for coupled ocean-atmosphere prediction.***

   Short-term:
   - Hold a workshop to identify needed ASTZ measurements for CDA and process understanding, including the technology development needs (i.e., instrumentation and platforms) and data management needs (i.e., reduced latency and dedicated observations) to support those measurements.
   - Organize research to advance CDA capabilities.
   - Organize CPTs for scale-aware parameterization development for atmospheric boundary layer convection, surface fluxes (including surface wave and ice margin effects), and ocean cross-isopycnal mixing.

   Medium-term:
   - Test newly developed scale-aware parameterizations in a hierarchy of model configurations.
   - Assess the performance of new parameterizations and CDA strategies in S2S forecasts.

   Long-term:
   - Incorporate new parameterizations and CDA methods into operational forecast models (i.e., R2O activities).

2. ***Observe the ASTZ in strategic regions.***

   Short-term:
   - Pair existing sustained platforms with existing technologies to enhance ASTZ sampling across regimes and scales with an emphasis on MABL height, near-surface air humidity and temperature, and ocean vector winds and waves.
   - Initiate a program for technology development and testing with a focus on instrument size, battery weight reductions, and vehicle adaptations for long deployments (i.e., UUVs and UAVs).
   - Create ASTZ testbed sites by leveraging existing, accessible near-coastal sites for technology testing (i.e., surface-piercing towers and autonomous vehicle docking).
   - Initiate PPPs to identify available sites and adaptable technology for Super Site platforms for sustained Super Sites.

   Medium-term:
   - Test and refine ASTZ measuring instruments at coastal ASTZ testbed sites.
   - Coordinate with planned field campaigns to test newly developed ASTZ measuring instruments.
   - Leverage PPPs to expand locations, platforms, and vehicles for testing and collecting ASTZ measurements (i.e., aircraft, ships, and platforms affiliated with offshore energy production).

   Long-term:
   - Develop open ocean ASTZ Super Sites, beginning with the tropics, then moving to more challenging locations.

3. ***Expand observations of extremes and other challenging regimes.***

   Short-term:

   - Create ASTZ testbed sites by leveraging existing, accessible near-coastal sites for technology testing (i.e., surface-piercing towers and autonomous vehicle docking).
   - Initiate a program to develop or enhance sensors and platforms for key variables in extreme conditions, such as polar locations.
   - Initiate a program to develop additional instrumentation for air-deployed ocean surface and ocean profiling floats.
   - Test range and capabilities of AUVs for these challenging regimes.
   - Develop the modeling and assimilation communities for predictions, observations needed for improvements, and parameterization development.
   - Coordinate with satellite observing and CDA communities to identify needs for satellite observations and assess their priorities and values.

   Medium-term:

   - Test sensors for key variables in extreme conditions at coastal ASTZ testbed sites and in field campaigns of opportunity.
   - Test air-deployed ocean surface floats, autonomous vehicles, and other platforms as developed under this program.
   - As measurements come online, assimilate them into CDA models and test improvements and changing needs.

   Long-term:

   - Develop and maintain a suite of rapid-deployment vehicles and instruments to provide observations needed for CDA in regions where extreme events are thought to be imminent.
   - Improve CDA capabilities to take advantage of new observations.
   - Expand and enhance platforms, sensors, and models as observational and modeling needs are further developed. Continuous refreshment of the deployment needs is needed.

4. ***Develop a global observing network to monitor key air-sea coupling variables.***

   Short-term:

   - Coordinate and maintain existing observational networks and strategies (i.e., Argo, global moored and drifting arrays, and TPON recommendations).
   - Assimilate ASTZ data from existing satellite missions and moored arrays into operational models and reanalyses.
   - Develop and improve the parameterization of fluxes from ASTZ state variables.
   - Maintain coverage of satellite missions, buoy networks, and float networks observing key state variables for air-sea fluxes.
   - Initiate programs to develop sensors to routinely measure coincident ASTZ state variables missing from global satellite and in situ observations (i.e., near-surface air temperature, humidity, and ocean currents).

- Inform the observational strategy with deficiencies in ASTZ reanalysis (i.e., accurate flux estimation, near-surface state variables, and conservation of heat and momentum across the interface).

Medium-term:

- Design remote sensing of key ASTZ state variables for fluxes. Determine wavelengths for passive and active remote sensing.
- Demonstrate sensors for atmospheric near-surface temperature and humidity.
- Test observing technology during process studies.
- Develop sensors for state variables for deployment on existing in situ and remote sensing platforms.
- Test adaptive and autonomous sampling techniques.
- Assess the effects of ASTZ variables on prediction. Demonstrate prediction with OSSEs.
- Initiate programs to develop sensors to measure MABL height and OML depth as well as surface wave directional spectra.

Long-term:

- Improve existing platforms and develop new platforms to better sample ASTZ variables, including capabilities to measure more ASTZ variables coincidently or throughout vertical profiles.
- Optimize, scale, and deploy newly engineered platforms or vehicles for collecting global operational observations.
- Launch satellite missions to measure ASTZ state and flux variables coincidently.
- Combine remote sensing observations, in situ observations, and models to estimate fluxes across the interface and throughout ASTZ vertical profiles.
- Demonstrate the ability of MABL height and OML depth sensors. Assess model representation of ASTZ responsiveness to fluxes and MABL height and OML depth measurements.
- Assess sampled and unsampled variability of ASTZ variables and quantify their impacts on weather, ocean, and climate models.

4.6 Conclusions

This study provides the motivation and strategies for implementing a revolutionary ASTZ observing and modeling system within the next decade that will accelerate improvements in ESP by exploiting predictability arising from coupled air-sea interactions. The conceptual advance at the core of the strategies toward improved observation, modeling, and understanding of the ASTZ is that the lower atmosphere and upper ocean behave as one unified system rather than two separate systems that meet at an interface.

Useful ESP at longer lead times requires coordinated national interagency- and international-scale systems for observing, data management, and numerical prediction. Many individual research projects have observed and helped advance understanding of specific ASTZ processes. Fewer projects have observed the atmospheric and oceanic boundary layers at complementary and simultaneous scales. Additional value could be extracted from these and future studies if their findings were a source for a dedicated pipeline wherein advances in understanding from observations systematically flow toward model development and prediction improvement.

This work requires coordination among disciplines, institutions, and agencies to implement practices that transcend barriers between ocean and atmospheric observing, between process studies and prediction models, between private industry and government agencies, and between research and operations. For some of the tasks presented in the roadmaps, the technological development needed is already underway and only a push toward implementation and completion is needed. For others, significant engineering is needed, and currently disparate communities need to be brought together in an accessible and equitable way to determine how to accelerate development and implementation.

The completion of this study marks the start of a dialogue with and among federal agencies and the research and forecasting communities to consider recommended actions. Commitment to sustained observing and modeling capabilities, the infusion of new technologies, and synthesis of in situ and remote sensing measurements with coupled models is essential to progress. Scientific readiness is high, technological needs are determined, capabilities are assessed, and strategies are defined to confidently embark on the implementation of a new, integrated coupled ocean-atmosphere observing-modeling system to meet the expanding demand for significantly improved weather and climate predictions.

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Appendix A: Study Group members

Study Group members

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Appendix B: One-Year Study on the Roles of Air-Sea Interactions in the Earth System Predictability (ESP)

The air-sea transition zone includes the upper ocean, air-sea interface, and atmospheric marine boundary layer as a single identity. The exchange of heat, moisture, momentum, and gases across this transition zone plays critical roles in the Earth system predictability (ESP), impacting its fundamental cycles of energy, water, and biogeochemistry and timing and locations of water cycle extremes (e.g., droughts, drought-related wildfire, atmospheric river, floods, hurricanes, winter storms, tornadoes). Due to its large heat capacity, the oceans provide long-term memory within the Earth system and exert direct impact on shorter time scale atmosphere processes, both through air-sea coupling. Therefore, an improved understanding of processes relevant to air-sea coupling has great potential in advancing the understanding of predictability of many high-impact phenomena.

However, understanding and numerical representations of processes of atmosphere-ocean interaction suffer from large uncertainties, especially small scale (< 25 km) processes. These small-scale processes include synoptic-scale, mesoscale, and sub-mesoscale eddies, oceanic and atmospheric boundary layer turbulence, diurnal effects, barrier layers, surface warm layer and freshwater lenses, bubble- and spray mediated fluxes under high winds, spatial variability induced by biologically produced surfactants at low winds, and the role of the directional wave spectrum in general including disequilibrium due to spatial and temporal variability in wind forcing. These processes are thought to be particularly important near strong horizontal gradients of the western boundary currents, equatorial cold tongue, and marginal ice zones. These processes not only directly impact local weather through air-sea coupling but also larger atmospheric and oceanic circulations. In particular, there is a lack of understanding of the role of meso and synoptic scale variability in the upper ocean dominated by eddies. A growing body of research suggests that mesoscale eddies (5-100km) have a leading order impact on air-sea coupling. At slightly smaller scales, sub-mesoscale (1-10km) eddies have a dominant impact on mixed layer depths, which will change the heat flux to the atmosphere. The turbulent boundary layer (the top 100 – 1000 m of the ocean) communicates fluxes (e.g., heat, carbon dioxide, oxygen) between the atmosphere or cryosphere with the deep ocean. The dynamics in this shallow top layer are crucially important for our climate, as 95% of the anthropogenically created heat in the atmosphere is communicated to the ocean through this mixing layer. Therefore, understanding these multi-scale processes and accurate, high resolution numerical representations are essential for harnessing ESP.

Despite progress in observing and modeling capabilities, including global satellites and multi-scale models, current observations and modeling of the air-sea transition zone remain rudimentary. Estimates of flux products suffer from large uncertainties and remain inadequate to evaluate the fidelity of the small scale variability in higher-resolution models. Some potential research activities are described in following paragraphs to expedite progress in observing, understanding, and modeling processes in the air-sea transition zone to advance studies on ESP. Future studies on the role of air-sea interaction in ESP should build upon recent advances in sensor/platform technology, model development, and understanding to (i) further new satellite and in situ autonomous platform/sensor observing technology of simultaneously measure all variables necessary to capture the processes of ocean-atmosphere interaction, including estimates of turbulent air-sea fluxes of heat and moisture over the global oceans and their transport into the rest of the atmosphere through the marine boundary layer, (ii) improve hierarchy of model representation of small scale processes in the air-sea transition zone to enable accurate representation of interactions between small and large scale processes influencing weather, subseasonal-to-seasonal, and climate scales, and (iii) advance understanding the role of the air-sea transition zone in ESP.

While the critical role of sea surface temperature on hurricane formation and maintenance has been known for decades, less understood has been the role of subsurface ocean heat content and its local variation in driving intensification of hurricanes as they extract heat through surface fluxes. Recent studies, including those of the hurricane Katrina, suggest that SST alone might not be a key predictor of hurricane tracks because they are primarily determined by the interaction between the sub-mesoscale storm and the large-scale circulation patterns. Meanwhile, ocean conditions are substantially affected by hurricanes. The role of variable sea state on momentum flux and hurricane intensity through air-sea coupling is poorly understood.

Air-sea coupling is an integrated component of the Madden-Julian Oscillation (MJO), which dominates the tropical intraseasonal (30 – 90 days) variability. The MJO over the tropical Indian and Pacific Ocean is known to affect extreme events in remote regions, such as the occurrence probability of Atlantic hurricanes, and tornados, floods, and lightning over North America. Through modulating the strength and eastward propagation of the MJO, air-sea interaction in the tropics affects these extreme events and their predictability. Prediction skill of the MJO is currently limited, owing to both inadequate initial conditions in both the tropical ocean and atmosphere, and deficiencies in prediction models. It has been demonstrated that atmosphere-ocean coupled models in general have better MJO prediction skill than atmosphere-only models, highlighting the importance of air-sea coupling on prediction of the MJO and its remote impact.

ENSO affect global society in many ways. It alters the normal global precipitation patterns and causes drought in certain places and floods in others. ENSO is fundamentally a phenomenon driven by air-sea coupling. While ENSO prediction has progressed substantially during the past three decades, current ENSO prediction skill is often limited. Advanced understanding of ENSO dynamics and enhanced ocean atmosphere observations in the tropical Pacific are key to improving prediction of ENSO and its global impact.

Arctic warming is faster than the rest of the world. This is caused by amplification of the anthropogenic warming through a feedback of the reduction in sea ice and exposed Arctic ocean. Air-sea energy fluxes is a critical component of this feedback. This coupling between the atmosphere and ocean (including sea ice) determined the speed of losing Arctic sea ice, which has significance consequences to regional economy (cargo shipping, fishing), the life of Arctic community, and lower latitude weather and climate.

The ability of mesoscale ocean features such as ocean temperature fronts to drive atmospheric convection, cloud formation and mesoscale weather steering is critically unsampled and under-represented mode of potential ESP. In terms of global model bias, erroneous sea surface energy flues due to the lack of representation of stratus cloud decks over eastern boundary current regions (California, Humboldt, Canary and Benguela) is a fundament limitation in climate models to correctly represent the Intertropical Convergence Zone (ITCZ) and cause the 'double ITCZ problem'.

Air-sea coupling is one of the primary mechanisms through which coastal extremes such as flooding and groundwater salinification are developed. Enhanced earth system research into coupled atmosphere-ocean dynamics of momentum transfer and propagation into predictability of waves and swell has the potential to improve emergency preparedness and response to coastal inundation. To advace our capability of observing and understanding the role air-sea interaction in ESP, a one-year study is proposed to provide detailed scientific recommendations. The objective of this study is to leverage existing coordinating efforts of the interagency (e.g., US Clivar, ICAMS) and community to determine the requirements for air-sea interaction observations for significant advances in ESP studies. More accurate measurement of air-sea fluxes and better understanding of the ocean's role in the effort of harnessing extended time scales of predictability will result from observations that treat the air-sea transition zone (the upper ocean, air-sea interface, and marine atmospheric boundary layer) as a single identity that will include processes from sub-mesoscales to regional and global scales.

This one-year study will (i) identify current capabilities, key gaps, lessons learned from the past, and best practices in data, technologies, understanding, and modeling requirements; (ii) assess the relative importance to ESP to resolve various space and time scales, interactions among different scale processes, and addressing model biases; (iii) explore possibilities of using modern statistical and modeling tools and co-designing air-sea observing and data assimilation (DA) systems to optimally use available data, fill observational blind spots, and minimize cost while harnessing predictability and providing broader societal benefits. This study will accelerate model development (advanced parameterization of air-sea interaction processes), support Earth system analyses (adequate observation-model comparison), and improve forecasts (accurate initial conditions through coupled DA). It may recommend observational technologies that need to be further developed for a streamlined observing system at representative locations first and over the global oceans eventually. It will pave the way to achieving global coverage as an integrated component of the national and international global observing systems that incorporates in situ and satellites assets and provide broad scientific and societal benefits on weather to climate timescales.

The envisioned outcome of this one-year study is: A well-defined strategy to advance observing and modeling capabilities and understanding of air-sea interaction at all required scales for harnessing ESP.

This study may be organized by the US CLIVAR Office and assisted by an ad hoc committee (consisting of representatives from NASA, NOAA, NSF, ONR, and DOE) under the guidance of ICAMS. The study team will consist of experts from academia, government agencies, and private industries.

Appendix C: Acronyms and abbreviations

ADCP	Acoustic Doppler Current Profiler
AI	Artificial Intelligence
AIRS	Atmospheric Infrared Sounder
AMO	Atlantic Multidecadal Oscillation
AOS	Atmosphere Observing System
AR	Atmospheric River
ARM TWP	Atmospheric Radiation Measurement Tropical West Pacific
ASTZ	Air Sea Transition Zone
ATMS	Advanced Technology Microwave Sounder
CAO	Cold Air Outbreak
CARE	”Collective benefit, Authority to control, Responsibility, and Ethics”
CDA	Coupled Data Assimilation
CPT	Climate Process Team
CTD	Conductivity-Temperature-Depth
DA	Data Assimilation
DCFS	Direct Covariance Flux Systems
DNS	Direct Numerical Simulation
DYAMOND	Dynamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains
DYNAMO	Dynamics of the Madden-Julian Oscillation
ENSO	El Niño-Southern Oscillation
ESM	Earth System Model
ESP	Earth System Prediction
FAIR	”Findability, Accessibility, Interoperability, and Reuse of data”
GDP	Global Drifter Program
GNSS	Global Navigation Satellite System
GoMRI	Gulf of Mexico Research Initiative
GOOS	Global Ocean Observing System
GRUAN	GTS and GCOS Reference Upper-Air Network
HFR	High-Frequency Radar
IABP	International Arctic Buoy Programme
INCUS	Investigation of Convection Updrafts
IPO	Interdecadal Pacific Oscillation
IR	Infrared Radiation
LES	Large Eddy Simulation

MABL	Marine Atmospheric Boundary Layer
MAS	Marine Aerosol and Spray
MHW	Marine Heat Wave
MJO	Madden-Julian Oscillation
MOST	Monin-Obukhov Similarity Theory
NAO	North Atlantic Oscillation
NPO	North Pacific Oscillation
NWP	Numerical Weather Prediction
OASIS	Observing Air-Sea Interactions Strategy
ODYSEA	Ocean Dynamics and Surface Exchanges with the Atmosphere
OHC	Ocean Heat Content
OML	Ocean Mixed Layer
OOI	Ocean Observatories Initiative
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PACE	”Plankton, Aerosol, Cloud, ocean Ecosystem”
PAL	Passive Aquatic Listener
PIRATA	Prediction and Research Moored Array in the Tropical Atlantic
PPP	Public-private partnerships
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
RO	Radio Occultation
S2S	Subseasonal to Seasonal
SAR	Synthetic Aperture Radar
SCDA	Strongly Coupled Data Assimilation
SLP	Sea Level Pressure
SMMR	Scanning Multichannel Microwave Radiometer
SOLAS	Surface Ocean-Lower Atmosphere Study
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
sUAS	Small Uncrewed Aircraft Systems
SWOT	Surface Water and Ocean Topography
TAO	Tropical Atmosphere and Ocean
TKE	Turbulence Kinetic Energy
TME	Tropical Moisture Export

TOGA/COARE	Tropical Ocean Global Atmospheres/Coupled Ocean Atmosphere Response Experiment
TPOS	Tropical Pacific Observing System
UAV	Uncrewed Aerial Vehicle
US CLIVAR	US Climate Variability and Predictability Program
USV	Uncrewed Surface Vehicle
UUV	Uncrewed Underwater Vehicle
WASL	Wave-impacted Atmospheric Surface Layer
WCDA	Weakly Coupled Data Assimilation
WOSL	Wave-impacted Ocean Surface layer
WSRA	Wide Swath Radar Altimeter

US CLIVAR

US Climate Variability &
Predictability Program

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