Island Arc Turbulent Eddy Regional Exchange (ARCTERX): Science and Experiment Plan

The ARCTERX Team*

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INTRODUCTION

Submesoscale flows such as front, eddies, filaments, and instabilities with lateral dimensions between 100 m and 10 km are ubiquitous features of the ocean. They act as an intermediary between the mesoscale and small-scale turbulence and are thought to have a critical role in closing the ocean's kinetic budget by facilitating a forward energy cascade, where energy is transferred to small scales and dissipated (*Thomas et al.* 2008, *McWilliams* 2016). In addition, submesoscale flows drive strong vertical motions and thus are effective at creating temperature/salinity intrusions and stratification anomalies that can modify the propagation of sound in the ocean. Simulating the effects of submesoscale flows on circulation energetics and ocean acoustics is well motivated. Given the inherent chaotic nature and faster evolution relative to the mesoscale, however, submesoscale currents have more limited predictability and require assimilation of higher-resolution observations to create accurate forecasts.

There have been a handful of field campaigns of short duration in select locations that provide anecdotal evidence of a forward cascade associated with submesoscale processes (e.g., *Nagai et al.* 2009, *D'Asaro et al.* 2011, *Johnston et al.* 2011, *Thomas et al.* 2016, *Peng et al.* 2020). There has never been, however, a field study that has characterized submesoscale energy cascades integrated over regional and seasonal scales. Nor has there been a concerted effort to make in-situ, submesoscale-resolving observations over a wide swath of the ocean and assimilate such data into forecast models. Such an endeavor would be necessary to assess the larger-scale impacts of the submesoscale on the circulation and its predictability, but presents a grand technological challenge given the vast range of space and time scales involved. Standard ship-based measurements are not well suited for this task. It requires observations from a multitude of autonomous platforms that can be deployed over a large area and long durations, yet with a sufficient density to capture submesoscale flows. The Island Arc Turbulent Eddy Regional Exchange (ARCTERX) initiative aims to tackle this challenge using a suite of measurements from autonomous platforms and ships combined with regional simulations to characterize the submesoscale flows in the western Pacific Ocean between the Luzon and Mariana Island arcs, which we refer to as the ARCTERX region.

The ARCTERX region is an ideal location to study submesoscale currents and their impacts on the circulation because it hosts a variety of submesoscale generation mechanisms and there is evidence that submesoscale currents shape the seasonal variations in mesoscale eddy kinetic energy observed there. Submesoscale instabilities derive their energy primarily from mesoscale eddies and currents, which are in abundant supply in the ARCTERX region. Specifically, the region has a maxima in mesoscale eddy kinetic energy centered around the Subtropical Counter Current (STCC; Fig. 1a, b). In addition, the Kuroshio and North Equatorial Current (NEC) are key features of the circulation that can generate vigorous submesoscale instabilities when they interact with the myriad of islands in the region (e.g., Fig. 1c). These island wake instabilities tend to form in the bottom boundary layer (BBL) via processes that are not well understood or observed. One of the objectives of ARCTERX is to target these processes using intensive surveys in the wake of Green Island off of Taiwan and Rota Island north of Guam and use high-resolution simulations to aid the interpretation of the observations.

The other main objective of ARCTERX is to study the seasonal cycle of submesoscale motions and its relation to the pronounced annual variation in mesoscale eddy kinetic energy observed in the region (Fig. 1d). Mesoscale eddy kinetic energy peaks in the late spring and has a minimum at the start of the year when submesoscale instabilities tend to be strongest in the subtropics. This suggests a causal relation where kinetic energy is exchanged between the two scales of motions on seasonal time scales. The ARCTERX initiative aims to test this hypothesis by deploying a fleet of autonomous platforms in mesoscale eddies, track the eddies for several months as they propagate westward across the ARCTERX region, survey the submesoscale instabilities that develop within their circulation, and quantify energy exchanges. It is an ambitious goal that will only be made possible by collaborations with Taiwanese colleagues, use of the latest technology, and state-of-the-art numerical simulations. The submesocale-resolving observations collected will be assimilated into forecast models to assess their improvements of model predictability.

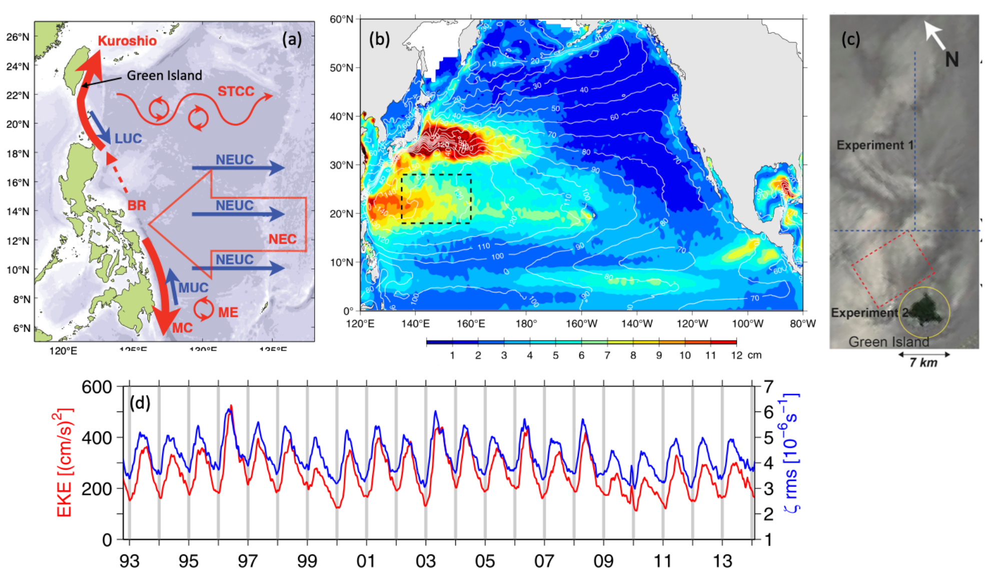


Figure 1. *(a) The ARCTERX region and its currents. (b) Root-mean-square sea surface height variations from satellite altimetry (color), a metric for mesoscale eddy kinetic energy, highlighting the maximum near the core of the STCC around 20°N. (c) MODIS image illustrating the wake that forms as the Kuroshio impinges on Green Island off of Taiwan. (d) Time series (in years) of the mesoscale eddy kinetic energy (red line) averaged over the STCC region [dashed box in (b)] highlighting its pronounced seasonal cycle. Figures adapted from Rudnick et al. (2015) (a), Qiu et al. (2014) (b) and (d), and Chang et al. (2019) (c).*

BACKGROUND

The ARCTERX region is known for its rich eddy field. The combination of the Kuroshio western boundary current, large variations in seasonal forcing, strong tides, and dramatic topography and island geometry lead to a rich physical forcing environment. The focus of the ARCTERX research initiative is the turbulent eddy exchanges throughout this region, and specifically on the class of submesoscale oceanographic variability that is poorly constrained in numerical models. This class includes oceanographic eddies, rings, vortices, fronts, and filaments, and their interactions with surface waves, inertia-gravity waves, and smaller-scale phenomena. An overview of these processes is described here.

Characteristics of Submesoscale Currents and Their Role in Turbulence Cascades

Submesoscale currents are an intermediate-scale phenomena that were little known until recently. They have distinctive scale ranges — 100 to 10,000 m horizontally, 10–100s m vertically, hours to days temporally — and distinct dynamical behaviors. Compared to basin and mesoscale currents, they only partly adhere to the strong constraint of geostrophic and hydrostatic momentum balances, and compared to microscale currents, boundary layer turbulence, and surface and internal gravity waves, they are much more strongly influenced by Earth's rotation (Coriolis force) and stable density stratification in a partly momentum balanced way (*McWilliams* 2016). Framed in terms of non-dimensional parameters, this submesoscale regime is characterized by flows with Rossby and Richardson numbers that are of order one (*Thomas et al.* 2008). And unlike larger and smaller scale currents, the submesoscale regime has little relation to linear dynamical models; it strongly resembles the chaos, turbulence, and limited predictability of nonlinear fluid advection.

The core issue for the role of submesoscale currents in the general circulation and material tracer distributions is its turbulence cascades: i.e., in which ways and to what extent are fluctuations on larger scales connected to dissipation and mixing on smaller scales? The overall context is the global forcing sources of circulation and material contrasts in the ocean and their limitation by microscale sinks that are necessary to maintain an overall equilibrium in the ocean. The submesoscale regime lies in between these sources and sinks (*Müller et al.* 2005, *McWilliams* 2016).

The source of submesoscale currents is energy transfers from large-scale and mesoscale currents, especially the latter. Within the surface boundary layer, the pathway is through the horizontal density gradients associated with the mesoscale eddies and an associated conversion of its potential to kinetic energy. For currents adjacent to topographic slopes and island edges, the pathway is through shear generated by the bottom drag that occurs within the BBL (*Molemaker et al.* 2015, *Gula et al.* 2016, *Srinivasan et al.* 2019). In addition, diapycnal mixing in the BBLs on sloping boundaries can generate available potential energy that can fuel a form of submesoscale baroclinic instability (*Brink* 2012, *Wenegrat et al.* 2018). Thus, the origins of submesoscale currents usually involve a strong relation to the turbulent boundary layers. It is presently unknown, though certainly possible, if there are important interior sources of submesoscale currents, although there is ample evidence that they do disperse widely through the interior as subducted pycnocline lenses and long-lived submesoscale coherent vortices (*McWilliams* 1985).

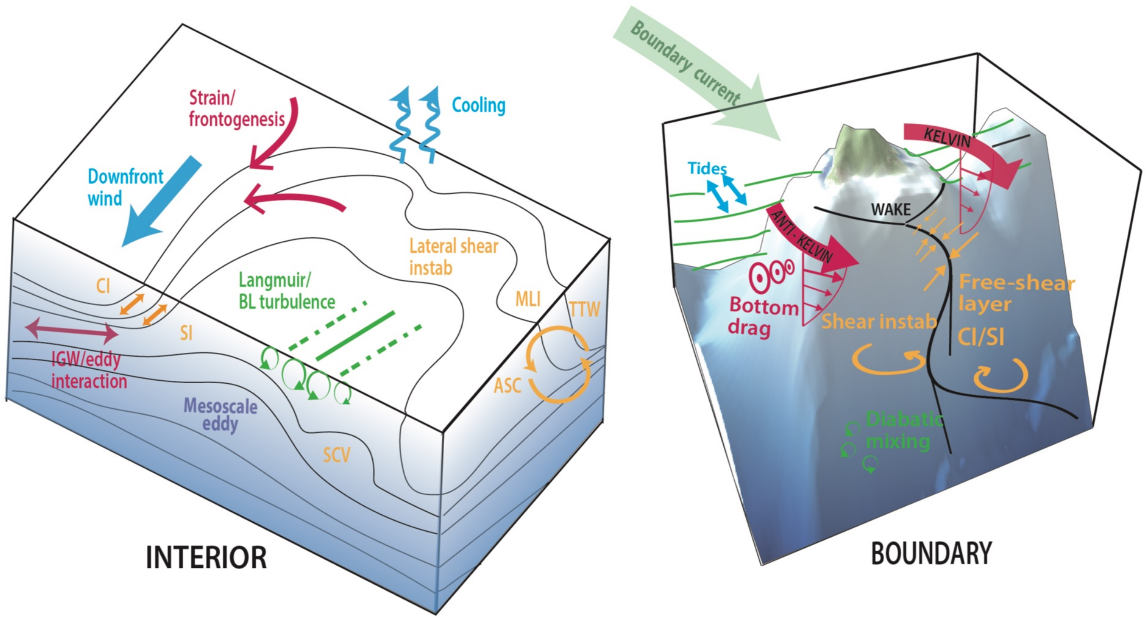


Figure 2. *Submesoscale processes of interest in interior and boundary currents in the ARCTERX region. In the interior, mesoscale eddies supply energy for various types of submesoscale instabilities. Mixed layer instability (MLI) feeds off the available potential energy in the fronts that bound the eddies, while lateral shear instabilities, centrifugal instability (CI), and symmetric instability (SI) extract kinetic energy. Both CI and SI typically form under destabilizing atmospheric forcing such as downfront winds or cooling in strong fronts. Mesoscale strain can intensify fronts via frontogenesis as well as ageostrophic secondary circulations (ASC) associated with boundary layer turbulence/front interactions (as encompassed by turbulent thermal wind theory). Langmuir turbulence can drive vertical mixing while ASCs can subduct surface waters and form submesoscale coherent vortices. In boundary currents, in the proximity of islands, bottom drag and tides can trigger submesoscale instabilities. On the side of the island where the current flows in the direction of Kelvin wave propagation, conditions for CI and SI can develop. In the lee of the island, a wake and free shear layer can form, shedding submesoscale vortices through shear instabilities and driving microscale turbulence and diabatic mixing.*

Once submesoscale kinetic energy is present, then there are dual cascade pathways to larger and smaller scales, termed inverse and forward cascades, respectively. Currents influenced by geostrophic dynamics primarily exhibit an inverse cascade, partly returning kinetic energy to the mesoscale, while ones that escape this constraint (i.e., are partly ageostrophic) manifest a forward cascade toward microscale fluctuations and hence to dissipation and material mixing (*Molemaker et al.* 2010). An important ARCTERX goal is to determine the cascade rates of these two pathways and how the transition scale between them varies with the current regime and seasonal cycle. In particular, the ARCTERX region has both boundary and interior currents (e.g., the STCC) with strong seasonal variability, along with a modulation of the mesoscale eddy kinetic energy (e.g., Fig. 1d). Submesoscale processes that form in interior and boundary currents are the focus of the ARCTERX DRI (Fig. 2).

Frontogenesis and Frontal Instabilities

The surface-layer submesoscale population may be generated by a mixed-layer baroclinic instability of the mesoscale near-surface currents (*Boccaletti et al.* 2007, *Callies et al.* 2015), or by a scale contraction of existing mesoscale horizontal density gradients through frontogenesis (*McWilliams* 2021). Both processes are more likely on the edges of mesoscale eddies with a surface density anomaly. Frontogenesis induces a forward kinetic energy cascade by this contraction. It occurs either through the effect of mesoscale horizontal shear (i.e., strain) or through the secondary circulation associated with boundary-layer momentum mixing, known as turbulent thermal wind (*Gula et al.* 2014, *McWilliams et al.* 2015). Once the horizontal scale shrinks to having only a marginal Coriolis influence, the secondary circulation becomes a run-away positive-feedback process, as long as the strain and boundary layer turbulence persist, until some kind of frontal instability disrupts this progression, culminating in a frontal arrest at a scale near the lower limit of the submesoscale range.

This process works equally well on density fronts (a one-sided gradient) and dense filaments (a density maximum in the center). The frontal instability can be of various types — horizontal-shear (*Gula et al.* 2014, *Samelson and Skyllingstad* 2016, *Sullivan and McWilliams* 2018), baroclinic (*Fox-Kemper et al.* 2008), anticyclonic-ageostrophic (*McWilliams and Yavneh* 1998), and overturning instabilities associated with negative potential vorticity [i.e., centrifugal, symmetric, and convective (*Hoskins* 1974)] — and it is likely that most of these occur sometimes. For overturning instabilities to form, however, some non-conservative process is required because negative potential vorticity cannot be generated by advective processes alone. Destabilizing atmospheric forcing, such as buoyancy loss or down-front winds that drive an upward Ekman buoyancy flux, can generate negative potential vorticity and open an energy pathway to dissipation via overturning instabilities (*Taylor and Ferrari* 2010, *Thomas and Taylor* 2010, *Thomas et al.* 2013). Once the frontal configurations are fractured, then the dual kinetic energy cascade pathways take over. Another goal of ARCTERX is to document these instability and arrest behaviors.

Submesoscale Features Generated at Topography

The topographic submesoscale population is generated as a wake-instability phenomenon. Currents passing along slopes experience bottom drag that causes strong local shears with vertical and potential vorticity anomalies (*Molemaker et al.* 2015). The friction associated with bottom drag lowers the potential vorticity if the bottom currents flow in the direction of Kelvin wave propagation, while increasing the potential vorticity for currents flowing in the opposite direction (*Benthuysen and Thomas* 2012). These and other processes can lead to an asymmetry in the strength of cyclonic and anticyclonic vorticity in the wakes of islands in flows with high Rossby numbers (*Srinivasan et al.* 2019). Subsequent current separations lead to interior currents that are then susceptible to strong instabilities of many of the same types listed above. There is also the possibility of pressure-topography fluctuations generating lee gravity waves. The partition between wave or vorticity generation depends on the slope, current strength, and stratification (*Schär* 2002). After wake instability occurs, there can be both a forward energy cascade and a local kind of inverse cascade into the submesoscale coherent vortices that are widely observed in the ocean (*Molemaker et al.* 2015, *Gula et al.* 2016). ARCTERX will also investigate island and western boundary current wakes.

Internal and Surface Waves Interacting with Submesoscale Features

Besides these central submesoscale processes, important interactions can occur with other upper ocean phenomena. Inertia-gravity waves have been understood to mostly have their own, separate kinetic energy cycle, but recent evidence indicates that they do sometimes have significant influences on the mesoscale-submesoscale-microscale kinetic energy cascade routes, especially for near-inertial waves (*Xie and Vanneste* 2015, *Thomas* 2017, *Rocha et al.* 2018, *Barkan et al.* 2021). In the surface layer, surface gravity waves, through their Stokes drift, both modify frontal evolution and connect the small-submesoscale currents to Langmuir turbulence, with strong cross-scale kinetic energy exchanges between them (*Hamlington et al.* 2014, *Suzuki et al.* 2016, *Sullivan and McWilliams* 2019). Conversely, submesoscale currents can affect the surface wave field, with implications for air-sea fluxes (*Villas Bôas et al.* 2020). And air-sea interaction involves modulation of the near-surface wind gradients and the loss of oceanic eddy kinetic energy through SST gradient and surface current feedbacks on the surface heat flux and wind stress (*Dewar and Flierl* 1987, *Chelton et al.* 2007, *Small et al.* 2008, *Renault et al.* 2018). The ARCTERX program will further assess these interactions.

ARCTERX PROGRAM OBJECTIVES AND GUIDING HYPOTHESES

The overarching goal of the ARCTERX program is to ***characterize the strength and spectral properties of the turbulent cascade of kinetic energy on the submesoscales in the ARCTERX study region and understand the processes that control energy transfers across scales and their seasonal variability***. Here we are using the most general definition of a turbulent cascade, namely the process that distributes kinetic energy across wavenumbers, which encompasses both forward and inverse cascades and processes ranging from the nearly 2D turbulence of interacting geostrophic eddies to the fully 3D turbulence in boundary layers, for example. The general objectives include: 1) quantifying the sign and magnitude of the cascade; 2) defining and understanding the hierarchy of processes that contribute to the cascade; and 3) quantifying the conversions of kinetic to potential energy, and vice versa. These objectives have been formulated in terms of guiding hypotheses for processes in the interior near the STCC, in the Kuroshio, in island wakes in the Kuroshio, and in the lee of the Mariana Islands Arc.

Guiding Hypotheses for Processes in the Interior

1. Submesoscale instabilities, frontogenesis, subinertial ageostrophic motions driven by advective or frictional processes (for example, associated with the turbulent thermal wind balance) and inertia-gravity wave-mean flow interactions (involving near-inertial waves and possibly the internal tides) in the STCC inhibit the inverse kinetic energy cascade and enhance the forward cascade by submesoscale currents.
2. The submesoscale range exhibits both an inverse kinetic energy cascade at larger horizontal scales (where it tends to follow more balanced dynamics) and a forward cascade at smaller scales. The transition scale moves toward smaller scales and the submesoscale currents are weaker in summer compared to the other seasons, but they are always present where there are lateral buoyancy gradients at the surface.
3. The forward cascade in the STCC is intensified in the late fall and early winter when the flow is more susceptible to submesoscale instabilities and frontogenesis is stronger due to destabilizing atmospheric forcing.
4. The inverse cascade in the STCC is intensified in the late winter and early spring when mixed layers are deepest and mixed layer instabilities grow in the subtropical front.
5. Air-sea coupled processes involving thermal and current feedbacks can potentially modulate the submesoscale and mesoscale production in the ARCTERX region.
6. The submesoscale range terminates at its smallest scale in frontogenesis, frontal instability, and frontal arrest. During the later stages of this life cycle, small-scale turbulence, dissipation, and material mixing are all enhanced. Strong surface

gravity waves acting through the Stokes vortex force enhance the submesoscale currents and couple them with the Langmuir turbulence at very small horizontal scales, 10–100 m.

7. Upper ocean turbulence is modulated by vorticity, divergence, and/or strain at the submesoscale.
8. Preferential steepening of surface waves in energetic submesoscale flow fields causes enhanced air-sea fluxes and can modify the transfer of surface wave energy across wavenumbers. The modifications of surface waves by submesoscale flows could be exploited to detect gradients in the velocity field.
9. During their westward propagation in the STCC, individual mesoscale eddies can gain or lose kinetic energy through submesoscale instabilities depending on the atmospheric forcing and structure and polarity of the eddies.
10. Numerical models that properly represent the submesoscale are able to represent the observed evolution at these scales.
11. The inverse cascade of the submesoscale will impact the predictability of the mesoscale eddying field at scales of days to weeks.

Guiding Hypotheses for Processes in the Kuroshio and Island Wakes

1. The Kuroshio's path and strength are modified by interactions with the surrounding eddy field. Eddies are absorbed by the Kuroshio, moving energy up-scale. These interactions are modulated by finescale processes, including the large internal tides generated in the region.
2. The Kuroshio interacting with its western boundary slope and islands (e.g., Green Island), and wakes in general, are the source of small-scale vortices, which are themselves subject to strong submesoscale shear instabilities.
3. Submesoscale currents typically exhibit inverse cascade at their larger horizontal scales and forward cascade at smaller ones. The transition scale becomes larger in more energetic flows.
4. Submesoscale eddies with different signs of vorticity decay and/or exchange energy with the mesoscale differently. This is likely the key to understanding the much greater anticyclonic abundance of boundary-generated submesoscale coherent vortices throughout the world ocean, even though their topographic generation processes are more symmetric. (Slope currents in the direction of Kelvin wave propagation generate anticyclonic vorticity and vice versa.)
5. Westward-propagating mesoscale eddies collide with the Kuroshio, disrupting the current and destroying the eddy, both initiating local energy cascades.
6. Energy transfer rates from submesoscale motions (upscale or downscale) are impacted by internal tides and inertial currents and their associated energetic turbulent mixing. In particular, sometimes near-inertial waves inhibit the inverse cascade.

EXPERIMENTAL STRATEGY

The ARCTERX field campaigns focus on submesoscale processes in the interior and the western boundary current and hence have two separate experiments to study their dynamics. The field campaigns are supported and complemented by process-oriented and data-assimilative numerical simulations.

Plans for each experiment are described below, as well as those for a pilot cruise where surveying techniques will be tested prior to the main field campaigns and eddies in the lee of the Mariana Islands Arc will be explored. The experimental components of the ARCTERX program are carried out over five years (Fig. 3).

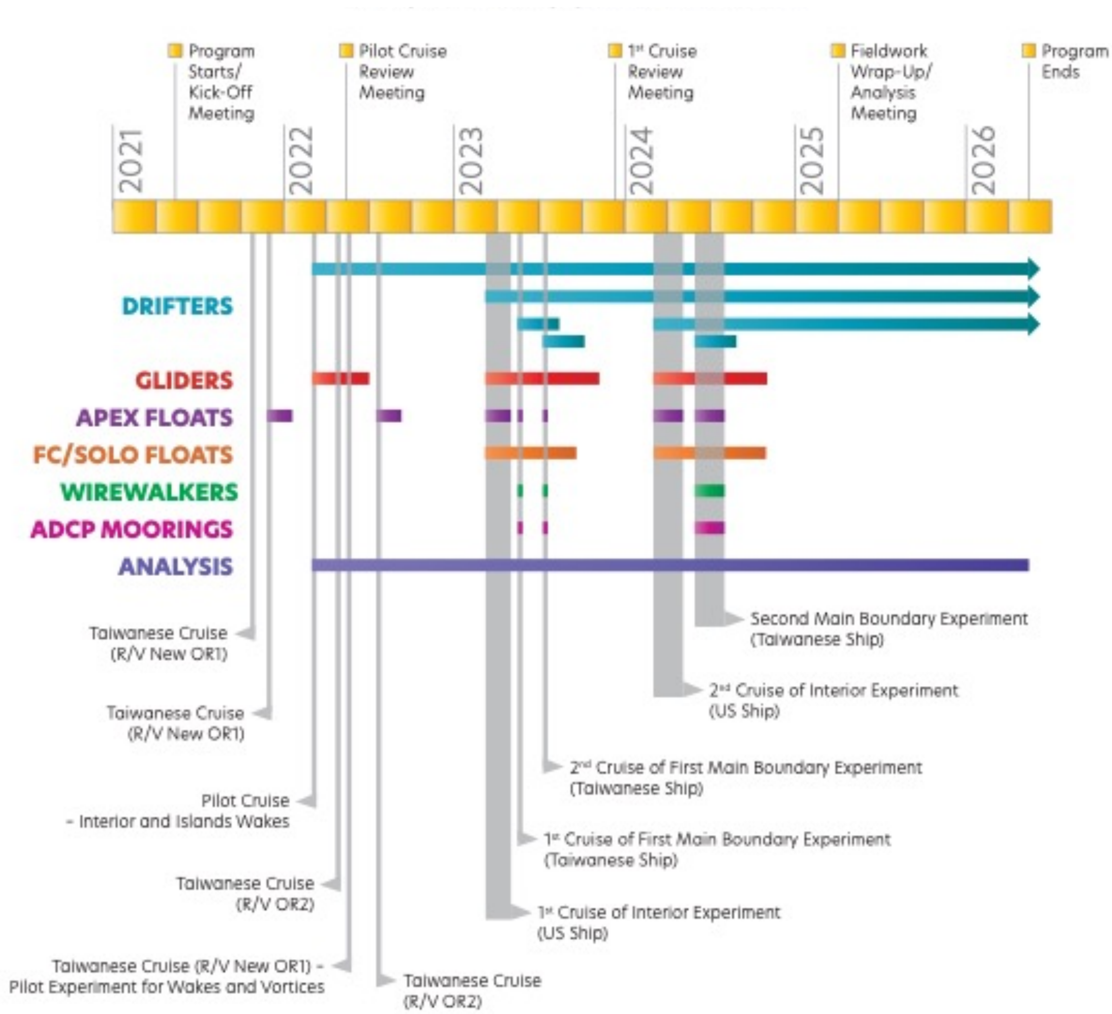


Figure 3. *ARCTERX program timeline.*

Pilot Cruise

The pilot experiment is scheduled for 21 March – 14 April 2022 with 24 science days aboard R/V *Roger Revelle* (Fig. 3). Divided into two legs, the first focuses on submesoscale variability within a mesoscale eddy outside an island wake, and the second on the near-field variability of the island wake near Guam.

The goals of Leg 1 are to assess the state of submesoscale variability within a mesoscale eddy, and to test sampling strategies to best resolve submesocale instabilities and associated turbulent mixing. The science tools available for the pilot experiment are two VMP-250s (Vertical Microstructure Profilers), an RBR Concerto (profiling CTD), and a towed chain comprised of RBR Solos (thermistors) and Concertos (CTDs), spanning the surface to 35 m depth. One Wave Glider will be available and will be run in pairs of parallel tracks for part of the cruise to determine how effective this strategy is for calculating statistics of submesoscale vorticity, divergence, strain, and density gradients using the "two-ship method" of *Shcherbina et al.* (2013). It is important to test this strategy because it could have an essential and unique role during the interior experiments for characterizing the statistics of the submesoscale flow field during the fully-autonomous periods of the intensive observation periods (IOPs) since none of the other autonomous platforms can be run in such a mode. A Slocum glider will be coordinated with the ship-based sampling efforts and run in parallel with the ship for a portion of the cruise.

For Leg 1 we will identify a mesoscale eddy within 2 days transit from Guam using satellite SSH observations. Once on site, we will survey submesoscale features rapidly for ~ 4 days, picking a region where the winds are down front. Then we will move to a new region where winds are not down front and repeat the survey process. The results will give a description of submesoscale features, quantify the strength and scales of variability, and provide preliminary tests of the mixing associated with submesoscale structures within the eddy.

The goals of Leg 2 are to sample the atmospheric and oceanic variability associated with wake dynamics at Rota Island. Rota is a small island with steep side walls and an aspect ratio of 20 km by 6 km, located just north of Guam and in the path of the westward flowing NEC. Rota is similar in geometry to Green and Orchid islands near Taiwan, which will be studied in a separate experiment. Scientific goals of the Leg 2 pilot are to: characterize the incident flow structure prior to interaction with the island, study the generation of vorticity at the flanks of the island, characterize the contribution of tidal flows to the wake structure, and to study the downstream decay scales of wake generated vorticity. Island wakes are known contributors to the submesoscale variability in the Western Pacific and the Leg 2 pilot will address the near field generation at Rota. Tools available for Leg 2 include buoyancy gliders (Seaglider, Slocum), X-band radar, VMP-250, REMUS autonomous underwater vehicles, and Wave Gliders in addition to the ADCP, CTD, meteorological, and flow-through sensors on R/V *Roger Revelle*. Leg 2 will test sampling strategies for autonomous systems in energetic conditions near the island, as well as the seeding of these systems to simultaneously characterize the upstream and downstream conditions associated with wake development.

Interior Experiment

The overarching goal of the interior experiment is to characterize the properties and energetics of a turbulent submesoscale flow field as it evolves through a seasonal cycle using a large array of autonomous platforms. The subtropical front of the STCC will be the targeted feature of the circulation in the ARCTERX region because it is known to have a prominent seasonal cycle in mesoscale kinetic energy (e.g., Fig. 1d), which high-resolution numerical simulations of the region suggest is facilitated by energy exchanges with submesoscale instabilities. The portion of the STCC that intersects the northwest corner of international waters in the ARCTERX region (i.e., near 19°N and 128°E) is a favorable field site logistically due to its proximity to Taiwan and its EEZ and scientifically for the potential to connect the physics of interior processes with the physics of the western boundary current. The plan will be to identify coherent mesoscale eddies, seed one or several of them with the autonomous platforms to sample the submesoscale processes on their edges and possibly in their cores, and track the eddies as they propagate west and potentially interact with the Kuroshio (e.g., Fig. 4). The latitude band of 18–19°N is a known preferred pathway for the westward propagation of mesoscale eddies into the Kuroshio and will be targeted (*Cheng et al.* 2017). In principle, a coherent mesoscale eddy should reduce the dispersal of the Lagrangian platforms we plan to deploy (observing system simulation experiments – OSSEs – are being run to test this hypothesis) and is one of the reasons why such eddies would be selected for a field site (in addition to providing the necessary environment to test hypothesis 9).

Two field campaigns are proposed: spring 2023 and winter 2024 (Fig. 3). The campaign in 2023 will take place in April/May when the mesoscale eddy kinetic energy in the STCC approaches its annual maximum. The field campaign in 2024 will target the winter when regional simulations suggest submesoscale instabilities are most vigorous and a forward cascade is more prominent. The idea is to have the maximum number of assets in the water at the time of year when the highest resolution is required and to combine their observations with ship-based measurements. As the season progresses and mesoscale motions dominate the flow, in contrast, fewer autonomous platforms will be needed to sample the flow when regional simulations suggest energy is transferred upscale (e.g., *Qiu et al.* 2014). Contrasting the observations from the two field campaigns in different seasons will allow tests of hypotheses 3 and 4.

Each field campaign is broken into two stages. The first stage involves a ~40 day cruise (U.S. R/V) where autonomous profiling floats, surface drifters, and mobile assets are deployed and intensive ship-based surveys are undertaken. Some floats may be recovered at the end of the first (2023) cruise, while in 2024 it is possible that they will be left to continue sampling through the year. The second stage involves autonomous platforms solely, sampling with underwater gliders, Wave Gliders, and floats redeployed at the end of the cruise. These autonomous platforms will survey the selected mesoscale eddy for several months to characterize the seasonal variability of the submesoscale turbulence within its boundaries and track the eddy as it propagates west to possibly capture its interaction with the Kuroshio. The autonomous platforms will drift with the Kuroshio and possibly be recovered in Taiwanese waters by Taiwanese R/Vs or vessels chartered out of Taiwan. A more detailed description of the field work strategy and the role of each observational asset is described in subsequent sections.

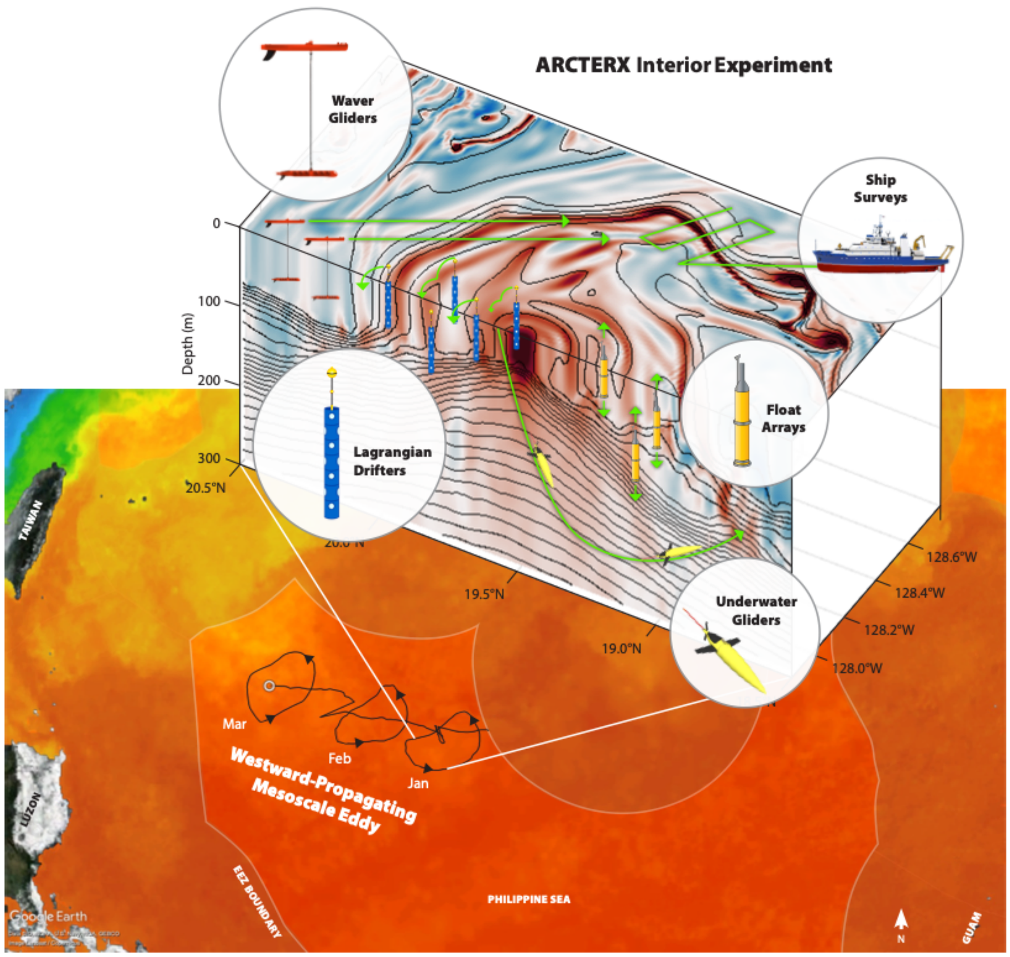


Figure 4. *Proposed plan for the interior experiment. A mesoscale eddy in the region between EEZs will be targeted. The eddy will be seeded with an array of floats and surface drifters. A fleet of underwater gliders, surface Wave Gliders, and one or two research vessels will survey the mesoscale environment and submesocale features within and around the float array during the ~40 day cruise. After the cruise, the autonomous platforms will continue to sample the eddy while it propagates to the west for a span of several months to capture the seasonal evolution of the flow and energy exchanges across the ARCTERX region.*

Underwater Gliders

Underwater gliders provided by Oregon State University (OSU), Scripps Institution of Oceanography (SIO), and University of Washington (UW) will be used in a coordinated adaptive survey of a westward propagating eddy. Taken together, the fleet will include about eight gliders equipped with a range of sensors to measure pressure, temperature, depth, velocity, turbulent dissipation, chlorophyll fluorescence, and dissolved oxygen. Profiles may be as deep as 1000 m with a complete dive cycle taking roughly 6 hours while covering 6 km horizontally through water. All data will be reported in real time for use by assimilating models. An initial plan might have the gliders making radial sections from the center of the eddy and back (Fig. 5). Assuming an eddy of 100 km radius, such a track would take 100 h to go from the center to the rim of the eddy. The eddy will be tracked for a period of 4 months, after which time the gliders will be recovered.

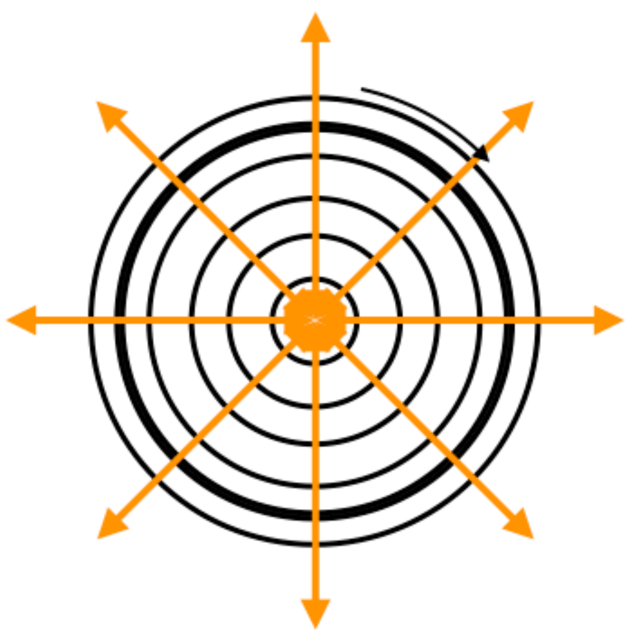


Figure 5. *Glider survey of an eddy. Gliders transit radial lines (orange arrows) in a mesoscale eddy while it propagates to the west.*

Profiling Floats

ARCTERX profiling floats come in three species, each with different capabilities. Profiling depth ranges and intervals can be changed during surface intervals via satellite communications.

EM-APEX floats (8–15 units)

EM-APEX floats (APL-UW) profile to 2000 m at the rate of 0.15 m/s. They measure CTD plus an electromagnetic measure of current shear and currents. These units also include fast thermistors from which estimates of temperature variance dissipation rate (χ_T) and turbulence kinetic energy dissipation rate (ε) are made.

SOLO II floats (15 units)

SOLO II floats (SIO) will profile to 200 m and back every ~45 min for about 2 months. Five floats are equipped with CTD and another 10 with CTD + chlorophyll fluorometer.

Flippin' χSOLO floats (FCS, 8 units)

FCS floats (OSU, SIO) profile to 200 m every 45 min for about 2 months. These are newly-developed variants of SOLO II floats that carry a full suite of turbulence sensors (2 fast thermistors, 2 shear probes, 1 pitot tube) at the nose end as well as CTD sensors. The turbulence sensors are always exposed to undisturbed fluid, on both up and down profiles, by flipping at the top and bottom. This enables profiles through the sea surface, where stratification is often nil and shear probes are required to measure the turbulence.

Strategy for a float array

The combination of floats, gliders, surface drifters, and ships should resolve the scales and evolution of vorticity and divergence. A preliminary plan might be to deploy an array of all three types of floats along a radial line that extends from an eddy's center to beyond its margin. This configuration is embedded in the glider tracks (Fig. 5), which cross the periphery of an eddy and its large gradients. Initially the floats might profile as quickly as possible, while later the floats might park at 200 m to extend their missions. This strategy maximizes the chance that floats will remain in the eddy as it moves westward. Near the end of the cruise in 2023 we may recover some FCS or EM-APEX floats if 1 day of ship time can be allocated; this action would benefit field work in 2024.

Surface Drifters

Lagrangian (i.e., water following) satellite tracked drifters will be deployed during ARCTERX. Previous drifter work in the Western Pacific suggests that drifters are not an optimal tool for dispersion studies near the boundaries and in the presence of swift currents. Therefore, the focus of the drifter component will be in the interior region. Over 200 drifters will be available for this effort (approximately 100 drifters for each cruise).

The main goal of the drifter component is to infer the dissipation rates using pair statistics and velocity structure functions and determine the separation scale between forward and inverse energy cascades.

The deployment will be repeated in different seasons to contrast the effect of atmospheric forcing on the submesocale regime. As such, the drifters will contribute to the study of hypotheses 1–4.

Because a large number of drifters will need to be deployed in a short period of time to allow other ship-based experimental activities, they will be deployed in clusters of 5–10 drifters on stations distributed in a pattern (i.e., a circle, an s-shaped, or butterfly) that can be executed quickly.

Wave Gliders

Several Wave Gliders instrumented with ADCPs, CTDs, meteorological and surface wave sensors, and possibly winches to make profiles (although this technology is still being tested), are available. One proposed sampling strategy for the platforms is to run pairs of Wave Gliders in parallel lines within the underwater glider/float array to calculate gradients in velocity and density to build statistics of the vorticity, strain, divergence, density gradient, and higher order quantities like the frontogenesis function and the Ekman buoyancy flux. These metrics will be useful to test hypotheses 3 and 6. Measurements of the surface wave field and air-sea fluxes combined with the estimates of vorticity, strain, and divergence will be used to test hypotheses 5 and 8 that the submesoscale flow significantly affects these fields.

Ship-based Surveys

Coordination of autonomous and ship-based sampling provides opportunities for multiscale, quasi-synoptic sampling of submesoscale variability associated with the target eddies. In the weeks immediately following the deployment of autonomous assets, rapidly repeated, high-resolution ship-based surveys, ideally conducted using a towed profiler (e.g., SeaSoar, Triaxus, or VMP), will be used to document the evolution of select submesoscale features. Nesting these surveys within the region sampled by the extensive array of autonomous platforms allows simultaneous characterization of mesoscale to submesoscale variability, including vorticity, divergence, and strain.

Synoptic survey efforts must overcome the challenge of isolating variability driven by submesocale dynamics from that resulting from other energetic phenomena, such as near-inertial motions, that unfold at similar spatial and temporal scales. The nominal 36-hour inertial period and relatively large internal deformation radius of the target region should ease these challenges (relative to that experienced in previous mid-latitude experiments). For example, at tow speeds of 8 knots, survey patterns of 100 km length can be repeated five times within an inertial period. Assuming the use of a towed profiling asset, ship-based surveys will provide profiles of velocity, temperature, salinity, temperature variance dissipation rate (χ_T), chlorophyll fluorescence, and dissolved oxygen from the sea surface to a few hundred meters, at horizontal resolutions of hundreds of meters to a few kilometers. Survey scope and resolution are governed by a balance of tow speed, profile depth, and horizontal resolution. Ship-based sampling will provide high-quality measurements of atmospheric forcing over the target region.

Interior Experiment Modeling Strategy

The interior observational campaign will be assisted by numerical simulations that capture the submesoscale and its interaction with the background environment. Process-oriented, nested, high-resolution regional simulations run by the UCLA and Stanford teams will be used to explore the physics of the submesoscale processes in the Philippine Sea and to run OSSEs to test proposed sampling strategies for the various autonomous platforms to be used in the interior IOPs. These simulations will be performed prior to the IOPs to provide guidance in the design of the field campaigns. After the IOPs, additional process-oriented simulations configured with flow parameters representative of the observations will be run to delve more deeply into the governing physics and aid in the interpretation of the data.

Data-assimilative models will be used to perform a series of OSSEs to test the efficacy of the different deployment strategies for the various autonomous assets. The OSSEs will be based on an identical twin approach where a “nature run” of the model will provide reference circulations for the ARCTERX observational periods. The simulated observations will be assimilated into the models (starting from an incorrect background circulation) in an effort to recover the true solution. One of the objectives of these simulations is to demonstrate improvements in the predictability of submesoscale currents when high-resolution observations are assimilated into the models.

Boundary Current Experiment

Flow-topography interactions are important generation processes for submesoscale currents and for energetic turbulence and mixing. The ARCTERX program’s Kuroshio island wake component is focused on the dynamics of submesoscale variability generated by a major western boundary current, the Kuroshio, interacting with small islands east of Taiwan.

The Kuroshio generates island wakes as it passes Green and Orchid islands with 1–1.5 m/s mean speed. Green Island, located about 28 km (~15 nm) off the southeast coast of Taiwan, has an area of 17 km^2 and Orchid Island, located roughly 60 km (~30 nm) off the south coast of Taiwan, has an area of 45 km^2. Surface signatures of the Green Island wake extend roughly 100 km downstream and are often captured by satellite images (Fig. 6). Surface signatures of the Orchid Island wake are less apparent and extend over similar downstream distances.

The main objective of this study is to observe, understand, and quantify the evolution of island wakes from generation to decay, and to compare with existing numerical model results and theory. We hypothesize that the vorticity is generated by frictional torques and pressure drag at the bottom boundary, and that the wake structure evolves as vorticity advects downstream, submesoscale instabilities form, and mixing entrains surrounding water masses. Turbulent mixing and submesoscale vertical transports within the wake can lead to significant water mass exchanges, interleaving/subduction, and enhanced biological productivity.

Potential parameters that might impact island wake generation, evolution, and decay include the Kuroshio strength and direction, bottom slope and slope asymmetry, barotropic and baroclinic tides, westward propagating mesoscale eddies, and submesoscale eddies generated upstream of islands. Even though tides in this area are not as strong as in Luzon Strait, we suspect that they can influence energy transfer and enstrophy rate of change due to enhanced internal wave energy, which can lead to high turbulent kinetic energy dissipation and turbulence mixing.

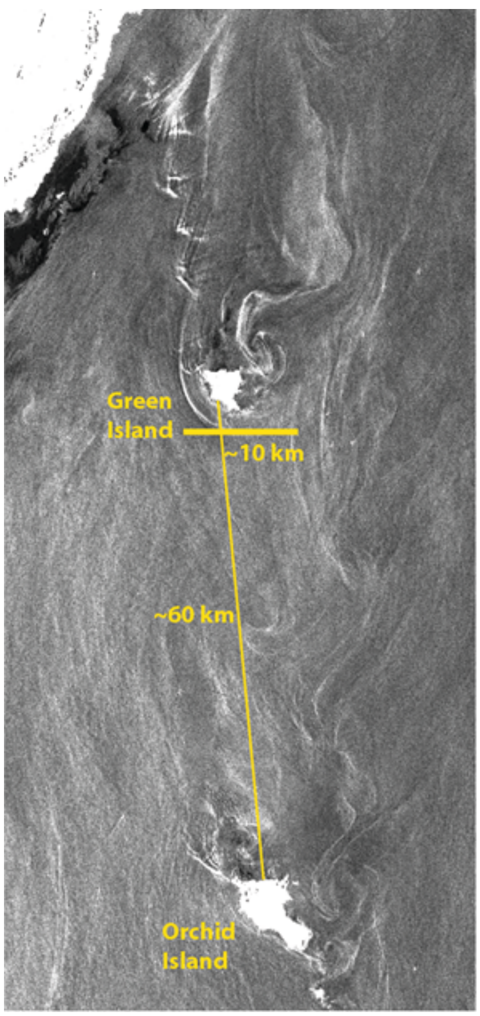


Figure 6. *Synthetic aperture radar (SAR) images from Sentinel-1 of the island wakes in the lee of Green Island and Orchid Island on 20 May 2021. The SAR image displays the scattering strength representing the surface roughness. The bright regions reflect rough, convergent flow and dark regions smooth, divergent flow.*

Motivation

Theory and model results suggest that both bottom frictional drag and pressure drag around island bathymetry may lead to flow separation and generation of downstream submesoscale vortices and lee waves (*D'Asaro* 1988, *McCabe et al.* 2005, *Gula et al.* 2015). Along the western boundary current off Taiwan, island wakes and formation of submesoscale eddies have been observed, especially on the lee side of the Green Island (e.g., *Chang et al.* 2013, 2019). However, there are no detailed submesoscale to small-scale observations to quantify wake dynamics and impacts on the mean flow, motivating a detailed set of measurements to evaluate relevant dynamical parameters as well as comparison with numerical simulations to improve the understanding of wake dynamics and forecasting skills in wider regions of the western boundary. Here we propose to make direct measurements of bottom stress, relative vorticity, and potential vorticity (PV) in the BBL near an island and within the island wake, and to compare observational findings with model results.

Vorticity generated in the BBL (and pre-existing vorticity in the upstream flow) is advected downstream and evolves into an island wake. A set of experiments are planned to understand how the horizontal and vertical wake structures are formed and how they evolve downstream. The asymmetry of the bottom depth and slope around Green Island will receive special attention, as it might result in asymmetry in vorticity generation and affect the downstream wake structure.

Baroclinic and barotropic tides are particularly strong in the Luzon Strait area and propagate northward toward Orchid and Green islands. The effect of tidal strain on wake generation and decay is largely unknown. There are indications that the set of instabilities occurring in the lee of Green Island differs by tidal phase, suggesting that tidal shear and strain have decisive roles in the dynamics.

Strong turbulence mixing was observed at the edge of the wake (free-shear layer, FSL), where horizontal billows are reported with Rossby number O(10). Direct measurements of turbulent kinetic energy and thermal variance dissipation rates will help disentangle the mechanisms leading to strong turbulence mixing in the FSL. Potential candidates are shear and symmetric instability. It is an open question to what extent wake turbulence contributes to water mass transformation between the Kuroshio and surrounding water masses. Because vertical fluxes are enhanced, submesoscale variability and wake turbulence affect the biological productivity in the surface layer and export of organic matter into the deep ocean.

Field Work Strategy

Our strategy is to combine multiple ocean observing tools including ship-based and Lagrangian platforms to achieve our objectives. The Kuroshio island wake field work component will rely on the following assets: 11 EM-APEX floats (APL-UW), 3 Wirewalkers (NRL), 1 towed CTD profiling platform (ScanFish) (NRL), 1 VMP (NRL), 2 VMP (IONTU), 1 microstructure Seaglider (Institute of Oceanography National Taiwan University, IONTU), 1 Seaglider (APL-UW), 1 towed CTD chain (APL-UW, upon availability), 1 towed chain (IONTU), 1 BBL mooring (IONTU). The measurement program includes sampling of (a) upstream conditions, (b) flow instabilities, and (c) evolution and decay of the wake (Fig. 7).

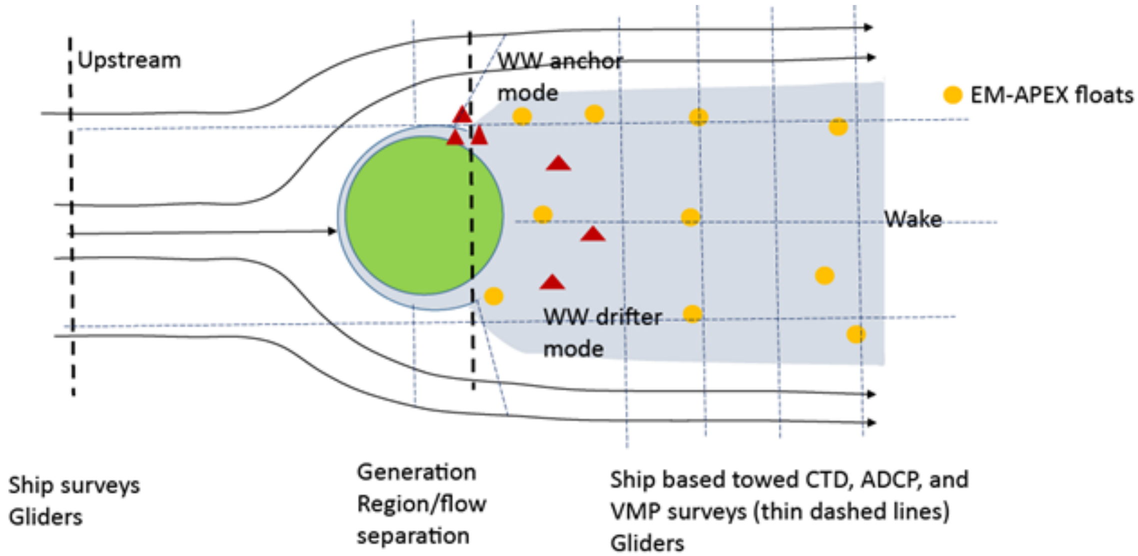


Figure 7. *Observing strategy around Green and Orchid islands.*

Upstream conditions

Upstream conditions will be monitored with cross-Kuroshio shipboard ADCP and CTD sections and long-term glider lines. These data will be complemented with numerical model output and remote sensing products to build up statistics on the upstream flow characteristics. Field work plans will depend on the strength and direction of the Kuroshio, which will determine the main axis of downstream wake vortices. Westward propagating eddies will influence the upstream flow conditions and vorticity, as they collide with the Kuroshio and disintegrate. Eddies will be monitored with satellite sea surface height anomaly and temperature observations in the weeks prior to an experiment.

Vorticity generation

The generation mechanisms take place in the BBL around the islands. Wirewalkers (WW) can be deployed in an "anchored mode," effectively converting them into moorings that profile over a defined depth range. A near-bottom boundary layer mooring will be deployed for long-term BBL measurements. WWs are of great help to sample Eulerian flow conditions in the vorticity generation sites.

To estimate the frictional drag, turbulent dissipation rate will be measured as close to the bottom as possible. EM-APEX floats can profile to the bottom. Additional VMP shipboard measurements, possibly tow-yowed, and mid-water dissipation rates from WWs will complement the float measurements and help to cross-validate the data.

Assuming a constant stress layer, near bottom momentum fluxes and roughness length scales can be estimated. Using a law-of-wall boundary layer assumption, bottom stress can be inferred from the velocity profile and the roughness length scale, which are estimated with velocity measurements into the BBL, e.g., by Wirewalkers, EM-APEX floats, LADCP, and the BBL mooring.

Downstream flow

The downstream evolution and decay of the wake takes place primarily in the surface layer O(200 m), extending O(100 km) downstream and island-scale O(10 km) in the cross-stream dimension. The primary goal is to characterize the wake structure and distribution of turbulence.

EM-APEX floats and WWs will be used in "drifting mode" and follow the semi-Lagrangian reference frame of wake vortices. Floats and WWs can measure turbulence, vorticity, shear, strain, and density structure. Due to the surface intensification of the flow, it is unclear how successfully the drifting assets can follow individual vortices. EM-APEX floats can be recovered and re-deployed multiple times during the experiment to gather multiple time series realizations of the wake properties and their statistics.

Two towed CTD chains will measure TS properties across the FSL with high vertical and horizontal resolutions. These will provide detailed visualization of the wake density structures, and estimates of 5-m Richardson number and Thorpe scales.

Clusters of EM-APEX floats and WWs can measure velocity differences and thus vorticity, lateral strain, and divergence. Their velocity measurements can be augmented with shipboard ADCP data. Potential vorticity estimation might be possible as long as the assets do not disperse significantly and stay coherent. If Taiwanese ship schedules allow, two-ship surveys will be planned in the downstream wake. These will allow measurement of velocity differences across the separation distance of the two ships (*Shcherbina et al.* 2013) and estimation of vorticity, lateral strain, and divergence statistics.

The far field evolution of the wake can be measured with long-term maintenance of cross-stream Seaglider lines. Drifters deployed in the wake may be useful to map the circulation but could be carried out of the target area within O(day).

Challenges

One of the major challenges is to deploy drifting assets (such as EM-APEX floats and WWs) in the fast-moving Kuroshio. Another technical challenge of the field campaign will be to separate mean flow, near-inertial and tidal components, and eddy fluctuations. This separation will rely on a definition of a space and/or time mean and may require long-term measurements. Eddy fluctuations of all measured quantities (u’, v’, T’, S’) and potentially horizontal eddy fluxes (<u’v’>, <u’T’>, <v’T’>) can then be computed.

Modeling and Remote Sensing

Field campaigns will be guided by multiple model simulations run at UCLA, NRL (Navy Ocean Nowcast/Forecast System), and Taiwan University (MITgcm). Model simulations will provide statistics on the upstream flow conditions. Observations will be compared with model output to obtain better understanding of various processes.

Offline tracking of simulated EM-APEX floats, Seagliders, and WWs in model simulations will guide the deployment and recovery strategies of assets and help design experiments such that velocity gradients and potential vorticity can be computed.

Field campaigns will also rely on satellite remote sensing products such as sea surface height anomaly and temperature. Wakes can be detected in synthetic aperture radar (SAR) imagery. If cloud cover and sea state permits, SAR images can be used to map the wake structures and plan field experiments.

Timeline and Logistics

All field observations for this component of ARCTERX will be carried out using Taiwanese research and commercial charter vessels, if needed. EM-APEX floats and Seagliders can be deployed and recovered from charter vessels, but WWs, moorings, and VMPs depend on research vessel availability.

A pilot cruise is planned for September 2022 and two further cruises are expected in 2023 and 2024 (Fig. 3). A two-vessel joint operation is planned with Taiwanese vessels, if permitted.

RESOURCES AND PROGRAM COMPONENTS

Measurement assets employed during the ARCTERX program include autonomous platforms, ship-based and remote sensing systems operated by many different institutions and groups:

- 15 AUV gliders
- 4 ASV SV3 Wave Gliders
- 1 AUV Remus 600
- 18–26 EM-APEX floats
- 16 Flippin χSOLO floats
- 15 Solo-II floats
- 30 wave buoys
- 200 SVP drifters
- 1 Scanfish towed profiler
- 3 VMP-250IR microstructure profilers
- 1 Triaxus towed profiler
- 1 towed instrument chain
- 3 Wirewalkers
- 4 HF radars
- 1 X-band science radar

Autonomous Underwater Vehicles – Gliders

Group	Platform Details	Deliverables
Shearman (OSU)	3 Slocum gliders; 4–6 month endurance, turbulent microstructure sensors	T, S, density, ε (turbulence kinetic energy dissipation), χ_T (temperature variance dissipation); surface to 1000 m with 1 m vertical and 5 km along-path resolution
Lee, Rainville, and Shapiro (APL-UW)	6 Seagliders and/or extended range Seagliders	T, S, density, velocity (ADCP), microstructure (temperature and/or shear), optics (F_{chl}, b_b), oxygen; surface to 1000 m
Rudnick (SIO)	6 Spray gliders; 3–4 month endurance, CTD, ADCP, fluorometer	T, S, density, velocity; surface to 1000 m with 1 m vertical and 6 km along-path resolution

AUV gliders are buoyancy propelled sensing platforms, characterized by long endurance (> 4 months) and slow speeds (< 1 m/s), and are capable of sampling from the surface to 1000 m. Gliders are capable of sampling proscribed surveys over long (many month) periods, using satellite communications to download near-real time observations and upload new instructions. Gliders can be outfitted with a range of sensors, including CTDs, ADCPs, optics, acoustics, and turbulent microstructure. Three different classes of gliders with varied sampling capabilities will be employed during the pilot (2022) and main (2023) ARCTERX field experiments. Gliders will be used in both the interior and boundary experiments.

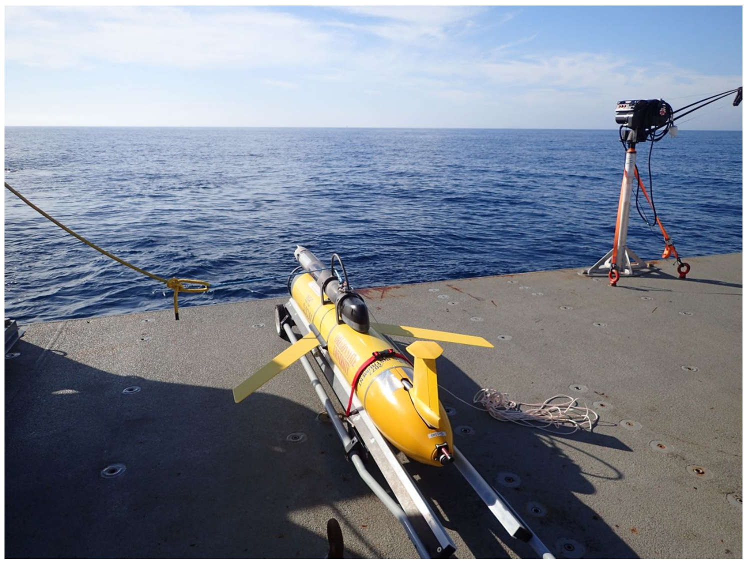


Figure 8. *Slocum glider with Microrider.*

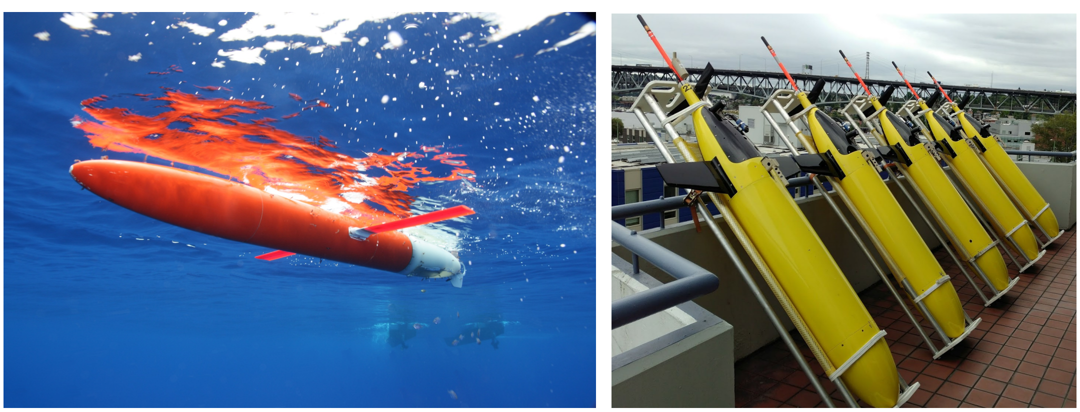


Figure 9. *(Left) Spray glider and (right) extended range Seagliders.*

Autonomous Underwater Vehicles – Remus 600

Group	Platform Details	Deliverables
Terrill, Merrifield (SIO)	2 REMUS 600	Currents, CTD

Autonomous Surface Vehicles – SV3 Wave Gliders

Group	Platform Details	Deliverables
Lee, Rainville, Shapiro (APL-UW)	2 Wave Gliders	Atmospheric and upper ocean sensors
Terrill, Merrifield (SIO)	2+ Wave Gliders	Bulk atmospherics, CTD, waves, currents (ADCP)

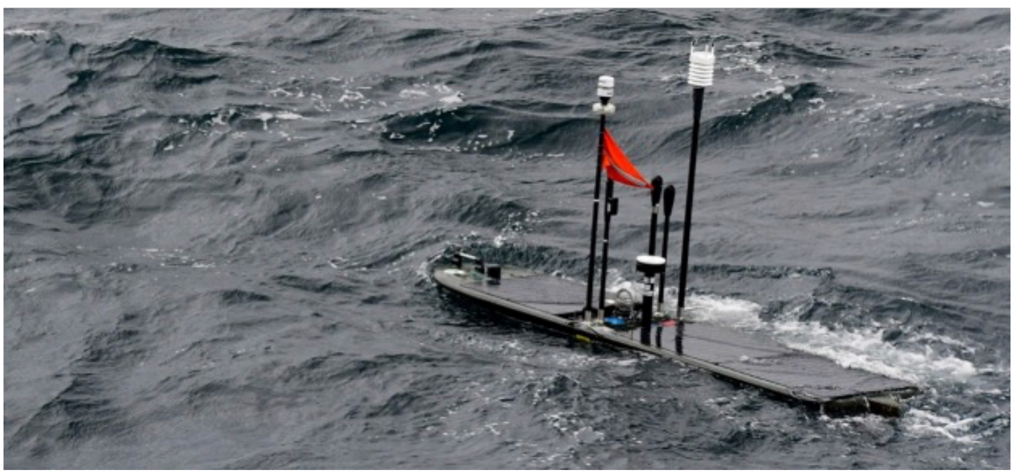


Figure 10. *Wave Glider.*

EM-APEX Floats

Group	Platform Details	Deliverables
Essink, Lien, Vladoiu (APL-UW)	11 EM-APEX floats	T, S, density, velocity, χ_T (temperature variance dissipation); ~ 5 m to 2000 m with 2–5 m vertical resolution
Whalen (APL-UW)	7–15 EM-APEX floats	T, S, shear/velocity, χ_T (temperature variance dissipation)

Figure 11. *Profiling EM-APEX floats are equipped with a sensor package to measure 2–3 m temperature and salinity with ~ 5 m horizontal velocity, and 1 m microscale temperature variance dissipation rate to a maximum depth of 2000 m. Velocity is inferred from the electric field induced by ocean currents moving through Earth's magnetic field, resulting in a voltage drop across the insulated float body. Microscale temperature is measured with a pair of Rockland Scientific fast thermistors.*

Flippin' χSOLO Autonomous Turbulence Profiling Floats

Group	Platform Details	Deliverables
Moum, Hughes (OSU)	8 Flippin' χSOLO profiling floats; 60–240 day endurance	T, S, density, depth-mean u, surface u, ε (turbulence kinetic energy dissipation), χ_T (temperature variance dissipation); 0–200 m, 1 m vertical resolution
Johnston, Rudnick (SIO)	SOLO II with integrated turbulence sensor package	Wave height spectra, significant wave height

Flippin' χSOLO (FCS) is outfitted with a fully-integrated suite of turbulence sensors together with SBE Glider Payload CTD on the standard SOLO II profiling float — two shear probes, two fast thermistors, and pitot tube as well as pressure sensor and 3-axis linear accelerometers. Turbulence sensors are housed antipodal from communication antennae so as to eliminate flow disturbance. FCS descends and ascends with turbulence sensors leading, thereby permitting measurement through the sea surface. By flipping at the sea surface, antennae are exposed for communications. The 60-day mission of FCS provides intensive profiling measurements of the upper ocean from 0–200 m.

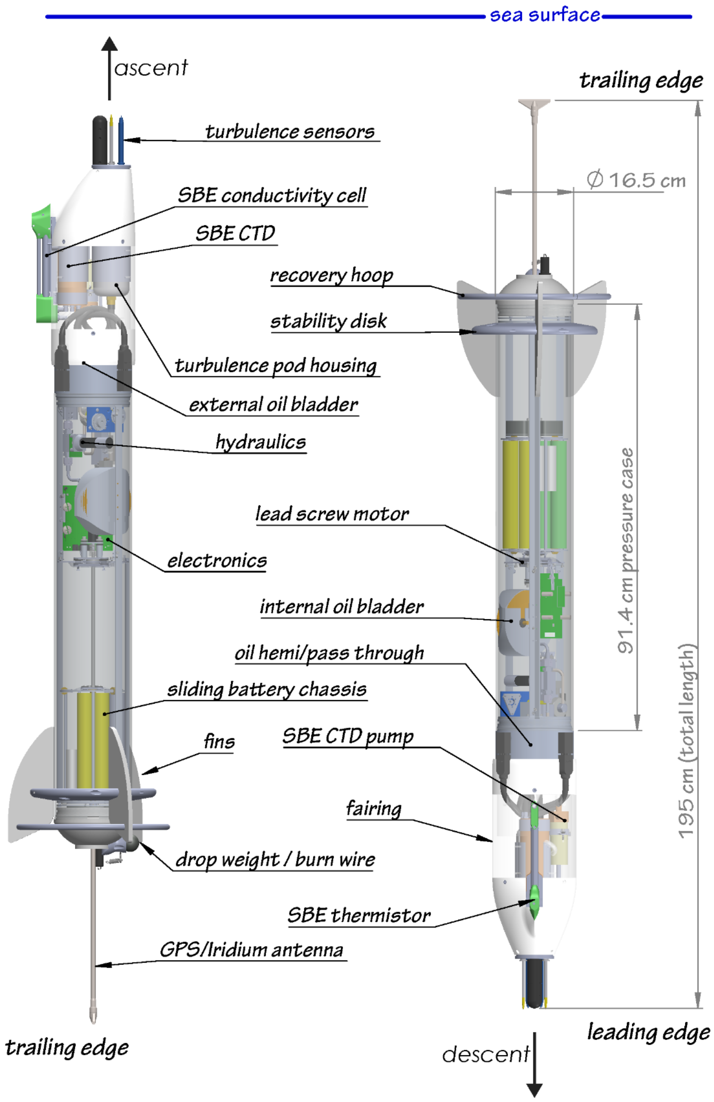


Figure 12. *Schematic of Flippin' χSOLO float.*

SOLO II Floats

Group	Platform Details	Deliverables
Johnston, Rudnick (SIO)	15 SOLO II floats with CTD + chl	T, S, chl, depth-mean u; 0–200 m range, > 2 month endurance with continuous 45 min cycles or longer endurance if not continuous

Wave Buoys

Group	Platform Details	Deliverables
Terrill, Merrifield (SIO)	30 Wave buoys	Directional wave spectra, SST, drift tracks

Surface Drifters and Directional Wave Spectra Drifters

Group	Platform Details	Deliverables
Centurioni (SIO)	200 Surface Drifters (SVP and MicroSVP) https://gdp.ucsd.edu/ldl/svp/	Surface currents (15 m and 1.5 m), SST
Centurioni (SIO)	50 Directional Wave Spectra Drifters https://gdp.ucsd.edu/ldl/dwsbd/	SST, atmospheric pressure at sea level, directional wave spectra

Wirewalkers

Group	Platform Details	Deliverables
Wijesekera (NRL)	3 Wirewalkers	T, S, density, velocity, TKE dissipation, optics (ECO Puck, transmissometer) in the upper 200 m; vertical scales, 1–4 m; lateral scales 1–10 km; temporal scales, 1 hr to several days

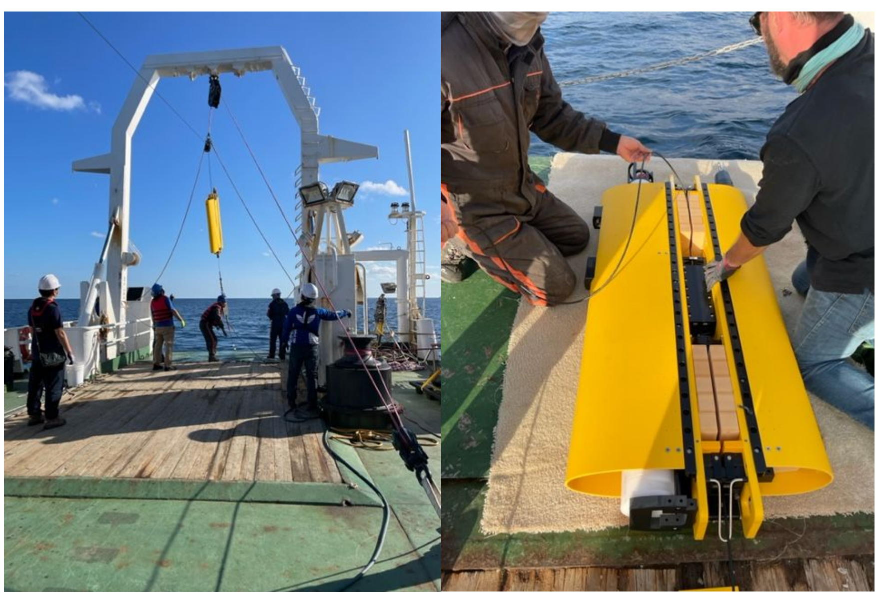


Figure 13. *Wirewalker deployment.*

Ship-Based Sampling

Group	Platform Details	Deliverables
Shearman (OSU)	VMP-250IR + LP Electric Reel, Bow-Chain	T, S, density, ε (turbulence kinetic energy dissipation), χ_T (temperature variance dissipation) from 5–250 m with 1 m vertical resolution; rapid profiling while underway at ~3 kts
Lee, Rainville (APL-UW)	Triaxus (option)	
Wijesekera (NRL)	Scanfish, VMP (limited)	T, S, density, ε (turbulence kinetic energy dissipation), ship ADCP currents, optics (ECO Puck, transmissometer)
Terrill, Merrifield (SIO)	X-band science radar	Phased resolved ocean surface waves

Remote Sensing — Satellite and HF Radar

The University of Miami team (Graber and Caruso) will produce a suite of satellite-based geophysical data products both at synoptic scales over the North Pacific Ocean and at meso- and submesoscales for tracking in-situ measurements. The satellite data include both publicly available and commercial data sets from radar and optical instruments. The commercial satellites will be specifically tasked for events and emerging situations. This flexible approach to satellite collections will allow high-resolution data products to be generated over evolving submesoscale features to provide improved boundary conditions for adaptive grids for the numerical modeling of small-scale ocean processes including meanders, rings, vortices, and filaments.

Specifically, the University of Miami team plans to use near-real time satellite observations to characterize the oceanic fronts and eddies associated with the Pacific North Equatorial Current. They will evaluate how typhoons modify the size and location of meanders, fronts, and eddies along the North Equatorial Current. They will determine the frequency meanders of the Kuroshio break up to form eddies and the spatial and temporal scales of these eddy features. The frequency of submesoscale events will be classified (e.g., meanders, rings, vortices, filaments). Finally, they will determine the effective spatial and temporal scales of satellite ocean topography from SWOT to be launched during this program.

For the pilot cruise, Terrill and Merrifield will use HF radars to quantify the surface currents around Palau out to 150 km.

MODELING EFFORTS

Modeling efforts for the ARCTERX program broadly fall into two categories 1) realistic, high-resolution nested regional non-assimilative simulations used to understand processes, and 2) data assimilative simulations for forecasts, hindcasts, and state estimates.

Non-Assimilative Modeling Efforts

Group	Model Details	Deliverables
McWilliams, Molemaker, Damien, Srinivasan, Hypolite, Delpech (UCLA)	Nested realistic process modeling with ROMS for submesoscale dynamics	Analyses of small-scale termination of submesoscale frontogenesis, surface and internal gravity wave interactions, and air-sea coupling

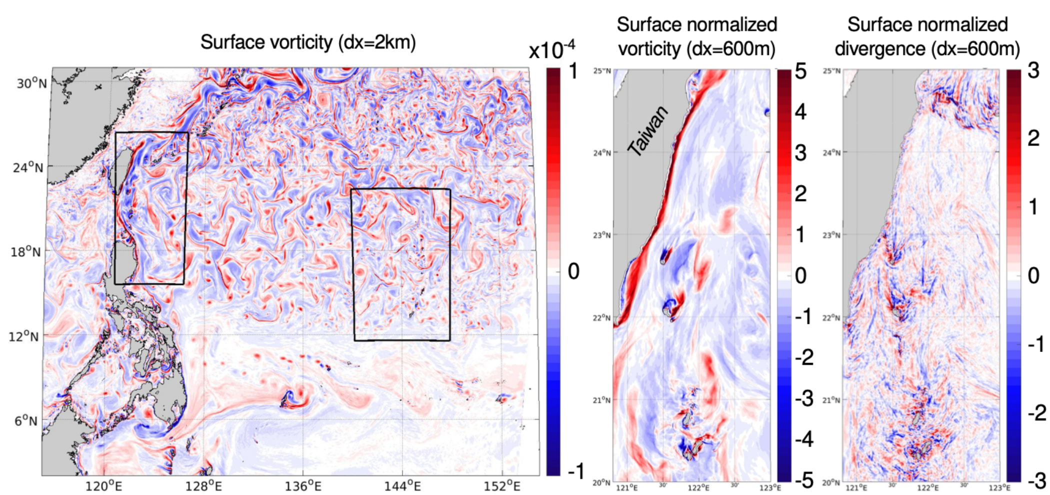


Figure 14. *Example of UCLA modeling efforts in support of ARCTERX. (Left) Daily-averaged, late-wintertime, vertical vorticity [1/s] at the surface in the Philippine Sea in a submesoscale-permitting simulation (dx = 2 km) nested in a whole-Pacific, tidally-resolving parent simulation, showing a broad band of submesoscale activity in the Subtropical Countercurrent (STCC). The black boxes show two further nested subdomains with island and coast interactions: Luzon Strait and the Mariana Islands Arc. (Right) Daily-averaged surface vertical vorticity and horizontal divergence normalized by the Coriolis frequency on the southeastern Taiwanese coast in the dx = 600 m resolution solution. Strong Kuroshio wakes are evident downstream of Green and Orchid islands as well as the shear layer emitted from the southern-most cape. (Damien, McWilliams, Molemaker, and Srinivasan, UCLA)*

Group	Model Details	Deliverables
Thomas and Postdoc (Stanford Univ.)	Nested, high-resolution regional simulations of the STCC run with the CROCO model; OSSEs with virtual autonomous platforms run using CROCO output to aid the design sampling strategies	Simulations of the seasonal cycle of submesoscale turbulence in the STCC; diagnostics of the energetics, balanced and unbalanced motions, and PV and frontal dynamics of the submesoscale turbulence; sampling strategies optimized to test hypotheses; idealized and realistic simulations configured with flow and forcing parameters representative of observations to aid interpretation post cruise

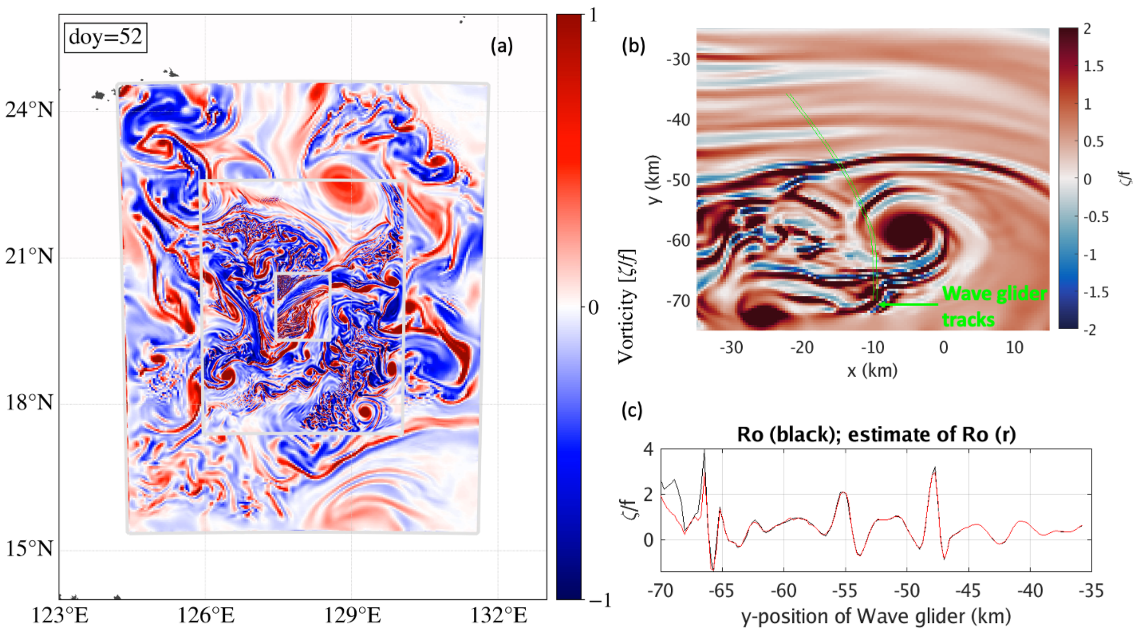


Figure 15. *Example of nested CROCO (Coastal and Regional Ocean Community Model) simulations from the Stanford group and an OSSE with virtual Wave Gliders. (a) Surface vorticity (normalized by the Coriolis parameter) in three concentric child grids with horizontal grid spacings of 4 km, 1 km, and 400 m, respectively. (b) Surface vorticity in the 400 m grid and the paths of virtual Wave Gliders (green lines) programmed to use their speed (which is a function of the winds as determined empirically from observations of actual Wave Gliders) to keep a distance 500 m apart and maintain a northward velocity (relative to the water). This is a possible Wave Glider deployment strategy for estimating the vorticity, strain, divergence, and tracer gradients using the "two-ship method" of Shcherbina et al. (2013). The OSSE suggest that the method can accurately estimate the surface vorticity [c.f. the red and black lines in (c)] for the simulated submesoscale flows, which are representative of those found in the STCC.*

Group	Model Details	Deliverables
Simmons (APL-UW)	Nested simulations within Univ. HI model during IOP and hindcasts	Predictions of cascade timescales and persistence as a function of spatial scale; assessment of how models best inform observational strategies and analysis

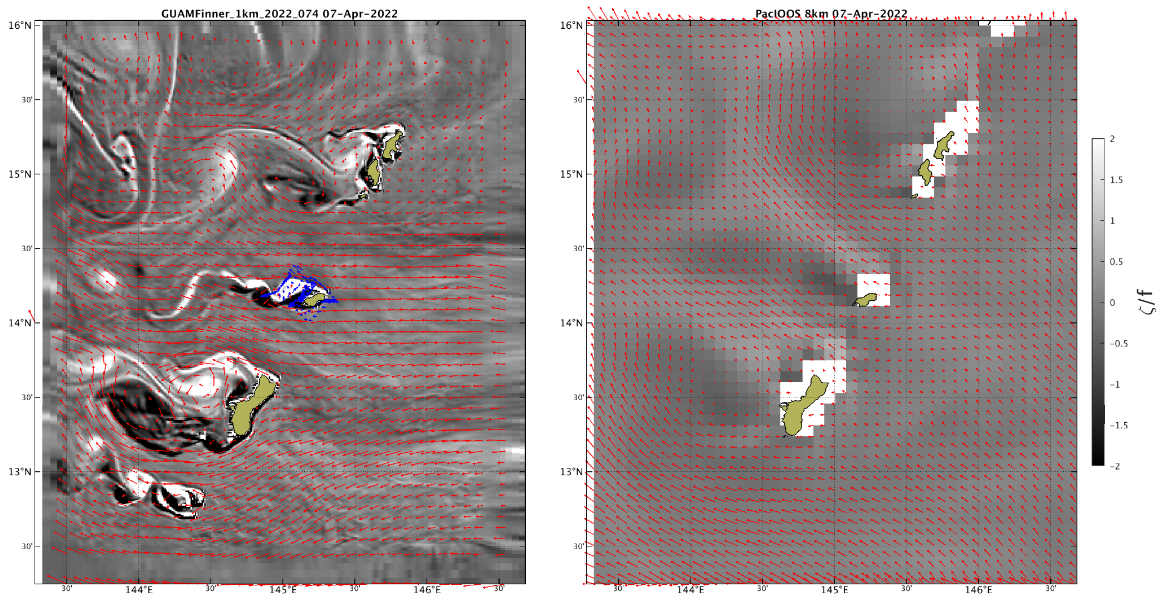


Figure 16. *APL-UW simulations in support of the ARCTERX pilot cruise. Regional surface flow simulated by a 1 km resolution ROMS model (left) nested inside PacIOOS (Pacific Integrated Ocean Observing System) 8 km parent model (right) for 7 April 2022. Blue vectors on left panel are the R/V Revelle ADCP currents in the upper 30–50 m over 6–8 April 2022. The domain size of the nest is 425 km (east-west) x 475 km (north-south). This domain size is small enough that the large scale structure of the NEC current and water masses over the nest footprint are controlled by the boundary conditions provided by the 8 km PacIOOS parent model but admit wake structures. Future APL-UW simulation plans are to conduct similar nested configurations in support of field operations with the purpose of at-sea situational awareness and decision making, OSSE exercises, and investigation of process physics.*

Assimilative Modeling Efforts

Group	Model Details	Deliverables
Zavala-Garay, Wilkin, Arango (Rutgers Univ.)	Data-assimilative high-resolution ROMS to be coupled with WRF to evaluate the possible impact of coupled processes in submesoscale production	Case studies for submesoscale production in the STCC, mainly targeting the observational campaign

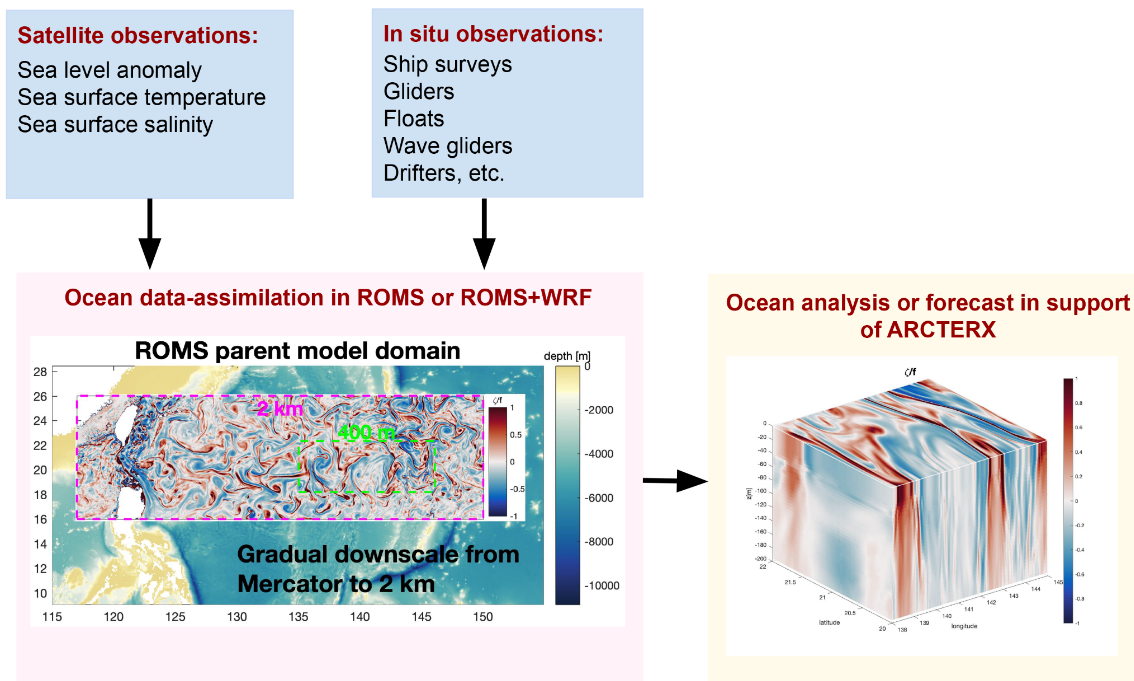
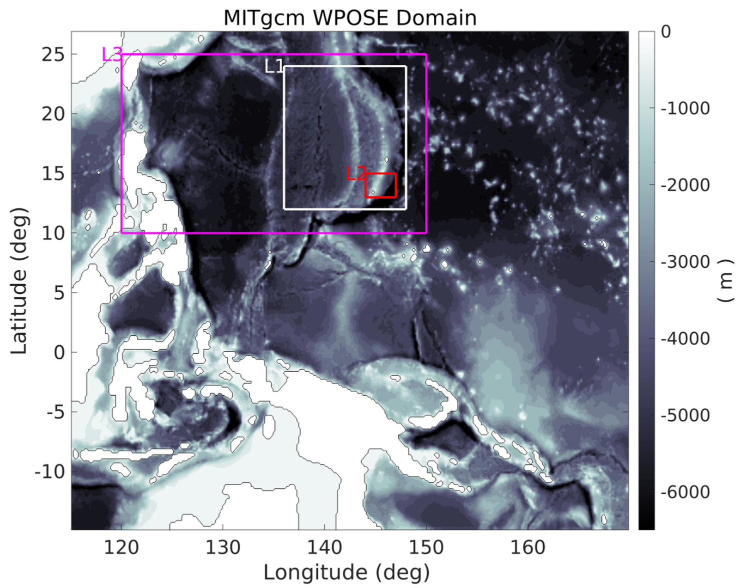


Figure 17. *Rutgers Univ. ROMS data assimilation system. Satellite and in-situ observations will be combined with the modeling system to produce an analysis/forecast in support of ARCTERX. (Left) the parent model domain, which gradually downscales the solution from global models to a constant resolution of 2 km within the magenta square. The child model domain (green square) will target the area of intense sampling during the interior experiment at a target resolution of 400 m. The vorticity field (normalized by the Coriolis parameter) from the parent model during the interior pilot experiment is shown in both panels.*

Group	Model Details	Deliverables
Gopalakrishnan, Cornuelle (SIO-UCSD)	Assimilate the observations and produce a hindcast analysis and cross-validation forecasts using nested MITgcm domains. If a broadened scope is desired, implement SKRIPS model (coupling WRF, MITgcm, and WaveWatch3) for the study region. This could include weakly coupled data assimilation (currently in development). This would provide another coupled model realization in addition to the Rutgers ROMS coupled model, but is not in our proposed work.	Deterministic model analysis and forecasts for the study period. Cross-validation by comparing withheld and future observations. Momentum budget analysis and estimate the energy fluxes between scales. Sensitivity to mixing parameters.

SIO maintains the Western Pacific Ocean State Estimate (WPOSE) 1/6 degree estimate for the period 2009–present, and it forms the basis for the nested data-assimilative modeling experiments in support of ARCTERX (Figure 18, top panel). WPOSE uses the MITgcm-ECCO 4D-Var assimilation system to produce optimized hindcasts by synthesizing global observations of satellite SSH, SST, temperature and salinity profiles from Argo, gliders, moorings, and XBTs over 1.5-month time periods. The dynamics are respected during each window, and the model can fit the SSH observations to within about 3 cm during the hindcast and the error grows slowly during 2-week forecasts (Fig. 18, bottom panel).

Group	Model Details	Deliverables
Powell (Univ. HI)	Development of research hybrid model for estimates of 4D-Var without the use of an adjoint and/or replacement of subgrid estimations. Near-real time state estimates of region using available data (including available ARCTERX data) during IOP. Reanalysis hindcasts with all data for STCC region of interest. Near-real time predictions at various scales (Simmons group will make very high-resolution nested predictions). Using TKE and other observations with high-resolution (Simmons) output for training hybrid model.	Operational state estimates and predictions during IOP. Possible analysis of predictability impact by submesoscale resolutions via energy cascade and mixing.



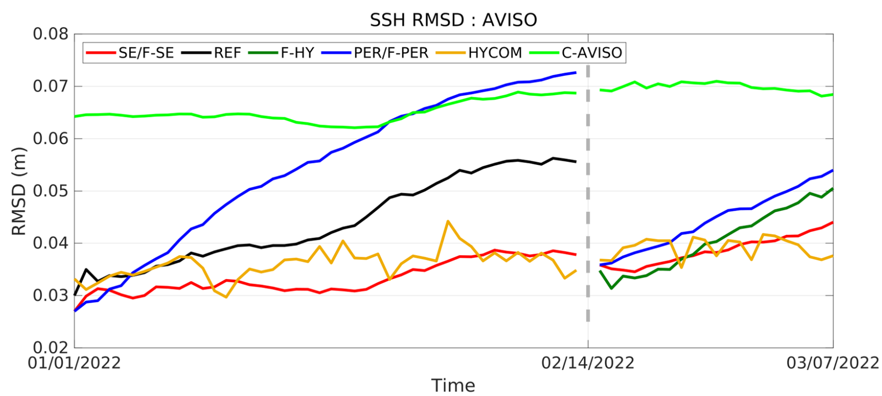


Figure 18. *(Top) The SIO WPOSE 1/6 degree domain. A series of nested model regions are also shown, which are either nested directly to the 1/6 degree or 1/12 degree (same region) parent model. Nested domains include L1: Leg-1 pilot cruise (white box at 1/48 degree), L2: Leg-2 pilot cruise (red box at 1/96 degree), and L3: interior experiment (magenta box at 1/24 deg). Nested data-assimilative modeling experiments will focus on ARCTERX observational campaigns. (Bottom) SSH root mean square (RMSD) point-by-point difference with AVISO, averaged over the assimilation region (5°N–20°N, 122°E–170°E) for a recent hindcast (1 January – 14 February 2022) and forecast (15 February – 07 March 2022). The hindcast and forecast are separated by the vertical dashed line. The red curve is the RMSD for the state estimate and forecast (WPOSE), the black curve is RMSD for the first-guess integration from HYCOM, the blue curve is for model persistence (keeping the initial state constant), the golden curve is for HYCOM-NCODA daily global analysis, the light green curve is the RMSD of the AVISO monthly climatology from 1993–2018, and the dark green curve in the forecast period is an MITgcm forecast initialized from the HYCOM-NCODA daily global analysis.*

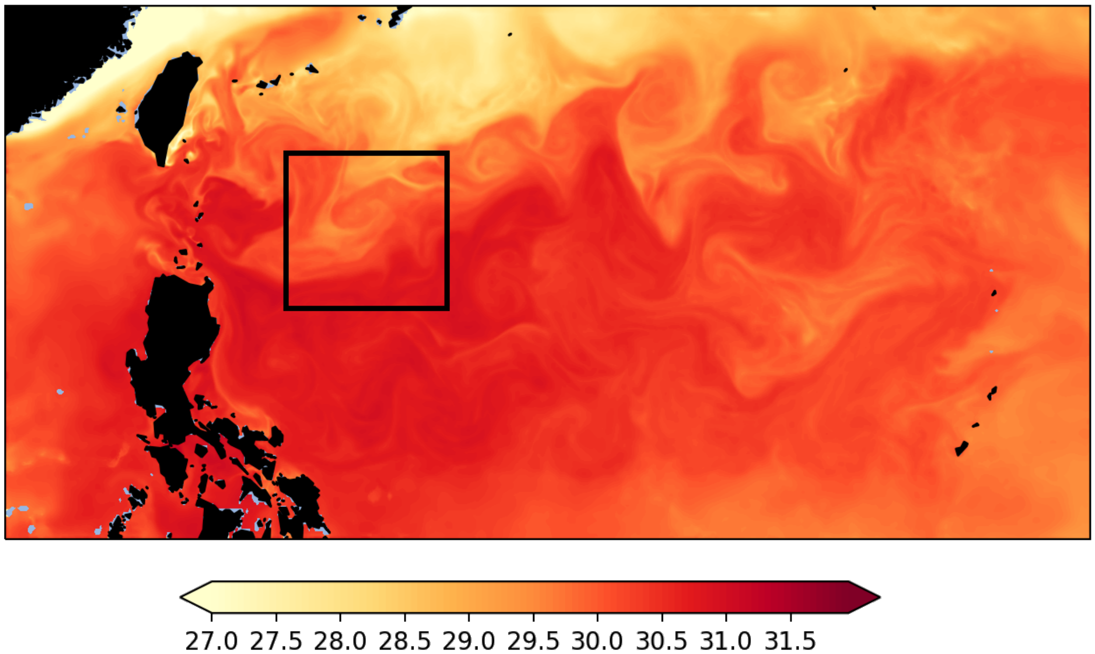


Figure 19. *The 4 km regional grid including tides that will use 4D-Var assimilation of all available data from near-real time sources (satellites, Argo, etc.) along with ARCTERX observations. Also illustrated is the open ocean regional box (approximate bounds) used for finer downscaling by the Simmons group (APL-UW).*

In collaboration with the Simmons group (APL-UW), we intend to train a physics-informed neural network (PINN) on the high-resolution data produced by the Simmons group to try to replace aspects of 4D-Var with a data-trained model to eliminate the need for an adjoint as well as exploring methods to replace subgrid estimation.

DATA POLICY

The Island Arc Turbulent Eddy Regional Exchange (ARCTERX) DRI and Kuroshio to Turbulence Exchange (KTEX) bring together multiple investigators and multiple coordinated scientific projects between Taiwan and the United States of America. The following data policy derives from experience in multiple ONR DRIs. Successful ONR DRIs share a distinguishing characteristic: tightly integrated experimental and numerical efforts followed by highly collaborative analysis efforts. This is essentially the difference between a single, large, coordinated experiment and a large collection of independent projects working in parallel. The single, large, coordinated experiment requires open data sharing to function. Moreover, rapid, open data release is becoming standard for large programs. The ARCTERX/KTEX data policy recognizes this and attempts to strike a balance with rapid, full release within the ARCTERX/KTEX team followed by public release sometime after the conclusion of the program.

ARCTERX/KTEX consists of all investigators participating in the integrated efforts associated with the programs. This includes the core team of ONR-supported U.S. investigators funded directly by the ARCTERX DRI, investigators from Taiwan involved in partner projects sponsored by Taiwan's Ministry of Science and Technology (e.g., KTEX), and investigators funded through other mechanisms, but coordinated as part of the ARCTERX/KTEX program. ARCTERX/KTEX data will include observations from field programs, remote sensing data, and model results, all of which will be treated equally for the purposes of the program data policy. Considerations should also be made for theoretical ideas and analysis techniques that are newly-developed for the program. All data are collected for basic research, and will be unclassified.

Given the complex nature of the science questions and challenges associated with collecting the necessary observations, the success of the ARCTERX/KTEX program depends on open, effective data sharing and collaboration. To facilitate sharing of data and collaboration between ARCTERX/KTEX scientists a program to archive data will be established. To further promote and support sharing and collaboration, ARCTERX/KTEX specifies the following policies to govern the use of data collected under the program.

Data Types

Data collected or used as part of ARCTERX/KTEX loosely fall into three categories: (a) routine or institutionalized data, (b) program or investigator specific data, and (c) sensitive data.

Routine Data

Examples of (a) routine data include (but are not limited to) sea level or weather buoy data and standard climatological data that are routinely collected and archived by others, and raw satellite data that are routinely available on the World Wide Web.

Program/Investigator Specific Data

Examples of (b) program/investigator data include (but are not limited to) data from oceanographic and acoustic moorings, towed and lowered CTD data, data from surface drifters and subsurface floats, data from unique underway sampling systems or from sensors mounted on autonomous vehicles, and satellite data that have been sufficiently post-processed and value-added that the investigator has a stake in its continued usage. Output from numerical models that are not routinely and operationally run should also be considered program/investigator data.

Sensitive Data

There are some Taiwanese data sets that are sensitive in nature and that should only be shared by the curators. If another investigator wishes to use such data they must make a request to the curator of the data directly and agree not to share it with anyone else, including other ARCTERX/KTEX scientists. This is to ensure that the curator of the sensitive data can keep track of who the data have been shared with.

Data Use

The primary tenets of data sharing within the ARCTERX team are:

1. Data will be shared freely within the team. ARCTERX team members are obligated to share their data with others in the team.
2. Data sharing promotes collaboration. Team members who use data are obligated to engage the data providers as detailed below.
3. Responsibilities for distinct lines of inquiry will be determined collaboratively, through discussion and agreement of all interested parties.

Guidelines for ARCTERX data sharing:

Publication of routine data generally does not require co-authorship, although citation and/or acknowledgement is expected of the investigator who uses the data.

It is not ethical to publish program/investigator specific data without proper attribution or co-authorship. The data are the intellectual property of the collecting investigator(s). Similar standards apply to theoretical ideas and analysis techniques newly-developed for the ARCTERX/KTEX program.

The intellectual investment and time committed to the collection of a data set entitles the investigator to the fundamental benefits of the data set. Publication of descriptive or interpretive results derived immediately and directly from the data is the privilege and responsibility of the investigators who collect the data.

There are two possible actions for any person making substantial use of program/investigator specific ARCTERX/KTEX data sets, both of which require discussion with and permission from the data collector:

1. *Expectation of co-authorship*

   This is the usual condition. Scientists making use of the program/investigator specific data should anticipate that the data collectors would be active participants and require co-authorship of published results.

2. *Citation and acknowledgment*

   In cases where the data collector acknowledges the importance of the application but expects to make no time investment or intellectual contribution to the published work, the data collector may agree to provide the program/investigator specific data to another scientist providing data reports are properly cited and the contribution is recognized in the text and acknowledgments.

In either of the above cases, discussion with the relevant PIs should occur before a new analysis is started.

Authors must share and discuss manuscripts with all ARCTERX/KTEX investigators who contributed data prior to submission anywhere.

Agreements about publication, authorship, or citation should be documented at a minimum by email between the investigators.

Expectations for sensitive data must be communicated by the data curator.

Roles and Responsibilities

Principal Investigators who are responsible for the collection of observational data or generation of model data during the ARCTERX/KTEX program are considered participating ARCTERX/KTEX scientists and may request data from and provide data to other participating scientists. Participating scientists have primary responsibility for quality control of their own data and making it available to the rest of the ARCTERX/KTEX participating scientists on a timely basis.

Data should be released as soon as possible, through the data archive, along with documentation that can be used by other researchers to judge data quality and potential usefulness.

The data contained in the archive are made available even though they may not be “final” (i.e., error free) data so it is the responsibility of the user to verify the status of the data and to be aware of its potential limitations.

Participating scientists who wish to use others' data sets are responsible for notifying those Principal Investigators of their intent and inviting collaboration and/or co-authorship of published results.

Participating scientists must consider the interests of graduate students and postdocs before publishing data. Plans for graduate student and postdoc projects must be discussed openly and effort made by all ARCTERX/KTEX investigators to facilitate and protect these efforts.

For the duration of ARCTERX/KTEX, program data will be restricted to ARCTERX/KTEX investigators. Dissemination beyond program investigators will require the agreement of *all* ARCTERX/KTEX investigators and the cognizant ONR program managers.

The ARCTERX/KTEX program prohibits third party data dissemination; participants are not allowed to redistribute data taken by other ARCTERX/KTEX investigators.

All potential users who access the data will be reminded of the ARCTERX/KTEX commitment to the principle that data are the intellectual property of the collecting scientists.

Program sponsors of participating scientists may arbitrate and reach agreement on data sharing questions when they arise.

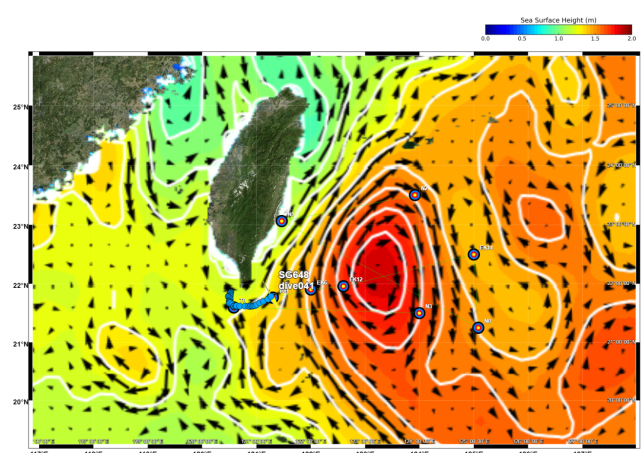
APPENDIX A: ARCTERX Investigators

Principal Investigator	Institution	Grant Number
Luca Centurioni	Scripps Institution of Oceanography, University of California San Diego	N00014-21-1-2793
Sebastian Essink	Applied Physics Laboratory, University of Washington	N00014-21-1-2753
Ganesh Gopalakrishnan	Scripps Institution of Oceanography, University of California San Diego	N00014-21-1-2726
Hans Graber	University of Miami	N00014-21-1-2798
Shaun Johnston	Scripps Institution of Oceanography, University of California San Diego	N00014-21-1-2762
Craig Lee	Applied Physcis Laboratory, University of Washington	N00014-21-1-2885
James McWilliams	University of California Los Angeles	N00014-21-1-2693
James Moum	Oregon State University	N00014-21-1-2878
Brian Powell	University of Hawaii at Manoa	N00014-21-1-2709
Daniel Rudnick	Scripps Institution of Oceanography, University of California San Diego	N00014-21-1-2747
Harper Simmons	Applied Physics Laboratory, University of Washington	N00014-21-1-2884
R. Kipp Shearman	Oregon State University	N00014-21-1-2792
Eric Terrill	Scripps Institution of Oceanography, University of California San Diego	N00014-21-1-2890
Leif Thomas	Stanford University	N00014-21-1-2886
Caitlin Whalen	Applied Physics Laboratory, University of Washington	N00014-21-1-2866
Hemantha Wijesekera	Naval Research Laboratory	
Javier Zavala-Garay	Rutgers University	N00014-21-1-2694

APPENDIX B: Notes on Taiwanese Efforts Relevant to ARCTERX

- Annual ship schedule is from 1 August to 31 July.
- Cruise dates will be confirmed every 4 months, i.e., in July (for August – November), November (for December – March), and March (for April – July).
- Taiwanese research interest on “boundary processes” will be focused on the details about the energy and water mass exchange of the Kuroshio and mesoscale eddies in the Luzon Strait and off the east coast of Taiwan in the next five years. These processes also comprise generation of instability waves, enhancement of turbulence, and biological influence of vortexes created when the swift current of the Kuroshio flows over abrupt topography or encounters islands. The Taiwanese will also arrange certain resources to join the field experiment for “interior processes,” particularly in the western North Pacific between Taiwan, Guam, and Palau.
- The division of oceanography research in Taiwan’s Ministry of Science and Technology (MOST) will support necessary ship time for relevant cooperative field experiments including in the Luzon Strait and off the east coast of Taiwan and between Taiwan and Guam in 2022, 2023, and 2024. A MOST ship time arrangement meeting will be held in June 2022.

Vessel	Schedule	Objectives
New OR1	18–25 Oct 2021	Interior: Fundamental observations to characterize eddies
		Boundary: Kuroshio transect
	2–4 Dec 2021	A Seaglider was launched off the southernmost tip of Taiwan on 3 December for anticyclonic eddy observations. The glider is being navigated toward the east. Glider’s position, proposed track, target points, and satellite SSH mapped (below).



New OR1	8 days in May 2022	Island wakes and vortices experiment
New OR2	7 days in April 2022 6 days in July 2022	Pilot experiment for wakes and vortices Wakes and vortices experiment (two ships)
New OR3	8 days in July 2022 7 days (TBD)	Wakes and vortices experiment (two ships)
New OR1	30 days in Spring 2023	Interior observations (ship time request has been submitted)

Notes:

1. *New OR1* cruise in October 2021 will launch a Seaglider off the east coast of Taiwan for the transect observations. (The launch was aborted due to glider pressure sensor failure.)

2. *New OR1*, *2*, and *3* cruises in July 2022 will be accompanied with observations using EM-APEX floats and gliders.

3. Historical data collected by R/Vs, moored PIESs, and ADCP arrays, data buoys, and gliders (e.g., Fig. A1).

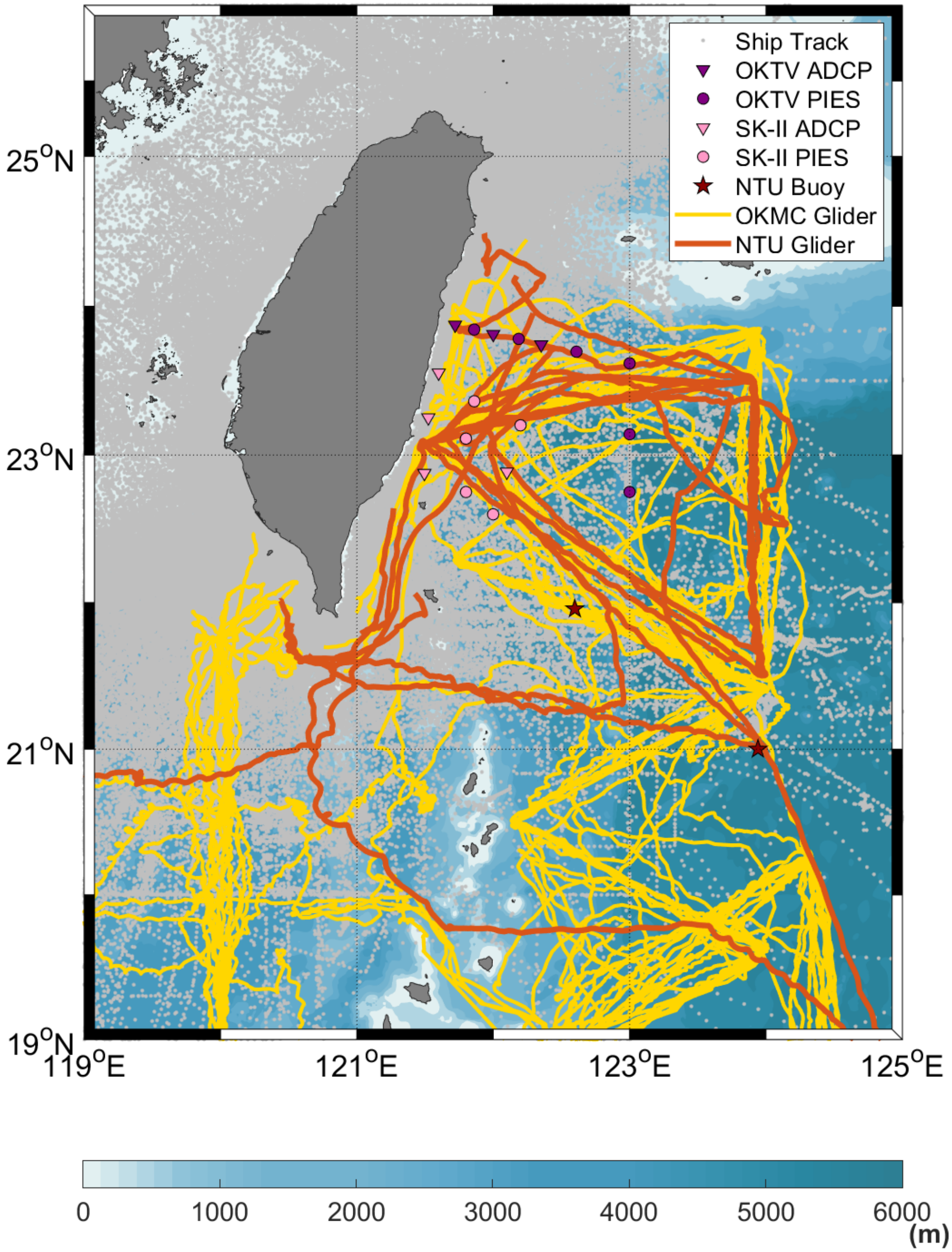


Figure A1. *Map of historical data collected by R/Vs, moored PIESs and ADCP arrays, data buoys, and gliders in the western part of the ARCTERX region.*

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