FLOW ENCOUNTERING ABRUPT TOPOGRAPHY (FLEAT)

A MULTISCALE OBSERVATIONAL AND MODELING PROGRAM TO UNDERSTAND HOW TOPOGRAPHY AFFECTS FLOWS IN THE WESTERN NORTH PACIFIC

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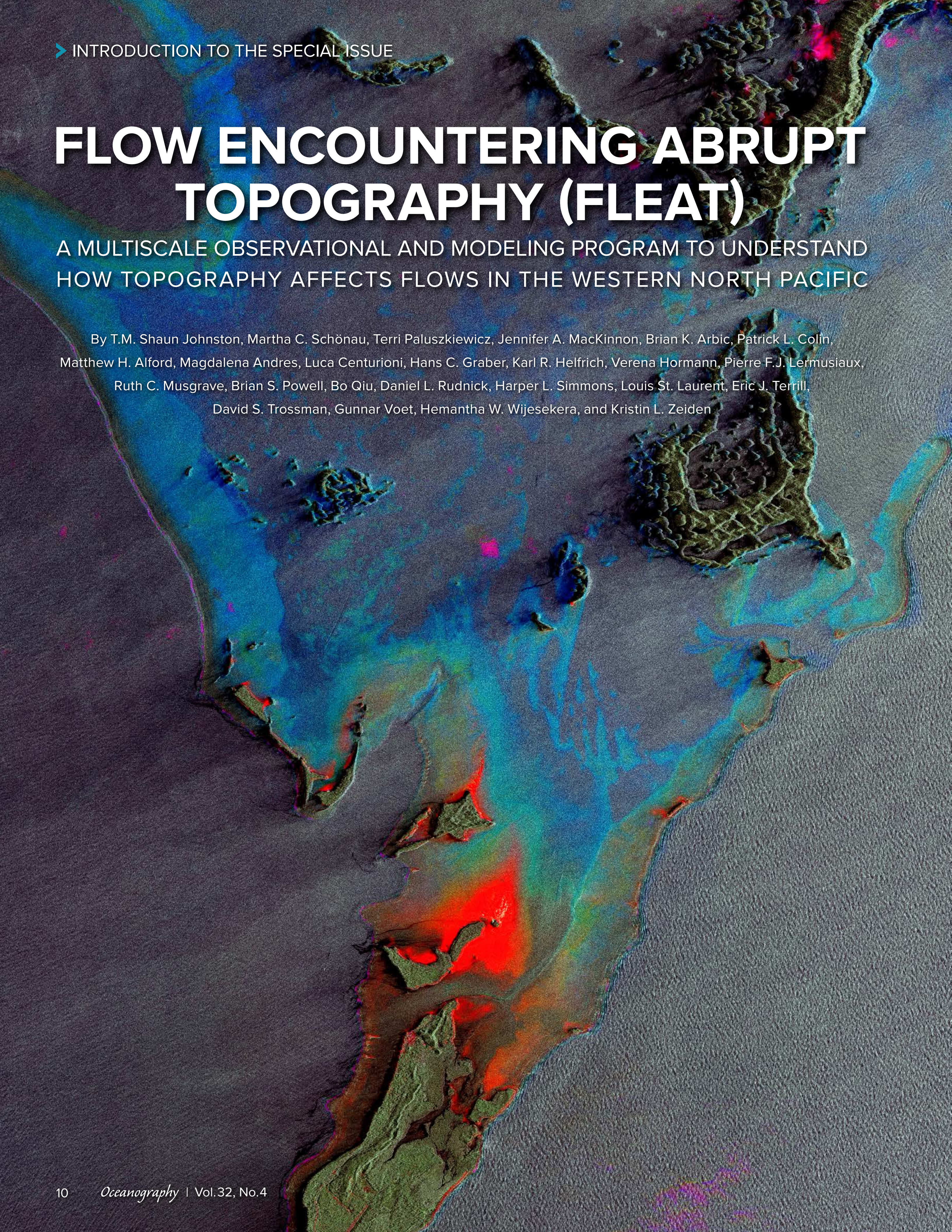


ABSTRACT. Using a combination of models and observations, the US Office of Naval Research Flow Encountering Abrupt Topography (FLEAT) initiative examines how island chains and submerged ridges affect open ocean current systems, from the hundreds of kilometer scale of large current features to the millimeter scale of turbulence. FLEAT focuses on the western Pacific, mainly on equatorial currents that encounter steep topography near the island nation of Palau. Wake eddies and lee waves as small as 1 km were observed to form as these currents flowed around or over the steep topography. The direction and vertical structure of the incident flow varied over tidal, inertial, seasonal, and interannual timescales, with implications for downstream flow. Models incorporated tides and had grids with resolutions of hundreds of meters to enable predictions of flow transformations as waters encountered and passed around Palau's islands. In addition to making scientific advances, FLEAT had a positive impact on the local Palauan community by bringing new technology to explore local waters, expanding the country's scientific infrastructure, maintaining collaborations with Palauan partners, and conducting outreach activities aimed at elementary and high school students, US embassy personnel, and Palauan government officials.

INTRODUCTION

Predicting how topography affects ocean currents has long interested scientists, coastal forecasters, ecologists, coastal communities, coast guards, navies, and others who rely on accurate ocean forecasts. Numerous studies have examined flow around headlands, over submarine ridges, and through constricting gaps to provide some understanding of these interactions (e.g., Wunsch, 1972; Signell and Geyer, 1991; Baines, 1995; Dong et al., 2007; Garrett and Kunze, 2007; Magaldi et al., 2008; Warner and MacCready, 2009; Chang et al., 2019); however, observing flow-topography interactions at resolutions that capture the energy and momentum of incoming large-scale flows through to their dissipation as they encounter topography is challenging, and has left gaps in our understanding of how these processes occur.

The goal of the Flow Encountering Abrupt Topography (FLEAT) research initiative was to improve understanding of the effects of island and ridge systems on major ocean currents and their downstream structure. Using data collected with unmanned systems, mooring arrays, and intensive island- and ship-based sensor systems, the experiment observed flow before and after passing over and around topography to understand the processes that contribute to energy and momentum loss at the topography. FLEAT vastly expanded the approaches employed by previous studies by integrating these observations with models to study processes down- and upstream of topography.

The FLEAT experiment considered a wide area of the western Pacific, including Yap and Guam, but focused mainly on the incident currents and wakes near the Palau archipelago (Figure 1). Palau sits on the Kyushu-Palau Ridge, which lies in the path of the equatorial current system between the westward-flowing NEC

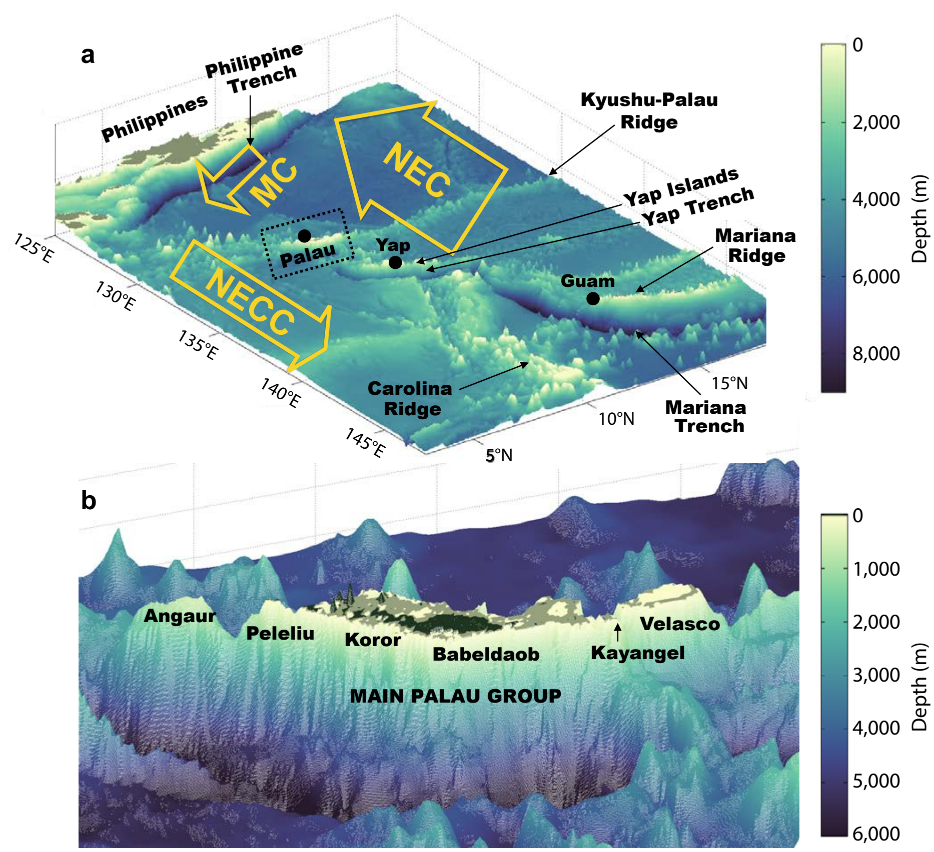


FIGURE 1 (right). (a) Circulation and topography in the western tropical North Pacific. Islands are located along ridges that are often separated by deep trenches, making the topography steep. The North Equatorial Current (NEC), the Mindanao Current (MC), and the North Equatorial Countercurrent (NECC) are the large-scale currents in the region. Not shown are current recirculations, quasi-permanent eddies, and the flow below the wind-driven surface layer. (b) An up-close view of the main Palau island group around which most FLEAT observations and modeling studies were focused. Separation points of the large-scale flow, at which vorticity is generated, are located at the northern, shallow Velasco Reef and at the southern point of Peleliu. The distance from Velasco to Peleliu is roughly 180 km.

FACING PAGE. False color synthetic aperture radar (SAR) Stripmap image collected by TerraSAR-X on April 3, 2013, at 20:59 UTC with VV (vertical/vertical) polarization. Green correlates with vegetation, while the blues indicate areas of wind shadows. The area of vivid red signifies wave breaking and other strong backscatter. *© DLR e.V. 2013, Distribution Airbus Defence and Space GmbH, downlinked and processed by CSTARS under Airbus Defence and Space license*

(9°N to 16.5°N) and the eastward-flowing North Equatorial Countercurrent (NECC; 3°N to 7°N; Figure 1). Topography in the region is exceptionally steep, with slopes commonly 1:1, descending rapidly from coral reefs near the surface to the 6,000 m depth of the ocean floor (Figure 1). As flows go *around* island headlands and *over* submarine ridges, wake eddies and lee waves are generated (Warner and MacCready, 2009). These processes occur simultaneously amidst broad variability on tidal, inertial, seasonal, and interannual timescales. The spatial scales cover a large range: the thousand-kilometer extent of the NEC, the mesoscale (defined by the Rossby deformation radius, R_d = 200 km), the island scale (about 100 km in the case of Palau's topography), the submesoscale (typically <10 km), and finally wave-breaking and turbulence scales (meters to millimeters). Thus, this environment provided all of the scales and features that FLEAT sought to examine.

This special issue of *Oceanography* assembles many of the principal results of FLEAT and addresses its broader, multidisciplinary impact. This overview highlights the collection of articles and provides the broader context for why this study is a meaningful, new contribution to oceanography. Though most FLEAT work considers the upper ocean, similar phenomena occur in abyssal flow, and two other relevant papers in this issue describe mixing processes over small-scale topography in the Samoan Passage.

FLEAT RESULT HIGHLIGHTS

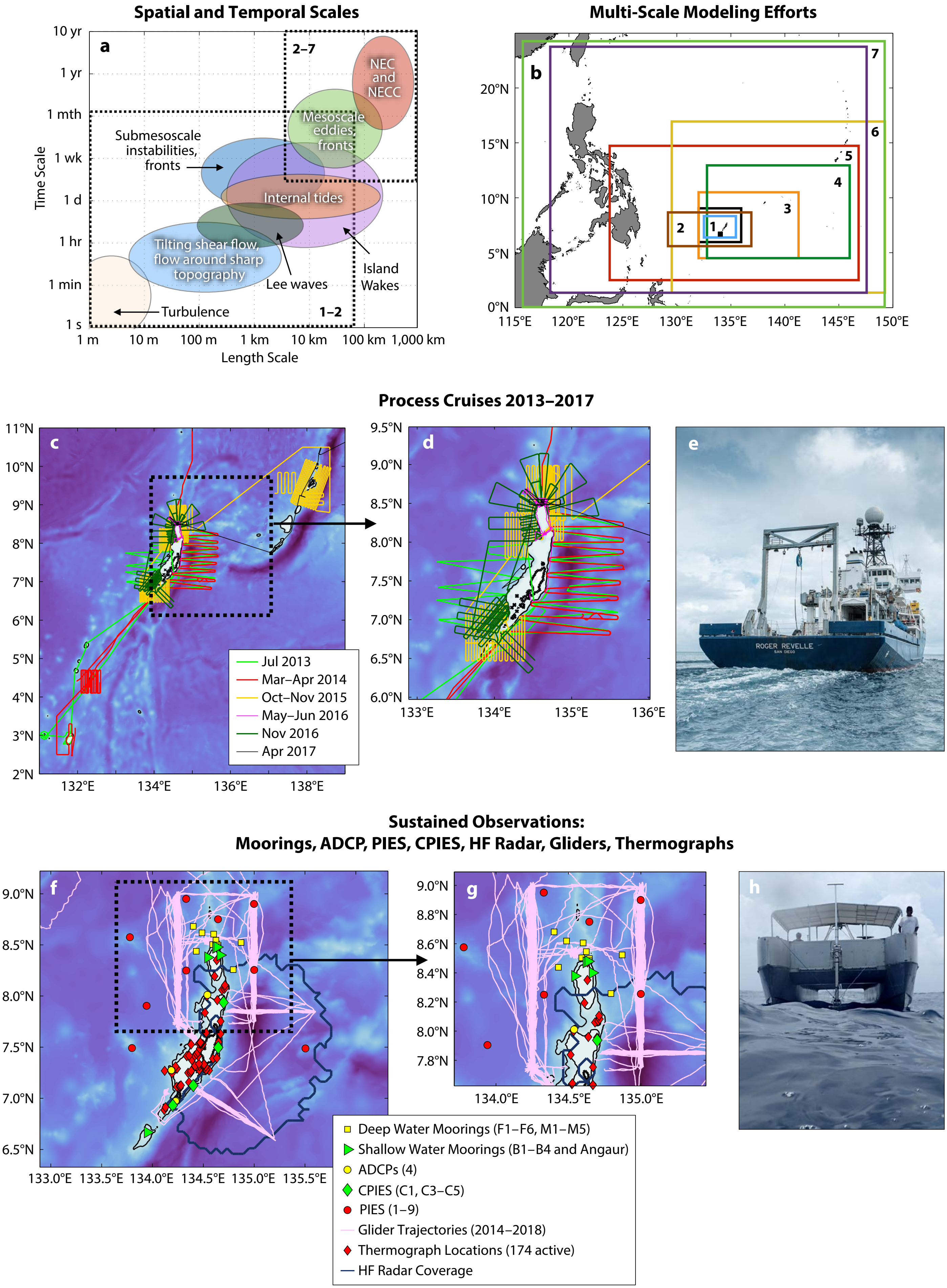
Modeling and Observational Approach

Targeted modeling and observations were needed to tease out the role topography plays in open ocean circulation, as well as how it affects the cascade of energy from the largest to the smallest scales. Ocean circulation modelers face a difficult problem in resolving islands and steep submarine topography. To model climate-related phenomena, forecast currents, or resolve the air-sea exchange that is critical to weather forecasting, the model domain must be large enough to capture the equatorial current system but also small enough so that fine-scale horizontal and vertical resolutions represent the topography. To capture all the spatial and temporal scales under consideration, from the large-scale flow to turbulent mixing (Figure 2a), a series of "nested" modeling efforts were undertaken using different modeling systems (Figure 2b). Model resolution was matched to that of field observations (Figure 2c,d and f,g).

To complement the nested model approach, an aggressive and expansive observational study was designed to capture the many scales of the wave and eddy structures generated by flows as they encountered the steep island topography. Six research cruises aboard R/V *Roger Revelle* (Figure 2e) were conducted around the main Palau group, its southern islands, and Yap (Figure 2c). These cruises included underway CTD, lowered acoustic Doppler current profiler (LADCP), turbulence, and SeaSoar surveys, as well as shipboard X-band Doppler marine radar observations. Some of this work was also done on *Kemedukl*, a research catamaran owned and operated by the Coral Reef Research Foundation (CRRF; Figure 2h). Cruises were complemented by sustained observations from autonomous gliders, deep and shallow water moorings, acoustic Doppler current profilers (ADCPs), pressure-recording inverted echosounders (PIESs) with optional current sensors (CPIESs), high-frequency (HF) radar, and thermographs (temperature loggers) (Figure 2f,g). Time series lasted roughly one to two years for moorings and PIES and CPIES measurements, and three years for gliders (Figure 2g,h). Ongoing observations include HF radar and Palau's temperature monitoring network, which began in 1998 following a coral bleaching event; it extends from a shallow depth (near intertidal) to 90 m and includes 119 stations with 210 instruments that gather 25 million data points every year (Colin, 2018).

The majority of the mooring and glider observations, as well as a number of research cruises, focused on the northern extent of Palau at the steep topography near Velasco Reef, where a persistent NEC was expected (Schönau and Rudnick, 2015). The deep- and shallow-water moorings and glider lines on either side of Velasco Reef were designed to capture the broad incident flows of the NEC as well as its variability, typically measured on timescales of a few months; the nearshore moorings and ship surveys measured wake eddies and lee waves at smaller temporal and spatial scales (Figure 2g). Gliders, moorings, and lowered probes measured turbulence during eddy generation and in the wake. At the southern end of the Palau island chain, research cruises observed flow structure and dissipation, complementing sustained observations from stationary ADCPs, moorings, and thermograph stations.

FIGURE 2 (facing page). (a) Length and time scales of processes that the multiscale modeling and observational efforts targeted, where turbulence includes overturns of about 10 m (internal waves breaking) to millimeter scales (viscous dissipation). (b) Domains of multiscale models ranged in size from the western tropical Pacific at 1/6° (18.5 km) resolution to 1 m grid resolution around individual reef structures. (c) Tracks of the six cruises during FLEAT that included towed CTD, lowered acoustic Doppler current profilers (LADCPs), and microstructure surveys to measure density structure, velocity, and dissipation. (d) Radiator surveys near Palau focused on the northern and southern points of Palau and the wake region. (e) Cruises took place on R/V *Revelle*, photographed here leaving port in Palau. *Photo credit: Thomas Moore* (f) Locations of sustained observations from pressure-recording inverted echosounders (PIES) and PIES with current sensors (CPIES), Spray gliders, thermographs (temperature loggers), and shallow- and deepwater moorings. The footprint of high-frequency (HF) radar coverage is also shown. Stationary observations (moorings, PIES, CPIES) were deployed for one- to two-year periods. Glider observations on either side of Velasco Reef were sustained from 2015 to 2018. HF radar and thermograph observations are ongoing. (g) Most of the observations concentrated around Velasco Reef, which was in the NEC most of the time. (h) Underway CTD surveys near Peleliu were carried out aboard the Coral Reef Research Foundation's research catamaran, *Kemedukl*.


Spatial and Temporal Scales
a
2–7
1–2
NEC and NECC
Mesoscale eddies, fronts
Submesoscale instabilities, fronts
Internal tides
Tilting shear flow, flow around sharp topography
Lee waves
Island Wakes
Turbulence
10 yr
1 yr
1 mth
1 wk
1 d
1 hr
1 min
1 s
Time Scale
1 m
10 m
100 m
1 km
10 km
100 km
1,000 km
Length Scale
Multi-Scale Modeling Efforts
b
1
2
3
4
5
6
7
20°N
15°N
10°N
5°N
0°N
115°E
120°E
125°E
130°E
135°E
140°E
145°E
150°E
Process Cruises 2013–2017
c
d
e
Jul 2013
Mar–Apr 2014
Oct–Nov 2015
May–Jun 2016
Nov 2016
Apr 2017
11°N
10°N
9°N
8°N
7°N
6°N
5°N
4°N
3°N
2°N
132°E
134°E
136°E
138°E
9.5°N
9.0°N
8.5°N
8.0°N
7.5°N
7.0°N
6.5°N
6.0°N
133°E
134°E
135°E
136°E
ROGER REVELLE
SAN DIEGO
Sustained Observations:
Moorings, ADCP, PIES, CPIES, HF Radar, Gliders, Thermographs
f
g
h
9.0°N
8.5°N
8.0°N
7.5°N
7.0°N
6.5°N
133.0°E
133.5°E
134.0°E
134.5°E
135.0°E
135.5°E
9.0°N
8.8°N
8.6°N
8.4°N
8.2°N
8.0°N
7.8°N
134.0°E
134.5°E
135.0°E
Deep Water Moorings (F1–F6, M1–M5)
Shallow Water Moorings (B1–B4 and Angaur)
ADCPs (4)
CPIES (C1, C3–C5)
PIES (1–9)
Glider Trajectories (2014–2018)
Thermograph Locations (174 active)
HF Radar Coverage

Large-Scale, Incident Flow

Topographically generated features such as wake eddies are sensitive to the strength, direction, and vertical structure of the incident flow. For this reason, understanding the incoming flow using satellite observations, data assimilating numerical state estimates, the Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS) nested model, and a series of Regional Ocean Modeling System (ROMS) models provided context for observations at island and smaller scales.

Data from drifters released near Palau from 2015 to 2019 during the FLEAT experiment show the large-scale currents (Figure 3a). The flow strength and direction of the equatorial current system in the western Pacific is variable on many timescales. The NEC varies on synoptic to seasonal to interannual scales, with the El Niño-Southern Oscillation (ENSO) causing the greatest variability (Qiu et al., 2015; Schönau and Rudnick, 2015). During the FLEAT observational period in 2015, an exceptionally large El Niño caused the NECC to strengthen (Figure 3b). At that time, gliders and thermographs near Palau recorded a shallow thermocline and cold water surrounding Palau. As the El Niño decayed in early 2016, the NECC turned northward, dramatically changing both the strength and direction of flow around Palau (Figure 3c; Qiu et al.; Schönau et al.). The moorings and CPIES captured the end of the transition from El Niño. Over 27 months, gliders measured westward flow 60% of the time, while eastward flow was noted 30% of the time, associated with changes attributed to El Niño (Figure 4a–d; Zeiden et al., 2019). This fortuitous change in direction also provided a case study for comparing HF radar observations and the ROMS model. Although FLEAT did not plan to observe the El Niño transition, it will be a subject of further research with our combination of models and observations.

The vertical structure of the inci-

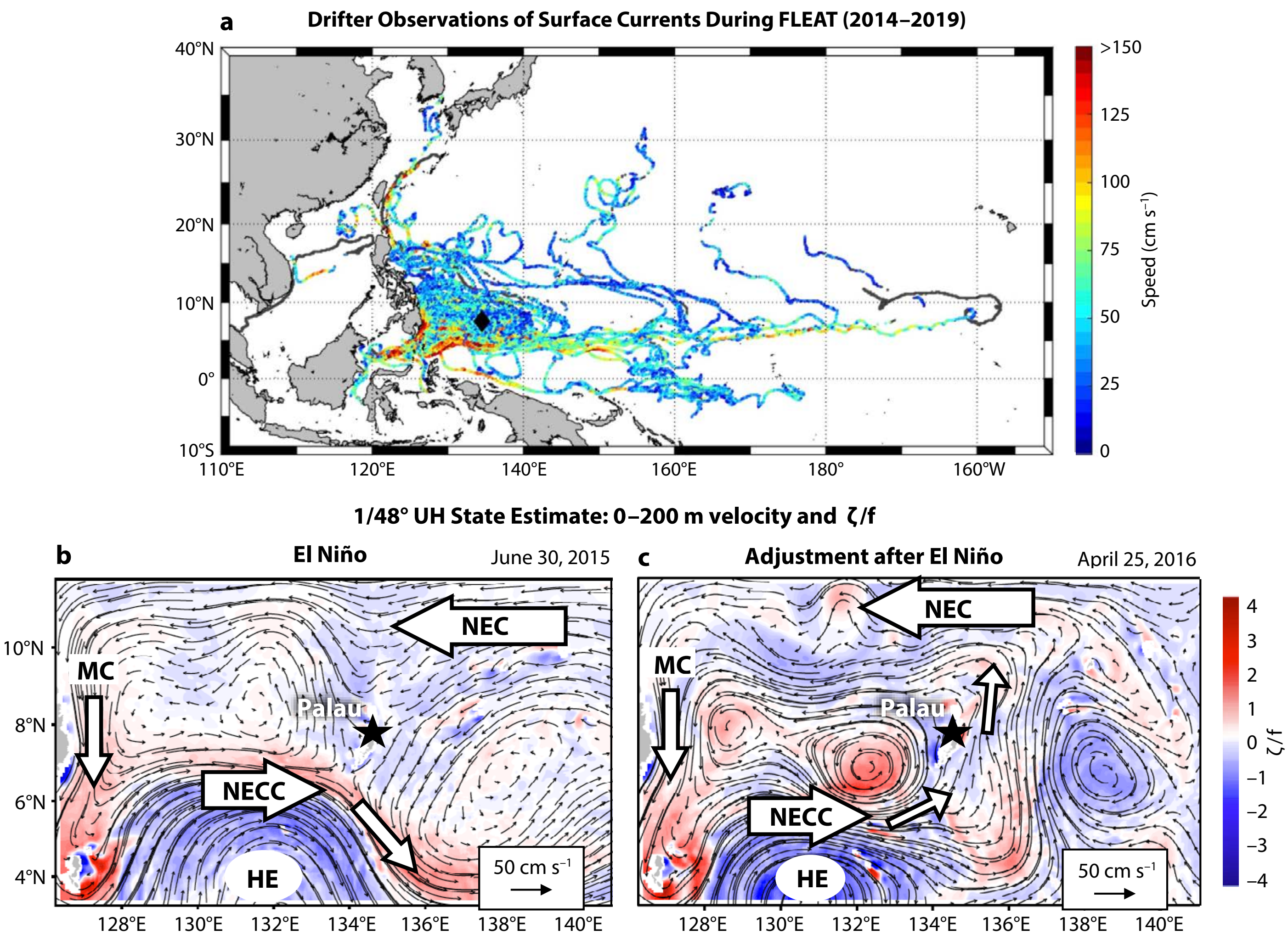


FIGURE 3. (a) Tracks from drogued drifters deployed during FLEAT from 2015 to July 2019 show the recirculation around Palau and the stronger currents in the NECC south of Palau (black diamond). Circulation of large-scale currents from a 2.5 km (1/48°) ROMS simulation during (b) El Niño conditions in June 2015, and (c) the breakdown of El Niño in April 2016, when some FLEAT research cruises began. During El Niño, the NECC was exceptionally strong and to the south of Palau. The quasi-stationary Halmahera Eddy is marked as HE. When the El Niño ended, the transition caused the NECC to veer northward past Palau, causing large changes in the direction and strength of the mean flow near Palau.

dent flow also affects the wake. There is an active, wind-driven surface-to-thermocline layer (roughly the upper 200 m) and a variable subthermocline layer. Below the westward-flowing NEC, the North Equatorial Undercurrents flow eastward at 9.6°N and 13.1°N, varying considerably in strength and location (Qiu et al., 2013; Schönau and Rudnick, 2015). The dynamics of the undercurrents are less understood; their magnitude is less than and often in the opposite direction of the surface flow. However, at times, the arrival of westward-propagating Rossby waves and eddies disrupt the flow pattern with impacts on the velocity field at depths of up to 4,000 m (**Andres et al.**).

Velasco Reef rises almost to the surface and blocks the incident flow south of 8.5°N (**Figure 4a–d**). Composites of eastward and westward flow from glider observations are separated into upper (0–200 m) and lower (200–600 m) layers that show considerable variability in strength and direction. At both levels during periods of westward flow, the current accelerates around the ridge, separates from the topography, and returns weakly in the wake. The deeper eastward flow shows a similar pattern. (We note two complications in our simple picture. **Rudnick et al.** observe that a deep channel between Velasco and the main lagoon at 8.1°N permits flow and somewhat obscures the wake. With eastward flow, there is stagnation at the surface because eastward flow is associated not with a coherent incident current, but rather with a stagnation of the westward flow or the El Niño termination.)

The direction of flow also has implications for the type of wake or wave response that is formed (**Merrifield et al. a**; Musgrave et al., 2018). In an idealized numerical model, during westward flow, both positive and negative vorticity form, but during eastward flow, the character is different (**Figure 4e,f**). Theoretical studies suggest that a Rossby wave can be arrested in a steady flow by an island (W.B. White, 1971; Musgrave et al., 2018),

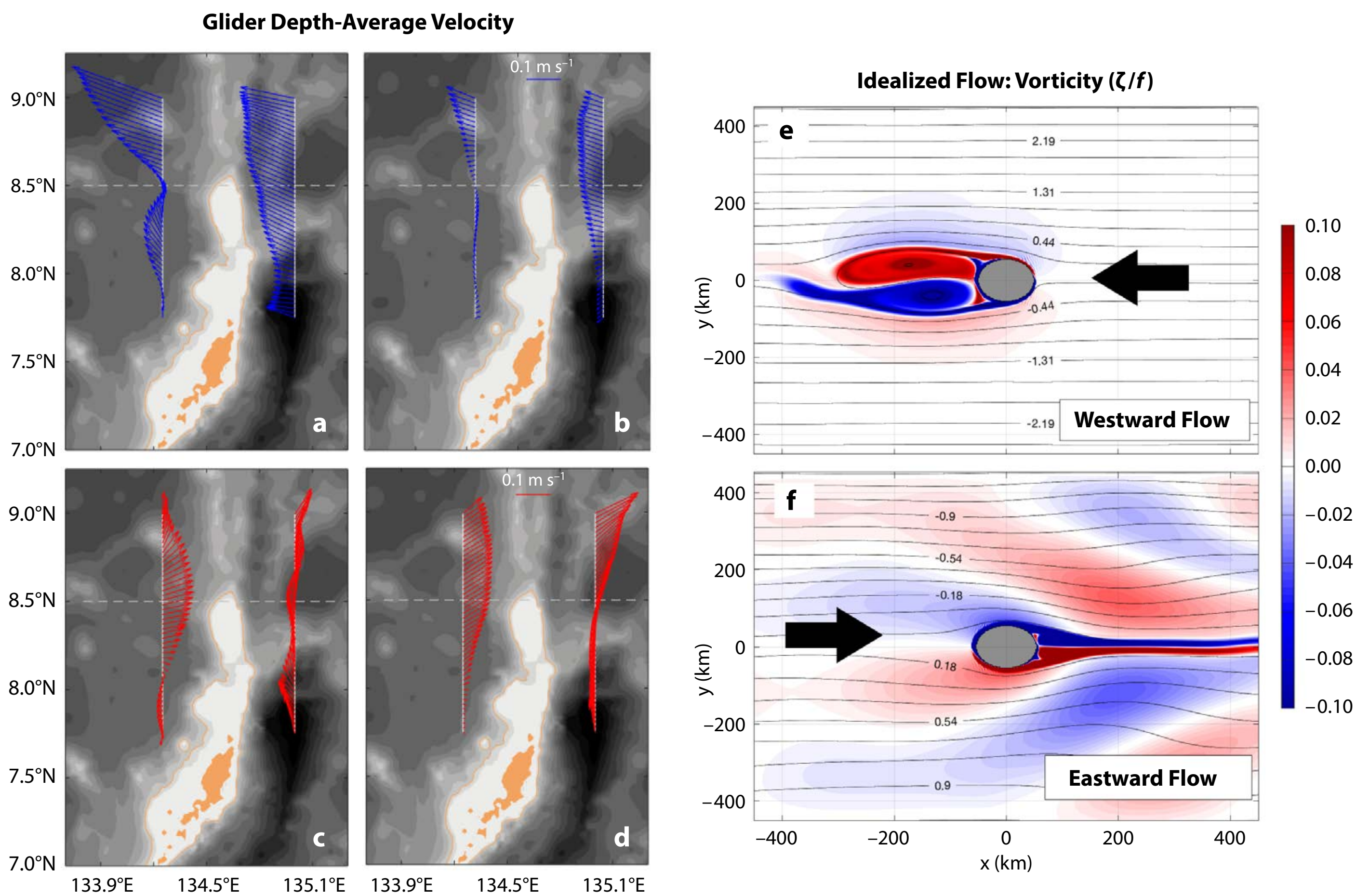


FIGURE 4. Composites of glider observations are shown around Velasco Reef for (a,b) westward and (c,d) eastward mean flow, averaged from (a,c) 0–200 m and (b,d) 200–600 m depth (adapted from Zeiden et al., 2019). During westward flow (a,b), the flow accelerates around the reef to the north, and is blocked to the south. This is more pronounced in the surface layer. During eastward flow, typical during the breakdown of the El Niño, the flow west of Velasco Reef is essentially blocked at the surface (c), while that in the subsurface layer (d) accelerates eastward. Potential vorticity (color) and streamlines (contours) from idealized numerical studies of the upper layer of a two-layer flow past cylindrical island for (e) westward and (f) eastward flow. *Adapted from Musgrave et al. (2018)* In (e), the flow is configured so that the geostrophic response is evanescent and the frictional boundary layer separates at the meridional tips of the island, causing large recirculating eddies that separate and advect downstream. In (f), the flow is configured such that a Rossby wave is arrested at the island, inhibiting flow separation and causing the frictional island wake to form recirculating eddies very close to the island that do not separate and are associated with narrow vorticity streamers downstream.

which is more likely to occur in an eastward current that has vertical shear (horizontal velocity varying with depth). This can modify the stratification and vertical shear at large scales. In addition to arresting Rossby waves, small islands can generate blocking modes that may alter the flow far upstream. Further work is required to determine the role that these processes play in a realistic setting. More details on further impacts of current direction on island wake and blocking characteristics are provided in the following section.

Island-Scale Dynamics

Incident flow includes tides, near-inertial motions, storm-driven currents, and wide equatorial currents. The wake eddies and lee waves produced by this broadband incident flow at the northern and southern points of Palau can greatly influence the ecology of nearshore regions because they transport larvae/eggs laterally and nutrients vertically. We highlight some model results and observations of wake eddies and lee waves along with direct measurements of turbulence. Furthermore, we demonstrate how including parameterization of some of these processes in global models allows simulation of considerable changes in upper and deep ocean flows.

Wake Eddies and Lee Waves

Wake eddies and lee waves form at two locations: the northern point of the main Palau group at Velasco Reef and the southern point at Peleliu (Figures 1b and 5b). Friction spins up energetic ocean eddies as flows encounter topography. The broad, incident flow sweeps the eddies hundreds of kilometers downstream (Figures 5a and 6). These so-called wake eddies are often turbulent and are highly variable in space and time (Figure 7e,f). As flow passes topography, drag in the frictional boundary layer causes the flow's speed to go to zero right at the boundary (Figure 7b–d). As the eddy grows large enough to alter flow and pressure gradients in the boundary layer, it causes the flow to detach from the topography at what is termed the separation point. Large-scale flows are in geostrophic balance and have a small Rossby number, Ro, of order 0.1. The Rossby number is a useful way to compare the strength of a wake eddy and is calculated as the ratio of the wake's rotation or vorticity to Earth's rotation (measured by f, the Coriolis frequency). As Ro approaches 1, the flow is no longer balanced and can become unstable.

Around Palau, wakes occur at two scales: island-scale eddies display Ro = 0.3 in the mean (length scales of about 70 km), while the submesoscale eddies right at their generation points at Velasco and Peleliu can be much more intense with Ro ~ 50 (Figure 6). (At mid-latitudes where f is larger, these wake eddies would have Ro ~ 10.) These counterclockwise rotating eddies become unstable as they separate from the topography, leading to considerable turbulence (B.L. White and Helfrich, 2013). Nyman et al. provide results showing the strong signature of wake eddy structures in synthetic aperture radar and also their interactions with internal waves.

In nature, a steady incident ocean current is accompanied by oscillating flow, such as tides or near-inertial motions. While this situation is prevalent, to the best of our knowledge, little description of the resulting wake is available. Around

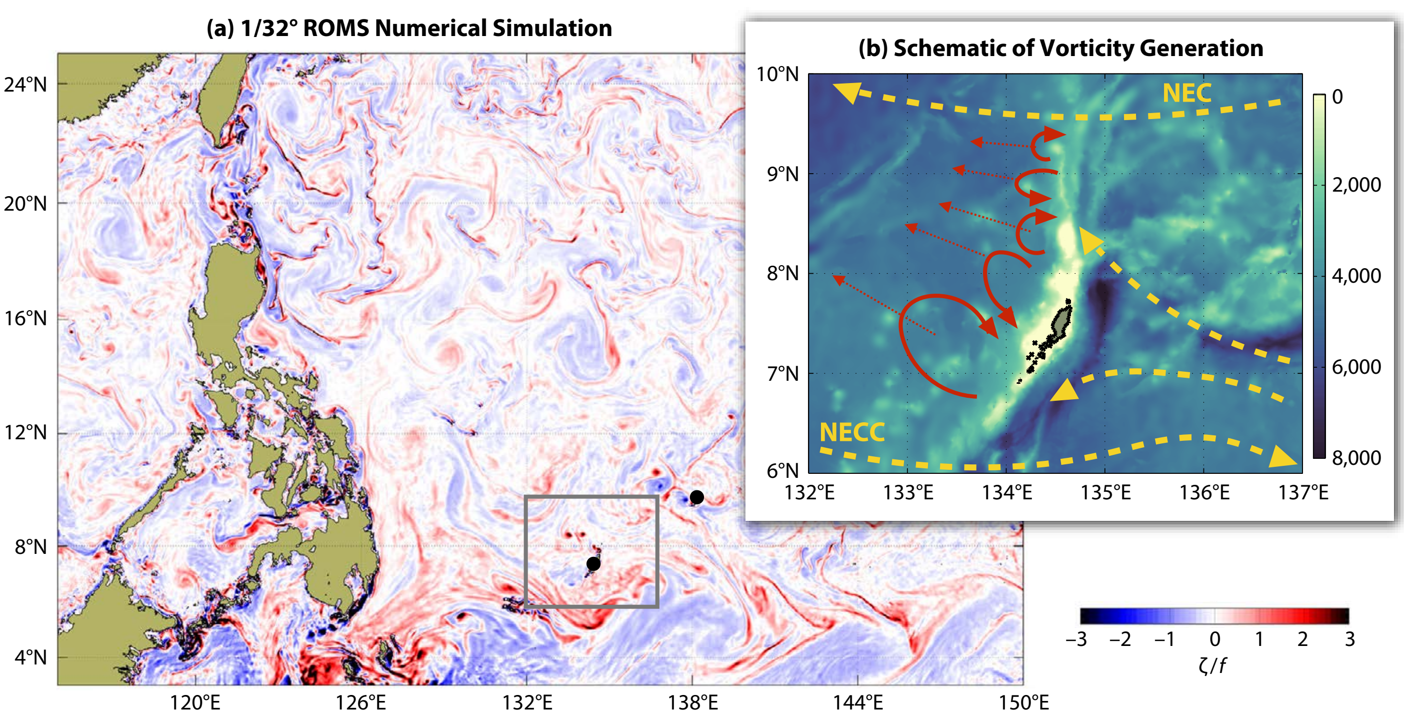


FIGURE 5. (a) Vorticity from a nested Regional Ocean Modeling System (ROMS) model with 3.5 km (1/32°) grid spacing. (b) A schematic of vorticity generation around Palau, with the large-scale NEC and NECC to the north and south (yellow dashed lines). Wake eddies (red lines) are advected with the flow (dashed red lines).

Palau, the tides are often as strong as the steady flow (>0.25 m s^{-1}), so the total flow can vary from 0 m s^{-1} to 0.5 m s^{-1} every tidal cycle (**Figure 7e,f**; MacKinnon et al., 2019). Near the surface, the wakes are, on average, a factor of two stronger than mean flow alone, while at depth the tides greatly exceed the mean flow and the wake can be factor of 25 stronger than expected from the steady flow alone. The implication is that models without tides will not adequately represent wakes. **Siegelman et al.** used mooring observations to show that near-inertial motions, generated by synoptic winds, sometimes contribute an oscillatory component to wake eddy formation at the northern and southern tips of Palau. The near-inertial motions have spatial scales that exceed the width of the islands. When the island blocks them, flows are coherently forced around the northern and southern points.

The models used in FLEAT have considerably higher resolution than those commonly used in ocean science. For instance, **Simmons et al.** employed a high-resolution numerical model (800 m) nested in a 2 km model to show the effects of the island and ridge on surface vorticity and near-surface currents (**Figure 6**). With a westward NEC, a "street" of vortices can be traced back to the northern point (**Figure 6c,d**). Conversely, during periods of eastward flow, strong transport through the channels between Velasco Reef and Babeldaob Island can create a different wake, forming a dipole that emanates away from Palau (**Figure 6a,b**). Combining the model and observations shows the role the channels play in generating the nearfield wake. In composites of HF radar (**Merrifield et al. a**), flow splits and reconnects 60 km up- and downstream of the islands and accelerates through passages in the island chain. The flows have an eddy-dipole structure, with coastal eddies having Rossby numbers of 5. In the model, these small-scale features are advected at least 100 km downstream, where they contribute to enhanced vorticity (**Figures 5a and 6c,d**).

Lee waves may also transport energy and momentum away from topography or contribute to local turbulence if they break near their generation sites. Mayer and Fringer (2017) examine nondimensional parameters relating flow, stratification, and topography to lee wave generation as a component of FLEAT. Lee wave surveys were carried out during both spring and neap tides to contrast conditions of strong and weak tidal currents that were superimposed on a steady background current, as described in recent work of author Voet and colleagues. During spring tide, turbulent dissipation was strong and symmetric across the ridge, but during neap tide, turbulence was weaker and biased toward the lee side of the ridge relative to the mean flow. At Merir Island (4.3°N, 132.3°E) and at the southern point of Peleliu, the momentum in the arrested internal lee waves or asymmetric internal tides may have acted to mildly decelerate the mean flow (**Johnston et al.**). If the energy transmitted from the mean flow to the lee waves dissipates at the submerged ridge near Peleliu, it would account for the dissipation measured there by microstructure.

Turbulence and Dissipation

Turbulence measurements were made during FLEAT near the separation points north and south of Palau, over submarine ridges and in Palau's wake. At the separation point and over a submarine ridge north of Velasco, turbulent dissipation reached 10^{-5} W kg^{-1} in shear layers at the point of separation and close to the topography (**Figure 7**; MacKinnon et al., 2019).

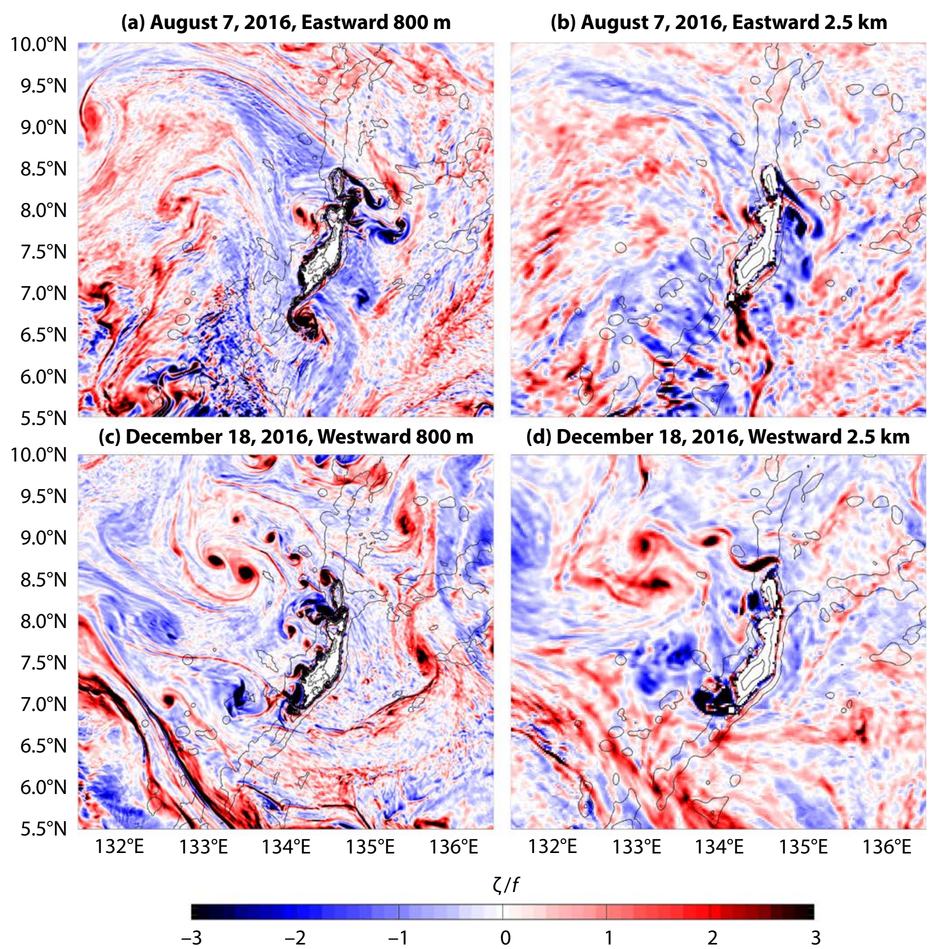


FIGURE 6. Potential vorticity from (a,c) an 800 m ROMS simulation nested in (b,d) a 2.5 km ROMS simulation for (a,b) eastward and (c,d) westward flow (**Simmons et al.**). During westward flow, wake eddies are observed, whereas during eastward flow the island creates a "blocking mode," and dipoles appear to form. ROMS simulations are compared to HF radar (**Merrifield et al. a**) and microstructure wake measurements (**St. Laurent et al.**). Fine model resolution (a,c) is essential to resolve these structures.

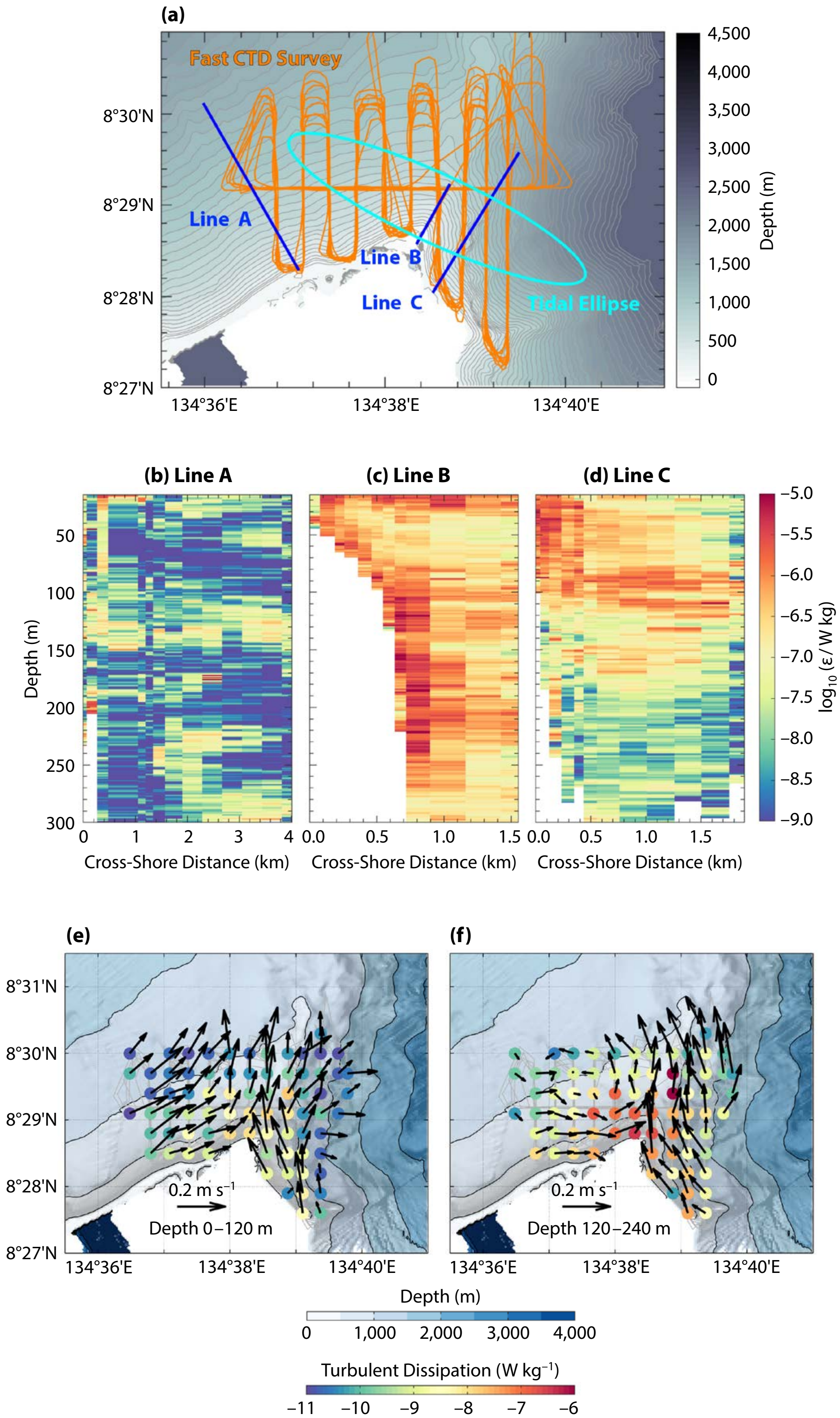


FIGURE 7. Observations of dissipation just north of the tip of Velasco Reef. (a) Elements of R/V *Revelle* sampling from June 2016 including repeat, cross-shore microstructure lines (dark blue, panels b–d), and fast CTD survey (orange, panels e,f). The barotropic tidal excursion is much larger than the width of the point (cyan, data from mooring F4 deployed for 10 months at approximately the 400 m isobath along the ridge). (b–d) The cross-shore lines highlight the differences in the mean turbulent dissipation rate's magnitude and depth structure. The strongest turbulence is observed right at the separation point (Line B), while the weakest turbulence is observed on Line A, which is furthest from the separation point. Depth varying patterns of flow (arrows) and turbulent dissipation rate (from Thorpe scale estimates, color) from the Fast CTD survey are shown averaged over four days from (e) 0–120 m depth and (f) 120–240 m depth.

To compare, open ocean, background values of dissipation are typically of the order 10^{-9} W kg^{-1}. In Palau's wake, gliders measured dissipation up to 10^{-6} W kg^{-1}, consistent with model results of strong dissipation in wakes (**St. Laurent et al.**). Direct wind-driven mixing only accounts for about 10% of the observed turbulence levels, suggesting that most of the energy for mixing is extracted from the shear created by the wake eddies. Below the surface layer, turbulence was well correlated with the phase and magnitude of the relative vorticity and strain levels of the island-scale flow.

Another way to assess the effects of turbulent mixing is to look at changes to the water mass structure. Spice, or the variability of temperature along a constant density surface, acts as a tracer; it is not a dynamical variable like density that can affect the speed of currents. A wide-ranging SeaSoar survey over the ridge showed continuous streamers of spice, just as model simulations showed high tracer concentrations drawn by eddies into streamers in the wakes at the northern and southern points of Palau. **Johnston et al.** provides an example over a smaller area at the southern point of Palau. Even greater spice variability is noted at the northern point in glider and SeaSoar data.

SUMMARY AND DISCUSSION

FLEAT collaborators integrated models and observations (1) to examine the effects of island and ridge systems on basin-scale, nearly geostrophic flow, (2) to understand relevant processes that contribute to energy and momentum loss when flows encounter topography, and (3) to quantify the cascade of momentum and energy down through finer scales to dissipation (and the upscale cascade of two-dimensional coalescing eddies moving energy to larger scales) as flows pass through the Palau archipelago. Given forcing by remote basin-scale winds, and local winds and tides, FLEAT scientists have been successful in observing and modeling currents, vorticity, temperature, and salinity down to scales comparable to the topography. Traditionally, these scales are examined separately, and capturing the small spatial scales and rapid temporal fluctuations noted here required a specific, regional program. The ability of FLEAT to link the ocean basin scales to the topographic lee/wake effects advanced (1) the science of island and submarine ridge circulation, boundary layers, and downscaling, and (2) models and forecasts of the relevant processes.

Incident and wake flows affect subsurface temperature structure (**Schramek et al.**), which in turn impacts ecosystems near Palau. While the downstream topographic effects appear to be limited in the case of Palau (**Gopalakrishnan et al.**), they are nevertheless noted in surface vorticity at least 100 km downstream, and parameterizations in global circulation models indicate these effects are considerable (**Arbic et al.**). During FLEAT, we found that the direction and vertical structure of the incident flow exerts major influences on wake eddies, lee waves, and turbulent drag. Further, a combination of steady and oscillating flow from tides and near-inertial motions is directly related to the strength of turbulent drag and can produce a range of submesoscale wake-eddy structures that vary with depth. The drag coefficient in global models could then vary widely depending on whether tides are included.

Simulating the near-field wake accurately requires model resolution on the order of hundreds of meters. Wake eddy generation at the northern and southern points of Palau was not captured in a 2.5 km resolution model but did emerge in the 800 m resolution model (**Figure 6**). There are at least two aspects of the resolution to consider: the steep topography and that the initial wake eddies appear to form with about 2 km diameters. Temperature changes across such eddies may be several degrees and velocity changes may exceed 1 m s^{-1}. The variability associated with lee waves is similar. Despite computing advances, resolving these wake effects remains challenging not only in terms of computing power but also in more mundane matters of data storage and transfer. Nevertheless, the scientific progress from the array of models used for FLEAT has complemented the observations and allowed assessments of the energy cascade from the incident flow into the wake (**Zedler et al.**), which cannot be obtained from observations alone.

Basin- and global-scale models cannot explicitly resolve many of the small-scale processes occurring at topography and so these processes must be parameterized in terms of the variables on the models' relatively coarser grids. Parameterizations of processes such as lee wave drag strongly affect energy budgets, near-bottom stratification, near-bottom eddy kinetic energy, and vertical structure of mesoscale eddy flows in the US Navy global ocean forecast model (**Figure 8**; Trossman et al., 2016). Process model studies (summarized by **Arbic et al.**) and insights from FLEAT measurements will advance further parameterizations of lee wave drag in forecast models. In addition to the need to better understand the combined effects of tidal and lower-frequency flows, as described above, a better understanding of the relative importance of hydraulic blocking effects versus linear lee wave effects is needed. In the future, as computing power increases, it may become possible to run global models at resolutions that are high enough to capture the type of steep topography described here. FLEAT researchers, along with those involved in other intensive process stud-

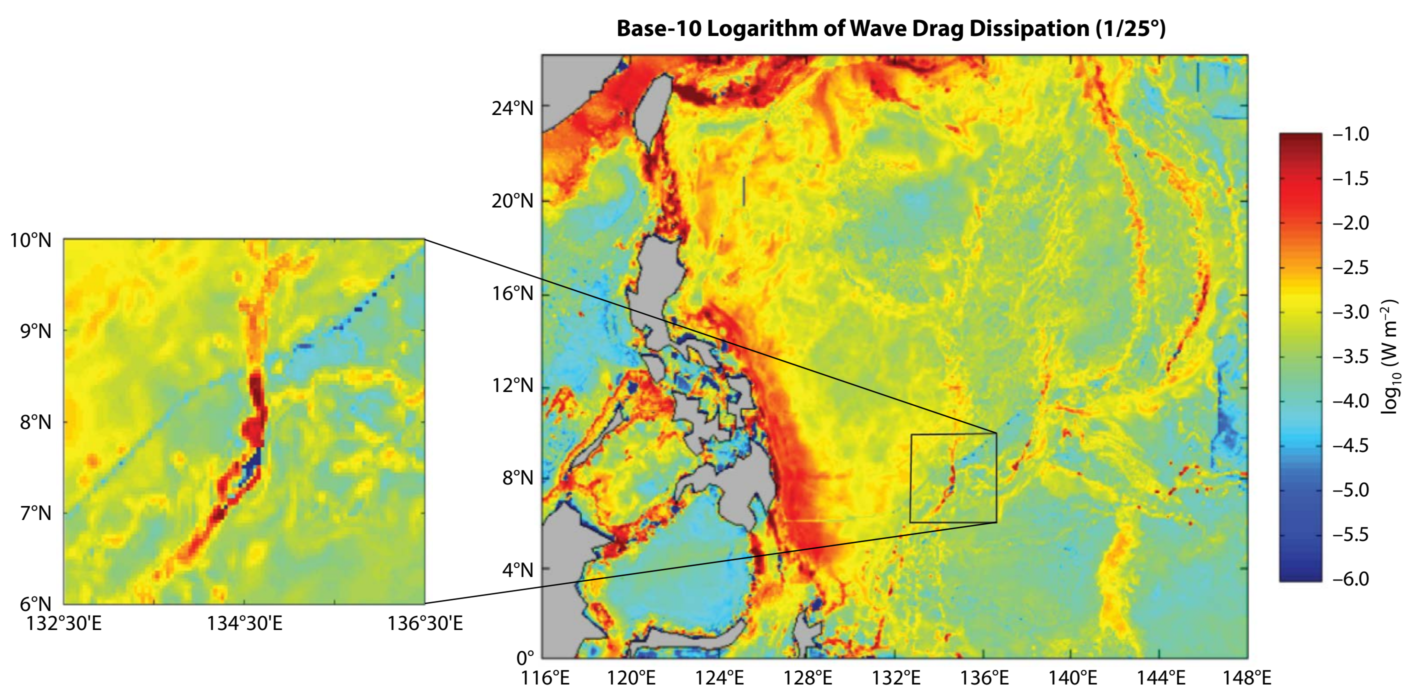


FIGURE 8. Map of the energy dissipation (log$_{10}$[W m^{-2}]), from parameterized topographic wave drag, in both the "outer" (right) and "inner" (left) FLEAT regions, in global 1/25° simulations of HYCOM that are run without explicit tides. *Adapted from Trossman et al. (2016).*

ies, such as those for the Samoan Passage experiment (**Girton et al.**, **Carter et al.**), will continue to investigate how these processes can be better parameterized and incorporated into global models.

Local Impact of FLEAT

FLEAT contributed new technology, expanded scientific infrastructure, collaborated with several partners, and catalyzed practical efforts that have ongoing impact around Palau. Lagoon and outer slope environments were mapped during extensive multibeam and side-scan sonar surveys. The multibeam bathymetric surveys covered the Palauan Exclusive Economic Zone out to 100 km. Two unusual environments, a deep photic ridge and an offshore pinnacle, were mapped and characterized. Shark City Ridge extends over 2 km out from a shallow reef with depths of 180 m along its peak where a "cool water" (10°–15°C) reef is found. Ngaraard Pinnacle, 1.6 km off the eastern fringing reef of Palau, has a shallowest depth of 92 m and a biological community transitional between very deep photophilic coral reefs and coral-lacking rariphotic zones (**Colin et al.**). The faunas at both sites are unusual and may be the first records of such an environment in the western Pacific.

Weather stations were established at critical locations in Palau that have been without much-needed meteorological sensors. One newly established station on Ongingiang Island, a tiny sand spit at the edge of the lagoon, samples upstream, westerly winds before they encounter the islands. Another station was established on Helen Reef, an atoll 500 km southwest from the main group. These stations provide marine weather monitoring, and they documented the passage of Super Typhoons Bopha and Haiyan (**Merrifield et al. b**). FLEAT also solidified the basis for assessing the future of pelagic (mostly tuna) fishing by spurring the development of management products such as a predictive model for future fishing effort (Cimino et al., 2019). Ongoing programs, such as the HF radar measurements of surface currents, will continue to benefit Palau after the FLEAT initiative has ended.

Community outreach was also part of the FLEAT effort. During numerous port calls, with help from the Coral Reef Research Foundation, the captains and crews of R/V *Roger Revelle* hosted tours that reached many high school students in Palau (**Figure 9**). The science party provided briefings on FLEAT science to the touring students, to US embassy personnel, and to Palauan government officials. Students at Koror Elementary School received an age-appropriate presentation on oceanography and decorated Styrofoam cups that were later shrunk—to their amazement—by water pressure during a deep CTD cast.

The FLEAT study is timely, as Palau's vitality is tied to the ocean. The scientific results support desperately needed knowledge of sea level rise, the prediction

FIGURE 9. (a) About 125 Grade 2 students at Koror Elementary School in Palau learned a little oceanography and decorated Styrofoam cups. The cups were later crushed (b) during R/V *Revelle* CTD operations while surveying a ridge near Palau. (c) Captain David Murline and the crew of R/V *Revelle* along with the science party provided tours for personnel of the Coral Reef Research Foundation and officials from the Palau National Weather Service. (d) Students and teachers from Mindszenty High School in Palau after tours with Captain Murline and Chief Scientist Gunnar Voet.

of coral reef thermal stress, fisheries management, including the Palau National Marine Sanctuary, typhoon impacts, maritime search and rescue, and containment of oil spills.

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