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Autonomous Multi-Platform Observations During the Salinity Processes in the Upper-ocean Regional Study

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SUPPLEMENTAL MATERIALS
An animation of the evolution of the SPURS-2 Lagrangian observing system can be found online at https://youtu.be/nYScDvmsyHQ.

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Abstract

The Salinity Processes in the Upper-ocean Regional Study (SPURS) aims to understand the patterns and variability of sea surface salinity. In order to capture the wide range of spatial and temporal scales associated with processes controlling salinity in the upper ocean, research vessels delivered autonomous instruments to remote sites, one in the North Atlantic and one in the Eastern Pacific. Instruments sampled for one complete annual cycle at each of these two sites, which are subject to contrasting atmospheric forcing. The SPURS field programs coordinated sampling from many different platforms, using a mix of Lagrangian and Eulerian approaches. This article discusses the motivations, implementation, and first results of the SPURS-1 and SPURS-2 programs.

INTRODUCTION

Local (air-sea interactions, mixing) and nonlocal (advection) processes govern the evolution of upper-ocean properties such as temperature, salinity, nutrients, and pollutants. Satellite remote sensing enables synoptic observation of many surface properties and their evolution, capturing a broad range of scales simultaneously. Because the electromagnetic radiation used for satellite remote sensing cannot penetrate water, measurements of subsurface properties still require the use of in situ instrumentation. It is difficult to achieve a similarly synoptic view of subsurface properties by deploying instruments from ships.

Observations of ocean salinity are critical for understanding the global water cycle and monitoring its changes (Durack and Wijffles, 2010). A new capability for measuring ocean surface salinity from space emerged with a number of recent satellite missions, for example, Aquarius (Lagerloef et al., 2012), Soil Moisture Ocean Salinity (SMOS; Font et al., 2013), and Soil Moisture Active Passive (SMAP; Meissner and Wentz, 2016). These satellite data made it clear that our understanding of the physical processes that influence upper-ocean salinity was lacking. To address this knowledge gap, NASA launched a multi-institutional Salinity Processes in the Upper-ocean Regional Study (SPURS) in 2012 (Lindstrom et al., 2015). From its origins, the SPURS program has had a strong focus on combining remote-sensing observations with autonomous multi-platform research, continuing NASA’s long tradition of autonomous exploration in challenging environments using cutting-edge robotics.

The SPURS campaigns build on several previous experiments where autonomous instruments provided sustained observations and a larger perspective than can be obtained from strictly fixed or ship-based instruments. Floats and other instruments have been used as drifting “targets” for shipboard surveys during many oceanographic field campaigns, including IronEx-I (1993; Coale et al., 1998), the CLIvar MOde water Dynamics Experiment (CLIMODE, 2006–2007; Marshall et al., 2009), Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP, 2006–2007; D'Asaro et al., 2011), North Atlantic Bloom Experiment (2008; Mahadevan et al., 2012), Scalable Lateral Mixing and Coherent Turbulence (LatMix, 2011–2012; Shcherbina et al., 2015b), and several others. In the LatMix program, for example, a variety of Lagrangian platforms (gliders, profiling and Lagrangian floats, surface drifters) and several vessels formed an observational array that moved with an evolving feature rather than remaining in a fixed coordinate system. However, as shipboard observations are too costly to sustain for more than a few weeks, their use is impractical for studying the seasonal and longer-term evolution of ocean processes. Mobile autonomous instruments—underwater gliders or self-propelled surface vehicles (wave, sail, or solar powered)—can provide a particularly strong capability for sustained controlled surveying.

A major goal of the SPURS program is to gain a better understanding of the global freshwater cycle through investigation of all the physical processes controlling the upper-ocean salinity balance—freshwater flux from the air-sea interface, transport, and mixing. The challenge in designing observational arrays to resolve these processes was to capture the wide range of spatial scales that also span time scales varying from days to a full annual cycle. SPURS-1 (Lindstrom et al., 2015) focused on the processes responsible for the formation and maintenance of the surface salinity maximum in the subtropical North Atlantic where evaporation and mesoscale processes were expected to dominate (Busecke et al., 2017). SPURS-2, currently underway, extends the study of upper-ocean salinity processes to a precipitation-dominated region under the Intertropical Convergence Zone (ITCZ) in the Eastern Pacific Fresh Pool (EPFP). Here, freshwater forcing occurs on the very short scales of time (minutes to hours) and space (a few kilometers) that are associated with precipitation in tropical convection but that are ultimately reflected in the seasonal and large-scale features captured by remote sensing. In both precipitation- and evaporation-dominated environments, linking the O(100 km) surface patterns captured by satellites with in situ point measurements remains a challenge, and this is the problem that was targeted using autonomous and Lagrangian platforms and sensors (ALPS) during SPURS.

In this paper, we describe the program's design philosophy and the way the different mixes of measurement platforms were used in SPURS-1 and SPURS-2 to address the science objective of better understanding the physical processes that influence upper-ocean salinity. We then describe the various autonomous platforms used in SPURS and how the SPURS experimental design was embedded in the larger, distributed ocean observing system. Next, we describe the "focused Eulerian observing system" that made heavy use of ALPS in SPURS-1 and contrast this with the Lagrangian approach that was used more heavily in SPURS-2. The paper concludes with discussion of some of the early results from the Lagrangian drift experiment conducted in SPURS-2.

ALPS IN SPURS: DISTRIBUTED, EULERIAN, AND LAGRANGIAN FRAMEWORKS

The changes in salinity at a particular place can result either from (1) surface freshwater flux (evaporation and precipitation), which changes the total amount of freshwater and thus the concentration of salt in the ocean, (2) turbulent mixing of waters of different salinities, or (3) advection of fresher or saltier water into the area by ocean currents (e.g., Farrar et al., 2015; Lindstrom et al., 2015). The first two effects (surface fluxes and mixing) actually change the properties of the fluid, but the third effect (advection) only moves the fluid around. In a Lagrangian reference frame that follows a fluid parcel, salinity tendencies are dominated by freshwater flux and turbulence mixing, in contrast to a fixed-in-space Eulerian reference frame in which advection by ocean currents dominates. To understand these effects, the SPURS campaigns used two distinct approaches: first, measure the gradients and advection field in a geographically fixed frame of reference (Eulerian), and second, move to a Lagrangian reference frame that follows water parcels and thus minimizes advection effects.

The complementary Eulerian and Lagrangian observing systems are central to the SPURS observational strategy. These approaches are further embedded in the broader distributed observing system formed by global drifter, float, and remote-sensing networks (Figure 1).

Both SPURS experiments involved a wide variety of autonomous platforms. Two-way communications allowed reallocation of some of the key instruments among these components by altering their navigation and sampling strategies. Together, these components formed a flexible, robust, and comprehensive nested multiscale autonomous observing system.

Autonomous Instrumentation

The primary ALPS used in SPURS-1 and SPURS-2 are described below.

LAGRANGIAN

SVP Surface Drifters

During SPURS-1, a total of 144 Surface Velocity Program (SVP) drifters, including 88 equipped with salinity sensors, were deployed with the goal of measuring salt fluxes associated with near-surface currents (Centurioni et al., 2015; Hormann et al., 2015). As of May 2017, 20 standard and 30 salinity-enhanced SVP drifters as well as five Directional Wave Spectra Drifters (Centurioni et al., 2017) had been released during SPURS-2, with about 75 more drifter deployments anticipated in the following months. Satellite-tracked Iridium drifters, which have drogues centered at 15 m depth, reliably measure near-surface currents with an accuracy of 0.1 m s^{-1} for winds up to 10 m s^{-1} (Niiler et al., 1995). The SVP drifters, designed and fabricated at the Scripps Institution of Oceanography, are tracked by the Global Positioning System (GPS) and return sensor data and geolocation at intervals as short as five minutes. All the SVP drifters measure sea surface temperature (SST). About half of the drifters are also equipped with a Honeywell high-precision barometer (or equivalent) to measure sea level air pressure (SLP), which is known to improve numerical weather prediction (Centurioni et al., 2016; Horányi et al., 2017). More than half of the SVP drifters used in SPURS-2 are also equipped to measure salinity at 0.5 m (Hormann et al., 2015, 2016).

SVP-S2 Surface Drifters

In order to study stratification in the upper 5 m of the water column and processes that determine it, six upgraded SVP-S drifters (SVP-S2) manufactured by Pacific Gyre and provided by the US National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory (NOAA-AOML) and NASA were deployed in the SPURS-2 region. Similar drifters had been deployed earlier in the evaporation-dominated subtropical South Pacific (Dong et al., 2017). The unique aspect of these drifters is that they are equipped with two sets of conductivity and temperature sensors (CTDs). One (Sea-Bird SBE 37SI) is mounted to the bottom of an upgraded (41 cm diameter) surface float to avoid direct radiative heating at about 0.2 m depth. The second CTD is tether-mounted at 5 m depth (SBE 37IM) just above the drogue. The sampling interval is about 30 minutes, easily resolving the diurnal cycle. As regular drifters, SVP-S2 drifters have a drogue centered at 15 m to follow currents at this depth. If the velocity shear between the surface and 15 m depth is small, then the drifters will tend to drift together with salinity anomalies caused by rather patchy rain events and, thus, be able to trace rain puddles until they dissipate, likely on time scales of hours.

APEX Profiling Floats

The Teledyne Webb Research Autonomous Profiling Explorer (APEX) floats have been used in the Argo program and elsewhere for nearly two decades. They typically drift for 10 days at their parking depth (usually 1,000 m), descend briefly to a deeper level (2,000 m), then collect a CTD profile from this deeper level to the sea surface. Data are transmitted via satellite while on the sea surface, followed by descent back to the parking level. This process is generally repeated 250–300 times over float lifetimes of six years or more. In recent years, new capabilities have been added to these floats, such as biogeochemical sensors (oxygen, nitrate, pH, chlorophyll, and particle backscatter) and the ability to collect and store data under sea ice in winter (see Jayne et al., 2017, in this issue). The history and evolution of these floats is discussed in Riser et al. (2016). For SPURS-1 and SPURS-2, extra CTDs were added to the floats, providing capability for high-resolution sampling in the upper 30 m of the water column, where direct air-sea interaction takes place. In a number of cases, the float mission was altered remotely to include profiling from 0 m to 300 m at two-hour intervals over a few weeks, instead of the usual Argo protocol described above. This float setting allows collection of data suitable for examining the diurnal cycles of temperature and salinity as well as the near-surface response to storms and rainfall events (J. Anderson and Riser, 2014). In addition to the auxiliary CTD unit, a passive aquatic listener (PAL) hydrophone (Nystuen, 2001) was added to many floats, allowing wind speed and rainfall to be estimated using passive acoustic methods along the float trajectory while the float drifted at its parking depth. This additional sensor deployment resulted in the collection of extensive rainfall and wind speed data sets from both SPURS field efforts (Yang et al., 2015).

Lagrangian Floats

These proven versatile platforms for upper-ocean observations were developed and built at the Applied Physics Laboratory of the University of Washington (APL/UW; D'Asaro, 2003). The 1.5 m long instruments were originally designed to measure turbulence in the ocean mixed layer by accurately following the three-dimensional motion of water parcels through a combination of actively maintained neutral buoyancy and high drag provided by controllable flexible drogues. Compared to other types of floats (e.g., Argo floats), Lagrangian floats have an adaptable automatic buoyancy control and a relatively heavy payload. These floats can provide uniform sampling of mixed layer turbulence in fully Lagrangian water-following mode. They can also operate in isopycnal or isopycnal/Lagrangian modes in the pycnocline, or profile across a given depth range. For SPURS, the Lagrangian floats were equipped with high-accuracy dual Sea-Bird CTDs and PAL hydrophones for acoustic quantification of wind and rain. For the SPURS-2 deployment, Lagrangian floats also carried upward-looking Nortek Signature1000 acoustic Doppler current profilers (ADCPs) to observe the evolution of upper-ocean velocity structure. One of the floats was used to define a drifting frame of reference during the SPURS-2 Coordinated Lagrangian Drift experiment.

AUTONOMOUS SELF-PROPELLED

Seagliders

Both SPURS experiments involved three APL/UW Seagliders collecting profiles of temperature, salinity, dissolved oxygen, temperature, and shear microstructure (see Rainville et al., 2017, in this issue), and, in SPURS-2, a PAL hydrophone providing estimates of wind and rain rates from passive acoustics (Yang et al., 2015). Seagliders profile from the surface to 1,000 m depth at a vertical rate of about 10 cm s^{-1}. Sensors sample at variable intervals depending on depth (from 0.5 s intervals near the surface to 30 s at depth). A full dive takes approximately six hours. Gliders steer through the water by controlling attitude (pitch and roll) and can thus navigate between waypoints to execute survey patterns and resolve the spatial distribution of oceanic properties in Eulerian or Lagrangian frames. Typical horizontal speed is about 20 cm s^{-1} (20 km per day).

Slocum Electric Gliders with Microstructure (T-Gliders)

Three Slocum electric gliders equipped with Rockland Scientific MicroRider (MR) turbulence packages were deployed in SPURS-1. The combined MR/Slocum platforms, which became known as a "T-Gliders," collected temperature and shear microstructure data in addition to standard CTD data over the upper 200 m of the water column during the September 2012 and September 2013 surveys. The T-Gliders were the only autonomous underwater vehicle (AUV) systems directly measuring the turbulent kinetic energy dissipation rate using velocity microstructure. Observations from the T-gliders indicated the surprising role of the upper-ocean diurnal cycle in enhancing turbulence levels in the near-surface stable layer (Bogdanoff, 2017; St. Laurent and Merrifield, 2017, in this issue).

Wave Gliders

Three Liquid Robotics SV-2 Wave Gliders participated in each of the two SPURS experiments. Wave motion propels Wave Gliders at typical speeds through the water of 50–75 cm s^{-1}. Each carried two Sea-Bird “Glider Payload” CTDs measuring temperature, salinity, and pressure at nominal depths of 25 cm and 6.5 m with sampling intervals of one to two minutes. Additionally, each Wave Glider carried an Airmar PB200 Weather Station on a 1 m mast, and an Airmar CS4500 ultrasonic water speed sensor from which surface current velocity can be estimated. In SPURS-2, one of the Wave Gliders also temporarily carried an experimental “salinity rake” measuring temperature and conductivity at 10 cm vertical resolution and 1 Hz sampling rate over the upper meter.

EcoMappers

Two small (30 kg) propeller-driven AUVs were deployed under low-wind conditions during the SPURS-1 deployment cruise in September 2012. The Iver2 AUV, made by OceanServer (but branded “EcoMapper” once outfitted with a YSI environmental sensor suite) has a maximum speed of 1.8 m s^{-1} and an endurance of about five hours. They carry Neil Brown CTDs sampling at 1 Hz, as well as YSI CTDs and optical sensors (Hodges and Fratantoni, 2014). Further EcoMapper experiments are planned for the SPURS-2 recovery cruise in October 2017.

MOORED

Although not traditionally considered ALPS, moorings are persistent, autonomous, and increasingly adaptive tools for measuring the ocean (e.g., Pinkel et al., 2011; Trask and Farrar, in press). Moorings served to anchor both the SPURS-1 and SPURS-2 experimental design in more than one way. Both the SPURS-1 and SPURS-2 experimental sites were chosen to fit within the framework of the existing tropical moored arrays used for long-term ocean-atmosphere monitoring (the Prediction and Research Moored Array in the Atlantic [PIRATA], Servain et al., 1998, and the Tropical Atmosphere Ocean/Triangle Trans-Ocean [TAO/TRITON] moored ocean buoy network in the Pacific, McPhaden et al., 1998).

In SPURS-1, a heavily instrumented surface mooring, known as the central mooring or the WHOI mooring, served as a center point for the experimental array, collecting time series of surface meteorology with high temporal resolution for accurate estimation of the air-sea exchange of heat, freshwater, and momentum (Farrar et al., 2015). The mooring also carried about 40 fixed-depth CTDs and several ADCPs for accurate estimation of the local evolution of upper-ocean temperature, salinity, and velocity. The SPURS-1 central air-sea flux mooring was complemented by two NOAA Pacific Marine Environmental Laboratory (PMEL) PRAWLER (Profiling Crawler; Osse et al., 2015) moorings, which are surface moorings with a profiling instrument that ratchets up the mooring line from 5 m to 500 m depth, powered by wave action, and smoothly profiles down. The PRAWLERs in SPURS each carry a CTD and a dissolved oxygen sensor, though other samplers can be added, and the mooring line supports real-time two-way inductive communication and Iridium data transmission to shore. The surface buoy makes SST and basic surface meteorological measurements. In SPURS-1, the three surface moorings were configured in a triangle to aid estimation of the horizontal gradients of temperature and salinity (Figure 2).

In SPURS-2, there were also three moorings, but they were configured in a north-south array (at 9°N, 10°N, and 11°N along 125°W; Figure 3) in order to capture the north-south seasonal migration of the ITCZ and associated changes in surface freshwater fluxes and salinity. A heavily instrumented WHOI air-sea flux mooring, similar to the one used in SPURS-1, was deployed near the location of maximum summertime rainfall in the eastern Pacific ITCZ, at 10°N, 125°W. PMEL PRAWLER moorings, also similar to the ones used in SPURS-1, were deployed at 11°N, 125°W and 9°N, 125°W.

Distributed Observing System

In both SPURS experiments, the focus areas were densely seeded with Argo floats and surface drifters (Figures 2 and 3). These distributed arrays improved the local density of global oceanographic observations. Because float and drifter data are routinely assimilated into operational predictive and analysis models (e.g., multiple projects within the Global Data Assimilation Experiment [GODAE]; Bell et al., 2009), these efforts enhanced the quality of ocean state estimation and regional modeling in support of the SPURS program, particularly for targeting deployment locations and sampling strategies for ALPS.

In SPURS-1, SVP drifters and profiling floats provided regional context for the program, and provided data to quantify the variability of the surface and near-surface temperature and salinity of the subtropical gyre on time scales from hours to decades (Centurioni et al., 2015; Riser et al., 2015).

The SPURS-2 experimental site was geographically located in the zone of intermittent influence of the westward-flowing North Equatorial Current (NEC) and the eastward-flowing North Equatorial Countercurrent (NECC; e.g., Farrar and Weller, 2006). As a result, the SVP drifters deployed during the experiment took different paths, rapidly dispersing across the North Pacific ITCZ (almost) from Hawaii to Mexico (Figure 3).

In order to accurately resolve highly dynamical regional oceanic circulation at the isolated SPURS-2 site, a novel and flexible approach for deployment and recovery of ALPS was needed. The schooner *Lady Amber* was chartered to conduct several cruises to the site, at much lower cost than that for traditional research vessels. Cruise tracks and durations are much more flexible, for example, allowing the recovery of instruments 1,800 km from the central mooring during SPURS-2 (Figure 3). However, the lack of a large organization backing operations and maintenance arguably means more risk, as mechanical or personnel issues can create delays and schedule changes. The *Lady Amber* component of SPURS-2 aims to sail to the site and deploy 15–20 surface drifters every two to three months, while providing the presence at the site required to recover, service, and redeploy autonomous instruments as needed. During their first three cruises (Figure 4), the *Lady Amber* crew deployed almost 50 drifters, recovered one Lagrangian float and two Wave Gliders, and re-deployed one Wave Glider, as well as collected additional near-surface and atmospheric measurements.

Focused Eulerian Observing System

One of the main objectives of the SPURS-1 experiment was to quantify the terms in the equation that govern the evolution of upper-ocean salinity in order to gain insight into processes affecting the large-scale salinity field in the subtropical high surface salinity region of the North Atlantic region. This calculation required measurements of the salinity, the surface freshwater fluxes, the salinity gradient, the ocean currents, and ocean mixing over time. To collect these data, a focused Eulerian observing systems was set up that consisted of a cluster of moorings and a small fleet of autonomous platforms sampling in the vicinity. The observational arrays were centered on the moorings and included Wave Gliders, profiling Seagliders, Argo floats, and drifters. The SPURS-1 mooring array also provided context for a focused AUV study of diurnal surface layer structures (Hodges and Fratantoni, 2014).

The central mooring provided accurate estimates of surface fluxes (Farrar et al., 2015). Estimating the horizontal advection term required estimates of the horizontal gradients and the horizontal currents, with horizontal currents occurring between 4 m and 300 m depth measured using several ADCPs. All available salinity data (from satellites, the moorings, Wave Gliders, profiling Seagliders, Argo floats, drifters, and shipboard measurements when available) were used to map the salinity field and estimate the horizontal salinity gradients. The various platforms were arranged with the goal of quantifying the role of lateral advection by mesoscale eddies and the low-frequency circulation, by resolving lateral gradients from spatial scales of 15 km and time scales on the order of the inertial period (three days) up to scales resolved by remote sensing (i.e., O(100 km) and O(1–2 weeks)). This approach proved reasonably successful during SPURS-1, in the sense that we were able to estimate most of the terms in the salinity balance of the surface mixed layer and achieved a budget that was closed within the measurement errors during the first six months of the experiment (Farrar et al., 2015). In spring and summer, horizontal advection contributes greatly to the salinity balance, which does not covary with the tendency term in the mixed layer, likely pointing to the importance of frontal restratification, intrusions, and other poorly resolved gradients.

A different approach was adopted in SPURS-2, in part because precipitation dominates the surface freshwater forcing. Whereas evaporation is largely controlled by the wind field, which has relatively large spatial scales of 100–1,000 km, precipitation is very patchy in time and space, with an approximately lognormal distribution (Kedem et al., 1997). Intense events occur on short temporal and spatial scales (as storms and squall lines), and create short-lived shallow (0.1–1 m) pools of very fresh water. Rather than trying to resolve these small and rapidly evolving features with a Eulerian array, we opted to use the fixed moorings to observe the temporal variability in and around the region of maximum summertime and annual mean precipitation in the Eastern Pacific ITCZ. The Eulerian array provides many realizations of these short-timescale rain events and the upper-ocean response to surface forcing, and it is well suited for examining the upper-ocean heat and salt budgets using gradient estimates from satellite measurements and the gliders patrolling around the central mooring. The strong ocean currents in the NEC/NECC system in SPURS-2 prompted innovative approaches to the use of ALPS in a Lagrangian mode, as described below.

Lagrangian Observing System

In a reference frame following any float or drifter, the temporal evolution of a water parcel is brought into focus, providing a view of ocean variability different from that of a fixed Eulerian observer. Casting a broad net of such instruments allows multiple realizations of process studies to be run concurrently.

In the SPURS-1 experiment, profiling floats were used to elucidate the details of diel variability of upper-ocean stratification in various forcing regimes (Riser et al., 2015) and to track the evolution of small-scale thermohaline interleaving features (Shcherbina et al., 2015a).

Even more insight into Lagrangian water mass variability can be gained by coordinated deployment of a cluster of autonomous instruments, each observing a particular aspect of the environment. In the SPURS-2 experiment, such a cluster of autonomous instruments was deployed near the central mooring on August 26, 2016, for a “coordinated Lagrangian drift” (Figure 3). The cluster initially consisted of a Lagrangian float, a Wave Glider, a Seaglider, an APEX/Argo profiling float, and three SVP-S2 surface drifters. *Lady Amber* deployed an additional batch of 15 SVP(-S) drifters about a month later. An animation of the evolution of the SPURS-2 Lagrangian observing system is included in this article’s online supplemental materials.

Each instrument in the cluster made a different contribution to the unified Lagrangian observing system. The Lagrangian float was set to continuously profile over the upper 50–60 m of the water column, thereby accurately tracking the lateral advection of the surface water mass. Its position and average drift direction were used to define a water-following “target” frame of reference. The Seaglider and the Wave Glider navigated pre-defined patterns in this frame of reference, recording the evolution of the three-dimensional hydrographic structure surrounding the float. The Seaglider dove to 1,000 m depth, observing the underlying hydrographic structure. The Wave Glider and SVP-S/S2 drifters ensured continuous high-resolution observations of rapidly evolving near-surface salinity structures. Additionally, the Wave Glider observed the local meteorological conditions directly over the cluster. Wind and rain were also monitored acoustically by PALs on the Lagrangian float, the Seaglider, and the APEX float.

Trajectories of the surface drifters and APEX floats could not be controlled like those of the Seaglider and Wave Glider, so they diverged rapidly from the track of the target Lagrangian float due to the strong shear of the upper-ocean currents. The only way to coordinate these instruments with the rest of the cluster was to carefully choose the deployment locations and re-seed the cluster periodically. *Lady Amber* carried out three additional deployments of supplemental SVP(-S) drifters in September–October 2016. The drifters were deployed in clusters of five upstream of the Lagrangian frame center.

The main challenge of the Lagrangian drift coordination was the prediction of instrument drift trajectories. A simple empirical model consisting of a combination of steady advection and inertial oscillations with the local inertial period (~3 days) was fit to the target float’s trajectory over the preceding 2.5 days. This model was then used to form a prediction for the Lagrangian frame orientation and advection over the following days. The influence of currents on Seaglider and Wave Glider progress was determined from these instruments' navigation offsets. All this information was combined to transform the survey patterns for the drivable instruments from the Lagrangian frame of reference to geographic coordinates, to define the corresponding waypoints, and to redirect the gliders. The skill of the drift track prediction was limited by the complex variability of upper-ocean current shear. Over the duration of the drift, the 24-hour prediction error varied from <2 km to >30 km, possibly depending on the meteorological conditions and prevalence of mesoscale advection; a typical RMS error of the 24-hour prediction was 12 km, which is comparable to the 20 km pattern scale. Because of that, prediction had to be updated every four to six hours (on each surfacing of the target Lagrangian float), and each forecast had to be evaluated manually. These efforts allowed us to keep the Wave Glider within close proximity of the Lagrangian float for the 100-day duration of the coordinated drift (Figure 3, inset).

DISCUSSION

A central challenge in modern physical oceanography is sampling the large range of temporal and spatial scales that are important in determining the evolution of ocean properties. The innovative use of a variety of measurement platforms in SPURS is one example of how different tools, each with its own set of strengths and weaknesses, can be used in a coordinated fashion to ensure broad-scale coverage while simultaneously resolving small-scale processes.

Much of the freshwater input in the Eastern Pacific is from intense atmospheric mesoscale systems in the ITCZ, which rapidly deposit large amounts of rain with a patchy distribution in time and space. One of the main scientific questions SPURS-2 seeks to answer is how these patches of freshwater become integrated into the slowly evolving large-scale ocean salinity field. An important feature of the large-scale salinity field is known as the Eastern Pacific Fresh Pool. This region of the Eastern Pacific has low surface salinity (<34 g kg^{-1}) that is maintained by an interplay between the north-south annual migration of rainfall associated with the ITCZ and the annual cycle of the equatorial zonal current system (Alory et al., 2012; Guimbard et al., 2017). In particular, recent results from satellite-derived products indicate that uncertainties in Ekman advection and mixed-layer entrainment/detrainment processes are among the main obstacles to accurately predicting the North Pacific ITCZ freshwater balance (Guimbard et al., 2017). The SPURS-2 Coordinated Lagrangian Drift experiment gives new insight into these processes by following the surface water masses on their eastward progress through the ITCZ and documenting both the accumulation of freshwater precipitation and its incorporation into the seasonal halocline. Lagrangian evolution of salinity was markedly different from the Eulerian moored record (Figure 5). This difference suggests that the surface waters being carried eastward in the NECC are accumulating freshwater from the ITCZ, while the increasing salinity at the mooring site points to the importance of advection and vertical entrainment for local salt balance. Both the trajectories and the salinity records of the Lagrangian cluster that advected at the average rate of the currents in the upper 50–60 m of the water column were different from the records of the SVP-S drifters that followed currents at 15 m depth (Figures 3 and 5). These data highlight the importance of understanding the vertical structure of highly sheared currents in this region. The different frames of reference, and the duration of averaging of currents, impact which dynamical processes are emphasized in a given analysis.

Simultaneous multi-platform observations collected during the Coordinated Lagrangian Drift experiment provide a detailed picture of the evolution of upper-ocean stratification and shear structure, more comprehensive than could be obtained from the individual instruments. Figure 6 is an example of a multi-platform observational synthesis for the period September 13–23, 2016 (10 out of 100+ days of the Lagrangian drift). During this period, the instruments drifted 180 km northeastward under NEC influence. In this quasi-Lagrangian frame of reference, the dominant processes affecting the evolution of the upper-ocean structure observed by the drifting Lagrangian cluster should be either surface fluxes or vertical mixing. During this 10-day portion of the drift, the mixed-layer salinity observed by the Lagrangian float and the Wave Glider stayed mostly steady until a series of rain events on September 18 freshened the upper ocean. The shallow Wave Glider CTD (marked “1” in Figure 6b) first observed the formation of a near-surface low-salinity “puddle” following a rainstorm. Within a few hours, the low salinity signal was transported downward (presumably, by turbulent diffusion), incorporating the rainwater into the mixed layer (marked “2” in Figure 6c). The freshening was relatively large on September 20 when the rain was heaviest, but the mixed-layer salinity gradually increased, presumably as a result of vertical mixing across the shallow halocline, which had become as shallow as 10–20 m (Figure 6c) and exhibited very high vertical shear (Figure 6f). During the rain event on September 20, the freshening of the upper few meters was accompanied by cooling—this feature stands out because it appears to be a reversal of the normal diurnal cycle of temperature (with warming of the near-surface water during the daytime). This observation is qualitatively consistent with the expectation that the surface waters should be cooled by the rain, which can be several degrees cooler than the SST (approximately at the wet-bulb temperature) when it reaches the ocean surface (S.P. Anderson et al., 1998). Abrupt changes in the upper-ocean structure on September 21–23 were accompanied by a reversal in the direction of the drift (Figure 3), and were likely a result of interactions with a strong mesoscale eddy.

During the warm clear days preceding the rainstorm, progressive amplification of the diel cycle of near-surface temperature can be seen (“3” in Figure 6d,e). Strong vertical shears (“4” in Figure 6f) were associated with the diurnal warming, characteristic of so-called “slippery layers” (Kudryavtsev and Soloviev, 1990). Interleaving structures in stratification and shear (“5” in Figure 6e,f) were also occasionally observed in the upper pycnocline, reminiscent of similar features observed during SPURS-1 (Shcherbina et al., 2015a).

As more data are now available from other platforms, the challenge is to link and synthesize the SPURS-2 observations. The estimated rain rates from patchy rain events (both from in situ and from remote sensing) will be combined with the mixed layer evolution observed at the moorings, as well as with measurements collected by drifters, floats, Seagliders, and Wave Gliders that span scales from a local profile to the broader regional hydrographic properties at the surface available from remote sensing and from the Argo program. Comparisons of the timing of rain-induced freshwater pulses in the drifter records, and those captured by the moorings and other instruments, will allow investigation of the temporal intermittency and spatial patchiness of ITCZ precipitation events (as in Hormann et al., 2016), which constitute another critical factor for understanding EPFP dynamics.

Given the recent advances in ALPS described in this special issue of *Oceanography* and elsewhere, such coordinated, multi-platform experiments are going to become more common. The NASA Physical Oceanography Program is using SPURS to develop strategies for sustained ocean observing that employ satellite and in situ platforms together to span the spatial and temporal scales required to address physical processes in the upper ocean. The ultimate goal is to create a “smart network” of disparate instruments capable of interaction and self-coordination to achieve given research objectives. Future experiments will build on the lessons learned from the SPURS-1 and SPURS-2 programs and expand on the approaches presented here, within the framework of remote sensing and the Global Observing System. Both at NASA and in the broader field of oceanography, ALPS will continue to be key components that “drive advances in science, technology...to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth” (NASA’s mission statement, NASA Strategic Plan, 2014).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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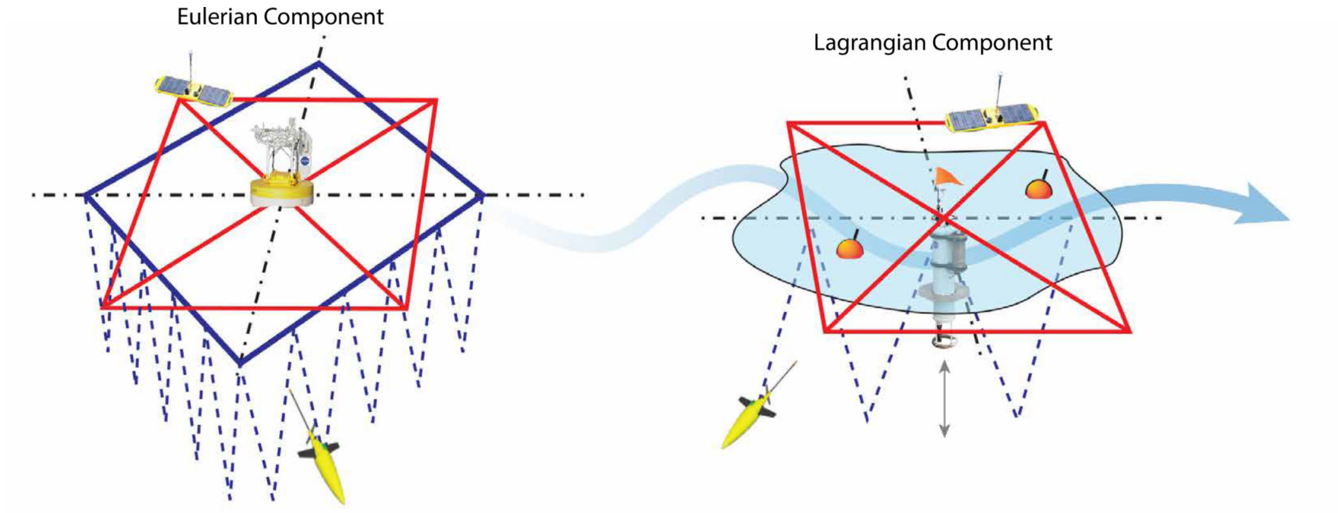

FIGURE 1.

Schematic illustration of (left) SPURS-2 Eulerian and (right) Lagrangian components. The former is “anchored” to a mooring site, while the latter follows the advection of the surface water mass tracked by a Lagrangian float and SVP drifters. Wave Gliders and Seagliders navigate pre-defined patterns in both the fixed and advected frames of reference.

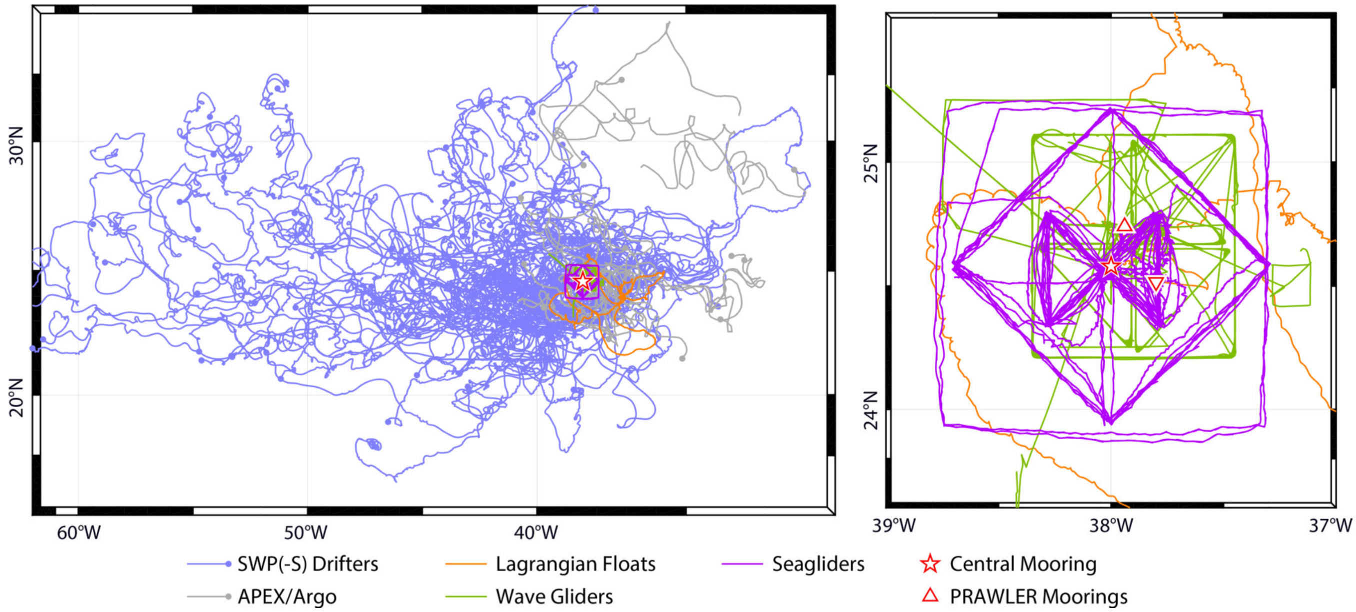

FIGURE 2.
(left) Overview of the tracks of SPURS-1 ALPS, September 13, 2012–October 1, 2013, with (right) a close-up showing the details of the Focused Eulerian component. The tracks of SVP drifters and APEX floats are omitted from the latter plot for clarity.

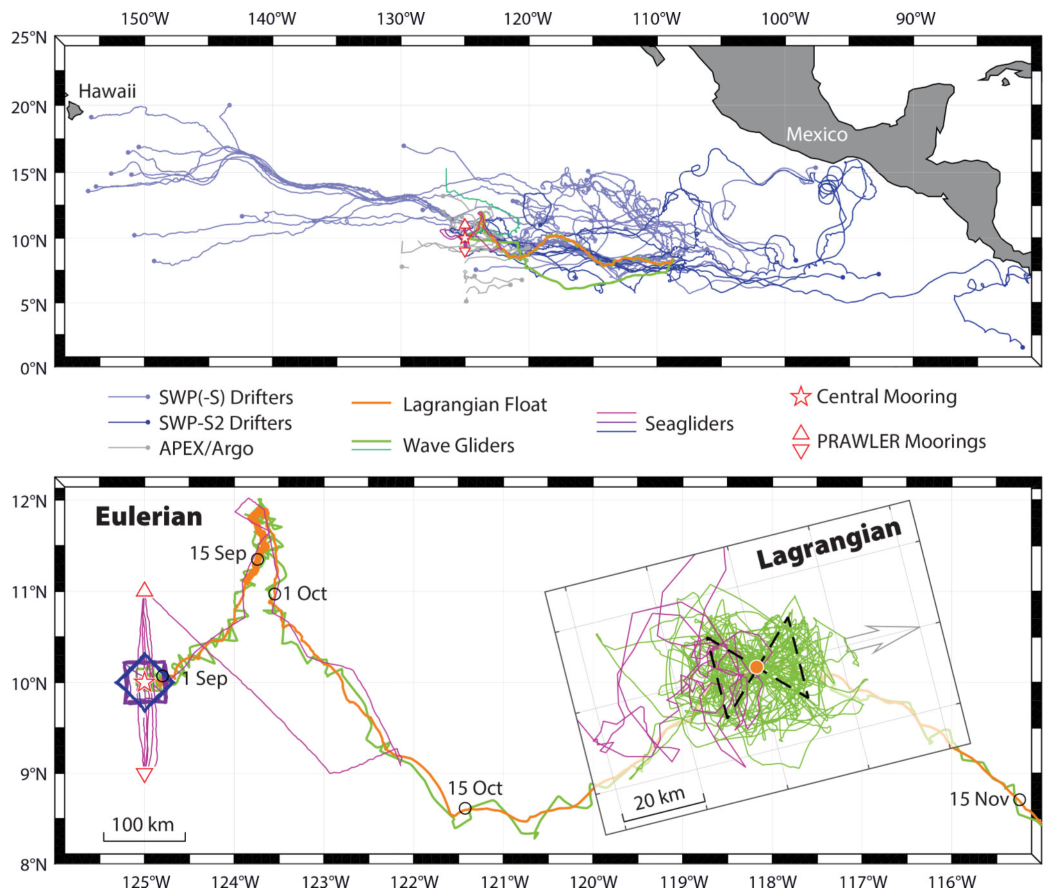

FIGURE 3.

(top) Overview of the tracks of SPURS-2 ALPS, August 26, 2016–June 7, 2017, with (bottom) a close-up showing the details of the Focused Eulerian and Lagrangian components. The tracks of SVP drifters, Eulerian Wave Gliders, and APEX floats are omitted from the latter plot for clarity. Progression of the Coordinated Drift is indicated by date marks; a 10-day segment of the drift (September 13–23), shown in Figure 6 and discussed in the text, is marked by a thicker orange line. The inset shows relative trajectories of the Wave Glider (green) and the Seaglider (purple) in the drifting frame of reference defined by the Lagrangian float. In this frame of reference, the Lagrangian float (orange) is always at the center; the frame is rotated so that the x-axis is aligned with the geographic direction of the float's drift. Intended Wave Glider navigation pattern, a 20 km × 20 km "butterfly" is shown by black dashed line.

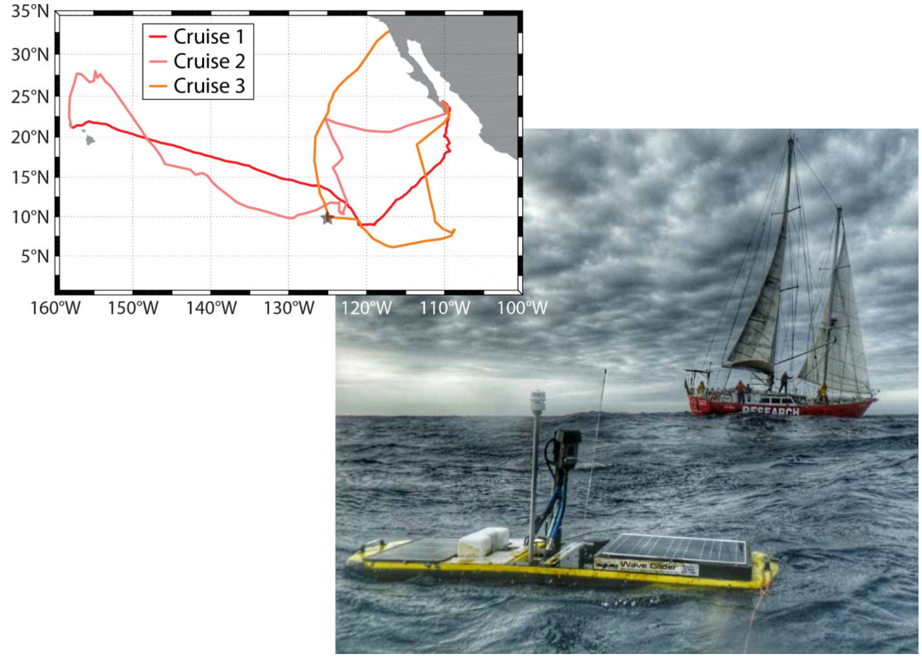

FIGURE 4.
(right) The schooner *Lady Amber* is shown recovering a Wave Glider in the Southern Ocean before the beginning of SPURS-2. (above) Tracks of the first three *Lady Amber* cruises to the SPURS-2 site (star): Cruise 1, June 9–July 5, 2016; Cruise 2, August 29–October 25, 2016; and Cruise 3, December 1, 2016–January 16. 2017. *Photo by Capt. Peter Flanagan*

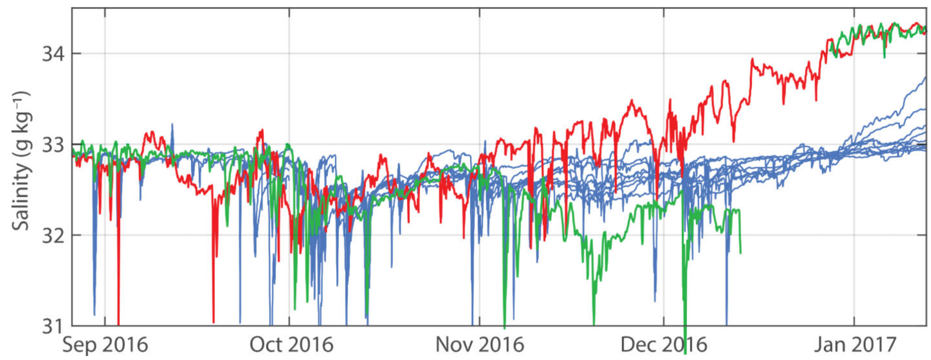

FIGURE 5.
Comparison of Eulerian and Lagrangian records of near-surface salinity evolution during SPURS-2. The Eulerian frame of reference is represented by near-surface salinity observations at the central mooring (red). The Wave Glider (green) followed the Coordinated Lagrangian Drift until December 11, 2016, and then relocated back to the vicinity of the central mooring site. Blue lines show Lagrangian evolution of near-surface salinity measured by SVP-S and SVP-S2 drifters that were released alongside the Lagrangian cluster, but later diverged from it.

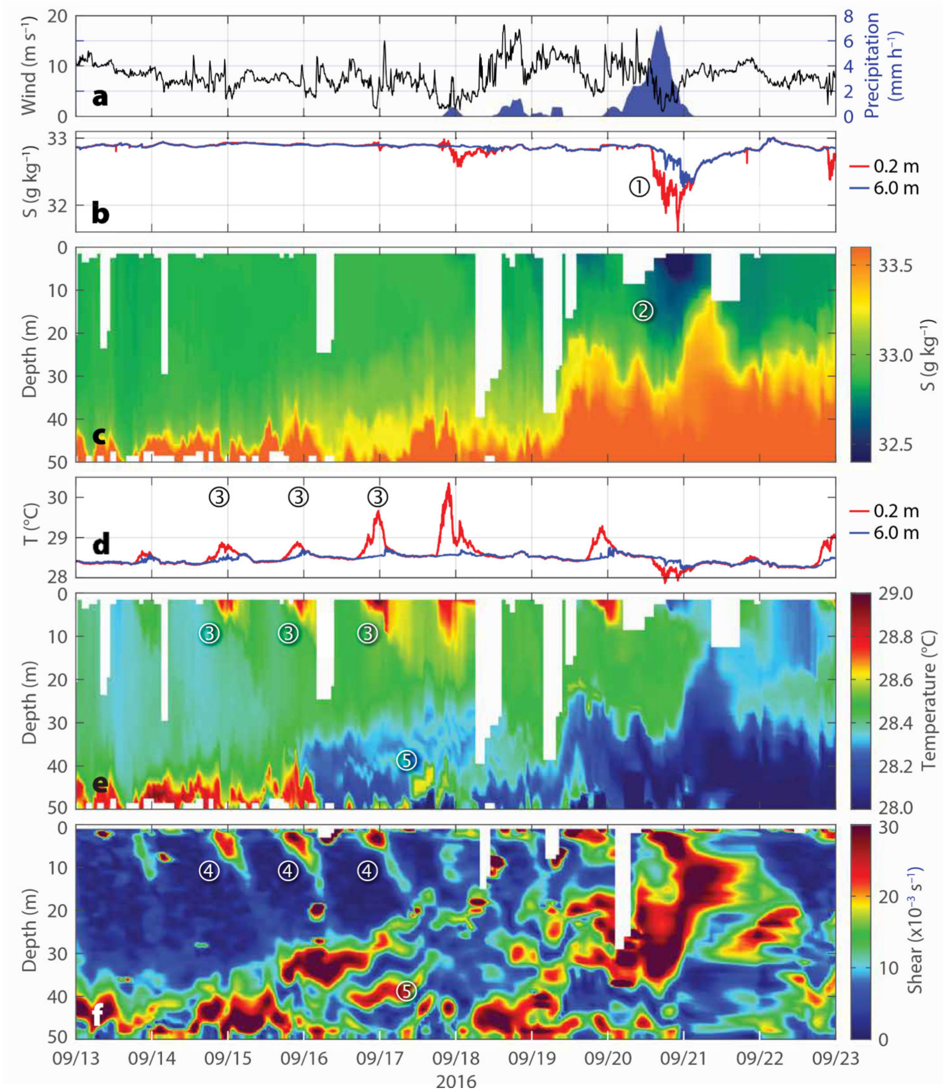

FIGURE 6.

An example of joint upper-ocean observations during the SPURS-2 Coordinated Multi-Platform Lagrangian Drift (10 out of 100+ days shown). September 2016 Wave Glider observations of (a) wind speed, (b) salinity, and (d) temperature at 0.2 (red) and 6 m (blue). Lagrangian float observations of (c) salinity, (e) temperature, and (f) shear. Blue shading in (a) shows NASA Global Precipitation Measurement/Integrated Multi-satellitE Retrievals for GPM (GPM/IMERG) satellite precipitation interpolated to the Lagrangian array location. Circled numerals mark the salient features of the record, discussed in the text.