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Data Management Support for the SPURS Atlantic Field Campaign

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ABSTRACT. We developed the data management system for the US National Aeronautics and Space Administration-sponsored Salinity Processes in the Upper-ocean Regional Study (SPURS) Atlantic field campaign (SPURS-1). Data management support means more than simply collecting and archiving static data sets. It involves a complex mixture of data visualization, interaction with principal investigators, Web development, public outreach, quality assurance, and archiving for posterity.

INTRODUCTION

In previous times, an oceanographic field program might have consisted of a ship or maybe two, a cruise plan, a small number of instruments, and 30–60 days at sea with little or no contact with the outside world. Generally, the plan would be followed with little deviation. The instrumentation used during the cruise would be brought back to the lab, calibrated, and the data extracted. After 6–12 months, a final data set would be produced that the principal investigators (PIs) could use to do scientific analysis, publish results, and formulate questions to use in writing proposals for future cruises. Such scientific activity worked very well for many years and produced fantastic results. However, this paradigm has shifted over the past two decades. Of course, this is an oversimplification. Many people have worked hard to make data collected from satellites, models, and field instrumentation more accessible at sea (e.g., Cornillon et al., 1988; Coleman et al., 2013, 2014) and to make field sampling more adaptable.

Since about 2000, a panoply of technological marvels, such as profiling floats, gliders, Iridium communication, and GPS, has fundamentally enhanced platform mobility, coordination of instrument deployment, and completeness of sampling. The availability of data-assimilating model analysis and prediction products has allowed scientists to use background atmospheric and oceanic conditions to guide their sampling. Field programs in the twenty-first century have become far more complex and sophisticated than they used to be. The Salinity Processes in the Upper-ocean Regional Study (SPURS) campaign in the North Atlantic (SPURS-1; Lindstrom et al., 2015, and Schmitt and Blair, 2015, both in this issue) epitomizes the transformation of oceanographic fieldwork from a preprogrammed and static undertaking into a decentralized, diverse, and dynamic enterprise.

In support of SPURS-1, we developed a data management system (DMS) that incorporates leading-edge information technology tools. This system was designed to meet the challenges imposed by the recent transformation in data collection and to elevate the level of collaboration and coordination among participating observation and modeling teams.

Our efforts have benefited from a number of sources. First, some of us were involved in the Monterey Bay Experiments of 2003 (Curtin and Bellingham, 2009; Fratantoni and Haddock, 2009; Ramp et al., 2009) and 2006 (http://www.mbari.org/mb2006; Leonard et al., 2010). These experiments involved developing a data visualization display for scientists to use, controlling a number of autonomous instruments in real time, and working with a highly interactive team of PIs. Adaptive sampling has long been used by the atmospheric science community (see, for example, the “Field Projects” area at the Earth Observation Lab, https://www.eol.ucar.edu, or the NASA Genesis and Rapid Intensification Processes [GRIP] mission, http://grip.jpl.nasa.gov), and we found a number of well-planned past oceanographic field campaigns inspiring because of the way information was displayed on their websites and how they made data easily accessible. These include

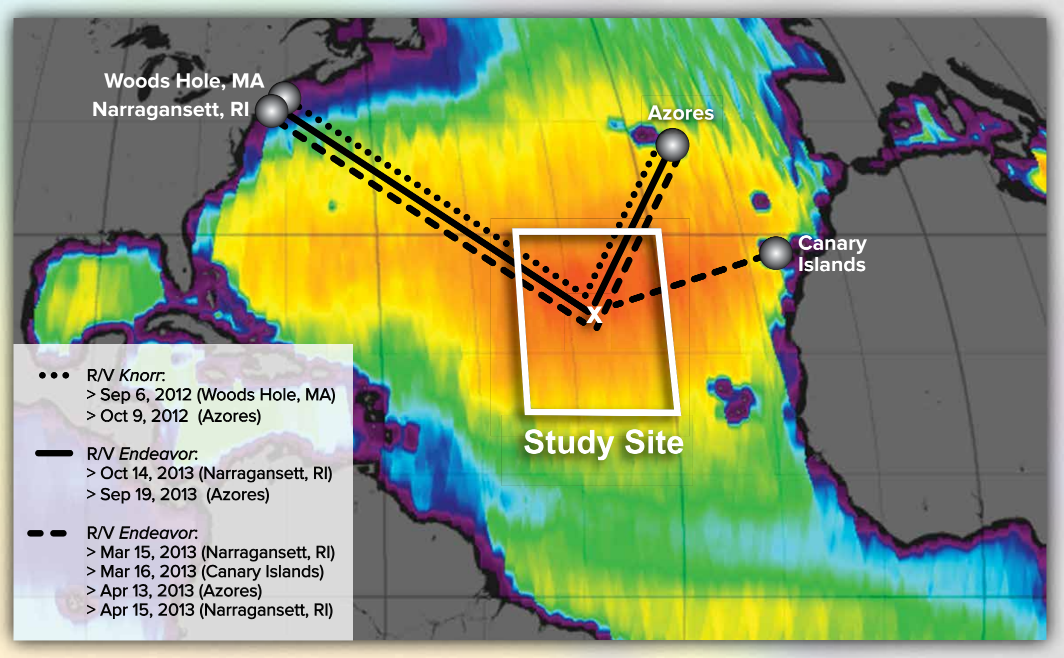

FIGURE 1. Map of the Salinity Processes in the Upper-ocean Regional Study (SPURS) study site in the North Atlantic (white box), with the white X denoting the salinity maximum area of intense data collection. Solid, dotted, and dashed lines show approximate tracks of the US cruises to and from the study site. Background color is the mean sea surface salinity in the North Atlantic measured by the Aquarius satellite.

the Kuroshio Extension System Study (http://uskess.org), the CLIVAR Mode Water Dynamic Experiment (CLIMODE; http://climode.org), and the Dyapicnal Mixing Experiment in the Southern Ocean (DIMES; http://dimes.ucsd.edu), among others. Finally, we have been associated with regional coastal observing systems whose real-time data display and quality control are crucial elements: the Coastal Ocean Research and Monitoring Program (CORMP; http://cormp.org), the Carolinas Regional Coastal Ocean Observing System (RCOOS; http://carolinasrcoos.org), the Southern California Coastal Ocean Observing System (SCCOOS; http://www.sccoos.org), the Central and Northern California Ocean Observing System (CeNCOOS; http://www.cencoos.org), and the Alaska Ocean Observing System (AOOS; http://www.aoos.org).

THE SPURS-1 IN SITU OBSERVING NETWORK

The SPURS research effort aims to address the ocean's essential role in the global water cycle by improving our understanding of upper-ocean salinity processes (Lindstrom et al., 2015, in this issue). SPURS-1 focused on the salinity maximum of the North Atlantic during 2012–2013, with a primary sampling region of 150 km × 150 km centered at 38°W, 24.5°N (Figure 1). The SPURS-1 field campaign was carried out to examine multiscale upper-ocean processes affecting salinity from mesoscale (~100 km) down to centimeter-scale turbulence in an evaporation-dominated region. Experiment scientists employed a wide variety and an unprecedented number of observing platforms and instruments, and they collected a great amount of data.

The content of this special issue and our Tables 1 and 2 provide a sense of the diversity of observing platforms involved in SPURS-1 and its five cruises. Standard shipboard data was collected using conductivity-temperature-depth (CTD) instruments, the thermalsalinograph (TSG), and acoustic Doppler current profilers (ADCPs). There were intense concentrations of floats (24 of them) and drifters (83), one fully instrumented flux mooring, two different types of autonomous platforms (Seagliders and Wave Gliders), along with more unusual types of instrument platforms, such as PICO (Prawler—wave-powered profiler) moorings, the sea snake, the surface salinity profiler, and EcoMappers (see Table 2 for definitions of terms). The total size of the data set from summing the fifth column of Table 2 is almost 1 gigabyte, not including several gigabytes of unprocessed data.

THE SPURS-1 DATA MANAGEMENT SYSTEM

The role of the DMS team in SPURS-1 was both to support the SPURS investigators through a variety of activities and to disseminate information about SPURS to the scientific community and the public. As we found during the course of SPURS-1, "data management" is about far more than corralling the data stream emanating from field instrumentation, models, and satellites. It is about understanding the configuration of a continually evolving array within a turbulent background flow field and visualizing that array in an interactive and intuitive way. It is about understanding the needs of researchers far into the future when they want to access and use the data collected during SPURS-1. It is about managing the communication associated with the experiment, between PIs, between ship and shore, between scientists and the public (who ultimately provide the funds), between today and posterity. It is about making sure the data are high quality and that the various observing platforms agree with each other. Thus,

TABLE 1. SPURS-1 Cruises.

Ship (Cruise #)	Dates	Chief Scientist (Nationality)
Thalassa	August 16 – September 13, 2012	Reverdin (France)
Knorr (209)	September 6 – October 9, 2012	Schmitt (US)
Endeavor-1 (522)	March 15 – April 15, 2013	Schmitt (US)
Sarmiento	March 14 – April 10, 2013	Font (Spain)
Endeavor-2 (533)	September 19 – October 13, 2013	Fratantoni (US)

TABLE 2. Information on the various SPURS-1 in situ data sets that we are aware of. **COLUMN DESCRIPTIONS — Cruises:** K = *Knorr*. T = *Thalassa*. E1 = *Endeavor*-1. E2 = *Endeavor*-2. D = *Sarmiento*. **Responsible Party:** PI or person most directly in charge of the collection. **N?:** netCDF format version of data set available as of paper submission date. y = yes. n = no; p = partially. **Size (MB):** Size of the netCDF version of the data in megabytes (not the size of any unprocessed version).

Data Set Name	Cruises	Type of Data	N?	Size (MB)	Responsible Party (Institution)†
TSG (Thermosalinograph)	K, T, E1, E2, S	Along-track temperature and salinity	y	3, 0.2, 12, 10, 9	none*
ADCP (Acoustic Doppler Current Profiler)	K, E1, E2, S	Along-track current profiles	p	K: 15, 11, 32 E1: 14, 11, 31 E2: 11, 8, 25	none*
CTD Casts	K, T, E1, E2, S	T/S profiles	y	32, 6, 17, 3, 1	none*
LADCP (Lowered ADCP)	K, S	CTD Station current profiles	n		Julian Schanze (Earth and Space Research) and Julius Busecke (LDEO)
Shipboard Meteorology	K, E1, E2	Along-track meteorology	y	35, 26	none*
UCTD (Underway CTD) Casts	K, E1	T/S profiles	p	4, 3	Tom Farrar (WHOI)
EcoMapper[1]	K	Short-scale T/S surveys	y	3, 0.3	Ben Hodges (WHOI)
Microstructure (VMP and T-glider)	K, E1	Microstructure profiles	n		Lou St. Laurent and Ray Schmitt (WHOI)
Meteorology Mast	K	Along-track meteorology	n		Jim Edson (U of Connecticut)
Surface Salinity Profiler[2]	T	Short-scale near-surface T/S surveys	y	19	Bill Asher and Andy Jessup (U of Washington)
ASIP (Air-Sea Interaction Profiler)	T, S	Microstructure profiles	n		Brian Ward (NUI Galway)
Sea Snake[3]	E1	Along-track skin surface salinity	n		Julian Schanze (Earth and Space Research)
SeaSoar	S	Towed undulating T/S profiles	y	3	Julius Busecke (LDEO)
STS Argo Floats[4] (Surface Temperature and Salinity)		T/S profiles	y	69	Steve Riser (U of Washington)
SVPS Drifters (Surface Velocity Program/Salinity)[5]		Along-track temperature and salinity	y	83	Luca Centurioni (SIO)
Seagliders		Autonomous T/S profiles	y	8, 51, 19, 53, 50	Charlie Eriksen and Craig Lee (U of Washington)
Neutrally Buoyant Floats		Mixed-layer T/S profiles	y	19, 26	Andrey Shcherbina and Eric d'Asaro (U of Washington)
Wave Gliders		Autonomous along-track temperature and salinity	y	0.6, 0.9, 0.9, 0.8, 0.8, 0.8	Ben Hodges (WHOI) and David Fratantoni (Horizon Marine)
Flux Mooring[6]		Moored temperature and salinity at multiple levels; Surface fluxes and meteorology; Current profiles	y	53, 0.6, 53, 0.9, 98	Tom Farrar (WHOI)
PICO (Platform and Instrumentation for Continuous Observatrions) Moorings[7]		Time series temperature and salinity profiles from "Prawler"	y	26, 11	Billy Kessler (NOAA/PMEL)
Tenuse Glider		Autonomous undulating profiler	y	23	Gilles Reverdin (IFREMER)

† Anyone interested in obtaining these data should contact the authors of this paper or visit the SPURS website.

* Many shipboard measurements were handled by technical staff not under the direction of any specific PI

[1] Hodges and Fratantoni (2014)

[2] Asher et al. (2014)

[3] http://spurs-fall-2013.blogspot.com/2013/09/snakes-on-ship.html

[4] Anderson and Riser (2014) and Riser et al. (2015, in this issue)

[5] Hormann et al. (2014) and Centurioni et al. (2015, in this issue)

[6] Farrar et al. (2015, in this issue)

[7] http://earthobservatory.nasa.gov/blogs/fromthefield/2012/10/05/prawlers-engineers-and-the-future-of-oceanography-at-sea

managing data and information from an experiment like SPURS-1 requires a high degree of knowledge, not only of data sharing standards, ocean instrumentation, and the scientific goals of the program, but also of the human dimensions of science.

Conceptually, SPURS-1 can be divided into two parts: a "wet side" consisting of instrumentation that goes into the water and a "dry side" that encompasses ocean models, atmospheric forecasts, satellite data, and the infrastructure that supports all of this (Figure 2). As discussed below, there are important feedback loops between the wet and dry sides. The SPURS-DMS was set up to facilitate flow of data and information between the two sides.

The SPURS-DMS, as it has evolved, has a number of components, some of which we discuss below. The components include:

- A visualization facility that SPURS PIs and anyone else interested can use to see the data as they are coming in and to understand the current status of the array
- The back end to this facility, or the database and communication protocols that ingest and incorporate SPURS data in near-real time
- Provision of the data into a data-assimilating ocean model
- Oceanographic field support on land and at sea
- A website (http://spurs.jpl.nasa.gov) that serves as a portal into SPURS data and educational activities
- Mailing lists and other forms of communication
- Collation of reports, presentations, and peer-reviewed publications
- Blogs and other public communication
- Data quality assurance
- Conversion of the SPURS data to a self-archiving format
- Submission of a final data set to the relevant federal agencies

Real-Time Visualization

The interactive SPURS data visualization system (see http://spurs.jpl.nasa.gov and click on "SPURS Data" and then "Visualization" in the dropdown menu) was designed to help PIs follow the progress of the array in real time, that is, to provide real-time situational awareness. It allows users to display and overlay multiple types of data sets on a three-dimensional Earth, to zoom and pan, and to interact with the data by clicking on placemarks to call up plots and measurements in text bubbles. The SPURS visualization system incorporates four different types of data:

1. Routine in situ measurements: Argo float profiles, PIRATA (Prediction and Research Moored Array in the Atlantic) mooring data, SVP (Surface Velocity Program) drifter data and paths
2. SPURS in situ data: ship tracks and underway data including TSG and ship-based meteorological data and information from flux and Prawler moorings, Wave Gliders, Seagliders, SVPS (SVP/salinity) drifters, and STS (surface temperature and salinity) floats. (Note that the visualization system used first-look versions of the data sets, and these were not updated. Calibrated scientific quality data will be made available through the archive.)
3. Satellite observations: Aquarius satellite gridded sea surface salinity (SSS), sea surface temperature (SST), Advanced Scatterometer (ASCAT) surface winds, and sea surface height (SSH)
4. Model nowcasts and forecasts for the SPURS domain: Regional Ocean Modeling System (ROMS) products (see later section on DMS and the SPURS-1 Modeling Group), wave height forecasts from the WAVEWATCH model operated at the National Center for Environmental Prediction (NCEP), and SSS analyses from the US Navy's global Hybrid Coordinate Ocean Model (HYCOM)

As an example, Figure 3 shows wind speed and direction as a ship (R/V *Endeavor*) is steaming northwestward away from the study site. The figure also shows SST. Wind information and SST data can be fully turned on or off within the display by clicking boxes on the left side of the screen. Figure 4 is a more detailed picture of the in situ observing assets as another ship (R/V *Knorr*) moves through them. This type of display

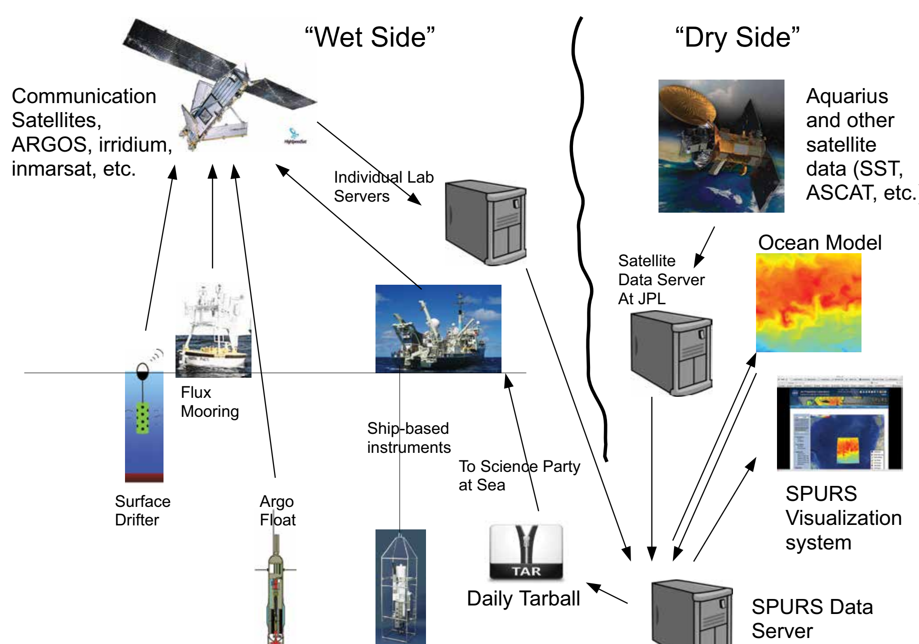

FIGURE 2. Architecture for the SPURS Data Management System (DMS) showing the data flow and the interfaces between the instruments and the SPURS data server.

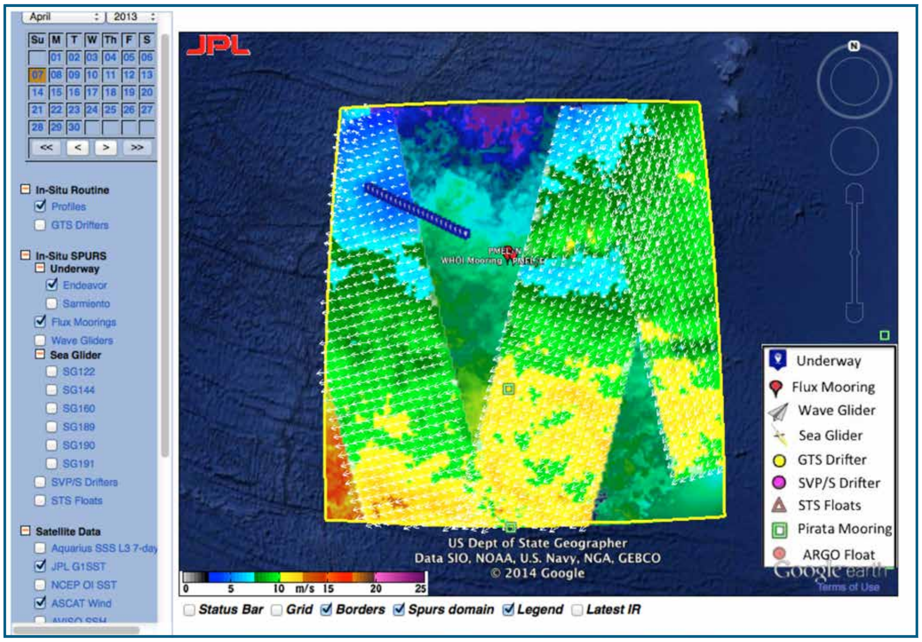

FIGURE 3. Screen capture of the visualization system display available on the SPURS website showing sea surface temperature (SST) and Advanced Scatterometer (ASCAT) surface winds in the SPURS-1 domain. Winds are displayed by arrows, and colors indicate speed in areas where there are arrows. The color bar at the bottom is a scale for the wind speed. SST is the color where there are no arrows. The blue symbols show the ship track of R/V *Endeavor* on April 7, 2013. The red placemarks in the center of the domain indicate SPURS moorings deployed by the Woods Hole Oceanographic Institution (WHOI) and the NOAA Pacific Marine Environmental Laboratory. A calendar and a list of data products are located on the left-hand side of the display. Users can choose any calendar date from the clickable calendar and one or more data products from different sources to examine and compare.

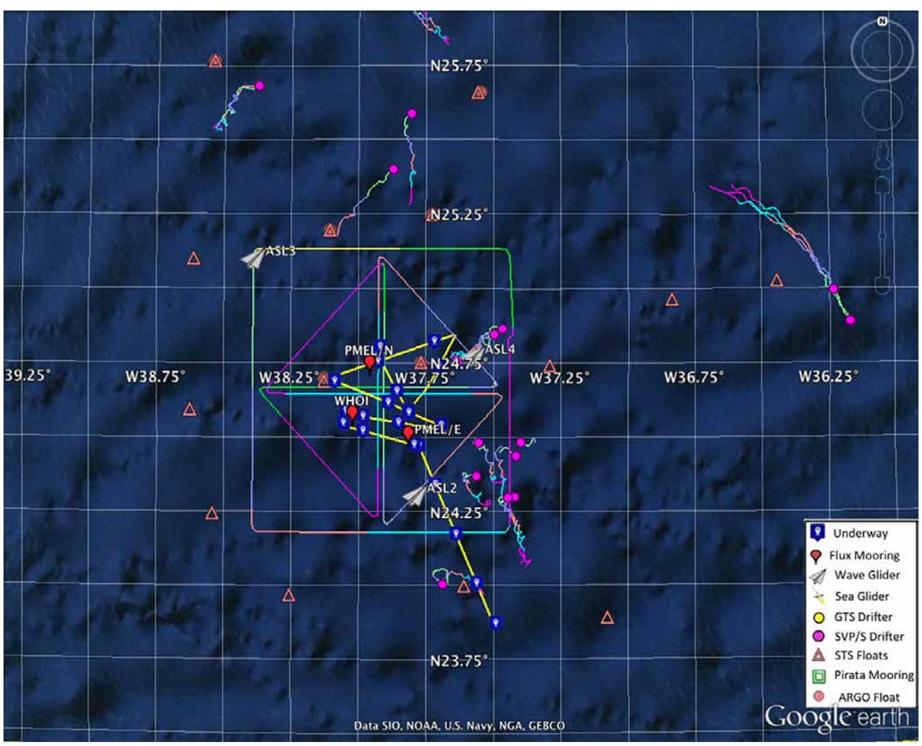

FIGURE 4. Screen capture showing the locations of all in situ measurements for a given day (October 4, 2012) in the Google Earth-driven visualization display. Different data sets are represented using icons as indicated by the legend at the lower right corner. The ship track shown is that of R/V *Knorr*.

is useful in planning instrument deployment and recovery. Clicking on any of the symbols in the Figure 3 display brings up information about the instrument or observation the symbol represents (e.g., Figure 5).

Oceanographic Field Support

During SPURS-1, the DMS group sent someone to sea during the September/October 2012 R/V *Knorr* cruise (author Bingham) and the March/April 2013 cruises of R/V *Sarmiento* (Julius Busecke, Lamont-Doherty Earth Observatory of Columbia University) and R/V *Endeavor* (Jessica Anderson, University of Washington). We also provided ship support for the September 2013 *Endeavor* mooring recovery cruise, maintaining contact with the ship, though no DMS personnel were there. Prior to the cruises, we held a series of meetings and training sessions to review system functionality so the DMS person on board could present and interpret data and model results for the chief scientist on the cruise. This hands-on support was a crucial part of our effort.

The wet observing system for SPURS-1 consisted of a highly heterogeneous set of platforms and sensors (Table 2, first and third columns), most managed by a separate PI (Table 2, sixth column). These observations were all returned to shore in real time, through different channels, at different frequencies, and in different formats. The data reported to shore in real time were collected by the SPURS-DMS, stored in a database, and disseminated through the visualization page at the SPURS website. The challenge for the SPURS-DMS group was to combine these data, apply appropriate visualization tools, and transmit the information back to the ship in a convenient way so that the science party at sea could use it to facilitate operational planning.

Rather than being accessible to shipboard scientists in real time through the SPURS website, the enormous file sizes required that the information be transmitted back to the ship in a highly

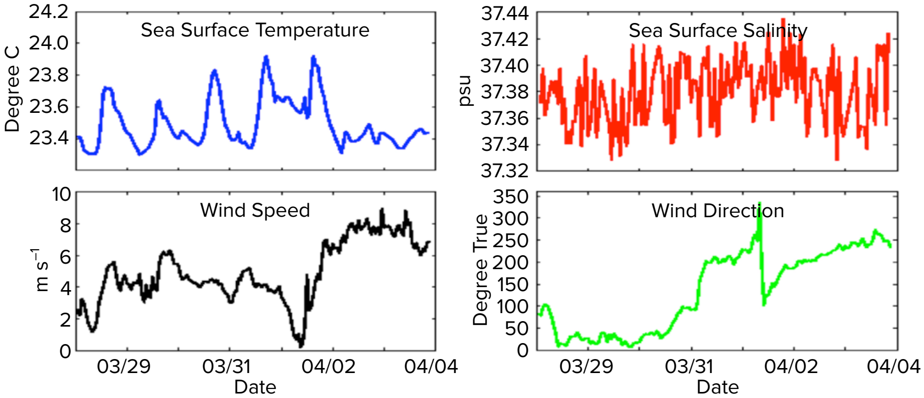

FIGURE 5. Some example plots available in the visualization system by clicking on one of the icons displayed in Figure 4. This one-week time series plots the central flux mooring measurements (red pin labeled "WHOI" in Figures 3, 4, and 6).

compressed archive file known as the "daily tarball" (Figure 2), mainly in the form of KML or KMZ files, readable by Google Earth (GE). The DMS person at sea accessed the downloaded files each day and used GE on a local computer to view and manipulate them. Accessing these displays locally through GE instead of using the online visualization system turned out to be highly advantageous. GE is a very powerful program that can be used to make different kinds of displays, calculate distances, create animations, and visualize the array at a variety of spatial scales. Using GE, DMS personnel worked closely with the chief scientists to plan operations, surveys, deployment or recovery of instrumentation, and transit from one part of the SPURS region to another. Figure 6 shows an example of the type of display used. In it, the ROMS model indicates a high-salinity filament located to the northeast of the ship's track, which was confirmed by the two drifters that are floating in the middle of it. The ship had just finished several crossings of that filament to sample it. This is an example of the importance of feedback among data management, modeling, and field sampling.

It should be noted here that the objectives of the system do not include delivering data in near-real time to SPURS PIs or anyone else. The goal is to deliver science-quality data to PIs and the public once the field campaign is finished via the permanent archive. As stated above, and detailed below, we delivered preliminary data in near-real time to the science party at sea and to the modeling group for use in data assimilation.

The SPURS Website

For SPURS-1, the DMS group designed, created, and managed the SPURS website (http://spurs.jpl.nasa.gov) with the help of Annette deCharon and her group. The website provides a link to all pertinent project information for the use of SPURS PIs, the science community, program managers, and the general public. It includes:

- A basic description of SPURS for non-participating scientists and the public
- Access to some data sets provided by SPURS PIs
- A GE-based, calendar-driven visualization system
- Links to publicly available SPURS data sources
- SPURS workshop reports, presentations, and scientific results
- Meeting agendas, registration, and logistics
- Cruise descriptions and access to cruise blogs
- Access to SPURS mailing list archives
- A SPURS calendar
- Access to educational and public outreach materials provided by the eSPURS group (deCharon et al., 2015, in this issue)

The information contained on the SPURS website is an important part of the SPURS record, just as important as the data themselves. Future researchers will want to know what has already been learned from the SPURS experiment, what the motivation was for doing it, and how decisions were made for conducting it. Most of the static part of the SPURS website will included in the permanent archive so that a record of the important work we have done is properly preserved.

Education and Public Outreach

SPURS-1 had a significant education and public outreach component for which the DMS served as a distribution point. Creating such content is rewarding and enjoyable, and is also a necessary part of the modern scientific enterprise. Fortunately, we had skilled partners to help (deCharon et al., 2015, in this issue).

Blogs and other similar social media are the best way of communicating the excitement of SPURS science in the short term, as they are immediately accessible to a wide audience. During SPURS-1, the DMS team managed and coordinated several blogs, including one for each cruise that allowed chief scientists (Table 1) the ability to communicate results to the outside world, including other SPURS PIs and program managers. One successful blog, written by Eric Lindstrom (NASA) while he sailed on R/V *Knorr* in September–October 2012, generated much interest on social media and over 47,000 page views (see http://earthobservatory.nasa.gov/blogs/fromthefield/category/spurs).

Data Quality Intercomparison

Because of the great variety of instrument platforms, some effort must be put into comparing different instruments and, where possible, calibrating to known high-quality standards. The individual PIs on the SPURS wet team (Table 2, sixth column) were all very skilled and dedicated to ensuring that their own data sets were of high quality. The role the DMS team played was to take a broad view, looking at the different data sets in comparison to each other. In traditional shipboard measurements of salinity, samples are brought on board and run through a salinometer that has been calibrated using standard seawater. For moored instruments, pre- and post-deployment calibration is the standard way of ensuring high data quality. Unfortunately, this was not possible for some of the instruments in SPURS-1 because they could not be recovered. This was of particular concern for the salinity drifters, which are continuously exposed to the mechanical stress and fouling of the near-surface ocean.

As the SPURS-1 experiment progressed, instruments came into proximity, whether by serendipity or on purpose. We created a database of all instruments that approached each other within 10 km and two hours (Baker et al., 2014) and analyzed the salinity differences between them. With some judicious elimination of redundant encounters, this amounted to nearly 28,000 instrument comparisons. The vast majority of these comparisons were drifter-drifter pairs. Choosing one sensor at random, Figure 7 documents the evolution of salinity difference for that particular drifter over time and compares that information with other SPURS sensors. It shows encounters with other sensors (bottom panel), a histogram of salinity differences (middle panel), and its own salinity time series (top panel). The vast majority of encounters for all instruments have an absolute salinity difference less than 0.05. For the SPURS data set as a whole, 91% of encounters had an absolute salinity difference less than 0.1—and this is before a final calibration was applied to some of the data sets. The small differences indicate that the SPURS data set is of high quality and that anyone working with it can be confident that the different sensors are measuring the same quantity.

Data Conversion and Submission

One of the most important lessons learned from our efforts in SPURS-1 was the importance of transforming the disparate data sets collected into a common format with unified metadata. Most SPURS PIs are focused on their own data collection efforts and creating the highest quality data possible for their own use. They do not have the time or interest to write metadata records or convert their data into a more universally exchangeable form for use by others. Data were turned over to the DMS team often in disparate ASCII formats. Although it had not been planned or funded as part of SPURS-1, the DMS team took on the task of writing the metadata and converting the raw data into a netCDF format for the final archive. This step has made archiving the entire set of experimental data much easier. The extent of data we are making available in this form is evident from Table 2 (columns 4 and 5) and includes most of the SPURS in situ data. Much of this conversion has been done using the available National Oceanic and Atmospheric Administration's National Oceanographic Data Center (NODC) CF-compliant templates (http://www.nodc.noaa.gov/data/formats/netcdf). According to the NODC statement on the use of the templates, "these best practices capture NODC's experience in providing long-term preservation, scientific quality control, product development, and multiple data re-use beyond its original intent."

Long-term archiving of the SPURS data set is one of the primary responsibilities of the SPURS-DMS team. We have worked with two different federal agencies with responsibility for data archiving. PO.DAAC (see http://podaac.jpl.nasa.gov) is the entity charged with archiving physical oceanographic data collected using NASA funding. Though PO.DAAC personnel have traditionally been associated with satellite data sets, they have also supported the archiving of in situ data sets, particularly those pertaining to salinity from SPURS, given the complementarity to PO.DAAC's Aquarius data holdings. The PO.DAAC group has provided guidance to the SPURS-DMS team on file and metadata standardization aspects. A copy of the archive has also been turned over to the NODC as required for all US-funded ocean field data. The archive is envisioned as being in two parts, quasi-raw and science quality. The quasi-raw part will contain data sets in their original formats. Future researchers may want to go back and access the SPURS data as they were originally collected, perhaps so they can be reprocessed using techniques that are not currently envisioned. The science-quality archive will be in a self-documenting (netCDF) format that most scientists can use immediately with a minimum of effort.

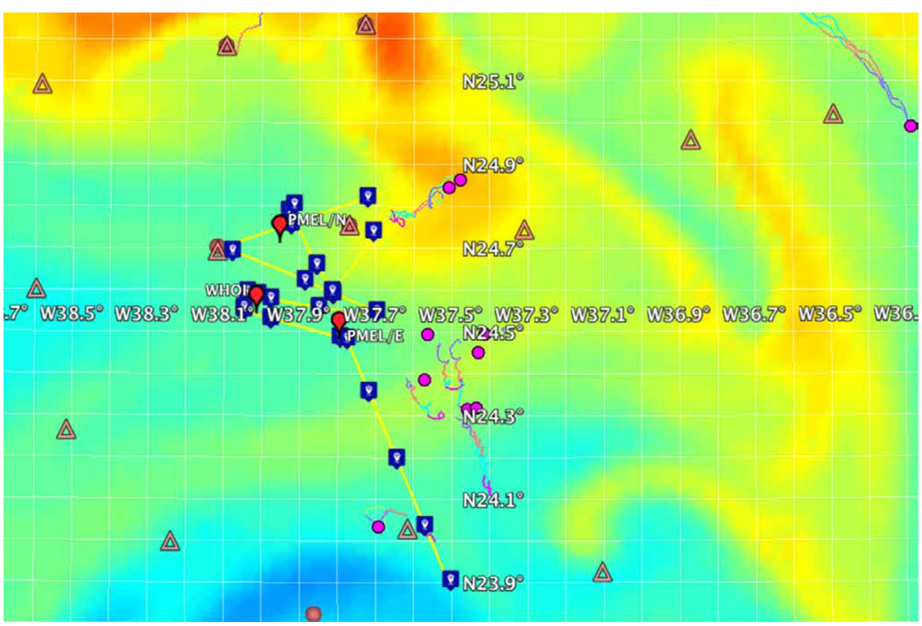

FIGURE 6. Screen capture of the Google Earth display available at sea for the same day as shown in Figure 4. The icons on the screen are observing assets as shown in the legend of Figure 4. The background color is the surface salinity from the Regional Ocean Modeling System (ROMS).

THE DMS AND THE SPURS-1 MODELING GROUP

During SPURS-1, the modeling team produced daily oceanic analyses and forecasts out to three days using a multiscale data assimilation and forecasting system developed at the Jet Propulsion Laboratory (Li et al., 2008, 2013, 2014) and based on the ROMS model (Shchepetkin and McWilliams, 2005). The SPURS-1 observations were dense enough to resolve eddies down to several kilometers. Accordingly, the model has a resolution down to 1 km.

During SPURS-1, we learned that model information needs to be delivered in a useful format that falls within the extremely limited bandwidth available at sea but still includes information that can be effectively used. Based on interactions between the wet and dry teams during SPURS-1, we developed a strategy to deliver model output in three forms. First, the modeling team prepared a concise summary of the oceanic and atmospheric conditions in the region and a small number of figures to highlight eddies, salinity fronts, and other features (Figure 8). This summary was delivered to the chief scientist, the program manager, and other wet team researchers through e-mail. Second, we prepared a netCDF file extracted from the model analysis and forecast system that could be grabbed by DMS personnel on the ship and the wet team. This netCDF file allowed those at sea to make quick quantitative analyses and comparisons with available measurements. Third, we made accessible KML files from the GE-based visualization with the same information that was available through the website (e.g., Figures 3, 4, and 5). These files could also be obtained by ftp. The KML files allowed the wet team to examine salinity features at a variety of spatial scales and keep track of the observing array.

In parallel with delivering model information to the wet team, the SPURS-DMS group directly supported SPURS modeling PIs by providing preliminary quality-controlled measurements converted from the original formats used by those collecting the data to one that could be ingested by ROMS. SPURS measurements were used by the modeling team for real-time monitoring of model performance and for assimilation into the ROMS model to constrain model forecasts. The data processing done by the SPURS-DMS team was a key step for implementing real-time data assimilation and forecasting. Many of the different types of SPURS-1 measurements have been assimilated.

SUMMARY, IMPACTS, LESSONS LEARNED, AND FUTURE PLANS

We learned many lessons from SPURS-1 and generated ideas that can be incorporated into management of future field campaigns, including the upcoming SPURS Pacific Field Campaign (SPURS-2). We describe a few of those lessons here.

1. **We need to further facilitate collaboration.** The SPURS-DMS was set up to facilitate data sharing and collaboration among SPURS PIs. Further, all SPURS PIs shared their data willingly and enthusiastically. We developed an array of collaboration tools, produced a variety of maps, and prepared a set of files on a daily basis. These products were not as heavily used as we would have liked—perhaps not surprising—primarily because of tight scheduling; the physical demands of deploying, monitoring, and/or operating the observing platforms; and disparate objectives of different groups of PIs. Thus, it continues to be a great challenge to coordinate and implement collective and adaptive sampling in response to observed or model-predicted features. However, during SPURS-1, there were two successful "feature-chasing" endeavors. During the *Knorr* cruise, model prediction of a high-salinity eddy successfully guided sampling (see Figure 6). During the second cruise period, a fresh intrusion from the south was sampled, again based on guidance from the model (Busecke, et al., 2014).

A suite of SPURS in situ measurements and a variety of satellite data, along with fine-resolution model data, forecasts, and diagnostics, made up an overwhelming flood of information that was passed along to the wet team PIs during the SPURS-1 cruises. They

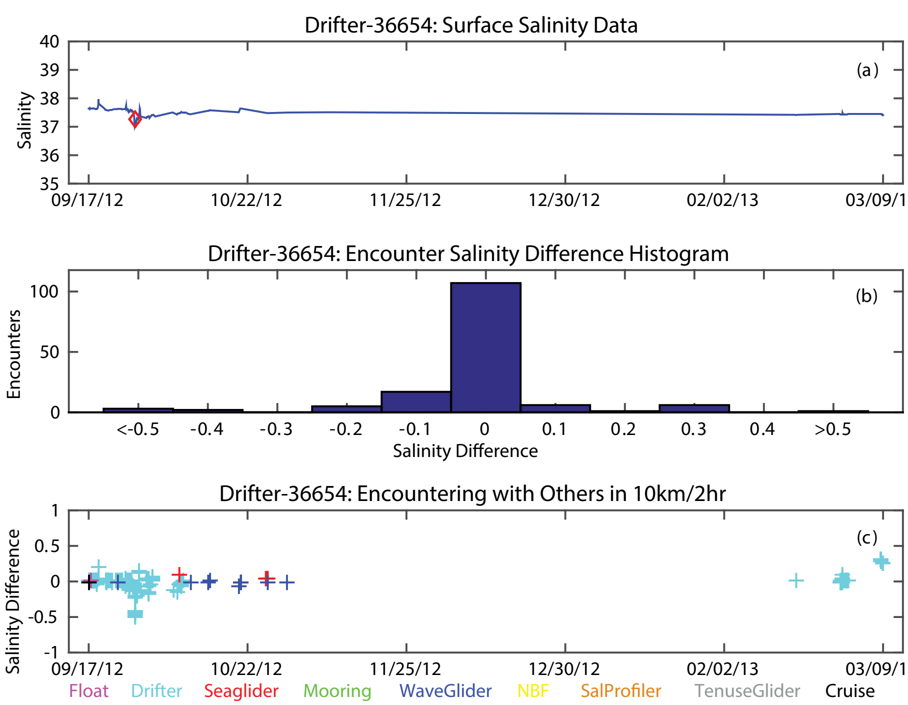

FIGURE 7. Intercomparison analysis for a SPURS salinity drifter. See text for details.

often found the information difficult to use and sometimes ignored or even misinterpreted it. How to present the information accurately, concisely, and usefully needs careful thought.

2. **Synergy of modeling and data management should be enhanced.** Ocean modeling and data assimilation have advanced during the past two decades, and thus have been extensively used in field campaigns. During SPURS-1, the ROMS data assimilation analysis and forecasting system provided forecasts of salinity extreme values, filaments, and eddies with encouraging skill (Figure 8). However, model results are not useful to PIs in the field without their being presented in a form that can be used for decision making. The inclusion of uncertainties is of particular importance.

   As detailed above, real-time data were assimilated into the ROMS model as they came in, and model output was fed to data management personnel at sea to help guide the field program. Thus, close integration of these two aspects is very important.

3. **Visualization system reliability should be improved.** The DMS has been developed with a large suite of functionalities. It collects, processes, and visualizes an amazing range of data in real time (Figures 4 and 5). If it breaks down due to hardware or software issues, recovery of the system is time and labor intensive. The reliability of the system is a concern.

   During SPURS-1, we used three methods to make the system ran smoothly. First, we had two systems: an operational system and a development and backup system. Second, a program was running constantly to automatically check system status and alert the DMS team of any problems. And third was eyeball checking. However, the system went down a couple times after the field campaign without our realizing it and despite the monitoring program. This technical and management issue requires attention.

   The reliability of the visualization of observations is challenging. This challenge arises from the fact that there are a lot of parts to it. We need to think about how long it will last after the ships have returned to port and the drifters have drifted away. For SPURS-2, we plan to make the system available after the field campaign in the form of KML files that interested users can open with GE and manipulate on their own time.

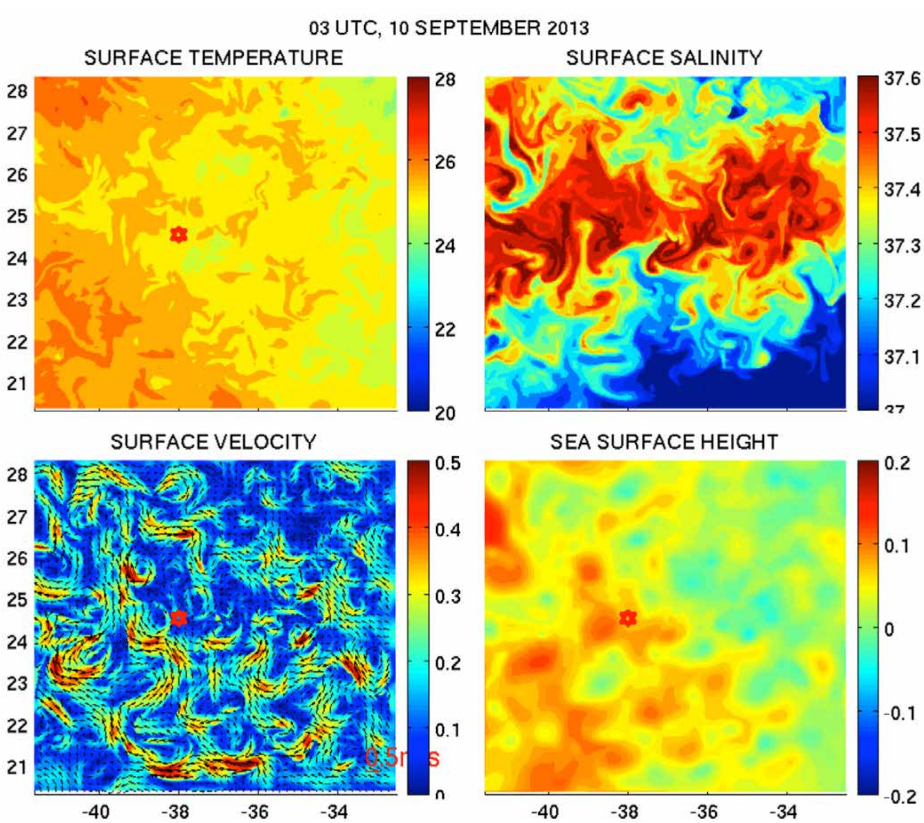

FIGURE 8. Forty-eight-hour forecasts from the real-time SPURS data assimilation and forecasting system, valid at 03 UTC, September 10, 2013. The red star indicates the location of the SPURS-1 central mooring (the "WHOI" mooring in Figures 3, 4, and 6).

4. **Continuation of data flow must be accommodated.** We are still getting updated versions of key SPURS-1 data sets. They will be incorporated into the archive over time in cooperation with PO.DAAC and NODC. We will also continue to post peer-reviewed papers and presentations to create a SPURS-1 bibliography. The intellectual capital that is derived from the data collection is just as valuable as the data themselves.

5. **Data quality evaluation should be more accessible.** Data management for a program like SPURS is a natural place to incorporate evaluation of data quality. We detailed some of our data quality work above (Figure 7). For SPURS-2, we are planning to make data quality assessments more accessible. In fact, we have plans to create a real-time instrument dashboard, with a display for each platform much like that shown in Figure 7. The dashboard would help PIs and program managers keep track of how their instruments are doing and isolate problems quickly.

Oceanographic field programs today require forethought about how the information they produce will be managed. Information includes not only bits of data streaming from field instruments but also model output and satellite data, peer-reviewed papers, gray-literature reports and presentations, internal e-mail, and public communications such as blogs and social media. The tech world has produced powerful tools for collaboration and for sharing, visualizing, and organizing data. These tools become all the more powerful when placed in the hands of people who understand the science as well.

Within the past couple of months, the SPURS-1 data have been turned over to PO.DAAC for long-term curation. Our hope is that researchers 10–20 years from now will go to the SPURS-1 archive page where they will be able to easily access the data collected, processed or unprocessed, get an idea of how the experiment was conceived and implemented, and see the important results that came out of it. Using software like Google Earth, they will be able to replay the paths of the various instrument platforms through space and search for the data that interest them. The archive will include model results from the current generation of ROMS. It is likely that a decade or two from now, ocean models will be much more sophisticated and skillful than they are today, and that the SPURS-1 data will make a good platform for testing them. Whether we have succeeded will not be known until then.

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