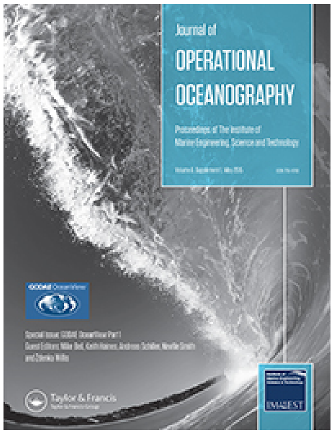

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Coastal Ocean Forecasting: system integration and evaluation

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Coastal Ocean Forecasting: system integration and evaluation

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Recent advances in Coastal Ocean Forecasting Systems (COFS) are discussed. Emphasis is given to the integration of the observational and modeling components, each developed in the context of monitoring and forecasting in the coastal seas. These integrated systems must be linked to larger scale systems toward seamless data sets, nowcasts and forecasts (from the global ocean, through the continental shelf and to the nearshore regions). Emerging capabilities include: methods to optimize coastal/regional observational networks; and probabilistic approaches to address both science and applications related to COFS. International collaboration is essential to exchange best practices, achieve common frameworks and establish standards.

Introduction

Within GODAE OceanView [GOV; http://godae-oceanview.org], the international Coastal Ocean and Shelf Seas Task Team (COSS-TT) aims to consolidate the foundation and support the advancement of coastal ocean forecasting science, systems, and applications. The main goal and central mission of the COSS-TT is to work within GOV, and in coordination with the Global Ocean Observing System (GOOS), towards the *provision of a sound scientific basis for sustainable multi-disciplinary downscaling and forecasting activities in the world's coastal oceans*. The initiative is built around three key concepts: 'international', 'scientific', and 'sustainable' and is driven both by science and through the promotion of good practices. These drivers emerge and advance through the international coordination of a broad range of scientific approaches and applications examined within individual Coastal Ocean Forecasting Systems (COFS).

The COSS-TT has initiated the consolidation of a broad coastal scientific community around the main disciplines of physics and interactions between physical and biogeochemical processes. The strategic goal is to help achieve a truly seamless framework from the global to the coastal/littoral scale. *Coastal ocean* is defined inclusive of nearshore and shelf regions, and of the adjacent deep ocean part that triggers or is influenced by shelf and shelf break processes (Robinson et al. 2004). It is recognized that the influence of coastal ocean processes is felt far beyond the shelf break, thus interacting with open ocean dynamics and controlling the connectivity of remote ecosystems. The innovative approach that this international activity advocates and oversees is that forecasting in the coastal and shelf seas must fully address land-sea, air-sea, and coastal-offshore interactions.

The goal of this paper is to showcase methodologies integrating observations and models in coastal areas, in synergy with larger scale observatories and modeling systems, in support of coastal ocean forecasting. The next section discusses recent advances and future challenges in coastal observational networks and models, employing examples of integrated systems over diverse coastal environments around the world and discussing methods to optimize array design. Then, emerging statistical approaches are introduced that also deal with forecast uncertainty. Conclusions synthesize international initiatives and future strategies. A more detailed discussion on specific scientific topics in support of coastal ocean forecasting and on COFS applications can be found in a companion paper (Kourafalou et al. 2015).

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Integrated coastal ocean forecasting systems (COFS)

COFS combine comprehensive observational networks and appropriate modeling systems to ensure the continuous monitoring of changes in the coastal ocean and support forecasting activities that can deliver useful and reliable ocean services. Oceanographic information, integrated with predictive models, is increasingly needed to: sustainably manage coastal and ocean areas; portray the ocean state today, next week and for the next decade; increase shipping efficiency; mitigate storm damage and flooding of coastal areas; sustain fisheries and fish stocks; protect important ecosystems from degradation; help decision-making in times of crisis; and improve climate forecasting in response to global change, among other direct applications.

Coastal ocean monitoring

To achieve reliable model simulations and predictions, COFS require quality-controlled data, either archived or real-time, on a routine basis. The data are used to: identify the important processes in the study area set-up the appropriate numerical models validate model simulations and assess their quality optionally carry out data assimilation, toward enhanced predictive skill or to perform reanalyses.

Although such needs are similar for large-scale ocean forecasting systems, there are distinct differences between coastal and global monitoring.

Specific aspects of coastal-ocean monitoring

There are several examples of how large-scale monitoring systems might not provide the types and/or attributes of data needed for COFS. For instance, present-day nadir satellite altimetry, instrumental in ocean forecasting, providing real-time global coverage, does not fully resolve all important coastal-ocean scales. Data from profiling floats are often not available in the shelf seas. Given the comparatively shorter space/time scales in coastal regions, the quasi-homogeneous sampling characteristics of open-ocean networks are often inadequate.

Coastal regions present the advantage that permanent, multivariate instrumented sites are easier to set up. *Coastal observatories* can thus employ various data sources. Regionally deployed technologies include telemetering moorings and fixed platforms, autonomous underwater vehicles (AUVs), Lagrangian drifters, profiling floats, and surface current measuring radar. These observatories complement global satellite observing networks by adding spatial and temporal resolution, or directly observing the subsurface ocean, which is critical to capturing density stratification that often exerts significant influence on coastal dynamics. They have gradually evolved to comprehensive *Coastal Ocean Observing Systems* (COOS), integrating a variety of data sources via networking. Data management is essential and usually covered at the national level. Examples are the Center for Operational Oceanographic Products and Services and the National Data Buoy Center in the US (under the National Atmospheric and Oceanic Administration, NOAA).

Although COOS have specific goals and features, they *cannot be considered as isolated from open ocean monitoring efforts*. Improving complementarity between coastal and open ocean observing systems can be beneficial: (a) COFS need validated boundary conditions; (b) open ocean forecasting systems need to be validated in the coastal ocean against local/regional data; (c) the benefit of coastal monitoring toward improvements in open ocean prediction (‘coastal signal upscaling’) has to be quantified; (d) downstream services and user uptake in the coastal ocean strongly depend upon the optimal functioning of coastal and larger-scale ocean forecasting systems, both validated against observations.

Advances in coastal ocean observing systems

International initiatives in science policy reflect the importance of coastal networks and observatories. For instance, the establishment of comprehensive COOS is being adopted as an important component of marine strategy by the European Commission and by most countries that are advanced in marine science research and with economically significant coastal areas (e.g. Committee on an Ocean Infrastructure Strategy for US Ocean Research in 2030, 2011) (European Commission 2010; European Commission, 2012; European Commission 2013). These new observatories, such as the Integrated Marine Observing System (IMOS, Australia), the US Integrated Ocean Observing System (IOOS) and the Ocean Observatories Initiative (OOI), St. Lawrence Observatory (Canada), Coastal Observing System for Northern and Arctic Seas (COSYNA, Germany), and POSEIDON System (Greece), are today discovering new insights for ocean variability. These discoveries will in turn trigger new theoretical developments, increase our understanding of coastal and near-shore processes and contribute toward a more science-based and sustainable management of the coastal ocean.

New approaches include multiplatform COOS (see next sub-section), which now allow us to characterize the coastal ocean in quasi-real time, both in terms of the ocean state and its variability at mesoscale and sub-mesoscale levels (Tintoré et al. 2013). The status of coastal observatories is expected to further advance through the integration with regional deep sea observatories or initiatives. Examples are JERICO (Joint European Research Infrastructure network for Coastal Observatories, [jerico-fp7.eu/]) and ESONET (European Sea floor Observatory NETwork). ESONET focuses on long-term multidisciplinary deep sea observatories around Europe, linking marine sensors to the shore by acoustic or cable connection in real or near-real time at relatively high frequency. This approach has been tried within the framework of the German COSYNA project (see next section), where cabled techniques have been implemented. Similar exchange of knowledge, tools, resources or personal support could enhance the durable operation of observatories and generate added products.

A multi-platform approach (Western Mediterranean example)

Studying complex coastal dynamics requires the implementation of synergistic approaches through the combined use of multi-platform observing systems able to resolve a wide range of spatial and temporal scales. Recent advances have been achieved in the Western Mediterranean Sea, where the circulation is characterized by the presence of multiple interacting scales, including basin, sub-basin scale, mesoscale and sub-mesoscale structures as well as coupled bio-physical processes and shelf-slope exchanges. SOCIB, the new Balearic Islands Coastal Ocean Observing and Forecasting System, is one such system, a new facility of facilities, open to international access (Tintoré et al. 2013).

There are several examples of value-added by such a multi-platform, multi-scale observatory. Positive insights concerning the use of autonomous underwater vehicles (gliders) in synergy with altimetry, in order to monitor dynamics in the Balearic Sea, have been provided (Ruiz et al. 2009). Innovative strategies have been developed to characterize horizontal ocean flows, specifically in terms of current velocity associated with filaments, eddies or shelf-slope flow modifications close to the coast (Bouffard et al. 2010). These methodologies were applied to a series of glider missions carried out almost simultaneously and well co-localized along the altimeter tracks. The value added by combining remote and *in-situ* sensors to validate, intercalibrate and improve observing data dedicated to coastal ocean studies has been shown (Pascual et al. 2010; Pascual et al. 2013). For instance, high-resolution hydrographic fields from gliders revealed the presence of permanent and non-permanent signals, such as relatively intense eddies, that were not correctly detected by standard altimeter fields. Qualitative and quantitative comparisons with drifters, glider, and satellite sea surface temperature (SST) observations reveal that when the new altimetry products are used, a better agreement is obtained (Escudier et al. 2013).

Figure 1 shows an example from the French-Indian SARAL/Altika mission with gliders along a selected track in the Western Mediterranean close to Ibiza Island, where the SOCIB High Frequency (HF)-radar facility provides hourly surface current velocities. Surface drifters were also deployed in the studied region. The glider mission (2-5 August 2013) and the passage of the satellite along the selected track were almost simultaneous. Comparisons (Figure 1) reveal a reasonable agreement between all platforms (drifter, along-track SARAL/AltiKa and HF-radar). The gradient of dynamic height measured by the glider was only on the order of 2-3 cm, but indicated the presence of a coherent meander with maximum associated velocities of about 20 cm/s. SARAL/AltiKa records (using 40 Hz along-track near real-time data) also captured the meander, with consistent size, amplitude and position compared to glider observations. SARAL/AltiKa was actually able to capture the northern edge of the meander, which lies on a shallow bathymetry less than 10 km from the coast. The combination of satellite altimetry with independent *in-situ* data has thus demonstrated benefits for improving knowledge on coastal and mesoscale dynamics.

Coastal ocean forecasting

Examples of coastal forecasting systems

An inventory of forecasting systems around the coasts of all continents is being kept and updated, to increase coherence between research developments within the framework of COSS-TT (see Systems Information Table, SIT, under [https://www.godae-oceanview.org/science/task-teams/coastal-ocean-and-shelf-seas-tt/]). This inventory includes: short description of COFS; their geographical domains, objectives and system status; generated products (hindcasts or forecasts and frequency of availability); data used for assessment and quality control methods. The SIT also describes different applications, including Coastal Eutrophication and Hypoxia, Human Exposure to Waterborne Pathogens or Radiation, Harmful Algal Blooms, Habitat Loss and Modification, Vulnerability to Coastal Flooding, Ocean Acidification and Food Security. Many systems share methodologies dictated by science drivers and user needs. These two topics are discussed in detail in a companion paper (Kourafalou et al. 2015). Here, a few examples are showcased, chosen as representative cases that highlight characteristic aspects, while offering some geographical diversity. Certain systems employ coupling capabilities with atmospheric and biogeochemical components; see further discussion on coastal coupled models and ecosystem modeling in the companion paper (Kourafalou et al. 2015). Partial information on a few system examples extracted from SIT is given in Table 1.

Example 1: A multi-nested modeling approach (China)

The Chinese Global operational Oceanography Forecasting System (CGOFS, [http://www.nmefc.gov.cn/cgofs_en/index.aspx]) has been recently developed by China's National Marine Environmental Forecasting Center (NMEFC). As a part of the CGOFS, the Yellow Sea and

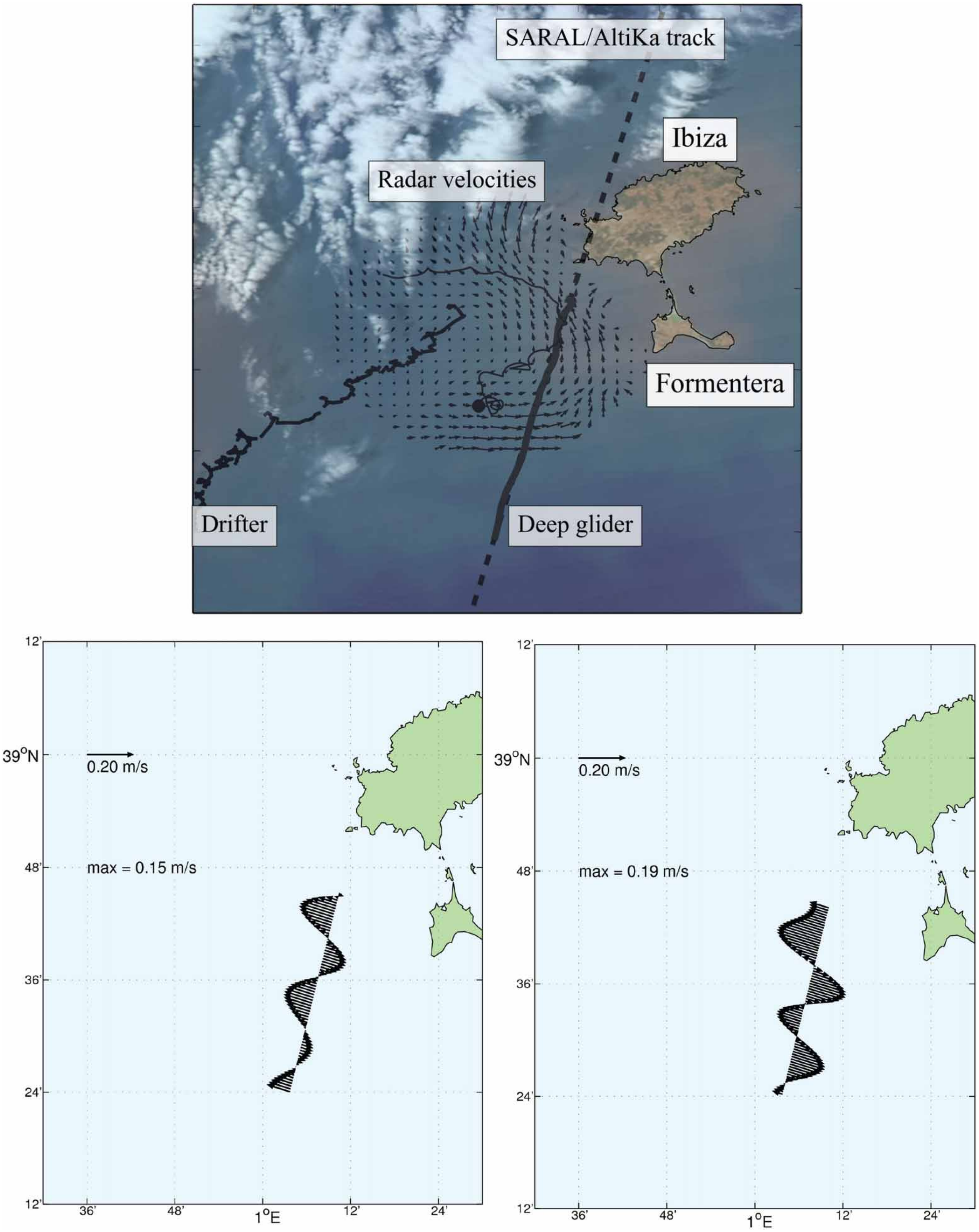


Figure 1. (Top): G-ALTIKA multi-platform experiment in the Ibiza Channel (Western Mediterranean): glider mission definition and drifter trajectories. The vectors correspond to the surface currents derived from SOCIB HF radar (*Courtesy: C. Troupin, IMEDEA, CSIC-UIB*). (Bottom): Across track surface geostrophic velocity obtained during the G-ALTIKA experiment: (Left) SARAL/AltiKa data (filtered 40 Hz SLA + SMDT-MED-2014) and (Right) glider data (Dynamic height computed with a reference level of 600 m).

the East China Sea operational oceanography forecasting system, CGOFS_ECS, has also been developed based on the Regional Ocean Modeling System (ROMS, http://myroms.org) at a horizontal resolution of ~3-5 km and 30 vertical layers (Shchepetkin & McWilliams 2005). The CGOFS_ECS model runs are separated into three

Table 1. Examples of systems (alphabetic order per Region) featured in the Systems Information Table maintained by the Coastal and Shelf Seas Task Team of GODAE/Oceanview. (Region I: Americas; Region II: Asia and Australia; Region III: Europe).

	Acronym	System Name	Country	Domain(s)
I	ESTOFS	Extratropical Surge and Tide Operational Forecast System	USA	US East, Gulf of Mexico and West Coasts, up to the Gulf of Alaska.
	FKeyS-HYCOM	Florida Straits, South Florida and Keys Hybrid Coordinate Ocean Model	USA	Florida Straits and the South Florida coastal and shelf areas
	NWPS	Nearshore Wave Prediction System	USA	Coastal Waters of all US territories
	NYHOPS	New York Harbor Observing and Prediction System	USA	Coastal waters of the Middle Atlantic Bight on the East Coast of the US (<200 m deep).
	OFS	Operational Forecast System	USA	All major estuaries and coastal systems of the US
	P-Surge	Probabilistic Surge	USA	Coastal and overland areas of all US territories
	REMO	Oceanographic modelling and observation network	Brazil	Western Equatorial and South Atlantic Ocean
	SLGO	St. Lawrence Global Observatory	Canada	Gulf of St. Lawrence
	WCNRT	West Coast Near Real Time Data Assimilation System	USA	West US Coast, California Current System
II	CGOFS	Chinese Global operational Oceanography Forecasting System	China	Global and Regional seas around China
	ESROM_MOM	Regional ocean modelling system	South Korea	East Sea (Japan Sea)
	eReefs	eReefs Marine Modelling	Australia	Australian coastal margins
	MOVE/MRI	MRI Multivariate Ocean Variational Estimation System / MRI Community Ocean Model	Japan	Global, North Pacific, Western North Pacific, Coastal region around Japan
	YS_ROMS	Korea operational oceanography system	South Korea	Yellow Sea and East China Sea
III	AFS	Adriatic Forecasting System	Italy	Adriatic Sea and Northern Ionian Sea
	COSYNA	Coastal Observation System for Northern and Arctic Seas	Germany	North Sea, German Bight, German Wadden Sea
	MFS	Mediterranean Ocean Forecasting System	Italy	Mediterranean Sea
	NEMO-FOAM	NEMO FOAM Operational Modelling	United Kingdom	European Northwest continental shelf
	POSEIDON	Regional monitoring and forecasting system	Greece	Aegean and Mediterranean Seas
	PREVIMER	PREVIMer Coastal observations and forecasts	France	Bay of Biscay / English Channel / Northwestern Mediterranean Sea

parts: (a) 10 years climatology run for spin-up; (b) 2000-2012 hindcast run; (c) forecast run (2013–present).

The climatology run is forced by monthly mean climatology wind stresses, net fresh water fluxes, surface heat fluxes from COADS (Diaz et al. 2002). Fields for open boundary conditions are from the monthly mean climatology Simple Ocean Data Assimilation (SODA) datasets (Carton & Giese 2008). Initialized from this run, the hindcast simulation is forced by the 6-hourly forecasted products from NOAA's National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010). Open boundary conditions are derived from the monthly mean of each year of the SODA datasets and are complemented by harmonic constants of 10 tidal constituents extracted from the Oregon State University Tidal Data Inversion [http://volkov.oce.orst.edu/tides/] (Egbert & Erofeeva 2002). Monthly mean climatology discharges of the Yangtze River are included. Buoy floats in the model domain are used for hindcast evaluation.

For the forecast run, the model started from the hindcast run on January 1st, 2013, and was forced by the NMFEC atmosphere forecasting system based on the WRF model (Weather Research and Forecasting) (Skamarock et al. 2005). CGOFS_ECS runs daily for 6 days (1-day nowcast and 5-days forecast). Daily updated 120-hour forecasting products (see examples on Figure 2) are used for: open boundary conditions for high resolution coastal ocean models (forecasting oil spill or red/green tide, marine search and rescue); navigation, fisheries management, marine environmental protection.

Example 2: Data assimilative coastal modeling (Japan)

The Meteorological Research Institute (MRI) of Japan Meteorological Agency (JMA) has been developing the MOVE/MRI.COM-Seto coastal monitoring and forecasting system, consisting of a fine-resolution (2 km) coastal model and an eddy-resolving (10 km) data-assimilative model. The coastal model (50 vertical layers) is based on the MRI Community Ocean Model (MRI.COM) and is one-way nested into the Western North Pacific (WNP) model (Tsujino et al. 2011). Four-dimensional variational

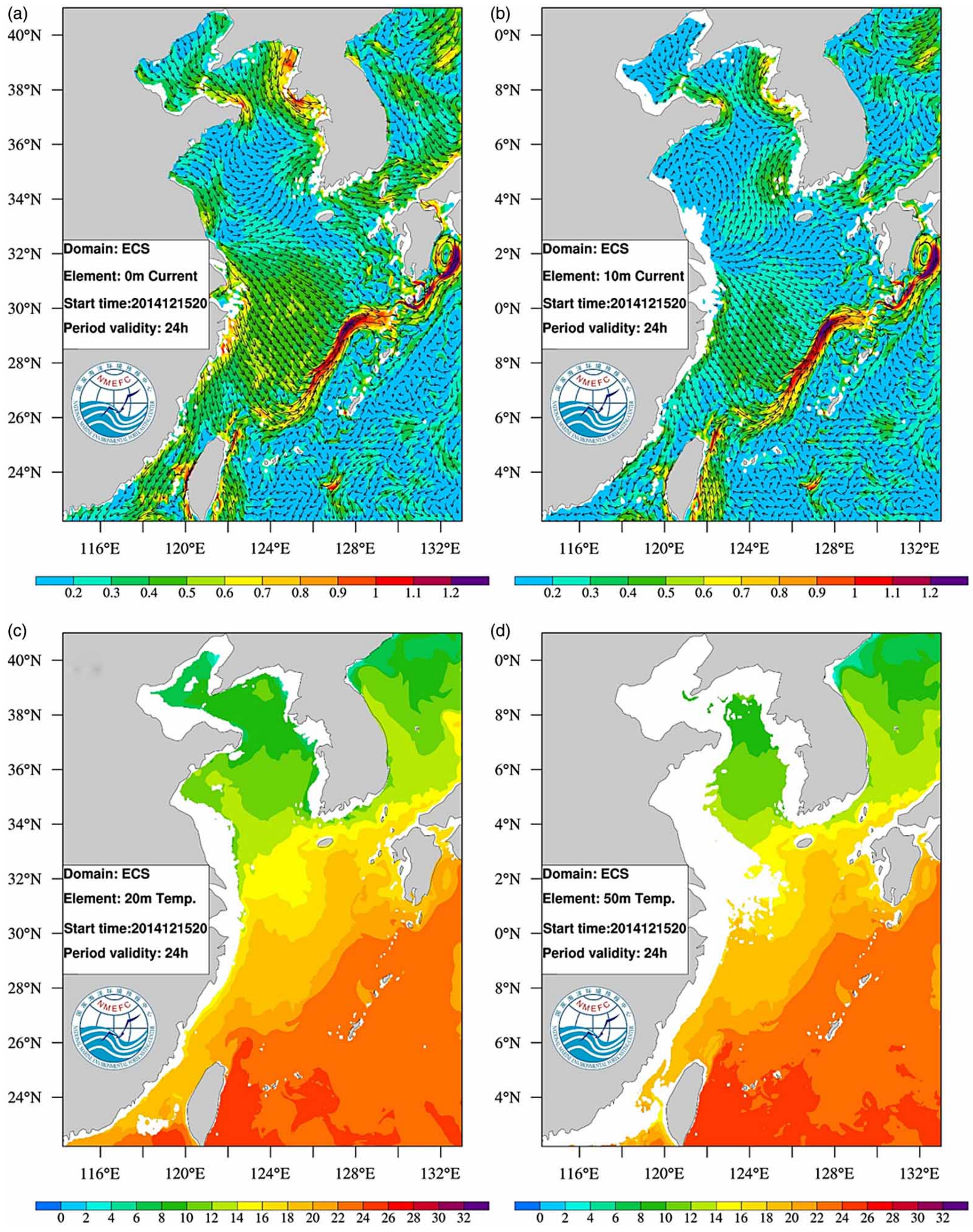


Figure 2. 24-hour forecast products of the CGOFS_ECS system on December 22, 2013. (a) Currents at the surface; (b) Currents at the 10 m layer; (c) Temperature at the 20 m layer; (d) Temperature at the 50 m layer.

(4DVAR) data assimilation is applied to WNP, based on a 4DVAR version of the MRI Multivariate Ocean Variational Estimation system (MOVE-4DVAR). The coastal model is initialized using the 4DVAR analysis fields of the WNP through incremental analysis updates after interpolation to the finer grid (Bloom et al. 1996).The one-way nesting technique is adopted in MOVE/MRI.COM-Seto. The coastal model is driven by 3-hourly atmospheric conditions (from the JMA atmospheric operational Meso-Scale Model, MSM) and 6-hourly radiative heat fluxes (from the Global Spectral Model, GSM).

MOVE/MRI.COM-Seto will be operated at JMA and will be mainly used for its warning system around the coastal region and possibly for fisheries, ship navigation, and marine leisure. There is also collaboration with Japan Aerospace Exploration Agency (JAXA), planning a new altimeter mission (Coastal and Ocean measurement Mission with Precise and Innovative Radar Altimeter, COMPIRA). COMPIRA will carry a wide-swath altimeter (Synthetic Aperture Radar Height Imaging Oceanic Sensor with Advanced Interferometry, SHIOSAI). To develop high accuracy COMPIRA coastal and open ocean products, JAXA has launched the 'COMPIRA coastal forecast core team'. In this framework, Observing System Simulation Experiments (OSSEs; see also next section) will be performed to evaluate the effectiveness of the new satellite data and the feasibility of developing high accuracy products using data assimilation schemes for coastal regions.

Example 3: Resolving intra-tidal cycles (Germany)

The Coastal Observing SYstem for Northern and Arctic Seas [COSYNA; http://www.hzg.de/institute/coastal_research/cosyna/] has been deployed in the German Bight, integrating near real-time measurements with numerical models and providing continuous coastal ocean state estimates and forecasts. COSYNA, which is operated by the Institute of Coastal Research, Helmholtz Zentrum Geesthacht (HZG), shows many similarities with advanced coastal observatories in the US and Europe (e.g. Glenn & Schofield 2009; Proctor & Howarth 2008). It consists of observational nodes, a data management system and data assimilation capabilities, streamlined towards meeting the needs for high quality operational products in the German Bight. The individual *in-situ* observing subsystems used are: FerryBox, gliders, buoys and HF-radar. The forecasting suite includes nested 3D hydrodynamic models running in a data assimilation mode, forced with meteorological forecast data.

Unlike most systems assimilating HF-radar data, which are concerned with low-pass filtered surface velocity measurements, COSYNA focuses on intra-tidal scales, which can be justified by the need to a) develop a better knowledge on the short-term coastal ocean variability, and b) enhance quality of data needed for special coastal operations. The blending of data and models (see also next sub-section) uses a spatio-temporal optimal interpolation (STOI) which enables dynamically consistent smoother within an analysis window of one or two tidal cycles. This method maximizes the use of available observations, as a step towards 'best surface current estimate'. Patchy observations over part of the German Bight sampled every 20 mins from three WERA radars are used to prepare 6-hr and 12-hr forecasts. COSYNA modeling products also include regular maps of wind, waves, salinity, and temperature. The latter two are enhanced by the assimilation of FerryBox data (Stanev et al. 2011).

Example 4: National initiatives in coastal ocean forecasting (NOAA/USA)

Coastal wave and surge modeling systems typically make use of phase-averaged spectral wave models such as SWAN (Simulating Waves Nearshore), and increasingly WAVEWATCH III, coupled to varying degrees with circulation models such as SLOSH, ADCIRC, FVCOM (Finite Volume Coastal Ocean Model) and SELFE (Semiimplicit Eulerian-Lagrangian Finite-Element), typically run in two-dimensional, depth-integrated mode (Booij et al. 1999; Tolman et al. 2002; Jelesnianski et al. 1992; Luettich et al. 1992; Chen et al. 2003; Zhang & Baptista 2008). The US federal agency that oversees operational oceanic prediction (NOAA) has developed operational guidance systems where these models are currently run in uncoupled (or one-way coupled) mode: ADCIRC-based Extra-tropical Surge and Tide Operational Forecast System (ESTOFS), the SLOSH-based Probabilistic Hurricane Storm Surge (P-Surge) and the SWAN/WAVEWATCH III-based Nearshore Wave Prediction System (NWPS) (Feyen et al. 2013; Taylor & Glahn 2008; Van der Westhuysen et al. 2013). In these systems, aspects of physical phenomena are shared between models (e.g. ESTOFS and P-Surge water levels are included in the NWPS wave model, see Figure 3), but there is no process feedback. An example of a fully-coupled wave-surge system is the ADICRC and SWAN-based ADCIRC Surge Guidance System (ASGS). Here the surge model transfers water levels and depth-integrated currents to the wave model, which, in turn, transfers wave radiation stresses and enhanced bed friction to the surge model.

Coastal three-dimensional baroclinic circulation modeling systems are designed to provide guidance on water levels, currents, salinity and temperature. Examples of such systems are NOAA's national network of Operational Nowcast and Forecast Hydrodynamic Model Systems (called OFS). An OFS consists of the automated integration of observing system data streams, hydrodynamic model predictions, product dissemination and continuous quality-control monitoring. Within these systems, hydrodynamic models such as ROMS, FVCOM and SELFE are driven by real-time data and meteorological, oceanographic, and/or river flow rate forecasts, receiving boundary conditions at the coastal shelf from NOAA's Global-RTOFS (Real-Time Ocean Forecast System), based on HYCOM [HYbrid Coordinate Ocean Model, http://hycom.org] (Chassignet et al. 2007).

To promote the next generation of operational forecasting, NOAA's Integrated Ocean Observing System [IOOS;

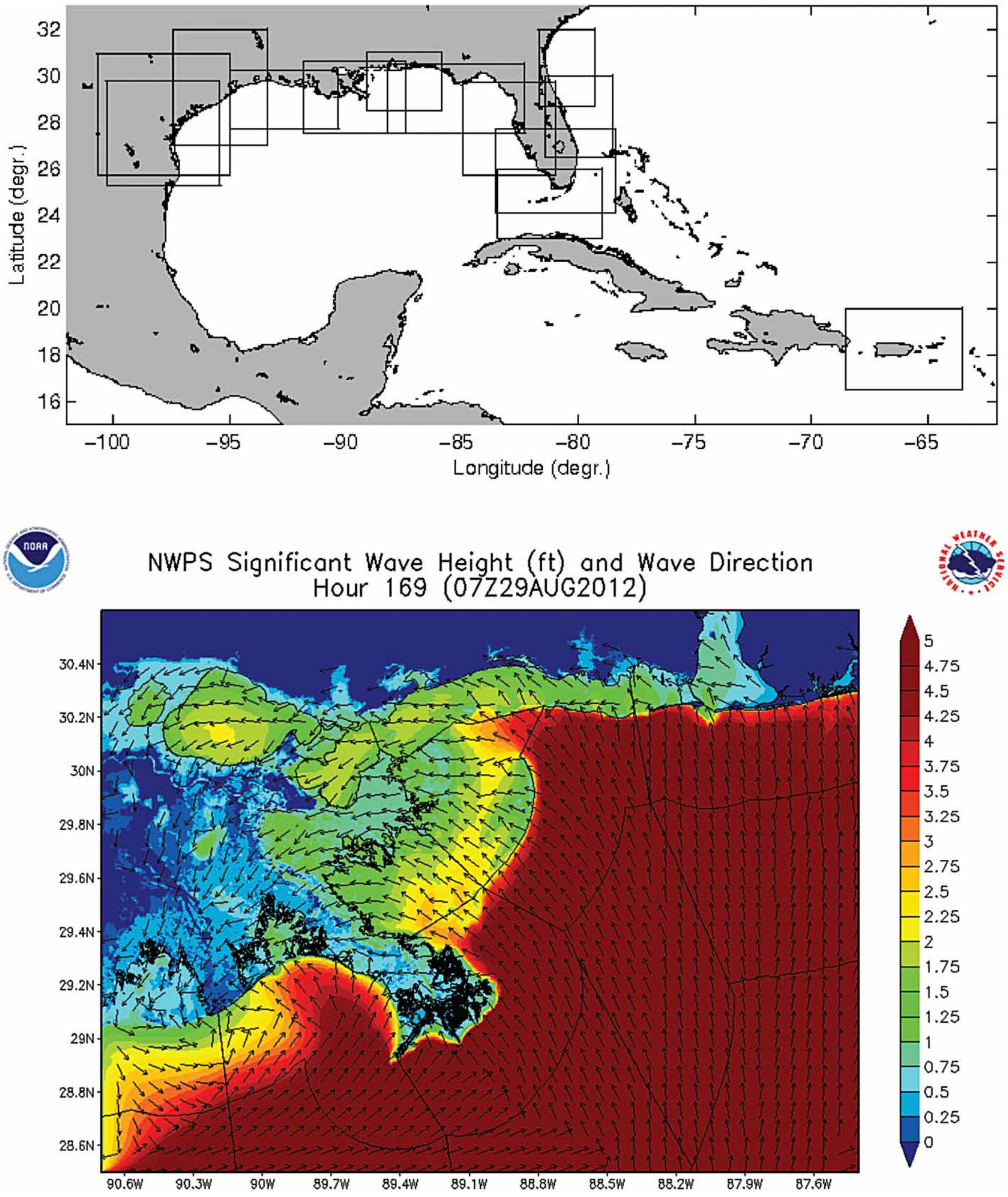


Figure 3. Implementations of the Nearshore Wave Prediction System over the US Gulf Coast (rectangles, top), and results over the domain of the New Orleans Weather Forecast Office, including probabilistic surge levels from NOAA's P-Surge.

http://www.ioos.noaa.gov/] has established eleven Regional Associations that form a national network of Regional Coastal Ocean Observing Systems (RCOOS). These state-of-the-art observational and complimentary modeling activities are supported by consortia of federal, state, academic and commercial partners.

Example 5: A coupled coastal system (USA)

This example is based on one of the RCOOS mentioned above, namely the Southeast Coastal Ocean Observing Regional Association (SECOORA). An integrated high-resolution, three-dimensional, coupled (ocean-atmosphere-wave) Nowcast/Forecast system has been developed for the Northwest Atlantic Ocean by North Carolina State University (NCSU). Covering the entire US east coastal ocean, the Gulf of Mexico and Caribbean Sea, the system is implemented based on the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al. 2010). COAWST couples ROMS, WRF and SWAN models representing the ocean, atmosphere, and wave environments. ROMS/SWAN is spatially collocated with the WRF domain (7-10 km grid, fine enough to resolve atmospheric forcing from tropical cyclones) (Halliwell et al. 2011). Boundary and initial conditions are provided by the global HYCOM.

These three models were coupled using the Model Coupling Toolkit (MCT), resulting in a COFS that exhibits several advantages over global forecasting systems (Larson et al. 2004; Jacob et al. 2005). These include: (a) finer resolutions in both horizontal and vertical directions that can better resolve regional and coastal processes (Hurlburt & Hogan 2000); (b) fully coupled model physics that include the interactions/feedbacks among ocean circulation, marine meteorology, and ocean waves; (c) an improved representation of coastal/shelf dynamics (e.g. tides). The coupled system performs routine nowcast and 3-day forecast on daily basis [http://omgsrv1.meas.ncsu.edu:8080/ocean-circulation-useast2] with an example provided in Figure 4. Near-real time model predictions are validated against HF radar surface currents, NOAA sea level data and buoy measurements. Interactive functions include: visualizations of user defined virtual station profiles or hydrographic transects and 72-hour surface trajectory 'virtual particle' simulations.

Example 6: From the ocean to the reef scale (Australia)

Reaching reliable model forecasts in fine coastal scales requires careful downscaling (see also Kourafalou et al. 2015). The eReefs project [http://www.emg.cmar.csiro.au/www/en/emg/projects/eReefs.html] is highlighted here as an example associated with a unique set of challenges (Schiller et al. 2014). This initiative aims to provide an information system, underpinned by models, for the iconic Great Barrier Reef (GBR) on Australia's north-east coast. The GBR is the longest stretch of coral reef in the world, one of the seven natural wonders of the world, a UNESCO world heritage site and home to abundant biodiversity. Reef cover has continued to decline over the last several decades, due to the effects of cumulative stresses, primarily nutrient loads from terrestrial runoff, Crown-of-Thorns Sea-star infestations and damage from tropical cyclones (Brodie & Waterhouse 2012). Some of

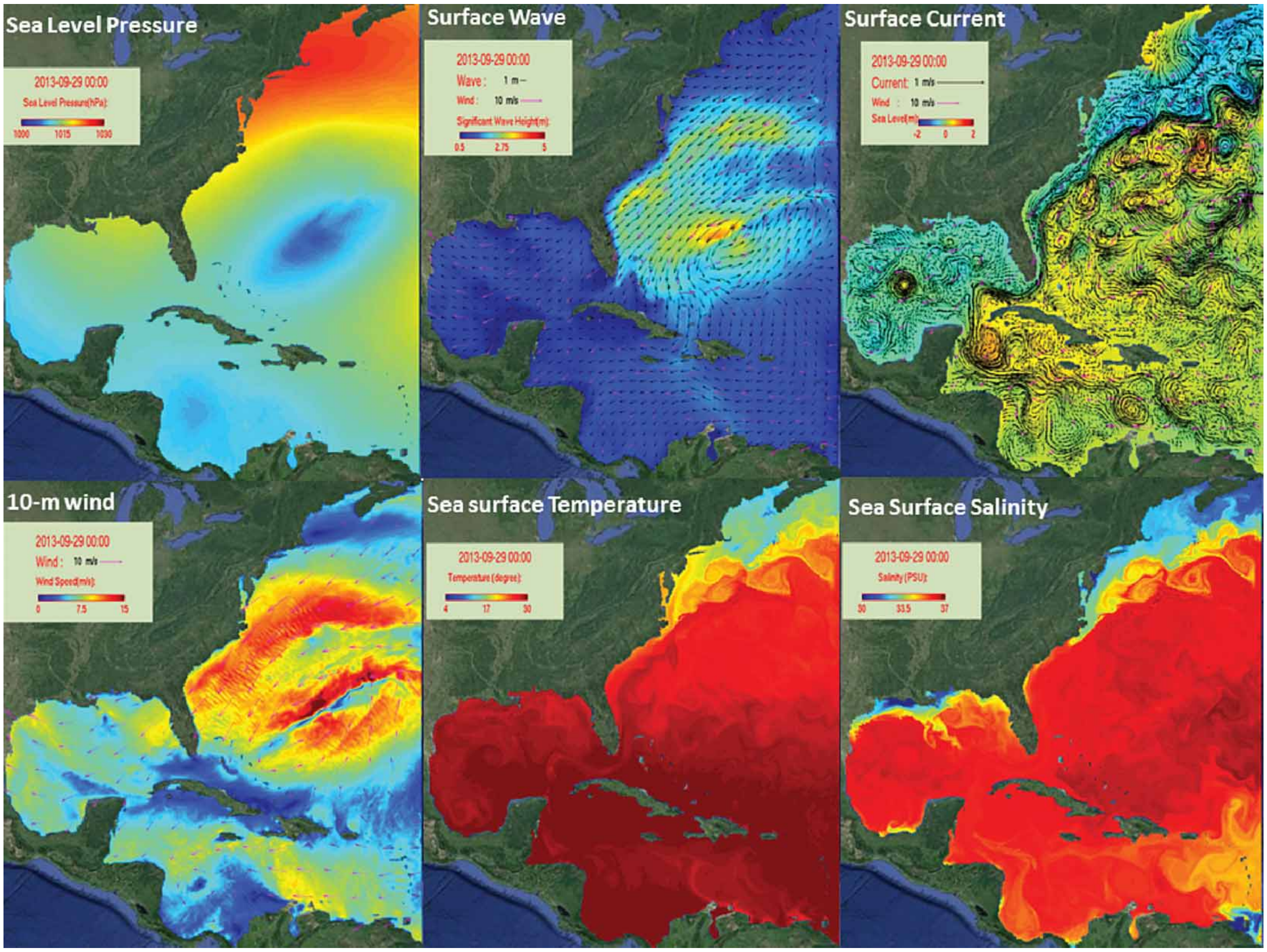


Figure 4. Concurrent snapshots of the coupled COAWST model simulated: (upper panels) sea level air pressure, surface wave height and directions, surface ocean velocity and sea level; (bottom panels) 10 m wind, sea surface temperature and sea surface salinity.

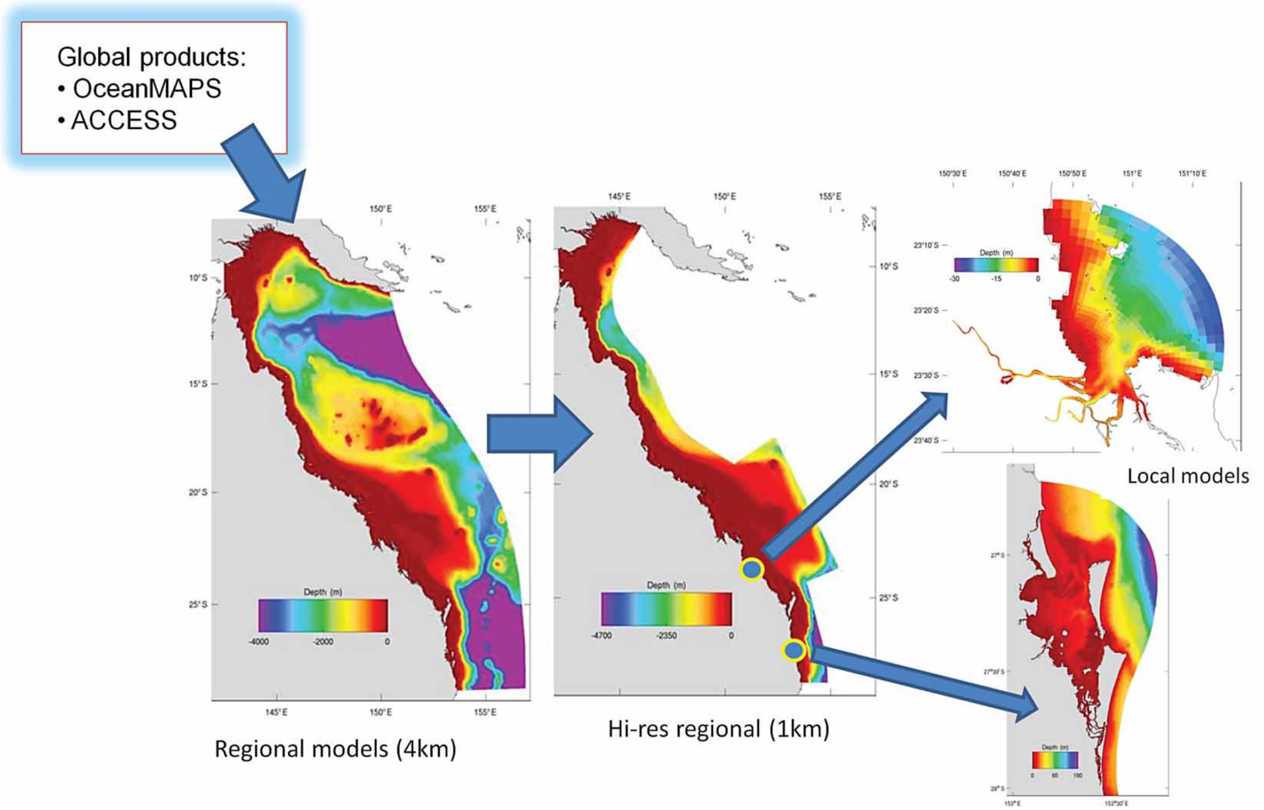


Figure 5. A nested approach to traverse scales (Greater Barrier Reef, color is bathymetry). The regional configurations span a portion of the Coral Sea between Papua New Guinea and Queensland, Australia. The local models cover the Fitzroy River estuary and Moreton Bay off Brisbane. This multi-nesting downscaling cascade achieves resolution at the local scale, while maintaining open boundary nesting ratios of less than 5:1 (2 regional nests at 4 km and 1 km, allowing local nests to go below boundary resolutions of ~200 m). Outer models are OceanMAPS (Oke et al. 2008) at 10 km resolution for the ocean initial and boundary conditions, and ACCESS for surface fluxes [http://www.bom.gov.au/nwp/doc/access/NWPData.shtml].

these stresses can be mitigated by targeted management strategies (e.g. nutrient load input), whereas others cannot (e.g. extreme weather events). The eReefs system, therefore, aims to provide managers relevant information to assist in the development of informed mitigation strategies to improve reef health. Consequently, any models contributing to the overall modeling system must span scales (from the catchment, through estuaries, across the lagoon, over the reef matrix and across the shelf to the deep ocean) and disciplines (catchment modeling, hydrodynamics, waves, sediment transport and biogeochemistry).

Nesting from the global to the reef scale requires several downscaling nests: eReefs (Figure 5) employs a 4 km 'bridging model' in global products and a 1 km regional model, with nested re-locatable models of estuaries/reefs (100s of meters) (Herzfeld 2009; Herzfeld et al. 2011; Herzfeld & Andrewartha 2012). The reef matrix can generate fine scale structure in the flow, which can feed back to the larger scale (Wolanski & Hamner 1988; Wolanski et al. 1996; Wolanski et al. 2003a; Wolanski et al. 2003b). To optimize runtime, complex curvilinear grids utilizing branching are employed to represent only areas of interest. Additionally, an unstructured coordinate system is utilized to 'house' state variable matrices within the model; this facilitates the representation of wet cells only in the state vector, which improves computational efficiency. Although the coordinate system is unstructured, the model is based on finite differences. The reef creates large topographic gradients, and individual reef lagoons are isolated from the surrounding waters by exposed fringing reefs at every tidal cycle (tidal range can be 6 m at the coast). Differential heating/evaporation can significantly modify water properties in these isolated lagoons, which feed back to the larger scale when the reef becomes wet again at high tide. These dynamics promote the use of a 'z' vertical coordinate system with true wetting and drying.

Model and data integration

The integration of the multiplatform observing and forecasting systems described previously is necessary to achieve a comprehensive description of the dynamics in the coastal ocean, where several phenomena are controlled by small-scale changes in time and space. Dynamical interpolation of data on the regional/coastal scale can play a key role in synthesizing the data derived information, toward monitoring and predicting variability from days/weeks to seasonal/decadal.

The past decade has witnessed the establishment of numerous regional coastal ocean observatories around the world. These have prototyped different approaches to coordinate multiple observing technologies for real-time coastal ocean monitoring, and support coastal forecasting. Examples include the US/NOAA Regional Associations under IOOS and the European Copernicus MyOcean project [http://MyOcean.eu], closely linked to products for decision-making to improve safety, enhance the economy, and protect the environment.

Initiatives to provide specialized data sets for COFS include the Group for High Resolution SST (GHRSTT). An example is given for the Great Barrier Reef (eReefs, described above) based on a 1-year simulation (Figure 6). There is a tendency for the model to underestimate the SST by between 0.5 and 1.0°C during the wet season (November - April). However, at the onset of the dry season, the bias reduces to <0.5°C and most of the values lie within the standard error of the GHRSST observations. Other efforts that are of particular utility for coastal ocean forecasting include Coastal Altimetry that is developing methods to expand the capabilities of standard altimetry products in the coastal areas (Cipollini et al. 2012).

A particular challenge is to combine observations and models in areas of strong coastal to offshore interactions. A range of appropriate scales needs to be satisfied, with

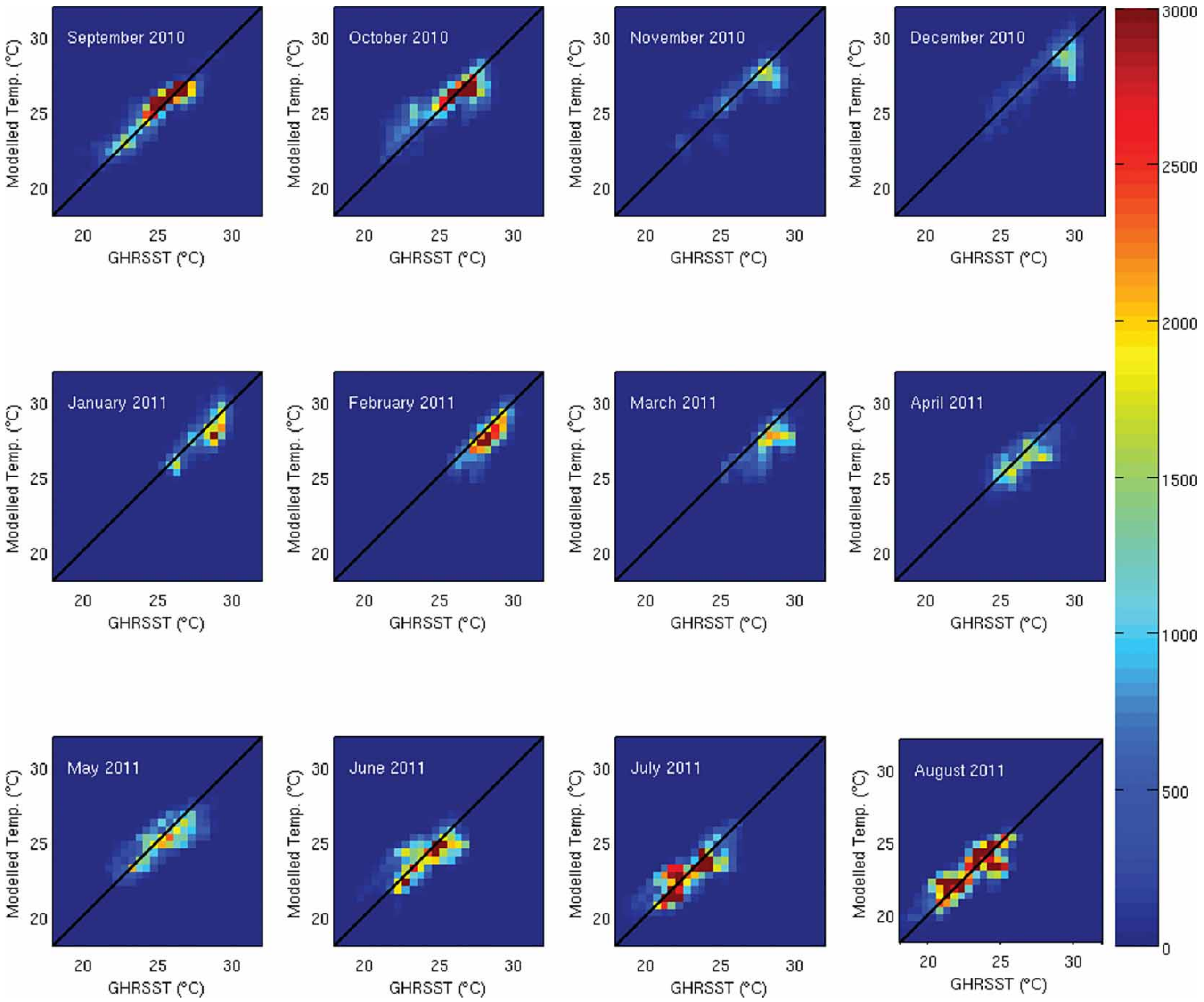
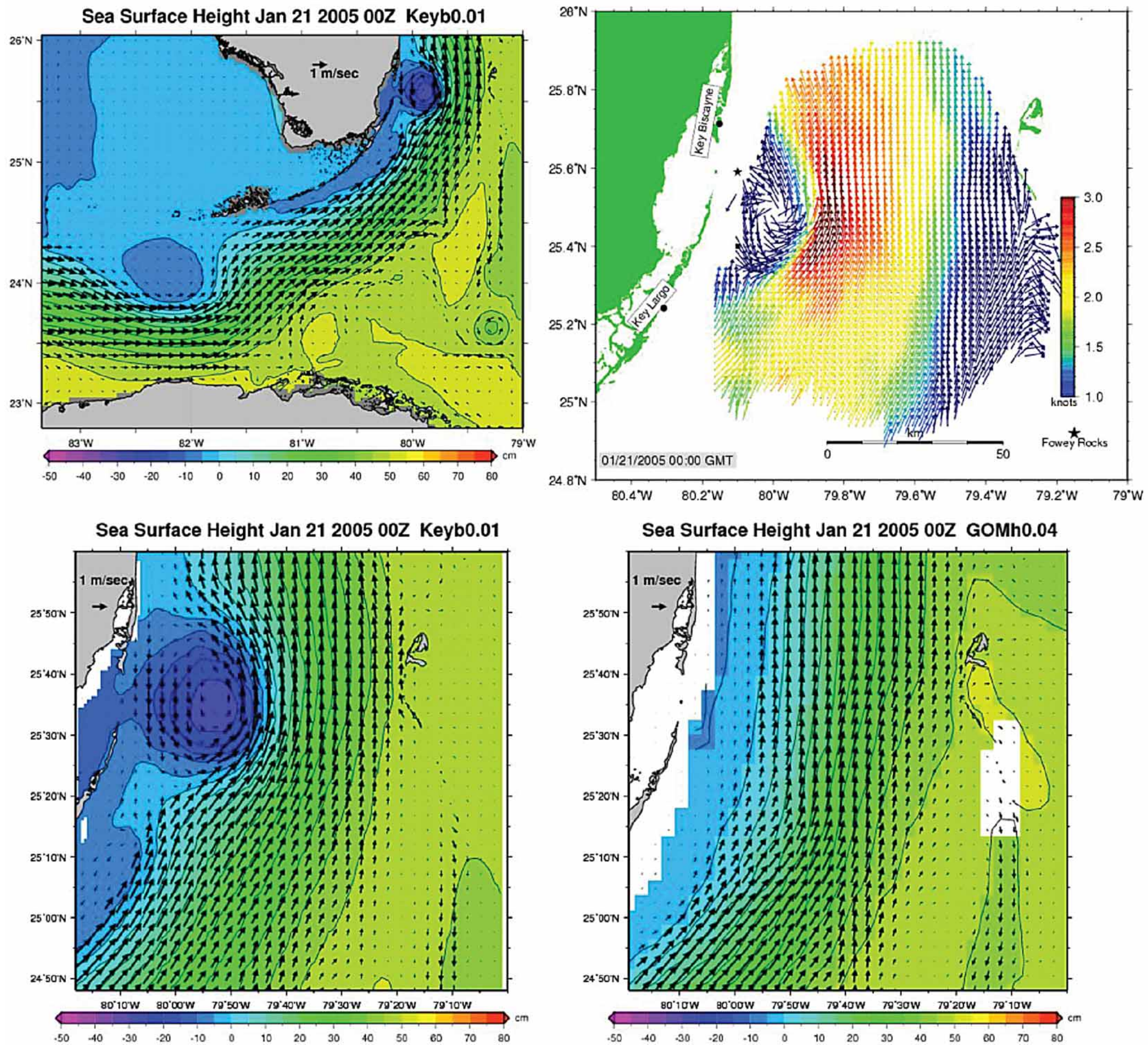


Figure 6. High resolution model to data monthly comparison for the Great Barrier Reef. Two-dimensional histogram of binned GHRSST data vs. model SST output during the period September 2010 - August 2011. Color denotes the number of observations (frequency) of a particular data/model combination. Dark red denotes the highest mass. The black line denotes the 1:1 relationship between the GHRSST data and model output. This analysis gives more insight than a typical scatter plot.


Sea Surface Height Jan 21 2005 00Z Keyb0.01

Sea Surface Height Jan 21 2005 00Z Keyb0.01

Sea Surface Height Jan 21 2005 00Z GOMh0.04

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Figure 7. (Top left): Sea Surface Height and near-surface current around South Florida and the Florida Straits from the FKEYS nested model (21 January 2005); the meandering of the Florida Current is depicted with two mesoscale cyclonic eddies (north of Cuba and east of the upper Florida Keys). (Top right): Observed surface currents from the WERA HF-radar (same date) showing the cyclonic eddy off the upper Florida Keys. Detail within the WERA covered area of the nested FKEYS model (bottom left) and the outer Gulf of Mexico regional model (bottom right); the regional model does not represent the observed eddy. Data from [http://iwave.rsmas.miami.edu/wera/]

models and data having complementary resolution in time and space. An example is given in Figure 7 for the impact of Florida Current meandering (a component of the Gulf Stream western boundary current system) on coastal flows along the South Florida coastal areas (which host the Florida Keys National Marine Sanctuary, the largest reef system in the continental US). As the Florida Current meanders between Florida and Cuba, cyclonic frontal eddies undergo synergistic changes that influence coastal flows, with implications on the reef ecosystem (Kourafalou & Kang 2012; Sponaugle et al. 2005). Two such eddies are evident in the fields predicted by the Florida Straits, South Florida and Florida Keys (FKEYS) HYCOM model, which is nested in the data-assimilative Gulf of Mexico (GoM) regional HYCOM model at a resolution of ~900 m, which is four times higher than the regional model and eight times higher than the global HYCOM model. Together with other attributes that enhance coastal performance, the location and eddy size in the FKEYS fields are in very good agreement with the observed cyclone in the upper Florida Keys, where a HF-radar (WERA) is maintained (data provided from [http://iwave.rsmas.miami.edu/wera/] and specific eddy event discussed in Parks et al. 2009). This is not the case for the regional model, which does not resolve this eddy and, therefore, misses the coastal southward flow along the Florida Keys reef system.

Land to sea interactions are another topic of particular importance in coastal forecasting, with challenges associated with both the monitoring of riverine discharges, as well as the correct representation of river plume dynamics and the resolution of the related buoyancy-driven flows (Schiller & Kourafalou 2010). When boundary currents interfere with the evolution of river plumes, additional complexities arise, presenting both monitoring and modeling challenges. An example is the interaction between the Mississippi River plume and the Loop Current (Gulf Stream system branch in the Gulf of Mexico), which depends on both coastal circulation and the complex, large scale boundary current and eddy field (Schiller et al. 2011). This process is not well represented in regional and global models, which are of coarser resolution and generally rely on relaxation to climatology for the salinity field, thus unable to replicate river plume observations as well as coastal models (Kourafalou & Androulidakis 2013).

Increasingly, model validation is being done within the context of standardized test beds such as NOAA's Joint Hurricane Testbed (JHT) and the Coastal and Ocean Modeling Testbed (COMT) (Rappaport et al. 2012; Luettich Jr et al. 2013). These make use of standardized metrics, test cases and advanced IT infrastructure for sharing and comparing model results. An emerging industry standard for coastal model validation is the Interactive Model Evaluation and Diagnostics System (IMEDS), developed with the support of the IOOS COMT (Devaliere & Hanson 2009). Evaluations of wind, wave and water level data can be made on large temporal and spatial scales to statistically reduce large volumes of model estimates to meaningful measures of prediction skill. A variety of time-series error metrics (such as root-mean-square error, bias, scatter index) are included. The system features three statistical approaches, namely Temporal Correlations (TC), Quantile-Quantile (QQ), and Peak Event (PE) analyses, representing industry benchmarks for operational model validation.

In addition to using observations for model evaluation, their direct insertion in models is achieved through data assimilation methods, which have to be specifically adapted for coastal systems (Kourafalou et al. 2015). Figure 8 presents an example of the impact of assimilating *in-situ* data from AUVs and ships of opportunity in the ROMS model with 4D variational data assimilation (4DVAR, Moore et al. 2011a) that is part of MARACOOS, the IOOS Regional Association for the Mid-Atlantic Bight (MAB). Figure 8(a) shows model-estimated temperature at the seafloor when only satellite SST and coastal-corrected along-track altimeter sea surface height (SSH) are assimilated. This pattern overestimates the extent of the MAB 'cold pool' (temperatures less than 11°C). Figure 8(b) is

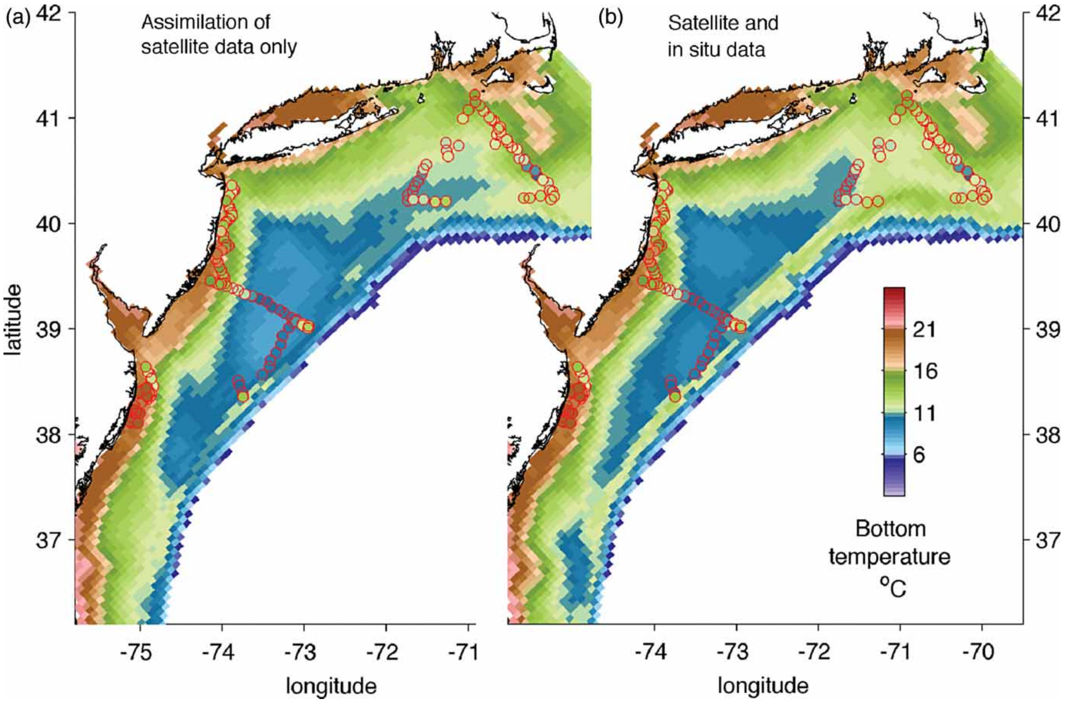

Figure 8. Bottom temperature on the Mid-Atlantic Bight shelf (in water depths < 1000 m) estimated by Rutgers University's near-real-time ROMS model with 4DVAR assimilation for 22 Sep 2013. (a) Analysis with assimilation of satellite data only. (b) Analysis with satellite data plus HF-radar surface currents and *in-situ* temperature and salinity from underwater profiling gliders. Red circles indicate bottom temperature observed by 4 gliders in the 15 days preceding the analysis time.

the corresponding analysis when MARACOOS glider bottom temperature data are added to the assimilation. As evident in Figure 8(b), *in-situ* data assimilation decreases the eastern extent of the cold pool and shows a filament of warm water at the shelf break that subsequently advects southwestward, beneath the shelf/slope front, in closer agreement to observations. The assimilated subsurface data were essential to overcome the limitation of remote sensing imagers, which miss the cold pool waters this time of the year (early fall), when surface temperatures are warm everywhere.

Array design methods

The optimization of observational networks is an important, cost effective, aspect of integrating data and models. Observation array design refers to numerical methods used to perform analyses of the performance of observation networks, with the purpose of evaluating existing arrays, testing alternate configurations, or estimating the impact of future deployments or instruments.

The most common approach for array design involves the use of data assimilation into a numerical model, in the framework known as Observing System Experiments (OSE), or Observing Systems Simulation Experiments (OSSE) (Oke et al. 2015). In OSEs, a set of data assimilation experiments is performed, using actual observations. The best simulation is the one into which all available observations are assimilated, achieving the largest error reduction with respect to a simulation in which no observation is assimilated. The performance of a specific observational array is then estimated by running an experiment in which all the observations are assimilated, except for the ones from the array under study. The change in error reduction between that latter experiment and the experiment in which all observations are assimilated allows quantifying the impact of that specific network. Although many studies based on OSEs have been performed to test the impact of various components of the global ocean observing system (see Oke et al. 2015), such work has started more recently for testing the impact of networks dedicated to the coastal ocean. For instance, the positive impact of ~3 months of glider observations, even after a few months, on the forecast of the Eastern Mediterranean Sea was demonstrated by Dobricic et al. (2010). More recently, an OSE took place in real time to show the benefit of adaptive sampling by sea gliders for constraining a model of the Ligurian Sea (Mourre & Alvarez 2012).

Other studies based on the assimilation of actual observations also focus on the impact of various observation networks or data type, without performing actual OSEs. This is especially the case of studies using 4DVAR data assimilation, which allows identifying the impact of a set of observations using the adjoint and tangent linear of the ocean model. A representer-based method was used to assess the improvement brought to a forecast model off Oregon by satellite observations of SST and altimetry, and by HF-radar observations (Bennett 2002; Kurapov et al. 2011; Yu et al. 2012). The sensitivity of simulated coastal current to different observation types or array setting was tested with a model of the California Current System, where a single 4DVAR simulation could be used to test the impact of various observation networks in a fashion similar to OSEs (Moore et al. 2011b).

OSSEs are based on the same principle as OSEs, except that the observations used during data assimilation are not true observations, but are sampled from a second, realistic simulation. This method avoids bias (which can compromise the results of OSEs) and allows testing instruments that do not exist yet, or testing alternate deployment strategies. Several studies using the OSSE framework have been performed to test the impact of various observing networks or deployment strategies in regional/coastal oceans, especially in the Mediterranean Sea: sampling strategies for temperature profiles and for a regional observing system combining moorings and gliders have been tested (Raicich & Rampazzo 2003; Alvarez & Mourre 2012). An approach comparable to OSSEs, but also taking advantage from a representer-based approach using a variational data assimilation scheme, was used to test various scenarios of glider deployment in the New York Bight (Zhang et al. 2010). Theoretically, the OSSE approach requires careful testing of the components of the system (Nature Run from which pseudo-observations are extracted, assimilative model, data assimilation procedure), to make sure that it produces realistic impact assessment. In particular, it requires that the Nature Run and the assimilative model are substantially different (type of model and attributes), which has not been the case in most of ocean OSSEs so far. Such a carefully evaluated OSSE system prototype has been recently demonstrated over the Gulf of Mexico (Halliwell et al. 2014).

The OSE/OSSE methodologies are very efficient in providing a quantitative assessment of the impact of a specific network. However, since they imply the use of several data assimilation experiments, their implementation has a high computational cost. They also face the same difficulties as any data assimilation experiments performed in coastal/regional areas, due to the superposition of various space and time scales. In particular, the estimation of the model error covariance matrix is not trivial. Coastal ocean processes are strongly constrained by topography, so that error structures, unlike in the open ocean, cannot be considered anisotropic. Ensemble approaches, such as the Ensemble Kalman Filter (EnKF), is a common approach for representing non-linear error evolution that is well adapted to the coastal ocean (Evensen 1994). The system performance can then be estimated by the reduction of the ensemble spread due to the assimilation of observations. Such approach has been used in an OSSE framework to test the impact of various altimetric observations scenarios, including the use of wide-swath altimeter such as the future Surface Water Ocean Topography (SWOT), over the North Sea (Mourre et al. 2006; Le Hénaff et al. 2008).

Alternative methods exist in observation array design that do not involve data assimilation. Some of these methods test the ability of an observation array to capture the variability of the ocean signal. Deploying *in-situ* observation arrays at locations associated with high amplitude in the spatial EOF of the dominant modes was found to be an efficient approach for reconstructing the full 3D signal over the Massachusetts Bay (Yildirim et al. 2009). This approach allows, for example, testing the impact of the number of moorings on the performance of the reconstruction. Other approaches are by design closer to a data assimilation approach, where the observations are used to constrain the error made otherwise by the model. The Representer Matrix Spectrum approach (RMspec) aims at quantifying the number of model error modes (estimated with an ensemble of simulations and in the observation space) a specific network can detect, taking into account the observation error covariances (Le Hénaff et al. 2009; Oke et al. 2015). A comparable approach, based on the representer method from the variational approach, and without data assimilation, was used to illustrate the positive impact of surface velocity measurements off Oregon for constraining the coastal upwelling system (Kurapov et al. 2009). Similar concepts from estimation theory were also invoked, in the Kalman formalism, for assessing a coastal network of HF-radar, tide gauges and altimetry in the German Bight area, showing the importance of continuous tide gauge measurements (Schulz-Stellenfleth & Stanev 2010). Other alternative approaches include using the Best Linear Unbiased Estimator (BLUE), adapted from meteorology and based on the exploration of uncertainties of both the ocean state and the observations; it was implemented to test an array of moorings in the Columbia River estuary (Frolov et al. 2008). Although the development and implementation of observation array assessment and design in the regional/coastal ocean are fairly recent, this research field is very active now.

Based on the RMspec method, alternative strategies have been evaluated for collecting vertical temperature profiles on fishing nets using the French RECOPESCA network [http://sih.ifremer.fr/], Leblond et al. (2010).

For the RMspec analysis, a 50-member model ensemble has been carried out using the MARS3D ocean model [http://wwz.ifremer.fr/mars3d] for 2006 (Lazure & Dumas 2008). The ensemble has been generated by perturbing atmospheric forcings, bottom friction, turbulent-closure coefficient, and the light extinction coefficient (mainly in river plumes). Several scenarios of *in-situ* observations of opportunity (depending on fishing activity) have been compared with each other. For each network, the number of representer matrix eigenvalues higher than 1 represents the number of model error modes which the network can detect. The RMspec analysis (not shown) revealed the importance of a geographically balanced distribution of measurements, including regions such as the western Channel and the South of the Bay of Biscay (Northeast Atlantic), as opposed to denser offshore measurements, which are associated with lesser uncertainties (and lesser variability).

Probabilistic approaches and risk assessment in the coastal ocean

As in the open ocean, the most straightforward approach to support coastal ocean forecasting and applications is based on two steps: deterministic, realistic numerical modeling and validation with respect to observations; and optional data assimilation, which in turn enables forecasting. An example of such an approach to risk assessment is the MOVE/MRI.COM-Seto system (described above), targeting coastal surge issues. A case study was conducted for an unusual tide event that occurred in September 2011 and caused flooding at several coastal areas south of Japan. Figures 9b-d shows time series of sea level anomalies at three tide-gauge stations along the south coast of Japan. Significant sea-level rise in the end of September corresponds to the unusual tide event. The assimilated results succeed in reproducing the observed sea-level rise. The model results reveal that coastal trapped waves induced by a short-term fluctuation of the Kuroshio Current around 34N, 140E caused the significant sea-level rise at south coast of Japan (Figure 9(a)). Forecast experiments starting from assimilated initial conditions (not shown) have indicated that this event is predictable half a month ahead.

Besides the above classical approach, probabilistic approaches could provide an interesting alternative in the coastal ocean. Probabilistic forecasting is used to account for uncertainty in a dynamical system by generating a representative sample of the possible future states. Due to the chaotic nature of the dynamics in the combined atmospheric, coastal and wave system, small errors in initial states or model parameterizations can grow to significant forecast inaccuracies in time. To address this, multiple runs with either realistic perturbations of the initial (analysis) state, or with different models (or model formulations) are made. The resulting ensemble of results of a given parameter can be analyzed either in terms of their mean (typically of greater skill than any one member), or their spread (indicative of the forecast uncertainty). Given a sufficiently large ensemble, the relative frequency of occurrences of an event from the ensemble can be used to estimate the probability of that event.

In many coastal regions of the world, there may not be enough observations to reliably estimate uncertainties of

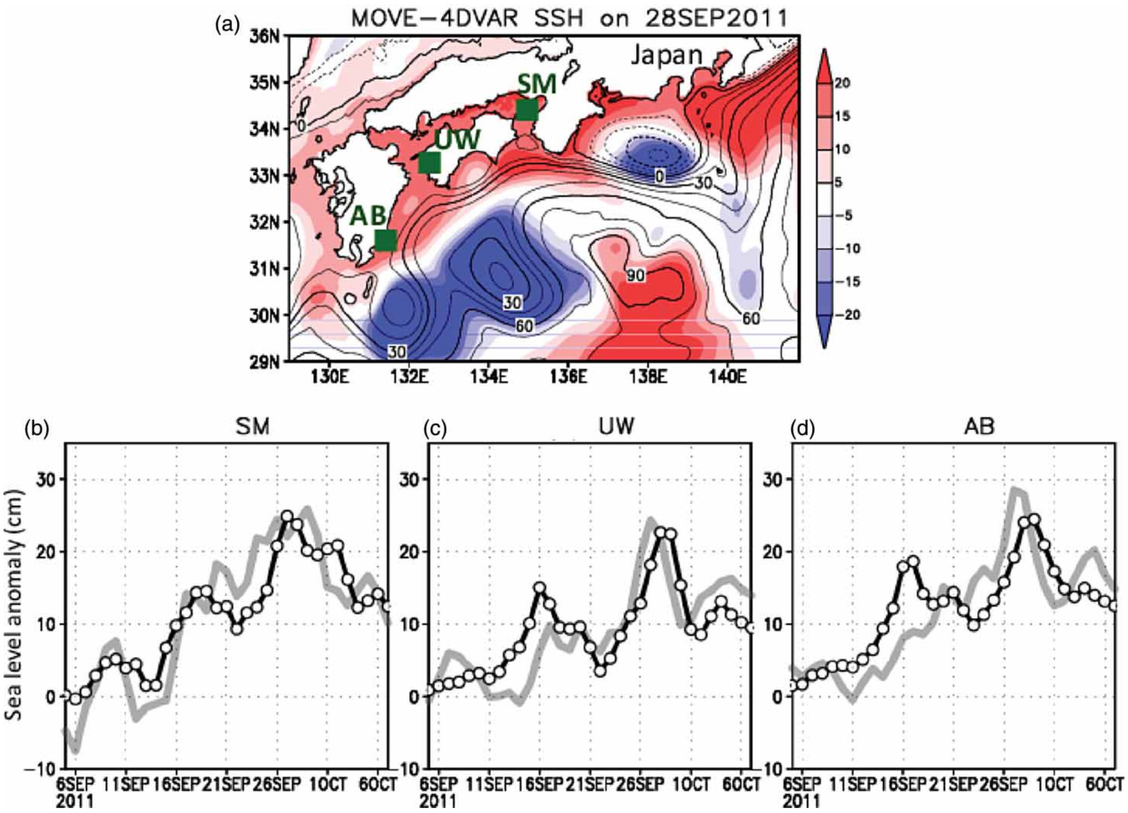

Figure 9. (a) Sea surface height (contour) and anomaly (color) on 28 September 2011 obtained from MOVE-4DVAR (unit in cm). Time series of sea-level anomalies at three tide-gauge stations: (b) Sumoto (SM), (c) Uwajima (UW), and (d) Aburatsu (AB). Gray thick lines denote observed sea-level anomalies and black lines with open circles are results of the coastal model. Sea-level rise in the end of September corresponds to the unusual sea level event mentioned in text. Sea-level anomalies for tide-gauge data, which are defined as deviations from astronomical tide including seasonal sea level change, are corrected for barometric pressure using sea level pressure obtained from the Japanese 25-year Reanalysis data (Onogi et al. 2007). Those for MOVE-4DVAR are anomalies from daily mean climatological sea level from long-term reanalysis data (Usui et al. 2006)

numerical models, to assimilate in those models, and to enable deterministic forecasts (Schiller et al. 2015). Therefore, it can be expected that probabilistic approaches will be widely used in the future, complementing the ‘deterministic’ approach, for quantifying uncertainties in coastal products, and for providing probabilistic forecasts. In addition, for authorities and service companies involved in applications, such as coastal flooding, fish stock management or surface drift predictions, probabilistic products have the potential to facilitate crisis-time decision-making, and the longer term policies aimed at the mitigation of risks, with respect to using deterministic, best-estimate products alone.

An example of probabilistic forecast system applied to storm surge is NOAA’s P-Surge. Due to the initial state and modeling uncertainties in tropical cyclones, NOAA’s National Hurricane Center (NHC) has been utilizing probabilistic storm surge and coastal inundation forecast guidance for the past decade. With P-Surge, thousands of SLOSH model runs are made, forced by hurricane model input parameters from normal distributions centered on the current NHC official forecast, but with standard deviations based on historical errors in official NHC track and intensity forecasts. These include along-track (forward speed) and cross-track errors, variation in the radius of maximum wind and variation in intensity.

Besides the above examples, the use of probabilistic methods is quite embryonic in the coastal forecasting community, even while they can be viewed as an extension of the now familiar Ensemble-based approaches (Chen et al. 2009). Other techniques include Monte-Carlo Markov chain (MCMC), Bayesian inference approaches, fuzzy logic, Bayesian hierarchical networks and methods to validate probabilistic forecasts, e.g. Brier score (Robert & Casella 2004; Pelikan et al. 2005; Jolliffe & Stephenson 2011). Several current uses of probabilistic methods are very relevant: coastal flooding and sea-level surges, forecasting extreme events and surface drift forecasting (Apel et al. 2006; Purvis et al. 2008; Abramson et al. 1996; Rixen et al. 2008; Vandenbulcke et al 2009).

Conclusions

Coastal Ocean Forecasting Systems (COFS) are operating in many regions of the world's coastal ocean, providing estimates of diverse marine variables of interest and serving local needs. At the same time, they obey similar principles and face similar challenges in data and methods. A challenge in itself is the fact that the coastal research community is traditionally more fragmented than the global ocean community.

Modern research and monitoring activities in oceanography have resulted in a rapidly increasing number of observing systems. Their networking, by establishing appropriate infrastructures, is capable of providing continuous and sustainable delivery of high quality environmental data and information products related to the coastal marine environment. However, the present-day situation is that coastal observations are usually carried out by individual countries, in isolation, and sometimes in a non-sustainable way. Dissemination strategies also vary considerably between different countries. End-to-end coastal monitoring from data acquisition to data dissemination is often missing. Similarly, available products for forcing coastal models have great limitations. Observations might not resolve the desired scales, while outputs of larger scale models (used for initialization and boundary forcing, both lateral and from the atmosphere) can be inadequate.

The need to increase the coherence and the sustainability of dispersed national coastal observatories is being recognized by putting in place common framework and standards. IOOS in the US and JERICO in Europe give some good examples, extending global and regional initiatives to the coastal ocean. Such efforts are important to streamline data gathering from coastal observatories to products suitable for decision- and policy-making in the socioeconomically vital and often environmentally stressed coastal regions.

New and strategic technologies need to be identified and implemented in the next generation coastal observatories. For example, using new satellites (e.g. SARAL/AltiKA, SWOT) or land-based networks (e.g. HF-radars) helps achieve better sampling in time and space. Using automated platforms and sensors systems, as well as ensuring autonomy over long time periods, are also desirable.

In addition to adequate observations, the integration of multi-platform observatories with models that resolve coastal dynamics is clearly a key feature of successful COFS. Such integrated systems must be linked to larger scale systems toward the achievement of seamless data sets, nowcasts and forecasts from the global to the littoral scale. The ultimate goal is for COFS to demonstrate added value on open ocean systems, in the context of variability over short and long scales.

Emerging capabilities have been discussed. In particular, OSEs and OSSEs, adapted for the coastal ocean, provide a rigorous, cost-effective approach for the optimization of existing coastal observing systems and the planning of future ones (e.g. SWOT satellite mission). Coastal/regional OSEs and OSSEs will be most helpful to: (a) establish how well the different platforms contribute to characterize coastal ocean state and variability; (b) examine the interactions and impacts between coastal and open ocean regions; and (c) study the processes and factors that control the accuracy of the reconstruction of the coastal ocean state. The strategy implies using OSEs/OSSEs to subsample the oceanic fields in order to quantify the errors in the reconstruction of the coastal ocean state and its variability.

Probabilistic approaches are another emerging topic that is expected to provide new venues in the field of coastal and shelf monitoring and forecasting. The various techniques available to date appear already quite mature to provide robust tools for helping decision makers in setting up future coastal observing systems. The COFS community is expected to benefit from applying probabilistic methods to coastal problems of interest and assess the value of new probabilistic product types for both science and selected applications. Collaboration with large scale forecasting systems would allow estimating Probability Density Functions for forcing of nested COFS systems.

In the context of rapidly developing coastal ocean forecasting capabilities worldwide, international coordination is essential to exchange best practices, optimize observing systems and evaluate common data sets, with appropriate feedback to the providers of forcing inputs. Examples of well integrated systems have been discussed to showcase the value added to global systems, over a variety of unique requirements. The Coastal Oceans and Shelf Seas Task Team in GODAE OceanView has been fostering international forums and activities that have been addressing key challenges in observing and predicting circulation and transport in the coastal and shelf seas. Building upon this history, it aspires to play an important role towards the international coordination of science in support of coastal ocean forecasting.

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