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IMPLEMENTATION OF THE WEST COAST OPERATIONAL FORECAST SYSTEM (WCOFS) AND THE SEMI-OPERATIONAL NOWCAST/FORECAST SKILL ASSESSMENT

Silver Spring, Maryland
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DEPARTMENT OF COMMERCE
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noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Center for Operational Oceanographic Products and Services
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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The Office of Coast Survey (OCS) is the Nation's only official chartmaker. As the oldest United States scientific organization, dating from 1807, this office has a long history. Today it promotes safe navigation by managing the National Oceanic and Atmospheric Administration's (NOAA) nautical chart and oceanographic data collection and information programs.

There are four components of OCS:

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> The Marine Chart Division acquires marine navigational data to construct and maintain nautical charts, Coast Pilots, and related marine products for the United States.
>
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Jiangtao Xu, Aijun Zhang
National Ocean Service
Center for Operational Oceanographic Products and Services
Silver Spring, Maryland

Alexander Kurapov, Gregory Seroka
National Ocean Service
Office of Coast Survey, Coast Survey Development Laboratory
Silver Spring, Maryland

Eric Bayler
National Environmental Satellite, Data, and Information Service
Center for Satellite Applications and Research
College Park, Maryland

May 2022

U.S. DEPARTMENT OF COMMERCE
Gina M. Raimondo, Secretary

National Oceanic and Atmospheric Administration
Dr. Richard W. Spinrad, Under Secretary of Commerce for Oceans and Atmosphere

National Ocean Service
Nicole LeBoeuf, Assistant Administrator

Center for Operational Oceanographic Products and Services
Richard Edwing, Director

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EXECUTIVE SUMMARY

In a collaboration with the National Environmental Satellite, Data, and Information Service (NESDIS) and the National Weather Service's (NWS) National Centers for Environmental Prediction (NCEP), the National Ocean Service (NOS) has developed and transitioned the West Coast Operational Forecast System (WCOFS) to operations. WCOFS became operational on March 22, 2021, and is running within NOS' Coastal Ocean Modeling Framework (COMF) on NOAA's Weather and Climate Operational Supercomputing System (WCOSS).

WCOFS is NOS' first coastal Operational Forecast System (OFS) that assimilates real-time oceanic observations to improve the accuracy of the model prediction. It is based on the Regional Ocean Modeling System (ROMS) and uses the ROMS 4-Dimensional Variational (4DVAR) method to assimilate satellite sea surface temperature, satellite sea surface height, and high frequency radar (HFR) surface currents. Incorporating the data assimilation capability into COMF will facilitate future development and applications of coastal ocean forecast systems.

The WCOFS domain extends from 24ºN (Baja California, Mexico) to 54ºN (British Columbia, Canada) along the western coast of North America and from the coastline to more than 1000 kilometers (km) offshore. WCOFS provides daily updates of 24-hour nowcast and 72-hour forecast guidance of currents, temperature, salinity, and sea level for the coastal communities in California, Oregon, and Washington. Data assimilation in WCOFS has led to more accurate forecasts of the hydrodynamic conditions of the region, such as upwelling temperature fronts, coastal ocean currents, and eddy locations. The system meets many user needs, including navigation, commercial and recreational fisheries, search and rescue, and environmental hazard response, among others.

1. INTRODUCTION

Coastal waters along the U.S. West Coast support many economic activities and offer a variety of societal benefits. As a key link between the U.S. and Asia, West Coast ports play a vital role in the U.S. economy. Cargo moving through the West Coast ports represents 12.5% of the U.S. gross domestic product (Martin Associates 2014). From the biological perspective, the seasonal coastal upwelling brings colder, nutrient-rich deep-layer waters up to the surface, fueling phytoplankton blooms and biological productivity further up the food web. Each year, commercial fisheries along the West Coast harvest close to a billion pounds of seafood, worth nearly $1 billion (West Coast 2022).

NOAA's new forecast system for the entire U.S. West Coast, the West Coast Operational Forecast System (WCOFS), produces forecast guidance for the total (i.e., tidal and non-tidal) sea level, currents, temperature, and salinity, which can be used by freight and fishing vessel operators for ship route monitoring and planning in order to save fuel, drive down operational costs, and reduce carbon footprints. The system also meets many other user needs, including search and rescue, environmental hazard response, management of marine protected areas, and other ecological applications.

WCOFS development was the product of collaboration between NOAA's National Ocean Service (NOS) and the National Environmental Satellite, Data, and Information Service (NESDIS). WCOFS served as a pathfinder for transitioning research and development into NOAA operations, building on results from an existing project within the U.S. Integrated Ocean Observing System (U.S. IOOS) Coastal and Ocean Modeling Testbed (COMT). The West Coast-focused COMT projects had multiple components and phases, including the development of biological and ecological applications. The operational implementation discussed in this report applies only to the physical hydrodynamic model.

WCOFS is based on the Regional Ocean Modeling System (ROMS), which is one of the core community ocean models that NOS uses in Operational Forecast Systems (OFS). Other ROMS-based OFSs in operations include the Chesapeake Bay OFS (Lanerolle et al. 2011), Delaware Bay OFS (Schmalz 2011a, 2011b), Tampa Bay OFS (Wei and Zhang 2011), Gulf of Maine OFS (Peng et al. 2018, Yang et al. 2019), and Cook Inlet OFS (Shi et al. 2020, Zhang 2022).

WCOFS is NOS' first 3-dimensional (3D) coastal ocean OFS to incorporate data assimilation capabilities. Data assimilation is used to sequentially correct recent ocean state estimates based on near real-time data to improve the accuracy of forecasts. WCOFS uses the 4-dimensional variational data assimilation (4DVAR) scheme provided as part of the ROMS community code. Data assimilated into the system includes sea surface temperature (SST) from 3 satellites, sea surface height (SSH) from 5 satellites, and ocean surface currents from the land-based high frequency radar (HFR) network. Incorporating data assimilation in WCOFS led to more accurate forecasts of the hydrodynamic conditions of the region, such as upwelling temperature fronts, coastal ocean currents, and eddy locations. The data assimilation capability was built into NOS' OFS infrastructure, which will enable future improvements in OFS forecast accuracy.

As part of NOS' new strategy of transitioning from individual port and estuarine models to a larger-scale regional approach, the WCOFS domain covers the coastal waters of California, Oregon, and Washington, bridging the coarser-resolution global models and the higher-resolution local models. The model runs once a day to provide 24-hour nowcast and 72-hour forecast guidance of water level, currents, temperature, and salinity to the coastal communities of the entire U.S. West Coast.

The initial development of the non-data assimilative model used a 2-kilometer (km) resolution model grid, and extensive hindcast simulations were carried out with the 2-km model grid (Kurapov et al. 2017a, 2017b). However, the 2-km resolution grid was too computationally expensive for operational 4DVAR data assimilation. Consequently, the model grid resolution was coarsened to 4-km. The 4-km resolution data-assimilating model was implemented into operations, with further research continuing with the 2-km resolution non-data-assimilating model (Kurapov et al. 2022). This report details the operational implementation on NOAA's Weather and Climate Operational Supercomputing System (WCOSS), as well as the skill assessment of the semi-operational nowcast and forecast results of the 4-km resolution data-assimilating WCOFS.

2. MODEL DESCRIPTION

2.1 The Model Domain and Grid

The WCOFS domain extends from Baja California, Mexico, to British Columbia, Canada, and from the coastline to more than 1000 km offshore (Figure 1). The model grid has 348 × 1016 points in the horizontal with grid resolution of approximately 4 km. The vertical coordinates have 40 terrain-following vertical layers, with enhanced resolution near the surface and bottom (Figure 2).

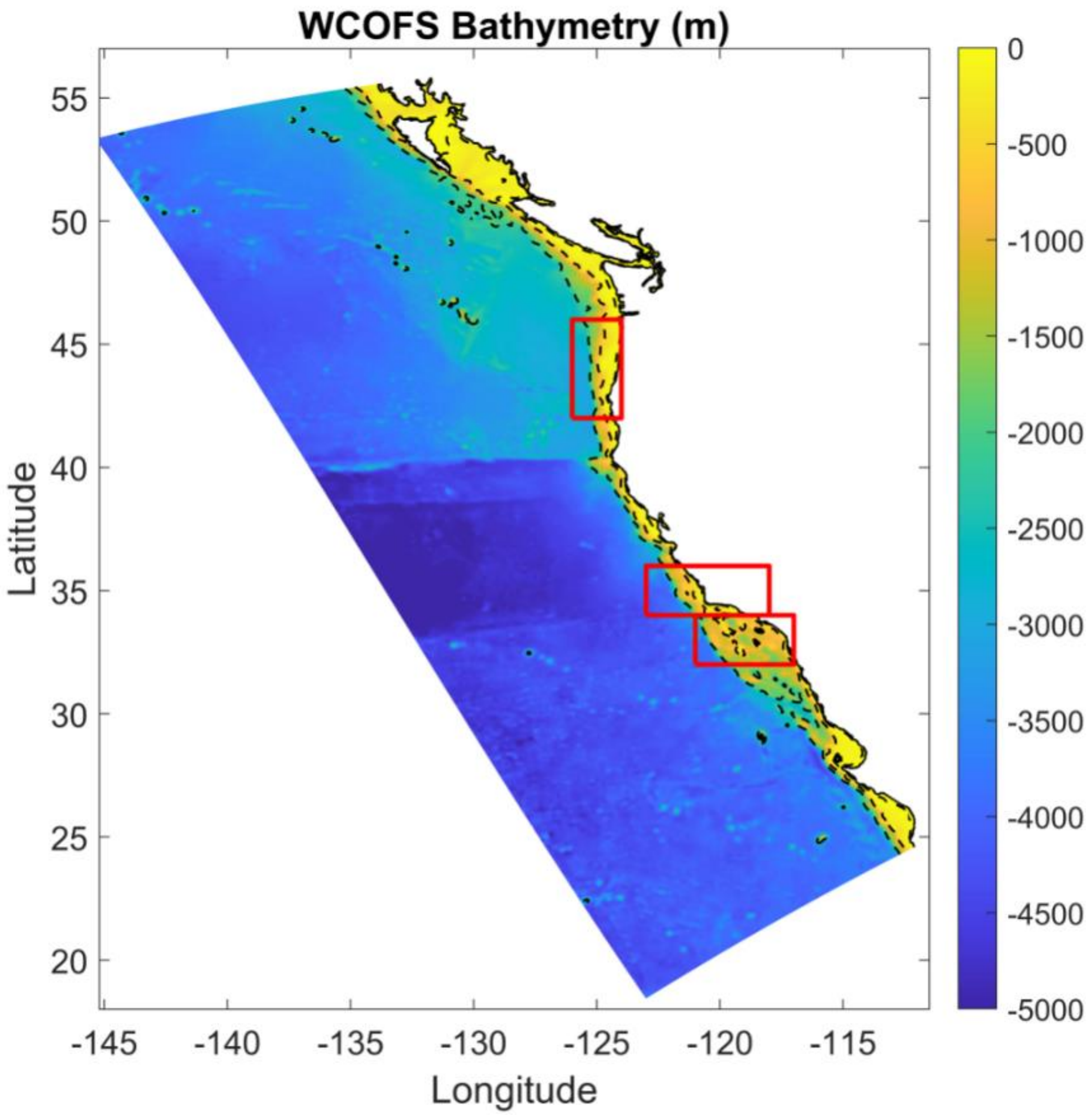

Figure 1. The WCOFS model domain and bathymetry. The dashed lines are the 50, 500-, and 2000-meter isobaths. The 3 red boxes are the areas where the surface ocean currents skill assessment were conducted in Section 5.1.

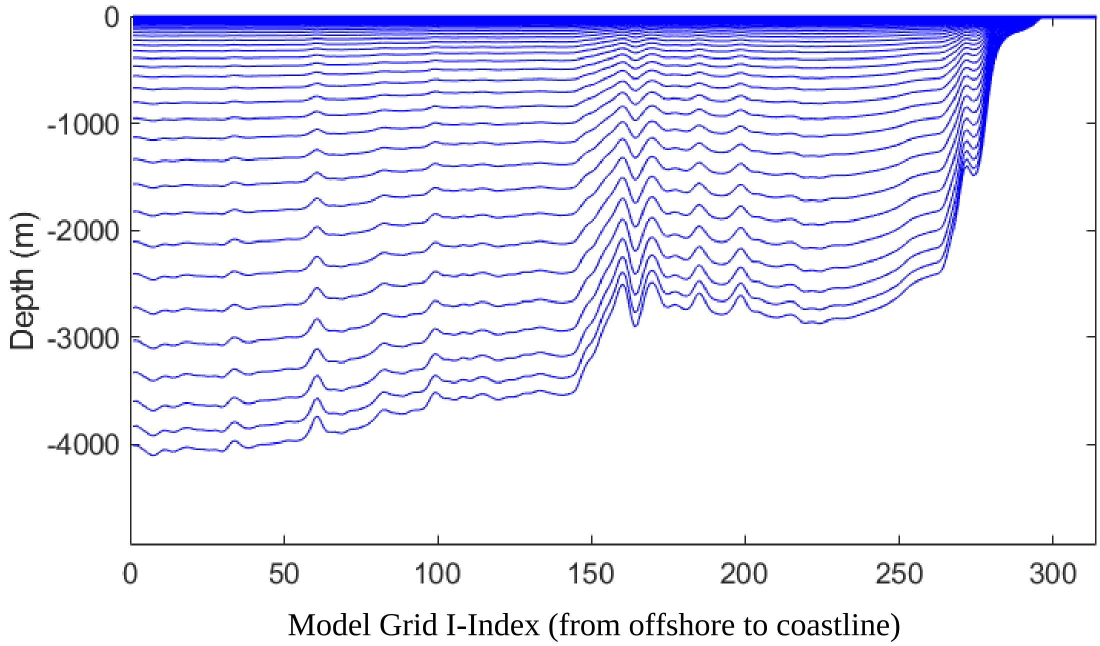

Figure 2. A schematic of the vertical coordinates at a cross-section in WCOFS showing enhanced resolution near the surface everywhere and enhanced resolution near the bottom over the shelf and continental slope.

Please note that with the 4-km resolution, the model does not sufficiently resolve the coastal bays and estuaries. The model results in these areas, if any, should be used with extra caution.

2.2 Boundary Conditions

WCOFS is composed of 2 components: the data assimilation component (WCOFS_DA) and the nowcast/forecast component (WCOFS). The forcing setup described below applies to both components.

The model domain has 3 open ocean boundaries (north, south, and west). The National Center for Environmental Prediction (NCEP) Global Real-Time Ocean Forecast System (RTOFS) is used to provide open boundary conditions for temperature, salinity, and non-tidal water level and vertically averaged velocity. Tidal currents and water level from 8 primary tidal constituents (M2, S2, N2, K2, K1, O1, Q1, and P1) are constructed from the Oregon State University's TPXO8 tidal database (Egbert and Erofeeva 2002). The 3D momentum equations use "the radiation with nudging" open boundary conditions (Marchesiello et al. 2001). A sponge layer (a band of relatively larger viscosity) is also applied around the open boundaries. The temperature and salinity equations also use radiation with nudging open boundary conditions. In addition, the temperature and salinity fields within a 100-km zone along the open boundary are nudged toward the RTOFS temperature and salinity fields averaged over the simulation time period.

Meteorological surface forcing conditions are derived from the National Weather Service's (NWS) North American Mesoscale (NAM) 2-km-resolution atmospheric model. The NWS Global Forecast System (GFS) serves as the backup for the meteorological surface forcing conditions in case NAM products are not available for both the nowcast and forecast runs.

Additionally, WCOFS uses U.S. Geological Survey (USGS) real-time river discharge and climatology river temperature for the Columbia River, as well as climatology discharge and temperature for 14 rivers in Washington and the Fraser River in Canada (Giddings and MacCready

2017) during the nowcast. River discharge and temperature are held constant from the last observation throughout the forecast period. Because no rivers south of the Columbia River are considered in this model, there is no freshwater input into the simulated salinity in the California estuaries and bays.

2.3 Observations Used in Data Assimilation

The WCOFS nowcast/forecast cycle starts with the data assimilation analysis in a 3-day time window. ROMS 4DVAR is used to improve the initial conditions at the beginning of the 3-day window. Currently, the following observations are assimilated: 3 sources of satellite SST (the Visible Infrared Imaging Radiometer Suite [VIIRS] onboard the Suomi National Polar-orbiting Partnership [NPP], the VIIRS on NOAA-20, and the Advanced Baseline Imager [ABI] on GOES-17), surface ocean currents from the national HFR network, and absolute dynamic topography (ADT) from Jason-3, Sentinel-3, Cryosat-2, and SARAL/Altika (Table 1). The ADT dataset is homogenized in the sense that the same geoid model is used for all the satellites, and it provides information on the non-tidal SSH. When the data assimilation system was initially set up for the pre-operational testing, only SST from NPP and HFR surface current observations were assimilated. In the real-time semi-operational runs, we started to assimilate SSH on November 1, 2019, and added SST from 2 more satellites (NOAA-20 and GOES-17) on September 3, 2020. Figure 3 depicts a sampling of the satellite observations assimilated in a 3-day data assimilation window by WCOFS.

Table 1. The observations used in WCOFS data assimilation.

Observation Type	Data Sources	Observation Error Standard Deviation
Sea Surface Temperature (SST)	NPP VIIRS L3U NOAA-20 VIIRS L3U* GOES-17 ABI L3C*	0.4 ℃ 0.4 ℃ 0.5 ℃
Surface Currents	High Frequency (HF) Radar: Hourly, 6-km mapped	0.05 m/s
Sea Surface Height (SSH)	RADS Absolute Dynamic Topography (ADT)** (Jason3, Cryosat2, Sentinel 3a/b, SARAL/Altika)	0.03 m

* Included in real-time simulations since September 3, 2020.

** Included in real-time simulations since November 1, 2019

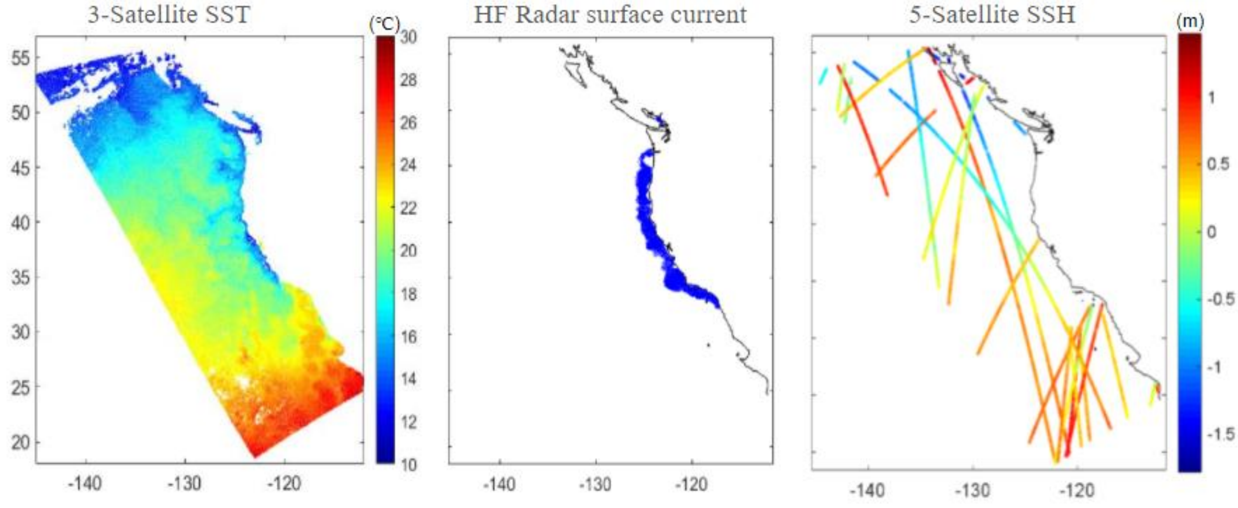

Figure 3. An example of available observations of sea surface temperature (SST), high frequency radar (HFR) current, and sea surface height (SSH) within a 3-day analysis window.

Observational standard deviations listed in Table 1 are chosen based on past experiences (Kurapov et al. 2011, Yu et al. 2012, Pasmans et al. 2020). A slightly larger standard deviation for the Geostationary Operational Environmental Satellite (GOES) data compared to VIIRS is used based on the comparisons of the satellite and in situ SST (see Section 4). Sensitivity studies have been performed to ensure that the forecasts are sensitive to assimilation with these standard deviations, yet the data are not over-fitted. Note that assigning very small error standard deviations usually results in overfitting the noise in data and produces noisy state estimates.

2.4 Nowcast/Forecast and Data Assimilation Setup

Figure 4 is a schematic of how the data assimilation (DA) analysis and nowcast/forecast components communicate. On each day, WCOFS_DA is run to improve the ocean state estimate at the beginning of the 3-day window and the nonlinear analysis is run again, which produces better model-observation agreement for the 3-day window. This analysis is used as the initial conditions for the next day nowcast/forecast. As shown in Figure 4, the data assimilation window has a 2-day overlap with the previous cycle. Using 4DVAR terminology, each DA cycle runs 2 outer loops and 7 inner loops (Moore et al. 2011). On the first outer loop, the prior nonlinear model run is used as the background for model linearization. The inner loops are used to find the correction to the initial conditions iteratively. The same operation repeats in the second outer loop where the once-improved nonlinear solution is used as the background state for the model linearization.

In order to provide a baseline for evaluating the effect of the data assimilation on nowcast and forecast skills, the free run of the model, WCOFS_FREE, with no data assimilation is also kept in operations parallel to WCOFS. Table 2 provides a quick reference of the 3 models mentioned in this report.

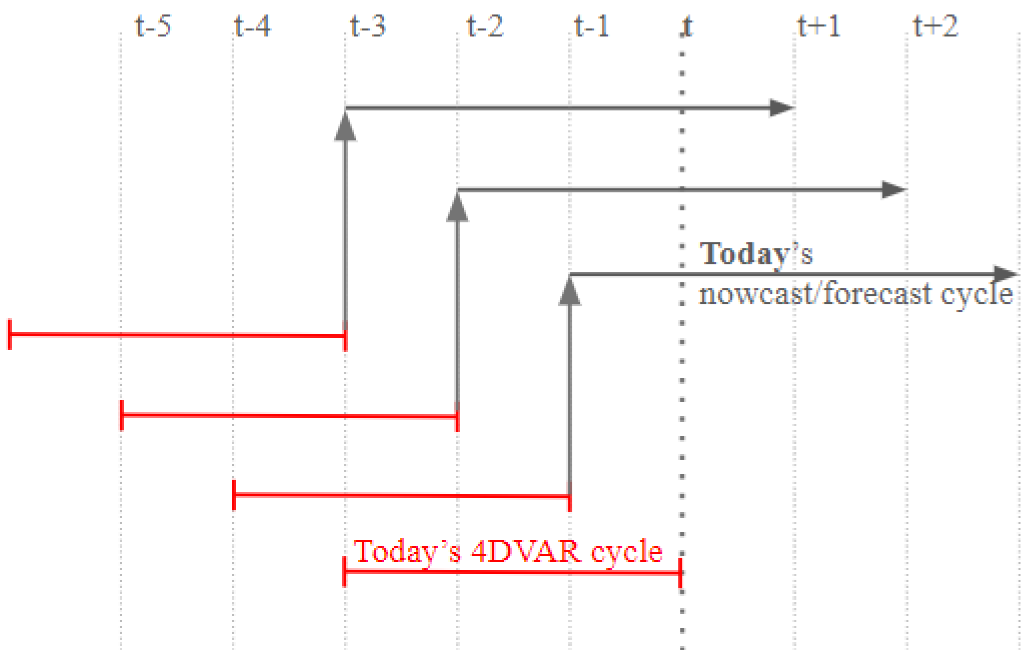

Figure 4. A schematic of how West Coast Operational Forecast System data assimilation (WCOFS_DA) and WCOFS are run with WCOFS_DA analysis informing the WCOFS nowcast/forecast.

Table 2. A description of the 3 models: West Coast Operational Forecast System data assimilation (WCOFS_DA), WCOFS, and WCOFS_FREE.

Model Name	Description
WCOFS_DA	The data assimilation cycle that assimilates available observations within a 3-day window to derive an improved initial condition for the 3-day analysis.
WCOFS	The nowcast/forecast model that starts from the analysis results from WCOFS_DA and provides the nowcast and forecast guidance.
WCOFS_FREE	The free run (non-data assimilating) nowcast/forecast model that starts from the previous cycle WCOFS_FREE results and has the same forcing conditions as WCOFS. It is used to provide a baseline to evaluate data assimilation effects on nowcast and forecast skill.

3. UPDATES TO THE COMMON COASTAL OCEAN MODELING FRAMEWORK

All coastal operational forecast systems running on WCOSS are operated under the Coastal Ocean Modeling Framework (COMF) (Gross et al. 2006, Zhang and Yang 2014). Various changes and updates were made in COMF to accommodate the unique requirements of WCOFS_DA.

3.1 The Observation File Generation

First and foremost, to run WCOFS_DA, we need to process the observations (HFR currents, SST, and SSH) and prepare the single observation file in the format required by ROMS 4DVAR. A set of python scripts was developed and incorporated into the COMF to prepare the observation file. Each observational type is processed separately before all types are merged into a single "obs.nc" file.

For SST, data from each satellite is first processed separately, and each observation point is mapped onto the model grid and averaged within each model grid cell. Polar orbiting satellites NPP and NOAA-20 pass over the WCOFS area several times per day, and the geostationary GOES-17 satellite provides hourly observations of the same region. To reduce data redundancy and avoid the dominance of the GOES data, the GOES-17 SST data is averaged over 3 hours and then combined with the individual SST granules provided by the Level 3 NPP and NOAA-20 SST products. A granule refers to a 10-minute (min) chunk of VIIRS data from either NPP or NOAA-20. To avoid situations where more than 1 SST set (GOES hourly image or VIIRS granule) is found within 1 ROMS time step, each set is assigned to coincide with an individual model time instance.

SSH observations are collected along the satellite passes (tracks). The data are de-tided such that the useful signal, specifically the along-track SSH slope, represents the relatively low-frequency (subtidal) dynamics. Presently, ROMS 4DVAR is able to assimilate only instantaneous observations. In the attempt to represent the ADT data as providing information on relatively slow changing, subtidal SSH variations, the SSH observations are "spread" in time, i.e. repeated every 3 hours within 12 hours (before and after) of the actual observation time. Because the model tidal harmonics do not match the observed tidal harmonics exactly, the model tidal harmonic constants are obtained from a long non-DA run. The model tides are added to the observations such that the data represent the total SSH in the tide-resolving model and the difference between the prior model and observations will be in the non-tidal component only. Therefore, any errors in the modeled tides will not impact the effectiveness of assimilating the non-tidal signals in the ADT.

The hourly 6-km HFR surface current observations are mapped to the model grid and rotate to the model coordinates. Observations with Dilution of Precision (DOP) less than 0.5 and in near-shore areas with depth shallower than 40 meters (m) are excluded.

All python scripts are organized under the new pysh directory in COMF. Observational errors, shown in Table 1, were added as control parameters in the main control file fix/wcofs_da/nos.wcofs_da.ctl and passed to the python scripts through environment variables.

The observation file preparation step is unique to WCOFS_DA. Although not dependent on the preparation of other forcing files, creating the observation file currently is set to run sequentially upon completing the prep step. Two scripts—jobs/JNOS_OFS_OBS and scripts/exnos_ofs_obs.sh—were added to control and run the job of preparing the observation file.

3.2 Modeled Tidal Harmonics Constants Adjustment

As mentioned above, modeled tidal water elevation needs to be combined with the non-tidal satellite ADT before being assimilated into the model. Similar to the open boundary conditions, the harmonic constants of each tidal constituent are adjusted using nodal factor and equilibrium argument. A Fortran code, using the existing utility code, was added to adjust tides on the model grid, which can be used to account for, or remove, the nodal factor and equilibrium argument adjustment. The code and its compiling instructions were added under sorc/nos_ofs_adjust_tides.fd.

3.3 The Compilation of WCOFS_DA

Different from other ROMS-based OFS, compiling WCOFS_DA requires the compilation of ARPACK, which is a Fortran library for solving large-scale eigenvalue problems. The sorc/ROMS.fd/Lib/ARPACK/ARmake.inc was updated with proper compiling options for use on WCOSS (when updating ROMS from the community repository, please remember to update this file accordingly). The compilation instructions were added in sorc/COMPILE.sh. It is worth noting that the use of the "-heap-array" option in the ROMS compilation would seriously slow the running speed of WCOFS_DA on WCOSS. Because the "-heap-array" option had no noticeable impact on other ROMS-based models, the option was removed for all ROMS-based OFSs on WCOSS.

3.4 Other Changes in COMF

The following new model control variables were added in the main control file for the DA setup:

LEN_DA: length of data assimilation window
ERR_TEMP: observation error for temperature
ERR_V: observation error for velocity
ERR_SSH: observation error for SSH
EPSDOP: quality control criterion for DOP for HFR currents
HF_HMIN: quality control criterion for minimum water depth for HFR currents
MODELTIDE: file name for the harmonic constants of the modeled tides on the modeled grid

Please note that ERR_TEMP was not used in the updated python script for preparing multiple satellite data. Instead, the errors were set for different data sources in d_sst_multiSat.py.

ush/nos_ofs_archive.sh and *ush/nos_ofs_create_forcing_obc.sh*:
Similar to other OFS, for proper handling of the large-size field output and selection of regional output from RTOFS, specific rules and region selection were added in these 2 scripts under the ush directory for all three WCOFS-related models.

ush/nos_ofs_create_forcing_obc.sh and *ush/nos_ofs_create_forcing_nudg.sh*:
Due to the unique overlapping running windows of WCOFS_DA, changes were made in these 2 scripts.

ush/nos_ofs_nowcast_forecast.sh:
Lines of code were added to address the need for a status file for internal use after the DA cycle is done, writing a new restart file from the DA cycle to replace the original restart file in the WCOFS

run directory and saving the new, improved initial conditions in the DA cycle for potentially rerunning only the analysis.

ush/nos_ofs_launch.sh:
The script was updated to handle the additional required input files for the DA cycle and to define the WCOFS restart file name being replaced by the analysis results from the DA cycle. Originally, the COMF constrained an OFS such that it could only be run in hot restart mode (continuing from previous run without spin-up) if the restart files were within 2 days of the nowcast start time. However, this needed to be modified for WCOFS_DA to permit its 3-day assimilation window. If no restart file is found from the previous 3 DA cycles, WCOFS_DA will start from the WCOFS nowcast history output.

4. EVALUATION OF USING SST FROM MULTIPLE PLATFORMS

When the WCOFS_DA system was initially established and tested, it only assimilated SST from NPP and HFR surface currents. The NPP VIIRS SST is a high-resolution (2 km) and high-accuracy dataset; however, this polar-orbiting satellite passes over the WCOFS model domain only a few times per day. The biggest disadvantage of this data source is that observation coverage is greatly impacted by clouds. For some areas along the U.S. West Coast, there can be days with no data coverage at all from NPP VIIRS SST, leaving the model to dynamically adjust to scarce data input without sufficient constraints. To improve the data coverage, additional observational datasets of SST from NOAA-20 (N20), GOES-17 (G17), and the Advanced Microwave Scanning Radiometer 2 (AMSR2) were evaluated. The AMSR2 SST product has much coarser resolution, approximately 10 km, but provides nearly full coverage every day. Most importantly, AMSR2 SST coverage excludes the coastal band out to about 40-50 km from the shoreline.

When comparing the daily SST map from each source, the quality of N20 and G17 SST was qualitatively similar to the NPP SST, while the AMSR2 SST often had a warm bias, especially near the coast. To quantify the accuracy of the different satellite SST products, satellite SST at seven National Data Buoy Center (NDBC) buoy locations in the coastal region (Table 3) were retrieved to compare against the in situ observations for the time period of August 2019 to April 2020 (G17 SST became available after October 2019). Figure 5 compares the biases of each satellite SST at each station. AMSR2 SST (black bar) bias stood out, with fairly large positive biases at 6 of the 7 stations (0.4-0.7°C). Figure 6 shows the time series comparison at station 46229. NPP and N20 SST closely followed each other and agreed with NDBC in situ observations very well. G17 SST also generally agreed with in situ observations, but it also showed some spikes in SST not observed in situ. Overall, the AMSR2 SST also followed the in situ observations in terms of the large variations and the seasonal pattern. However, it deviated from the in situ observations the most where the surface temperature decreased during upwelling events. In these instances, the error could be as large as +3 °C during strong events (Figure 6). The AMSR2 SST was found to be unsuitable for data assimilation in WCOFS. N20 and G17 were included to increase the data coverage and reduce data gaps.

Table 3. Selected National Data Buoy Center (NDBC) stations where NPP, N20, G17, and AMSR2 sea surface temperatures (SST) were retrieved for comparison.

NDBC StationID	Latitude	Longitude	Station Code	Station Name
46100	46.851	-124.972	ooiw	OOI Westport offshore
46248	46.133	-124.644	astc	Astoria Canyon, OR
46089	45.925	-125.771	till	Tillamook, WA
46050	44.677	-124.515	ston	Stonewall Bank, OR
46229	43.772	-124.549	umpq	Umpqua Offshore, OR
46012	37.356	-122.881	hmoo	Half Moon Bay, CA
46047	32.404	-119.506	tann	Tanner Banks, CA

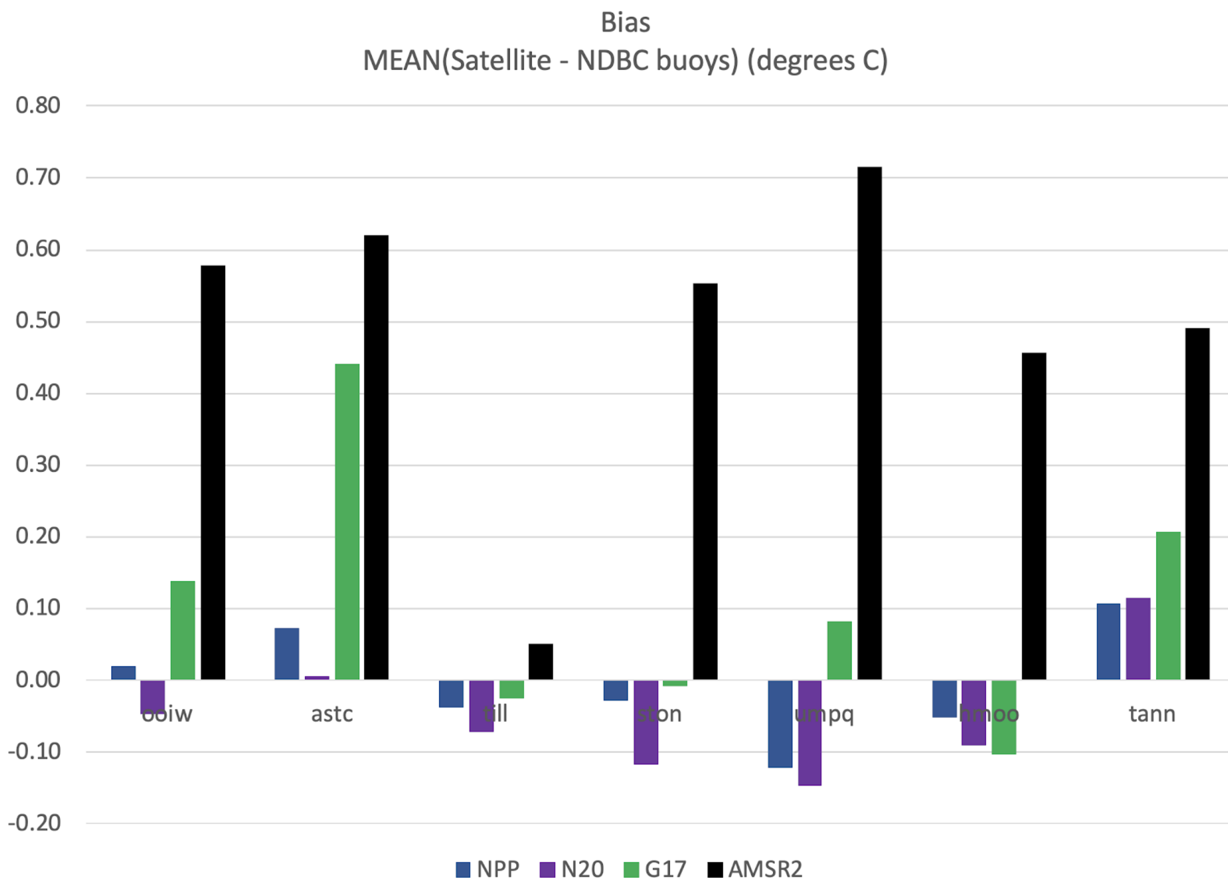

Figure 5. The time-averaged biases (℃) of NPP, N20, G17, and AMSR2 SST compared to in situ observations at 7 National Data Buoy Center (NDBC) buoys (ooiw, astc, till, ston, umpq, hmoo, and tann) for the period of August 2019 to April 2020.

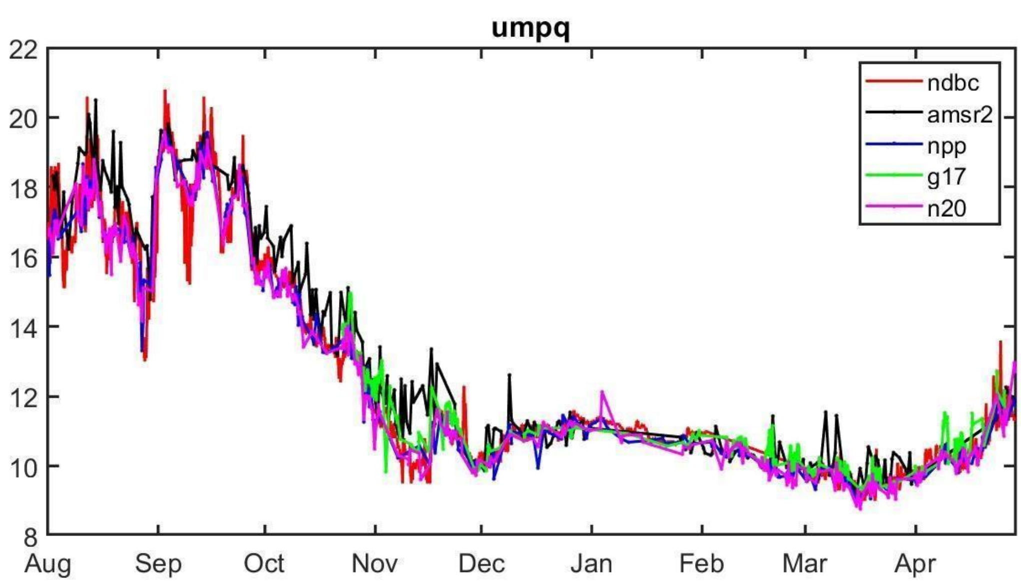

Figure 6. Comparison of satellite SST from NPP, N20, G17, and AMSR2 with the in situ observations (in ℃) at National Data Buoy Center (NDBC) buoy 46229 Umpqua Offshore, Oregon, from August 2019 to April 2020.

5. NOWCAST/FORECAST SKILL ASSESSMENT

The WCOFS nowcast/forecast cycles with data assimilation have been set up to run in real-time since August 2018. However, active system development and testing were still in progress, leading to multiple configuration and data stream modifications as WCOFS was being prepared for operational implementation. Initially, the system only assimilated SST from NPP and HFR surface currents. Starting in November 2019, the assimilation of along-track SSH from 5 satellites was added to the real-time runs and later updated in May 2020 to repeat each track every 3 hours for 12 hours before and after the actual observation time. Meanwhile, the data assimilation cycle configuration was changed from 1 outer loop and 15 inner loops to 2 outer loops and 7 inner loops in order to better fit the observations. In September 2020, SST from the NOAA-20 and GOES-17 satellites were added to the real-time data assimilation. All of these modifications were adopted into the real-time prototype system after successful hindcast testing following each update.

To evaluate the data assimilation and forecast system performance, efforts focused on the surface water temperature and non-tidal currents because of their importance for potential users. For instance, fishermen would like to know about temperature fronts and information about non-tidal currents is important for ship routing, search and rescue, and environmental hazard response. Additionally, although the performance of the analysis or data assimilation cycle was checked and monitored regularly, of greater interest and relevance to an OFS is to establish how well the model performs in the nowcast/forecast cycle. Therefore, this report presents skill assessment results for the 1-year collection of nowcast/forecast cycles (March 1, 2020, to March 1, 2021) prior to the system becoming operational in March 2021.

5.1 Ocean Currents

For ocean currents validation, we compare the modeled current forecasts with the HFR observations, with the observations used for the comparisons not yet included in the assimilation. Daily-averaged model and observed currents are compared using 2 major metrics: 1) the area-averaged amplitude and direction of the alongshore current (Durski et al. 2015, Kurapov et al. 2017b), and 2) the area-averaged Root Mean Square Error (RMSE). The RMSE is computed by taking the vector difference between the observed and modeled currents at the points where the daily averaged HFR observations are available; consequently, RMSE combines both the cross-shore and alongshore velocity differences. Comparisons are done in 3 coastal areas: Oregon (ORE) (42-46N), Central California (CCA) (34-36N), and Southern California (SCA) (32-34N) (Figure 1).

Figure 7 shows the daily averaged and area-averaged alongshore current for day 1 forecast in the 3 regions. WCOFS (green) and WCOFS_FREE (blue) forecasts are compared to HFR estimates (black). In each region, the modeled alongshore currents agree well with the observation, and WCOFS followed the observations better than the WCOFS_FREE. Off the Oregon coasts, the alongshore currents in spring and summer (March to August 2020) were mostly southward, driven by upwelling favorable winds. In the fall of 2020, the southward alongshore currents off the Oregon coast weakened, eventually becoming a predominantly northward winter flow, driven by the predominantly northward, downwelling-favorable winds.

In the central California region, both WCOFS and WCOFS_FREE correctly show the direction of the alongshore current but forecast weaker currents than observed in April/May. In the summer and fall, WCOFS, constrained by data assimilation, is noticeably closer to the observations than WCOFS_FREE.

The alongshore currents in southern California are the weakest among the 3 regions. The variation in the surface currents is more stochastic, influenced by geostrophic eddy variability in the offshore region (Washburn and McPhee-Shaw 2013).

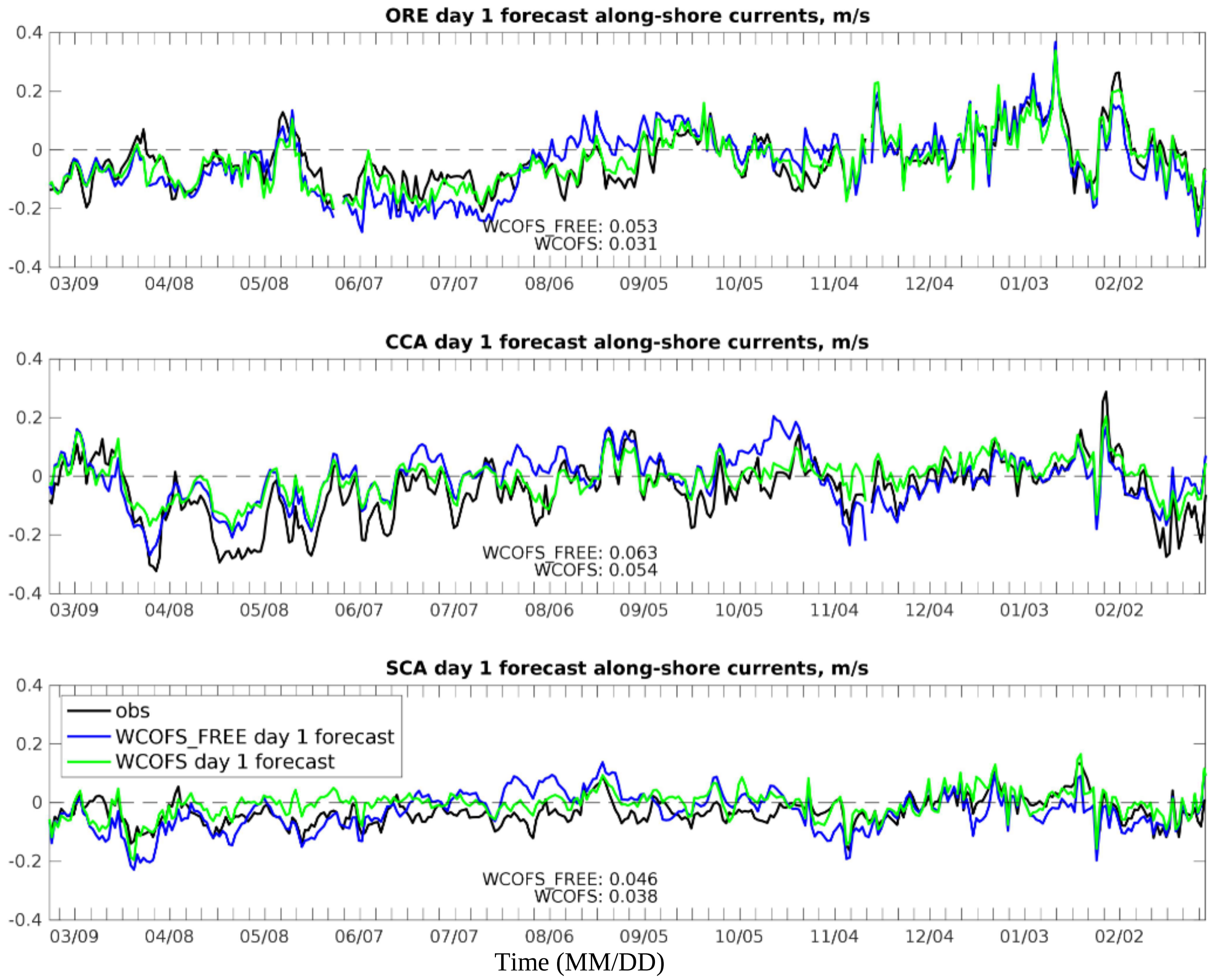

Figure 7. Comparison of modeled day 1 forecast alongshore current (green) with observations (black) in the 3 regions: (a) Oregon (ORE), (b) Central California (CCA), and (c) Southern California (SCA). WCOFS_FREE (blue) provides a benchmark. The numbers in each panel are the mean absolute error of the area-averaged alongshore currents over the 1-year time period.

Based on comparison of the daily average and area-averaged alongshore currents over the 1-year time period, WCOFS outperforms WCOFS_FREE in all 3 regions (the mean absolute errors in each region are provided in Figure 7). The initial conditions generated using data assimilation reduced the mean absolute errors in the day 1 forecast of alongshore currents by 1 to 2 centimeters per second (cm/s), which corresponds to an error reduction of 15-40%. The relative error reduction was largest along the Oregon coast and smallest along the Southern California coast because the prior error was already relatively smaller there.

Figure 8 shows the RMSE of the modeled day 1 forecast surface currents. To recall, these values are obtained by taking velocity vector differences point-by-point and then computing the area-averaged squared differences. The RMSE computed this way is a more stringent criterion than the area-averaged alongshore current or RMSE computed after the area-averages are computed (as discussed in reference to Figure 7). Overall, the RMSE of WCOFS (green) is smaller than that of WCOFS_FREE (blue) in all 3 regions. The numbers in each panel are the time-mean RMSE over the 1-year period. Data assimilation reduced the mean RMSE in day 1 forecasts by 1 to 3 cm/s, which corresponds to an error reduction of 8-15%. The decrease of RMSE in WCOFS is more consistent in Oregon and Central California where the currents are stronger.

Also in Figure 8, RMSE time series are compared to the RMS magnitude of the observed currents (dotted lines). Comparing these gives a sense of the signal/noise ratio for each region. Generally, the DA impact is greater where the WCOFS_FREE error ("noise") is larger than the observed current intensity ("signal").

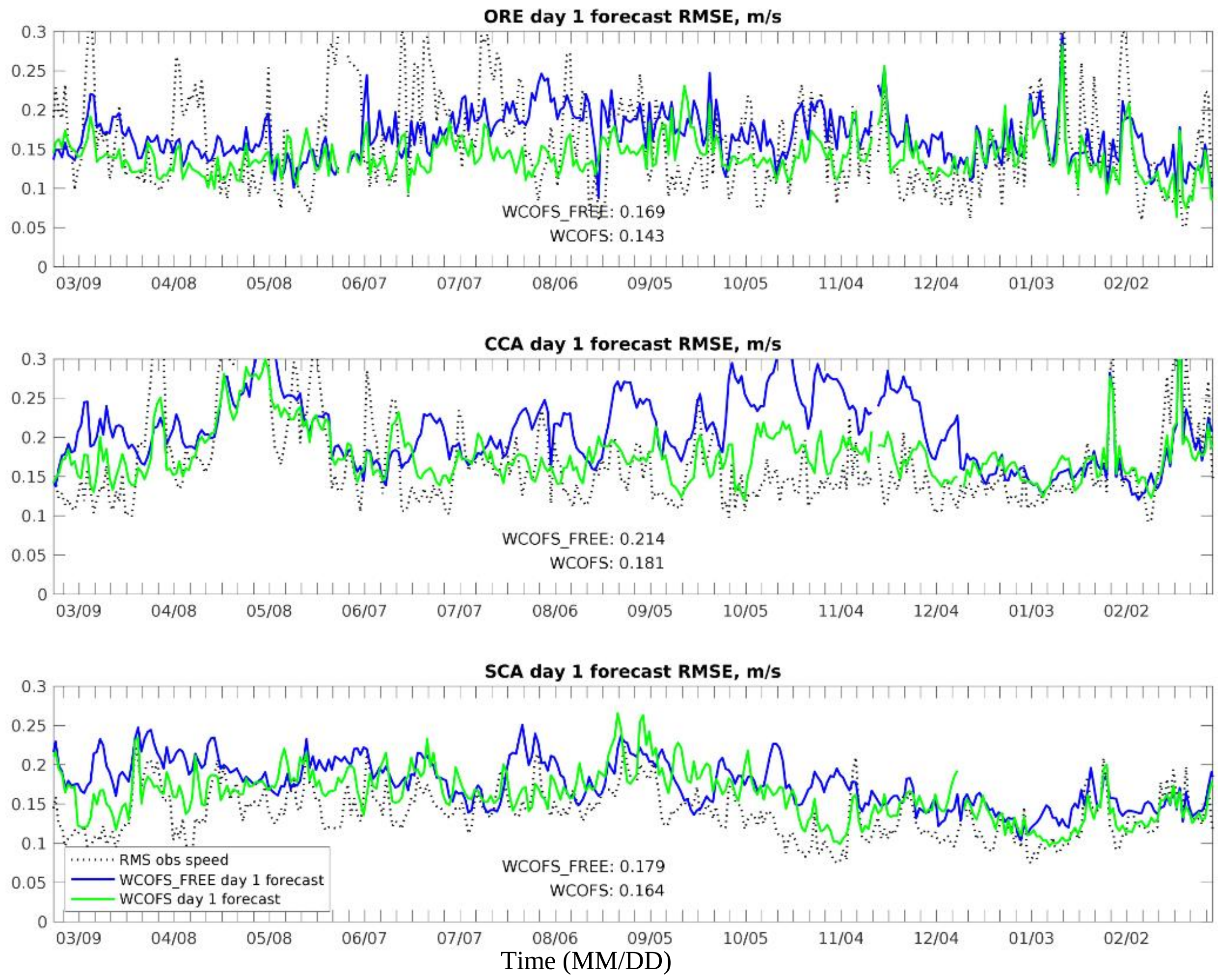

Figure 8. Root Mean Square Error (RMSE) of modeled day 1 forecast current (WCOFS in green and WCOFS_FREE in blue) for the three regions: (a) Oregon (ORE), (b) Central California (CCA), and (c) Southern California (SCA). The dashed black line is the RMS magnitude of the observed current, used as an indicator of the signal strength. The numbers in each panel are the root squared mean of the RMSE over the 1-year time period.

The day 2 and day 3 forecast currents compare similarly with the observations (not shown), with favorable skill holding through the 3-day forecast period. Data assimilation improved the forecast skill during the 3-day forecast in all 3 areas except for the SCA region, where the surface current signal is low and may be comparable to the error in HFR data (Figure 9).

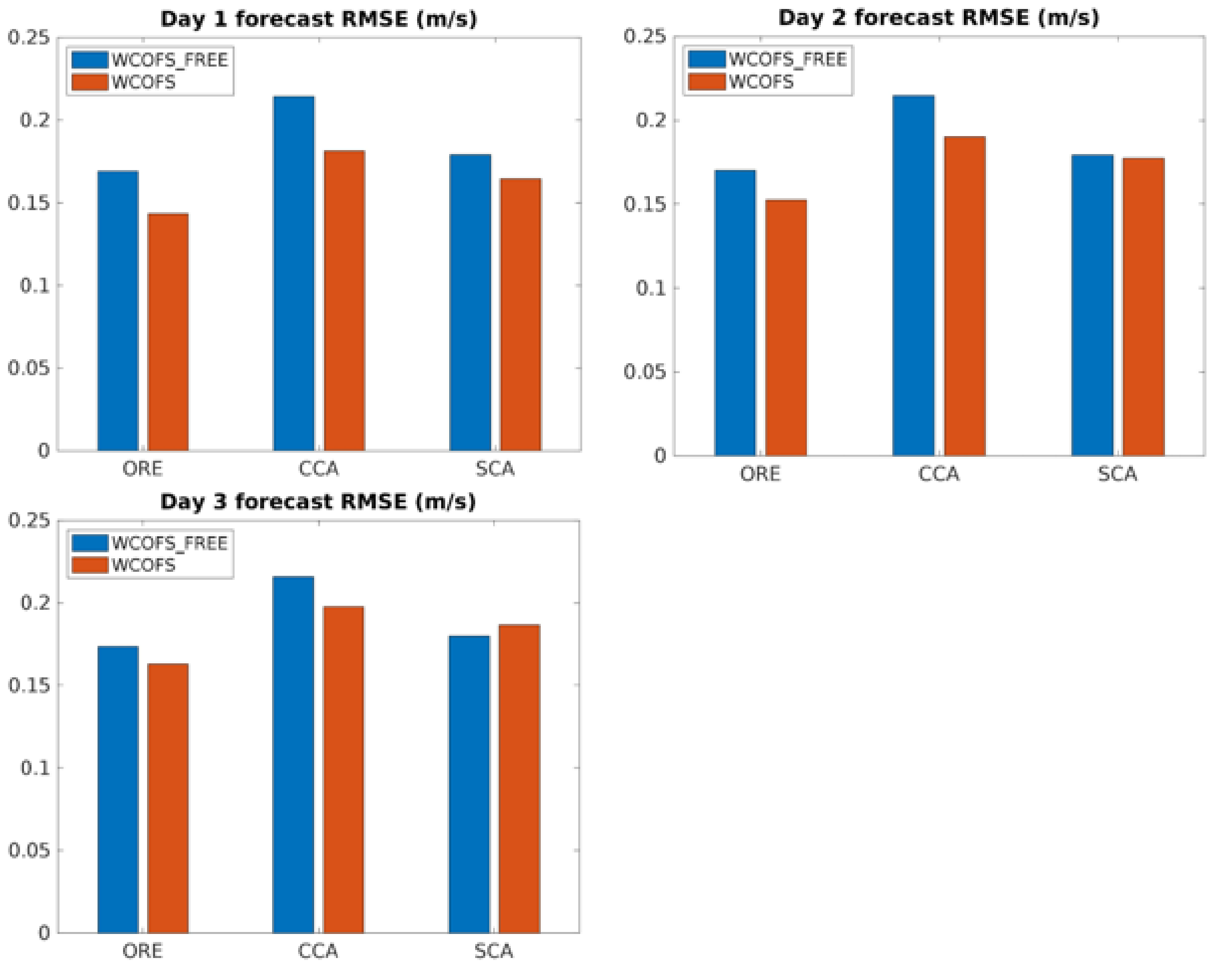

Figure 9. Root Mean Square Error (RMSE) of day 1 to day 3 forecast currents for WCOFS (red) and WCOFS_FREE (blue).

5.2 Water Temperature

For water temperature, we compare the model forecasts against future satellite SST that were not yet constraining the solution. For this comparison, we interpolate model results to the observational time and location of each SST observation and calculate the RMSE of the water temperature on each day. Figure 10 shows the daily RMSE of surface water temperature from the day 1 forecast compared to satellite SST. The RMSE ranges from 0.3 to 1.5 °C. Model results from WCOFS (with data assimilation) agreed with observations considerably better than the WCOFS_FREE (natural run) results. The mean RMSE over the 1-year time period is 0.58 and 0.79 °C for WCOFS and WCOFS_FREE, respectively.

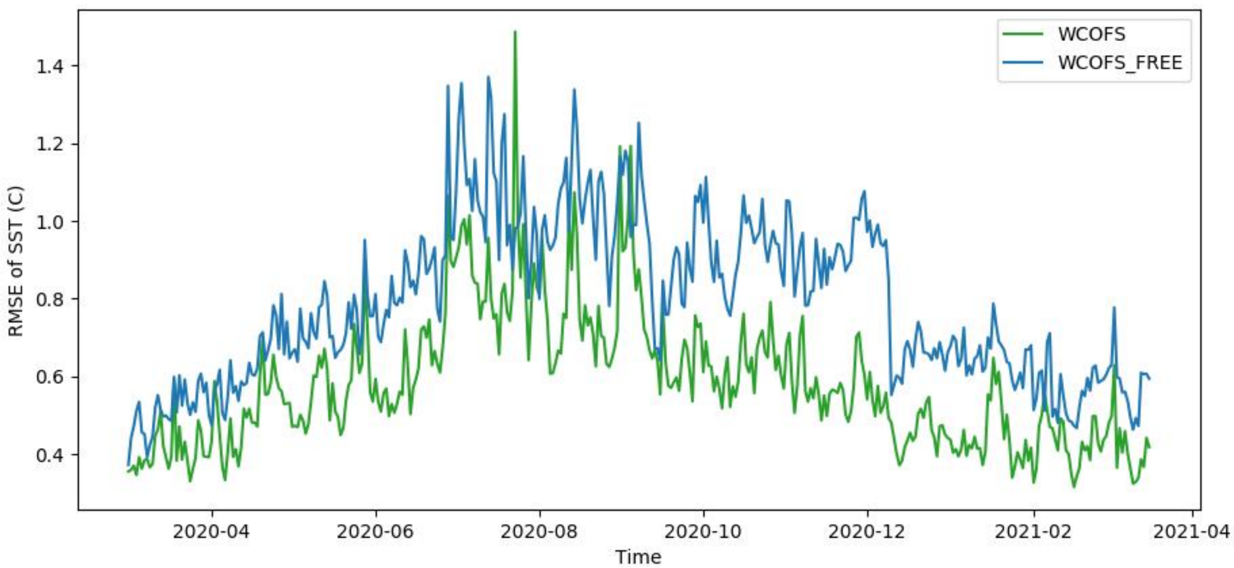

Figure 10. Root Mean Square Error (RMSE) of modeled surface water temperature day 1 forecast when compared with satellite SST.

For water temperature, we also run the standard NOS skill assessment package (Hess et al. 2003, Zhang et al. 2006, Zhang et al. 2010) to compare the model results with in situ time series observations from NDBC buoys and NOS tide gauges. These datasets serve as independent observations for evaluating model performance because the model does not assimilate in situ observations.

Figure 11 depicts the locations of the 69 stations with observations, along with the nowcast water temperature RMSE calculated from WCOFS at each station for the period spanning from March 2020 to March 2021. The nowcast water temperature's RMSE ranged from 0.36 to 2.69 ℃, and averaged 1.15 ℃ over all stations. The model performed very consistently over the full 3-day forecast time period (Figure 12).

In contrast to the notable improvement of WCOFS over WCOFS_FREE when compared with satellite SST, WCOFS and WCOFS_FREE both performed well when compared with in situ observations from the NDBC buoys and the NOS tide gauges. For example, the average RMSE of the WCOFS nowcast water temperature over all stations was 1.15 ℃, which is similar in magnitude to the RMSE of 1.18 ℃ from WCOFS_FREE.

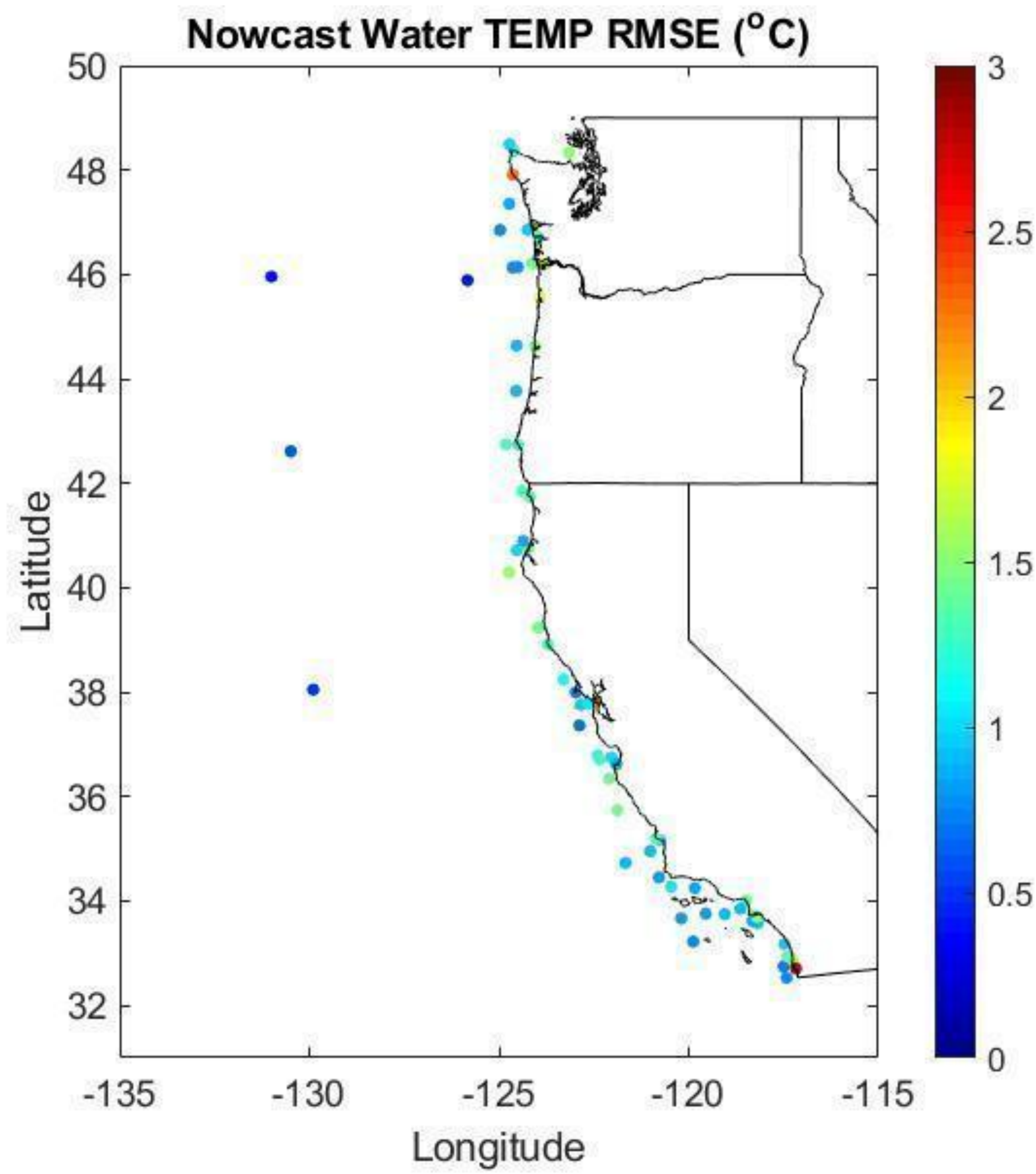

Figure 11. The Root Mean Square Error (RMSE) of nowcast water temperature from WCOFS when compared with in situ water temperature observations from NOAA National Data Buoy Center (NDBC) buoys and National Ocean Service (NOS) tide gauges.

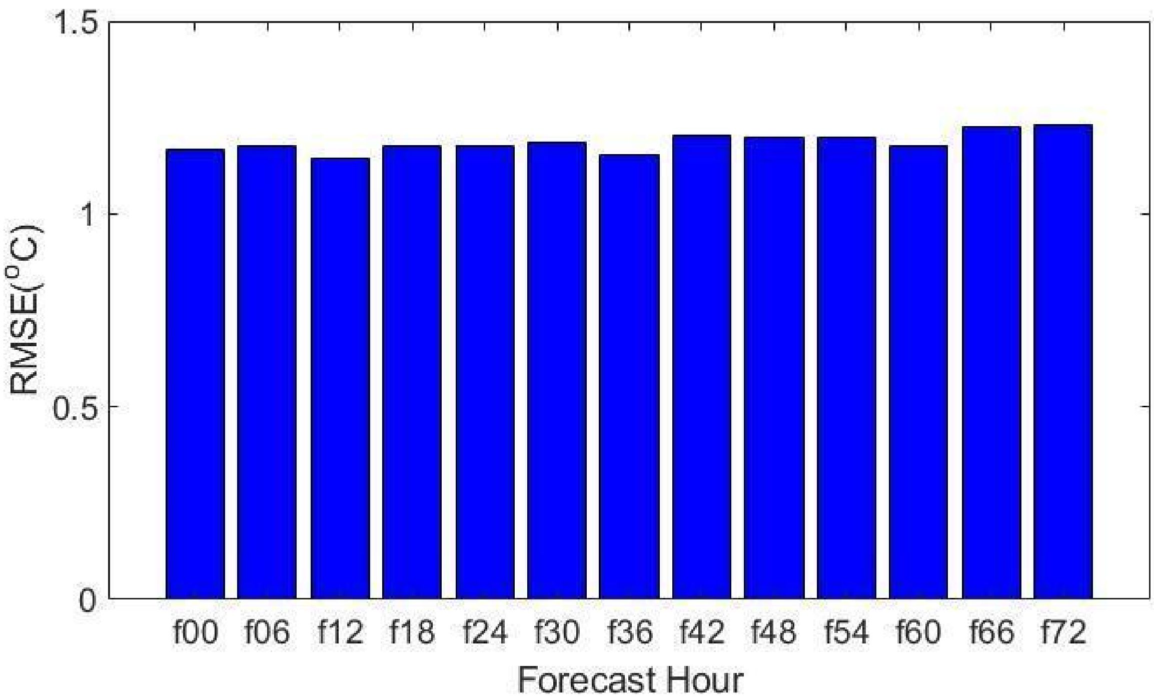

Figure 12. The Root Mean Square Error (RMSE) of WCOFS surface water temperature averaged over all stations at different forecast hours. The model temperature forecast skill did not change throughout the 3-day forecast period.

However, time series comparisons show that WCOFS was better than WCOFS_FREE during certain time periods or events. Figure 13 is an example of WCOFS and WCOFS_FREE nowcast water temperatures compared with in situ observations at West Washington (Station 46005). Both models reproduced the seasonal pattern and compared very well with observations. In the late summer and fall (October to November 2020), the transition months from upwelling to downwelling-favorable conditions, the data-assimilating model (WCOFS) was closer to the observations.

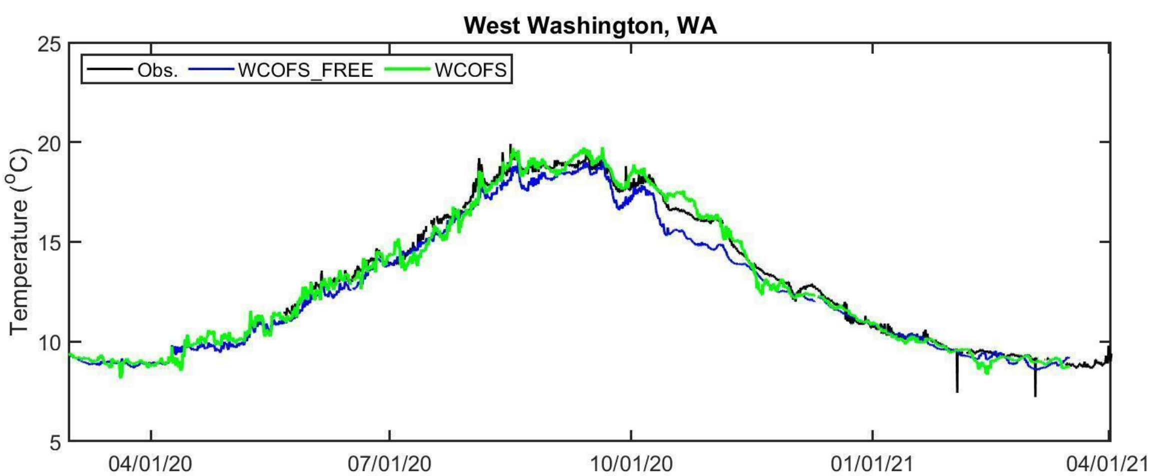

Figure 13. The surface water temperature comparison between model nowcast and observation at the National Data Buoy Center (NDBC) buoy at West Washington (Station 46005).

5.3 Sea Surface Height

As previously mentioned, our model evaluation did not focus on water level. All tide gauges are located along the coast; however, due to the coarse grid resolution, the WCOFS domain does not extend into all estuaries and bays and cannot resolve the bathymetry near the coast. During the model development, Kurapov et al. (2017a) examined, in detail, the water level variability along the coast in the 2 km version of the non-data assimilative WCOFS and recommended the total water level should combine the tidal water level from the best available shallow water inverse model, the atmospheric pressure correction, and the low-pass filtered (or non-tidal) water level from WCOFS. In the operational setting, with a 24-hour nowcast and 72-hour forecast simulation period, a low-pass filter cannot be successfully applied to the full time series. Instead, we recommend using the modeled tidal constituents to de-tide the water level. Because the NOS skill assessment package has not been updated to handle all of these requirements, the skill assessment for the total water level was not performed, as has been done for other operational forecast systems.

To assimilate along-track SSH from satellites, pre-generated model tides are added to the observations so the data assimilation scheme only corrects the non-tidal component. The slope in the non-tidal water level shows the location and strength of geostrophic eddies and fronts. Therefore, we routinely monitored and checked the along-track SSH fit during both the analysis cycle and the nowcast/forecast cycle. Figure 14 shows an example of a Sentinel 3b track and the along-track SSH comparison between the satellite observations and model forecasts from the run launched on September 25, 2020, at 03:00 Universal Time Coordinated (UTC). The along-track SSH showed a 25 cm sea level rise over a distance of about 200 km close to the northern California coast. WCOFS_FREE, without data assimilation, showed a slight depression of the sea level off the coast and a sea level rise much farther off the coast and further along the track. Although this exact track was not yet assimilated into the system, WCOFS was able to forecast the observed rise and fall of the sea level along the track, likely due to the effect of assimilating altimetry along earlier tracks and also assimilation of the HFR surface currents.

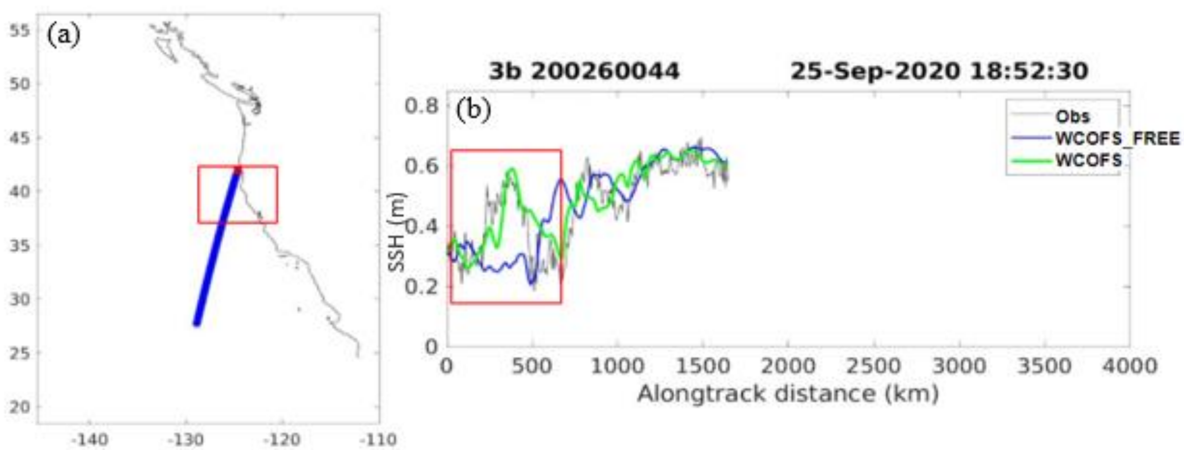

Figure 14. (a) Sentinel 3b track position within the WCOFS model domain. The small red dot on the track, showing the starting position inside the model, indicates a descending pass of the satellite. (b) The along-track sea surface height (in meters) comparison between models (WCOFS in green and WCOFS_FREE in blue) and satellite observations in black. The red box in (a) shows the part of the track highlighted as the red box in (b).

Figure 15 shows the SSH and circulation pattern from both WCOFS_FREE and WCOFS for the coastal area within the red rectangle shown in Figure 14. The blue dotted line shows the ground track of the Sentinel 3b descending pass discussed above, which went southwest from the coast at the Oregon and California border. Off the northern California coast, the ground track crossed an anticyclonic eddy in WCOFS, which was not generated in WCOFS_FREE. The existence of the eddy in this area corresponded with the satellite along-track SSH (Figure 14b). Data assimilation improved the eddy's position and intensity in WCOFS.

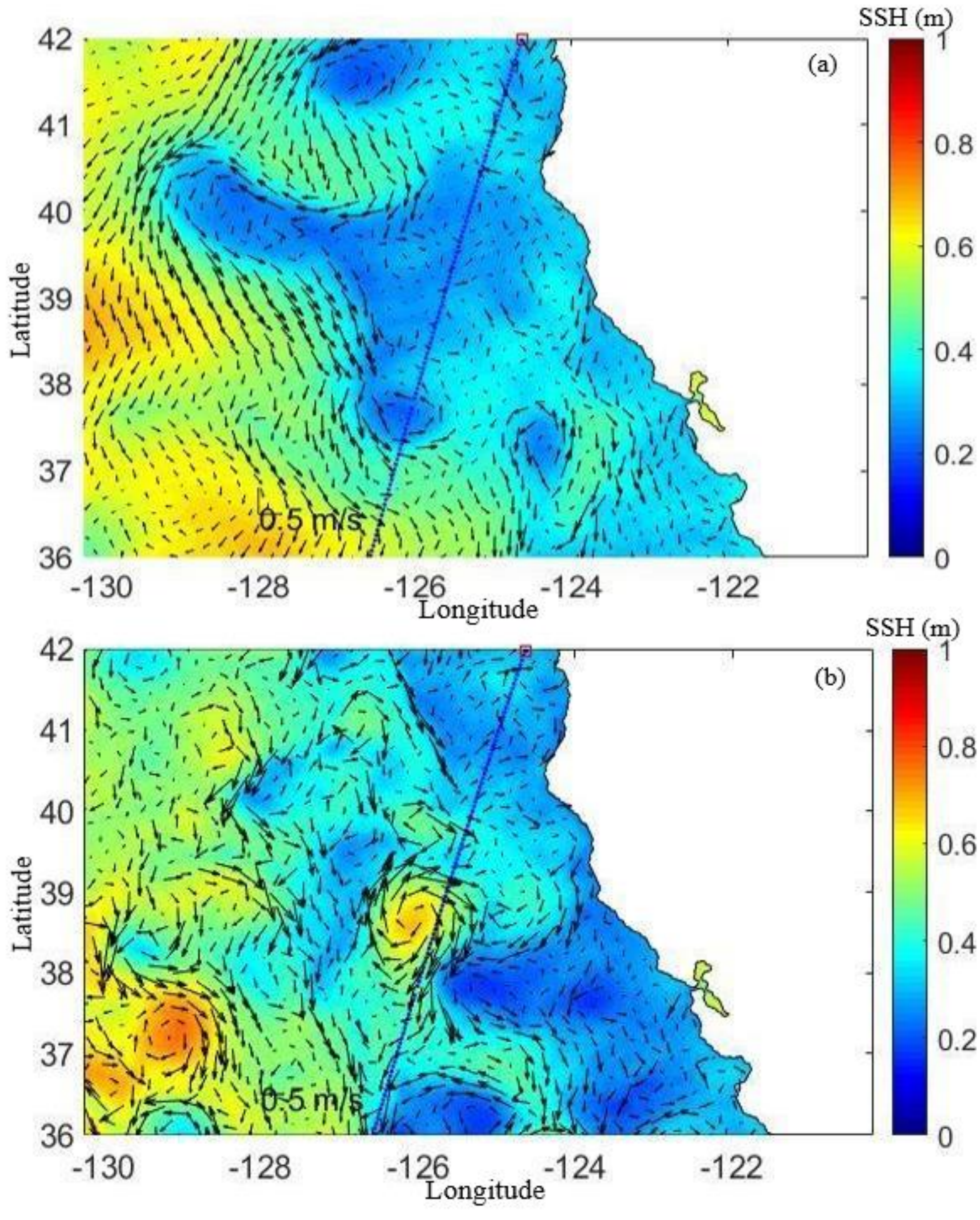

Figure 15. The sea surface height (SSH; color) and surface current (vectors, shown every 5 grid points) from (a) WCOFS_FREE and (b) WCOFS at 09:00 Universal Time Coordinated (UTC) on 9/25/2020. The blue dotted lines show the Sentinel 3b track with the red square indicating the track starting position within the WCOFS domain.

6. SUMMARY AND DISCUSSION

WCOFS, developed by NOAA's National Ocean Service, provides daily updates of 3-day forecast guidance of currents, temperature, salinity, and sea level to guide navigation, fishery operations, search and rescue missions, and environmental incident response, among other uses.

WCOFS is based on ROMS with 4DVAR data assimilation, and it assimilates satellite altimetry (non-tidal sea level), satellite SST, and HFR surface current velocities. Because WCOFS is the first coastal ocean operational forecast system with data assimilation, a natural free run, WCOFS_FREE, maintained throughout the development period and in operations, serves as a benchmark to help with understanding and, if needed, troubleshooting the data assimilative system. WCOFS with data assimilation was run semi-operationally on WCOSS beginning in August 2018 and was successfully transitioned into operations on March 22, 2021. The skill assessment was performed using the 1-year nowcast and forecast results from March 2020 to February 2021. Data assimilation in WCOFS improves the surface coastal currents, surface temperature, and eddy locations in the nowcast and forecast fields. To use the operational WCOFS sea level output would require additional post-processing to consider the datum offset, more accurate tides, and the atmospheric pressure effects (Kurapov et al. 2017a).

Surface salinity is not constrained by data assimilation in this system. Assimilation of the other observation types modifies the salinity fields through the dynamical coupling between the correction fields provided by the ROMS adjoint model. At this stage, the best strategy is to reduce the salinity adjustment and leave it closer to the model result before assimilating observations. In the real-time operational model, the background salinity standard deviation at the surface is assigned a relatively small number of 0.02 practical salinity units. Studies are still ongoing to examine the potential of assimilating salinity observations from satellites and in situ sources.

Even though WCOFS has been transitioned to operations, many questions remain, and significant work is still needed to further improve the system. With the data assimilation system in place, efforts can now focus on the sensitivity and impact of the observations on certain aspects of the model, such as temperature forecast errors, front locations, etc. Many areas of the existing system will benefit from further research and development. Better quality control and quality assurance of real-time observations are needed to remove bad observations from the system's data stream. The quality control for numerical weather prediction (NWP) systems is not fully automatic and employs operators. Similar requirements for operator-aided control can and should be established within NOS, particularly because the coastal ocean data assimilation systems are much less mature than NWP models. More observations, particularly subsurface observations, should be evaluated and assimilated to constrain and improve the model dynamics. Incorporating the in-situ data, such as Argo and glider profiles, must be done with care to avoid generation of spurious energetic large-scale eddies (Pasmans et al. 2019). In September 2021, the ROMS community model released a new version that included the tide generating forces. Tidal simulation in WCOFS should be performed and calibrated to improve the tides in the model.

In terms of modeling community efforts, specific advances of interest include:

(1) Improved background error covariance formulation. The covariance utilized in ROMS provides separate smoothing of errors for SSH, temperature, salinity, and 2 horizontal components of velocity. In reality, the errors in these fields are correlated (Weaver et al. 2005, Kurapov et al. 2011, Pasmans and Kurapov 2019). Proper

specification of the covariance yields better data fits, faster DA convergence, and improvement in the forecasts, in particular for the poorly observed fields.

(2) Better flexibility in data treatment. The present ROMS configuration only allows assimilation of data that is local in space and time. Modifications to assimilate radial component HFR data rather than the (u,v) maps is desirable because the former have a more uniform error model. The radial components will constrain the linear combination of u and v. The present system assimilates hourly HFR current observations, in which the high-frequency component contains poorly predictable and energetic internal tides and inertial oscillations. A better approach will be to filter the non-predictable component and assimilate daily-averaged data (Yu et al. 2012) or to include a more appropriate low-pass filter as part of the data assimilation system. With regard to the SSH assimilation, it will be better to assimilate the geostrophic slope than SSH itself and to treat the SSH data as daily-averaged instead of repeating the data within a 24-hour window. Microwave observations, such as surface salinity, are averages over the area of several tens of km across. These data must be matched by the assimilation system to the area averaged model fields (Pasmans et al. 2020).

(3) ROMS 4DVAR is rather slow and will not allow us to improve the resolution of WCOFS to 2 km, which is the coarsest resolution that still resolves slope processes. Ways to improve the efficiency of 4DVAR must be explored.

(4) Incorporate 4DVAR within the marine Joint Effort for Data Assimilation Integration (JEDI) system and build the coastal applications within the Unified Forecast System (UFS). Being part of the marine JEDI and UFS will enable us to better leverage and support the continued community efforts in improving the model physics, computation efficiency, and data utilization.

In many regards, despite these shortcomings, WCOFS presents important developments, including:

- providing useful regional scale oceanic forecasts of the surface currents, temperature, and other fields;
- serving as a pathfinder for future efforts in coastal ocean data assimilation and forecasting;
- increasing utilization of NOAA satellite data;
- creating synergy between the model and observations from different platforms; and
- establishing collaborations within NOAA (NOS/OCS/CSDL, NOS/CO-OPS, NESDIS), along with connections to external partners.

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ACRONYMS

4-Dimensional Variational	4DVAR
absolute dynamic topography	ADT
Advanced Baseline Imager	ABI
Advanced Microwave Scanning Radiometer	AMSR
Central California	CCA
degree Celsius	°C
centimeter	cm
centimeter per second	cm/s
Coastal Ocean Modeling Framework	COMF
Coastal and Ocean Modeling Testbed	COMT
Center for Operational Oceanographic Products and Services	CO-OPS
Coast Survey Development Laboratory	CSDL
data assimilation	DA
Dilution of Precision	DOP
GOES-17	G17
Global Forecast System	GFS
Geostationary Operational Environmental Satellite	GOES
High Frequency Radar	HFR
High Performance Computing	HPC
Integrated Ocean Observing System	IOOS
Joint Effort for Data Assimilation Integration	JEDI
kilometer	km
meter	m
meter per second	m/s
NOAA-20	N20
North American Mesoscale Forecast System	NAM
National Centers for Environmental Prediction	NCEP
NCEP Central Operations	NCO
National Data Buoy Center	NDBC
National Environmental Satellite, Data, and Information Service	NESDIS
National Oceanic and Atmospheric Administration	NOAA
National Ocean Service	NOS

numerical weather prediction	NWP
Suomi National Polar-Orbiting Partnership	NPP
National Weather Service	NWS
Office of Coast Survey	OCS
Operational Forecast System	OFS
Oregon	ORE
Radar Altimeter Database System	RADS
root mean square error	RMSE
Regional Ocean Modeling System	ROMS
Real Time Ocean Forecast System	RTOFS
Satellite with ARGOS and ALTIKA	SARAL
Southern California	SCA
Sea Surface Height	SSH
Sea Surface Temperature	SST
Satellite Applications and Research	STAR
Unified Forecast System	UFS
U.S. Geological Survey	USGS
Universal Time Coordinated	UTC
Visible Infrared Imaging Radiometer Suite	VIIRS
West Coast Operational Forecast System	WCOFS
Weather and Climate Operational Supercomputing System	WCOSS