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Development, implementation, and validation of a California coastal ocean modeling, data assimilation, and forecasting system

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ABSTRACT

A three-dimensional, near real-time data-assimilative modeling system for the California coastal ocean is presented. The system consists of a Regional Ocean Modeling System (ROMS) forced by the North American Mesoscale Forecast System (NAM). The ocean model has a horizontal resolution of approximately three kilometers and utilizes a multi-scale three-dimensional variational (3DVAR) data assimilation methodology. The system is run in near real-time to produce a nowcast every six hours and a 72-hour forecast every day. The performance of this nowcast system is presented using results from a six-year period of 2009–2015.

The ROMS results are first compared with the assimilated data as a consistency check. RMS differences in observed satellite infrared sea surface temperatures (SST) and vertical profiles of temperature between observations and ROMS nowcasts were found to be mostly less than 0.5 °C, while the RMS differences in vertical profiles of salinity between observations and ROMS nowcasts were found to be 0.09 or less. The RMS differences in SST show a distinct seasonal cycle that mirrors the number of observations available: the nowcast is less skillful with larger RMS differences during the summer months when there are less infrared SST observations due to the presence of low-level clouds. The larger differences during summer were found primarily along the northern and central coasts in upwelling regions where strong gradients exist between colder upwelled waters nearshore and warmer offshore waters. RMS differences between HF radar surface current observations and ROMS nowcasts were approximately 7–8 cm s^{-1}, which is about 30% of the time mean current speeds in this region. The RMS differences in sea surface height (SSH) between the AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic) altimetric satellite observations and ROMS nowcasts were about 2 cm. In addition, the system realistically reproduces the interannual variability in temperatures at the M1 mooring (122.03°W, 36.75°N) in Monterey Bay, including the strong warming of the California coastal ocean during 2014.

The ROMS nowcasts were then validated against independent observations. A comparison of the ROMS nowcast with independent profile observations of temperature and salinity shows RMS differences of 0.7 to 0.92 °C and 0.13 to 0.17, which are larger (by up to a factor of 2) than the differences found in the comparisons with assimilated data. Validation of the depth-averaged currents derived from Spray gliders shows that the flow patterns associated with California Current and California Undercurrent/Davidson current systems and their seasonal variations are qualitatively reproduced by the ROMS modeling system.

Lastly, the impact of two recent upgrades to the system is quantified. Switching the lateral boundary conditions from a U.S. west coast regional model to the global HYCOM (HYbrid Coordinate Ocean Model) model results in an improvement in the simulation of the seasonal and interannual variations in the SSH, especially south of Pt. Conception (120.47°W, 34.45°N). The assimilation of altimetric satellite SSH data also results in an improvement in the model surface currents when compared to independent surface drifter observations.

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1. Introduction

The California coastal ocean is one of the United States' most important resources, both economically for its fisheries and ecologically for its diversity. It is home to several National Marine Sanctuaries, including the Monterey Bay National Marine Sanctuary (montereybay.noaa.gov), a federally protected marine area offshore of California's central coast. Both fisheries and ecosystems are quite sensitive to changes in environmental conditions such as temperature, salinity, and currents as evidenced by the impacts of the major warming event of 2014-15 (Whitney, 2015; *Opar*, 2015; *NOAA*, 2016a, b). The need to understand and predict changes in these variables has been underscored recently by this unprecedented warming event in the region. Beginning in 2014, exceptionally warm temperatures developed across a wide area off the California coast (Bond et al., 2015; Zaba and Rudnick, 2016). Near-surface positive temperature anomalies exceeded 4 °C in certain regions and persisted for much of the year and into 2015 (Zaba and Rudnick, 2016).

With the goal of characterizing and predicting environmental conditions in California's coastal ocean in near real-time, we have developed a three-dimensional data-assimilative modeling system based on the Regional Ocean Modeling System (ROMS) code. This system has been producing nowcasts (analyses of the current ocean state) four times per day and a daily 72-hour forecast in near real-time since 2009 to the present time. By near real-time we mean that model nowcasts and forecasts are generally available about 9 h behind real-time; for example, the 03 UTC nowcast would be available at around 12 UTC. The ROMS modeling system is an integral part of the Central and Northern California Ocean Observing System (CeNCOOS, http://www.cencoos.org) and the Southern California Coastal Ocean Observing System (SCCOOS, http://www.sccoos.org), two regional associations of the national Integrated Ocean Observing System (https://ioos.noaa.gov/).

To place this current modeling work in the context of some of our previous California coastal ocean modeling work, we review here the model configuration used in Chao et al. (2009) and discuss some of the differences between that system and the one presented here. The most important thing to note is that these two modeling systems were designed to achieve different goals. The Chao et al. (2009) Monterey Bay (MB) system was designed with the aim of simulating (and forecasting) as realistically as possible the summer circulation within and around Monterey Bay (MB) with an emphasis on coastal upwelling and downwelling events and the transitions between them. In order to do this, a relatively high horizontal resolution ocean model and accurate, high-resolution wind forcing were necessary. A nested modeling approach was chosen that was focused on an innermost nest covering a relatively small area (MB and surroundings) at a relatively high horizontal (1 km) resolution. The CA system described in the current paper was designed to be much more comprehensive in terms of the region covered and phenomena we aim to reproduce (see Section 2.1 for a complete description of these phenomena), as we attempt to realistically simulate the environment further offshore – for example, the California current system and its associated mesoscale eddies - and tides (and tidal currents), while still aiming to do reasonably well in simulating nearshore phenomena such as upwelling.

These differences in goals are the reason behind many of the differences between the two systems. For example, in the current CA system we have chosen a uniform intermediate horizontal resolution (3 km) and a few more vertical levels (40 versus 32) applied to a much larger single domain compared to the 1 km resolution for the much smaller innermost domain of the MB system. Also, while tides are not essential for simulating coastal upwelling events and thus were not included in the MB system, they are included in the CA system as they are essential if we want to reproduce tidal phenomena. With the MB system's focus on upwelling, high-resolution coastal winds were essential and thus the COAMPS atmospheric model wind fields were used for the MB system since they were the highest horizontal resolution (3 km for the innermost nest) winds available during the period simulated (summer 2003), while we use the NAM (either 12 or 5 km) winds for the CA system because the high resolution COAMPS model domain does not cover our entire expanded CA domain. Similar considerations apply to the data assimilation, we have switched to a more comprehensive multi-scale 3DVAR methodology that assimilates temperature, salinity, sea surface height, zonal and meridional current data rather than only temperature and salinity (T, S) since while assimilating (T, S) only was adequate (assuming accurate wind forcing) for simulating the upwelling/downwelling events the MB system focused on, the more comprehensive CA system clearly benefits from assimilating all available data types. The advantages of multi-scale 3DVAR used here compared to the single-scale 3DVAR used in MB system will be outlined in Section 2.5 and the advantages of choosing HYCOM output for the lateral boundary forcing in the CA system as opposed to the Levitus climatology used for the outermost nest in the MB system are discussed in Section 4.

We present here the first comprehensive documentation of the model, the data assimilation method, and the performance of six hourly nowcasts. The performance of the ROMS forecasts will be reported in a separate study. We begin with a detailed description of the ROMS-based modeling system, including the external forcing and data assimilation methodology used, in Section 2. In Section 3, we present a comparison of the ROMS nowcasts with observations that are assimilated and a validation of the ROMS results by comparing them with independent (non-assimilated) observations. In Section 4, we explore the impact of several recent upgrades to the system. Finally, a summary and some concluding remarks are given in Section 5.

2. The ROMS-based California coastal modeling, data assimilation and forecast system

2.1. Ocean model

The California (CA) coastal ocean modeling system is based on the Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2000). The ROMS configuration used consists of a single domain covering the entire California coastal ocean from Ensenada, Mexico to north of Crescent City, CA and extending approximately 1000 km offshore at a horizontal resolution of 3.3 km (see Fig. 1). This particular model configuration was chosen to achieve several objectives: 1) to simulate the major flow features that characterize the California coastal ocean which include the near-surface equatorward California Current system (CCS) that lies several hundred kilometers offshore, the poleward California Undercurrent (CU) that peaks in strength between 100 and 300 m below the surface and the wintertime inshore Davidson current; 2) to resolve the mesoscale eddies associated with the CCS that are typically the flow type with the largest kinetic energy in this region (Capet et al., 2008a, 2008b); 3) to cover the entire area observed by the California HF radar surface current mapping network as well as all regions of interest for the Southern California and Central and Northern California coastal ocean observing systems (SCCOOS and CeNCOOS). Note that the system will not resolve the less energetic submesoscale fronts and eddies in the region discussed by Capet et al. (2008a, 2008b) and McWilliams (2016), nor the very small-scale circulations often generated very near shore (for example, rip currents). Eddies associated with the California Undercurrent (also known as Cuddies) are sub-mesoscale coherent vortices of horizontal scale less than 10 km and so are not represented in our system. Lastly, analyses are produced by the system every 6 h (see Section 2.5) because we aim to describe not only sub-tidal variabilities but also diurnal and semi-diurnal tidal currents and near-coastal wind-driven diurnal variability.

ROMS is a free-surface, hydrostatic, three-dimensional primitive equation regional ocean model (Shchepetkin and McWilliams, 2005, 2006; Marchesiello et al., 2001). The horizontal discretization uses a