# SURFACE TEMPERATURE AND SALINITY CHARACTERISTICS OF THE CALIFORNIA CURRENT SYSTEM

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## Abstract

Temperature and salinity (TS) conditions are a framework to characterize water masses that allow us to describe and understand dynamic processes like currents and how they change. While commonly used at depth, TS conditions at the ocean's surface and in coastal areas are not normally analyzed because of the concurrence of multiple processes that impact TS values in small scales. However, TS characteristics at the surface can give us information about regional changes in air-sea-land interactions and processes. Multiple platforms monitor salinity at all times, but it is expensive and mostly done at specific locations. The spatial coverage achieved with satellite data is still unsurpassed despite the shallow-depth and coastal limitations. Furthermore, for remote areas, satellite data might be the only available or continuous data. In this study, we investigate the use of remotely sensed sea surface temperature (SST) and sea surface salinity (SSS) data to identify regions with unique water characteristics along the California Current System (CCS), and assess their accuracy in comparison with data from 13 Saildrone cruises. We found that a cluster analysis of *in situ* data identifies six distinct TS regions, and that co-located and gridded satellite data did well at reproducing those areas at seasonal scales, despite biases. The only area that shows difference is the northern California coastal upwelling region, which can be due to coastal biases and/or the episodic nature of deep-water upwelling in this area during the summer.

## Introduction

Salinity is an important ocean variable of physical and biological interest. Normally studied at depth, it helps describe water masses and their movements, through density. Salinity is more dynamic at the surface and in coastal areas due to multiple boundary processes. In biological terms, salinity describes conditions favorable to different organisms, and this is of great importance in coastal regions. Salinity is not extensively studied, however, as it is expensive to measure *in situ*. Remotely sensed salinity is becoming increasingly used as its period of coverage and quality increases, but its application in coastal areas is still limited due to the coarse resolution and the land contamination related to its use of L-band microwave radiometry in salinity algorithms [7]. However, it has been shown [7] that SSS is accurate at distances greater than 50–100 km from land, regardless of ocean and atmospheric conditions, and that SSS gradients are well captured in coastal areas, even at biased magnitudes [8]. Therefore, SSS could now potentially be used to describe changing conditions along coastal regions.

In this study, we propose to use satellite SSS and SST to describe the surface water conditions of the CCS, a highly dynamic region due to the confluence of the subarctic water flowing year-round from the north along the California Current proper, the highly variable northbound undercurrent, and sporadic intrusions of northeastern Pacific water towards the coast. In addition, coastal processes like upwelling and river outflow also contribute to variability in CCS water properties [1]. We first describe surface water conditions with *in situ* data from Saildrone cruises. Then we compare the *in situ* data with remotely sensed SST and SSS, first using co-located data that match the Saildrone data, and later with gridded satellite data covering the CCS extent during summers with available data.

## Saildrone TS Data

Saildrone vessels are autonomous surface vehicles powered by wind that collect a range of ocean and atmospheric surface data [5]. Here we used SSS and SST data from 13 Saildrone cruises along the

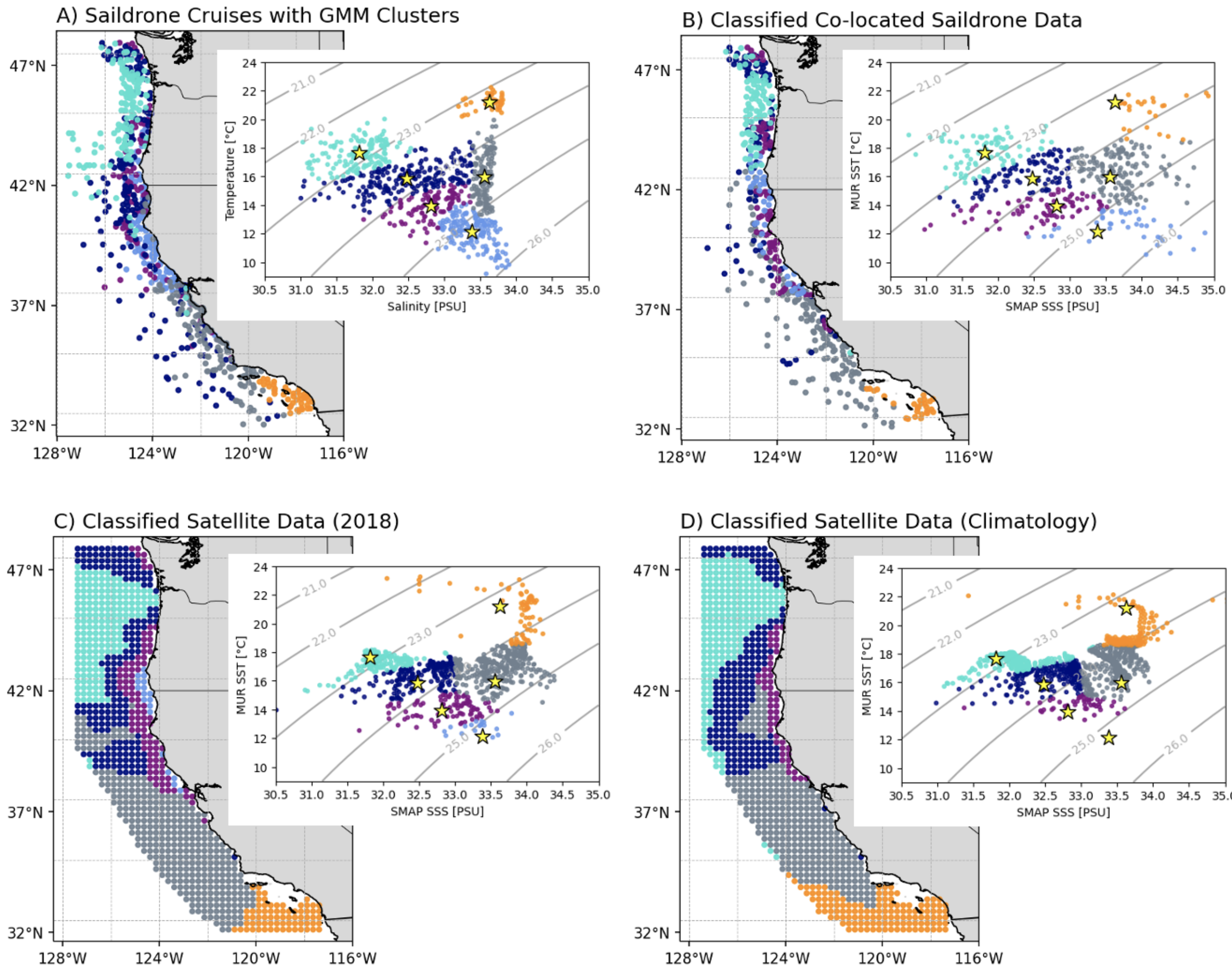


Figure 1. TS plots and maps showing summer data clusters by color based on clustering analysis of Saildrone SST and SSS cruises data in Jul.–Sept. 2018–2019. A) Saildrone data clustering analysis, B) satellite data co-located with Saildrone data, C) seasonal mean of satellite SST and SSS for summer 2018, and D) summer climatology (Jul.–Sept. 2015–2022) of satellite SST and SSS. Centroids from Saildrone data clustering analysis are indicated with a star. Data locations are shown in the maps, with color corresponding to clustering in the TS plots.

CCS during the summers (Jul.–Sept.) of 2018–2019 (see below for more details). Data were summarized daily and plotted in a TS (temperature-salinity) diagram (Figure 1a), and a gaussian mixture models (GMM) clustering algorithm was used to segregate points of similar characteristics. The centroids of these clusters were used to describe (and later classify) the satellite data, and the cluster identification number was then plotted back in a map to visualize the regions with distinctive surface TS characteristics.

The clustering analysis describes six different water types based on TS characteristics:

- Orange - High SSS, High SST: waters in the Southern California Bight
- Gray - High SSS, Mid SST: waters off central California
- Blue - High SSS, Low SST: northern California and southern Oregon coastal waters associated with coastal upwelling
- Purple - Mid SSS, Mid/Low SST: mostly waters along northern CCS and offshore of blue waters
- Navy - Low SSS, Mid SSS: mostly waters along northern CCS, between coastal upwelling waters and Columbia River waters
- Turquoise - Low SSS, High SST: Waters mixed with the Columbia River in the northern CCS, and its extended plume offshore and south.

**Co-located Satellite TS Data**

Daily Saildrone data were co-located with satellite SSS [3] and SST [2] (see Data section). First, we compared satellite SSS and SST values with Saildrone data to assess the uncertainty related to distance from the coast (Figure 2). The largest biases were seen in coastal pixels (<50 km) in both SSS and SST, decreasing in spread quickly for the 50–100-km band. Note that on average, satellite data magnitudes were larger in all distances for SSS and SST.

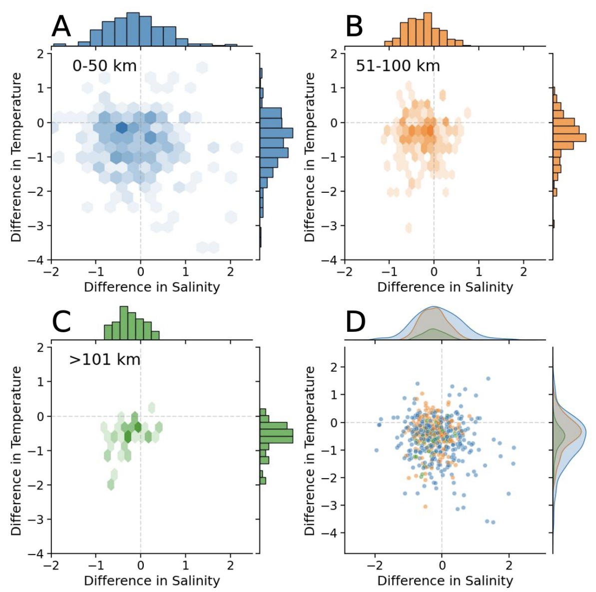


Figure 2. Distribution of differences between Saildrone and satellite data for SSS (x-axis, PSU) and SST (y-axis, °C) at distances A) 0–50 km from shore (blue), B) 51–100 km from shore (orange), C) farther offshore (green), and D) all distances combined.

We then used the centroids of the Saildrone cluster analysis to classify the co-located data into the designated clusters (Figure 1b). The TS diagram pattern differs from the Saildrone data, but once classified around the centroids of Saildrone clusters and plotted back in the map (Figure 1b), there is similarity in regional patterns for the orange, turquoise, navy, and gray clusters. Note that there are fewer points in the co-located data due to a gap in SMAP satellite observations in 2019 related to instrument problems. The blue and purple clusters, however, show different locations in the map, although they are clearly classified in the TS diagram. In the northern California region, rather than the solely coastal blue (high SSS, low SST) values of Saildrone, there are many more of the purple cluster (mid SSS, mid/low SST), while the blue ones are located further offshore.

**Satellite TS Data**

We then used gridded satellite data (SST regridded to match SSS grid) along the central and northern California Current System to classify each grid point using the centroids of the Saildrone cluster analysis. We did this for data averaged for the summer of 2018 and for the climatological summer (mean of all data Jul.–Sept. from 2015 to 2022; Figure 1C and 1D, respectively). Satellite data for summer 2018 shows similar distribution to the co-located data: southern California with high SSS and high SST (orange), while the central California coast and offshore areas are classified as high SSS, mid SST (gray). The Columbia River plume (low SSS and mid SST, turquoise) extends offshore and is surrounded by the navy cluster, also extending downstream. Northern California and Oregon coasts show areas of blue, representing high SSS and low SST upwelled water, surrounded by the purple cluster that shows slightly higher SST and SSS.

When all available satellite SSS years are considered (Figure 1D), summer conditions show similar patterns. The cold SST high SSS (blue) cluster is not present, however, and the purple water type is limited to a narrow coastal band off northern California and Oregon. This is likely due to the averaging of conditions in each grid point, as it includes a period of very warm water temperature during the 2014–2016 marine heatwave dubbed "The Blob" [4]. The Columbia River plume (turquoise) extends offshore and expands while also advecting downstream, and the central California water mass (gray) reaches the warm water of the southern California region.

**Discussion**

Surface salinity and temperature data allow us to see the spatial characteristics of the CCS in the summer beyond the classic SST view. Important features that this TS clustering framework highlights include the extent of the Columbia River plume and the three regions along the coast in relation to upwelling: i) northern California and Oregon with deep cold and saline waters with an offshore gradient, ii) central California waters that are saline and warm with less of an offshore gradient, and iii) the southern California warm waters.

The regional patterns of the TS cluster classification are consistent between Saildrone and satellite data at different time scales. The only cluster that differs is the blue one -high SSS and low SST and corresponding to upwelling of deep water. This cluster is seen in northern California and Oregon coasts, but not in all years or in the climatology. This could be caused by biases in the data, as satellite SST tends to be warmer than *in situ* data in strong upwelling conditions [6], however, satellite SSS also tends to be more saline (Figure 2), which would classify it as gray more often rather than purple (Figure 1B). Therefore, it is also likely that the reduced blue data in the satellite data is due to the episodic nature of upwelling, leading to periods of warmer and less saline waters in northern California, compared to colder waters further north in Oregon, where upwelling is strongest at this time of year.

In this work, we demonstrated that despite biases near the coast (<50 km) it is possible to use satellite SSS and SST data to describe regional characteristics of surface water in dynamic coastal areas. Removing or correcting the nearshore data might produce better estimation of nearshore areas, but we did not do so in this assessment in order to fully observe the effect of biases. The overall regional and regime descriptions, at seasonal scales, are not significantly impacted by the coastal biases. The climatology is, however, potentially due to large interannual change, which will be investigated in a future analysis.

## Data

Saildrone data collected during the North American West Coast Survey (NAWCS) in 2018 and 2019 were sponsored by NOAA, https://www.saildrone.com/data/west-coast-survey.

Soil Moisture Active Passive (SMAP) SSS from Jet Propulsion Laboratory (JPL) V5. Level 3 Product. Daily, 8-day running means. https://podaac.jpl.nasa.gov. Accessed: 1 March 2020.

The Multi-Scale Ultra-High Resolution Sea Surface Temperature (MUR SST). Level 4 Product. https://podaac.jpl.nasa.gov. Accessed: 1 March 2020.


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**Index Terms -** *sea surface salinity, sea surface temperature, SMAP, MUR SST, Saildrone, California Current System, upwelling*