OPEN OCEAN BIOGEOCHEMICAL IMPACTS OF EXTREME TERRESTRIAL PRECIPITATION

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Abstract. Extreme events reshape ocean ecosystems with significant implications for nutrient and carbon cycling. Here we demonstrate that flooding on land can be a significant driver of biogeochemical variability in the open ocean, even in dry climates. Using satellite observations, in situ measurements, and Lagrangian particle tracking, we present evidence that freshwater discharge from extreme precipitation during the 2023 water year was transported into the oligotrophic region of the California Current System. This transport was facilitated by submesoscale eddies and resulted in significant anomalies in surface salinity, stratification, nutrient concentrations and phytoplankton pigments. These observations, combined with an Earth system model, highlight the importance of episodic river discharge events in shaping offshore biogeochemical fluxes and ecosystem structure in eastern boundary current systems under a changing climate.

Extreme precipitation over the western US coast is projected to increase in frequency [Swain et al., 2018], which will have cascading effects on society and ecosystems. A likely direct impact will be an increase in flooding, resulting in increased episodic river discharge into the ocean in this relatively dry climate that does not typically experience large river discharges. Analysis of a climate model ensemble, the Community Earth System Model Large Ensemble (CESM LENS2), suggests that extreme river discharge into the ocean along the US West coast is likely to increase through the end of the century under a moderate climate change scenario (Figure 1A) alongside increased precipitation [Swain et al., 2018].

The impact of extreme river discharge on ocean ecosystems depends on the fate of the fresh water that enters the ocean. Coastal eddy dynamics facilitate rapid transport, which has the potential to carry fresh water into the open ocean. However, climate models do not fully resolve the mesoscale and submesoscale processes nor the full range of ecological responses to an extreme event. Observational analysis is necessary to understand the impacts of extreme events. Here, we report observational evidence that eddy dynamics transport river discharge into the open ocean in the California Current, a mid-latitude eastern boundary current in a Mediterranean climate. We demonstrate that extreme river discharge events have important implications not just for coastal regions but also for open-ocean biogeochemistry.

Observational Results

US West coast water year 2023 had anomalously high precipitation due to multiple landfalling atmospheric rivers (ARs). The open ocean region off the coast of California was anomalously fresh during spring 2023, as observed in the SMAP salinity record (2015–present; Figure 1B). The number of landfalling storms, combined with the rapid succession of storms, led to record-breaking precipitation, exacerbated hydrological impacts, and led to high discharges into the coastal ocean.

Remarkably, *in situ* sampling that took place April 6-30, 2023 during the S-MODE IOP-2 [Farrar et al., 2025] in the offshore region of the California current (Figure 2A) near the peak of discharge and precipitation revealed that the large discharge event impacted not only the coastal ocean, but also the more oligotrophic open ocean. A multiday AR event on March 10–15, 2023 with peak integrated vapor transport exceeding 750 kg m^{-1} s^{-1} impacted the San Francisco (SF) Bay, Russian River, and Gualala-Salmon River watersheds immediately prior to sampling. From March 11-15 the event generated average daily integrated precipitation of 147.97 mm in the Russian and Gualala-Salmon watersheds and 101.37 mm in the SF Bay watershed. Discharge was transported at least 100 km offshore and had significant regional-scale physical and biogeochemical impacts. The observed region was significantly more stratified than in climatological conditions (Figure 1C). This increased stratification could inhibit vertical mixing, and therefore exchange, of biogeochemical material between the surface and interior, both in the coastal region and offshore.

In contrast to a typical year where upwelling-driven productivity is associated with relatively high salinity (> 33 psu), in the observations reported here from early April 2023, some offshore high chlorophyll features were associated with relatively low salinity (~ 33 PSU), even in the fresh offshore environment. We use Lagrangian methods, tracking water parcels backward using AVISO and GLORYS surface velocities, to interrogate the origins of the high chlorophyll water. Most of the high chlorophyll water parcels (identified in a MODIS image from April 11) originate near the Russian River and near the SF Bay Estuary (Figure 1D). A forward tracking analysis of coastal water parcel using HF radar fields demonstrated that water parcels can effectively escape offshore to the open ocean.

The mode of the date of origin at the coast corresponds to a runoff pulse that began on March 8, 2023, but some of the water parcels appear to have originated during an earlier upwelling pulse on February 15 (Figure 1D). The discharge during this period from the Russian River and SF Bay (from estuaries of 70 m and 5 km, respectively) is of equivalent magnitude to the upwelling flux (CUTI) during this period. The observed open ocean water mass salinity is in the range 32.5–33.4 PSU. We anticipate that the freshwater discharge mixed with ocean water both in coastal areas and offshore and therefore had larger-scale impacts.

The majority of the water parcels that appear to have originated from within the SF Bay Estuary in these observations are in a coherent submesoscale eddy (box in 2A), which has the highest observed chlorophyll concentration (4 mg m^{-3}) and an average particulate organic carbon concentration of 25 mg m^{-3}. This feature has trapped water with very low nitrate:phosphate (N:P) ratios and very high Si:N ratios, indicating a probable estuarine source that may have alleviated micronutrient limitation, resulting in nitrate drawn down to near zero with excess phosphate (Fig. 2B). The SF Bay Estuary is known to have excess phosphate [Cloern et al., 2020]. This feature also harbored a unique community with a predominance of fucoxanthin pigments, suggesting a diatom-dominated community, which is consistent with the relatively high Si. This feature, which had a radius of approximately 5 km, propagated westward at 6.5 km day^{-1}, generating an offshore carbon flux of 0.16 mg m^{-2} day^{-1}. This value is comparable to the average eddy flux of organic carbon in this system [Nagai et al., 2015]. Submesoscale eddies such as this one are prevalent in the California Current system and are potentially a significant route of carbon supply to oligotrophic offshore regions through cross-shelf transport.

The remainder of the high-chlorophyll filament that was sampled appears to have been sourced from farther north, which may include water masses that advected north from the SF Bay Estuary along the coast and water masses that originate from runoff from rivers between Cape Mendocino and SF Bay, including the Russian River. The observations from this region

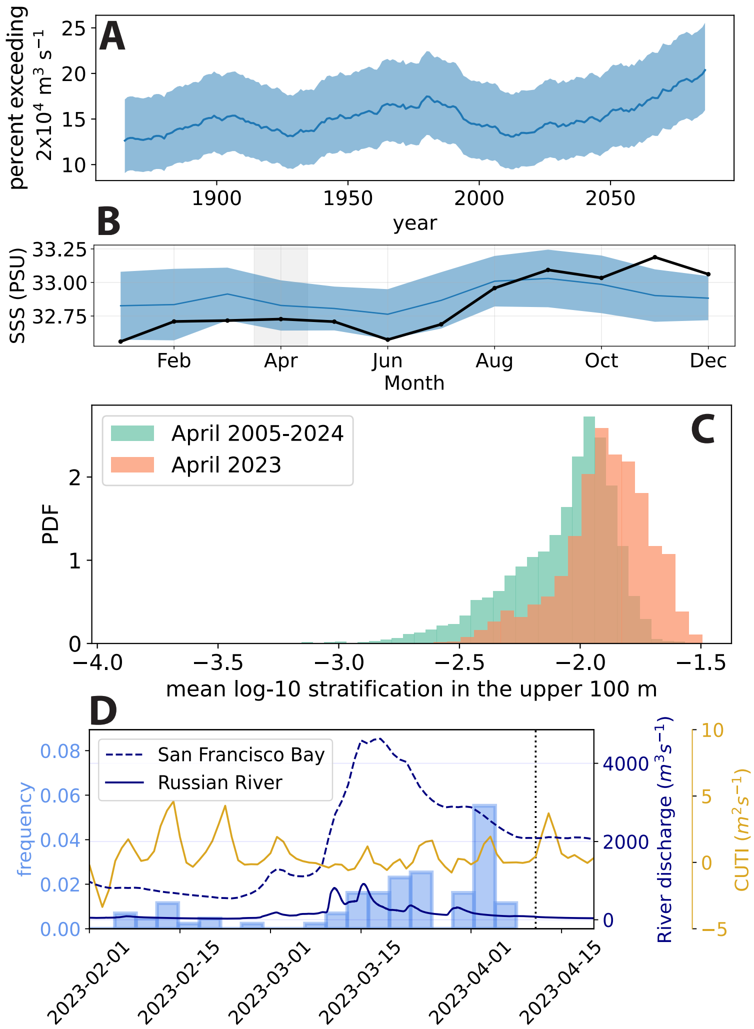

FIGURE 1. (A) Extreme river discharge to the ocean from the climate model ensemble CESM-LENS2 quantified as percent of 90 ensemble members with April discharge exceeding 20,000 m^3 s^{-1} integrated over the entire US West Coast. Shading is the 75% confidence interval. (B) Monthly average salinity and standard deviation (blue; 2015-2025, except 2023) in the California Current offshore of San Francisco from the SMAP satellite. Black line is monthly average in 2023. (C) Probability density functions of mean stratification in the upper 100 meters from the California Underwater Glider Network Line 66.7. (D) Particles are tracked backwards using GLORYS from regions with chlorophyll greater than 1 mg/m^3. Histogram in light blue shows date at which particles reach the coast. River discharge is in dark blue and the Coastal Upwelling Transport Index (CUTI) is in yellow.

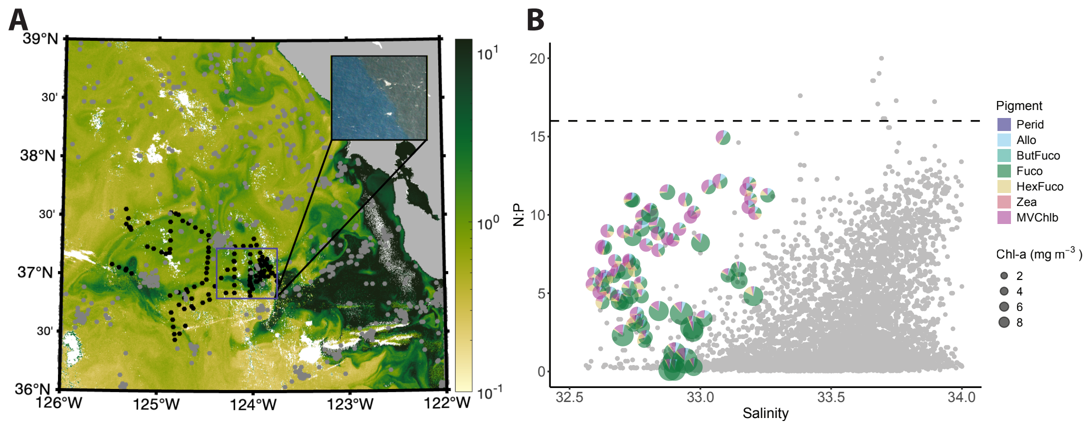

FIGURE 2. (A) Chlorophyll concentration in mg m^{-3} observed by Sentinel-3A on April 22, 2023. Black dots show the locations of nutrient samples. Grey dots show locations of CalCOFI stations. The inset image is a photo taken from a twin otter airplane showing the boundary between high and low chlorophyll waters. (B)Nitrate to phosphate ratio from surface CalCOFI observations, 1949–present (grey) and S-MODE observations (pie charts) as a function of salinity. The pie charts show the relative concentration of each pigment and the chart size is proportional to chlorophyll-a concentration. The dashed line is the Redfield ratio.

are anomalously fresh when compared with the historical CalCOFI record (1954–2024), consistent with the anomalously low regional salinity, but have a range of N:P that is similar to that of historical observations. This may indicate mixing along the water mass trajectories or N:P ratios in the source waters that are more similar to open ocean conditions. These water masses had high chlorophyll but significant concentrations of phosphate and nitrate, indicating potential limitation by micronutrients. The increased proportion of the pigments that are monovinyl chlorophyll-b suggest a green algae community. This presents a contrasting view of the impact of river discharge in which the biogeochemical anomalies are relatively limited.

Discussion

Nearly all of the precipitation leading to flooding in northern California is due to ARs, which transport moisture from the tropics to the mid latitudes [Ralph et al., 2006, Bartusek et al., 2021]. Extreme precipitation from ARs is projected to increase in frequency, which may lead to increasing land-ocean connections due to increased river discharge. Riverine runoff is one part of the salinity budget in the California Current, with advection and local precipitation also contributing, but it has unique implications for both circulation and biogeochemistry [Hoffman et al., 2022].

Nutrient conditions on land are typically different than in the open ocean, both with higher nutrients and different nutrient ratios. Terrestrial and coastal environments are also an important source of micronutrients such as iron, which is often limiting in the California Current system [Johnson et al., 1999, Hogle et al., 2018]. A release from micronutrient limitation may explain the low N:P ratios and predominance of diatom-associated pigments in the observations. This shift in composition could have ecological and biogeochemical implications. For example, diatom cells may sink more rapidly than other phytoplankton. Here we provide a nuanced view of the relevance of land-ocean nutrient transport with anomalous nutrient conditions leading to high chlorophyll observed in a submesoscale coherent eddy, but less anomalous biogeochemical signal in a chlorophyll filament. This adds to prior literature suggesting large offshore blooms in response to anomalous precipitation [Kudela and Chavez, 2004]. Thus, the biogeochemical implications of riverine-sourced runoff appear to be idiosyncratic and may vary depending on the timescale since the coastal origin as well as the biogeochemistry of the coastal source.

The biophysical implications of runoff-supplied nutrient input merit further study. In contrast to upwelling filaments, freshwater runoff is relatively light due to its low salinity. The dynamics of light filaments contrast with those of dense filaments [McWilliams et al., 2015]. Rather than sinking, light filaments may be dissipated by shear dispersion, resulting in an alternative pathway of carbon export and altered spatial distribution of offshore carbon flux and enhanced submesoscale lateral dispersion [Seitz and Freilich, 2025]. These shear-driven eddy dynamics may result in enhanced offshore transport rather than enhanced subduction [Gruber et al., 2011]. In addition, these observations highlight the need for a more nuanced understanding of the association between elevated chlorophyll and eddies. Submesoscale eddies such as that observed here might have high chlorophyll due to coherent trapping and water mass transport rather than upwelling in the eddy core and transport water quickly enough offshore to outpace loss due to grazing. Nonetheless, the observations demonstrate that coherent submesoscale eddies facilitate cross-shelf exchange [Jhugroo et al., 2024].

Our observations suggest that increasingly extreme precipitation on land may have ecological impacts in eastern boundary currents due to changing the nutrient regime, particularly alleviation of micronutrient limitation. These results may also be applicable in other regions with episodic riverine influence in the open ocean such as the Chilean coast, where precipitation is also dominated by atmospheric rivers and becoming more extreme [Lagos-Zúñiga et al., 2024]. Land management has biogeochemical implications for the open ocean, even in relatively dry eastern boundary current regions.

Materials and Methods

Monthly sea surface salinity was retrieved from the Soil Moisture Active Passive (SMAP) mission Level-3 v6.0 data with a spatial resolution of approximately 0.25 degrees. The SSS product was averaged for the S-MODE operations area [Farrar et al., 2025]. CESM2 Large Ensemble river discharge (Model for Scale Adaptive River Transport MOSART1.0) in the historical and SSP3-7.0 scenarios integrated over the US west coast was analyzed for the proportion of the ensemble members with discharge exceeding 2×10^4 m^3s^{-1}, which is 96th percentile of discharge. A 30-year running mean is plotted. Macronutrients and pigments were analyzed in samples collected from the shipboard underway system. Nutrients were analyzed with a Quickchem 8500 Lachat Flow Injection Analysis System while pigments were analyzed with an Agilent RR1200 HPLC. Precipitation estimates were obtained from the high-resolution ERA5-Land reanalysis, while integrated vapor transport (IVT) was obtained from the ERA5 reanalysis.

Acknowledgments

The authors are grateful to Pat Kelly, Dawn Outram, the S-MODE science team, the captain and crew of the R/V Sally Ride, and NASA grant 80NSSC24M0143.

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