Hypereutrophication, Hydrogen Sulfide, and Environmental Injustices: Mechanisms and Knowledge Gaps at the Salton Sea

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Key Points:

- The Salton Sea is a major source of elevated hydrogen sulfide emissions, with concentrations likely underestimated due to limited monitoring.
- Sensor placement and wind direction are crucial in H_2S monitoring, highlighting the distinction between measuring and detecting emissions.
- Environmental justice concerns arise as vulnerable communities are chronically exposed to harmful H_2S levels.

Abstract

The Salton Sea, California's largest lake, is undergoing significant environmental degradation, which has adverse health effects on nearby rural communities, who are primarily Latinx and Torres Martinez Desert Cahuilla Indian. Over the past two decades, the lake's water levels have steadily dropped. Water conditions in the Sea, characterized by low oxygen and high nutrient levels, favor the production of H_2S. This study investigates the connection between the Sea's changing conditions, particularly the worsening water quality, and hydrogen sulfide (H_2S) emissions using air quality and water quality data collected since 2013 and 2004, respectively. H_2S concentrations often exceed California's air quality standards, particularly in areas near the Sea during summer months. Wind patterns substantially impact detection of H_2S. When wind is blowing from the sea towards communities with sensors, which are located to the northwest of the sea, H_2S is detected significantly more often. Current monitoring efforts underestimate the frequency and distribution of H_2S that exceeds air quality standards. An air sensor deployed in shallow water over the Salton Sea by a community science program detected substantially higher concentrations of H_2S, particularly when wind was blowing over exposed sediment and shallow water, suggesting that these are a significant and overlooked H_2S source at the Salton Sea. These findings highlight the need for improved air quality monitoring and more effective environmental management policies to protect public health in the region. The study emphasizes the importance of community-led solutions and provides insights relevant to other regions experiencing similar environmental crises.

Plain Language Summary

The Salton Sea is a heavily contaminated shrinking lake that affects the health of surrounding vulnerable communities in the Coachella and Imperial Valleys. Due to high-nutrient agricultural runoff entering the lake and resulting low oxygen levels, the lake often emits hydrogen sulfide (H_2S), a harmful gas. The study aims to understand what causes H_2S emissions with the aim of predicting and reducing emissions. Using data collected over the past two decades, the connection between water conditions, air quality, and wind patterns was examined to understand when and where harmful H_2S levels occur. During the study period, H_2S concentrations near the Salton Sea frequently exceed California's air quality standards, especially during summer and when winds blow towards communities. Community-deployed sensors detected higher levels of H_2S due to the placement within the sea and suggested emissions from exposed sediment and shallow water. However, current monitoring efforts underreport the scale of H_2S impacts. These findings serve as evidence for the urgent need to improve air quality monitoring and policies to protect public health in the Salton Sea region. Community-led solutions as the ones employed in this study are critical for overcoming environmental injustices and serve as a framework for similar situations worldwide.

1 Introduction

Amidst accelerated climate change, the Salton Sea, the largest lake in California, poses a unique threat to the health and well-being of the surrounding rural environmental justice communities. The Salton Sea is located 262 km east of Los Angeles, California in the Colorado Desert subdivision of the Sonoran Desert (Figure 1) in a basin which experiences extreme heat with temperatures reaching over 43°C in the summers, and cold winters with lows of 1°C. The lake is 58 km long, 24 km wide, presently reaches depths up to 11 m and its present water level is 73 meters below sea level (USGS, 2023, Tompson, 2016). The Sea, as we currently know it, formed in 1905, when Colorado River water breached an irrigation canal and spilled into the Salton Sink. However, previous bodies of water such as Lake Cahuilla have intermittently occupied the Salton Basin across history (Voyles 2021, Ross 2020).

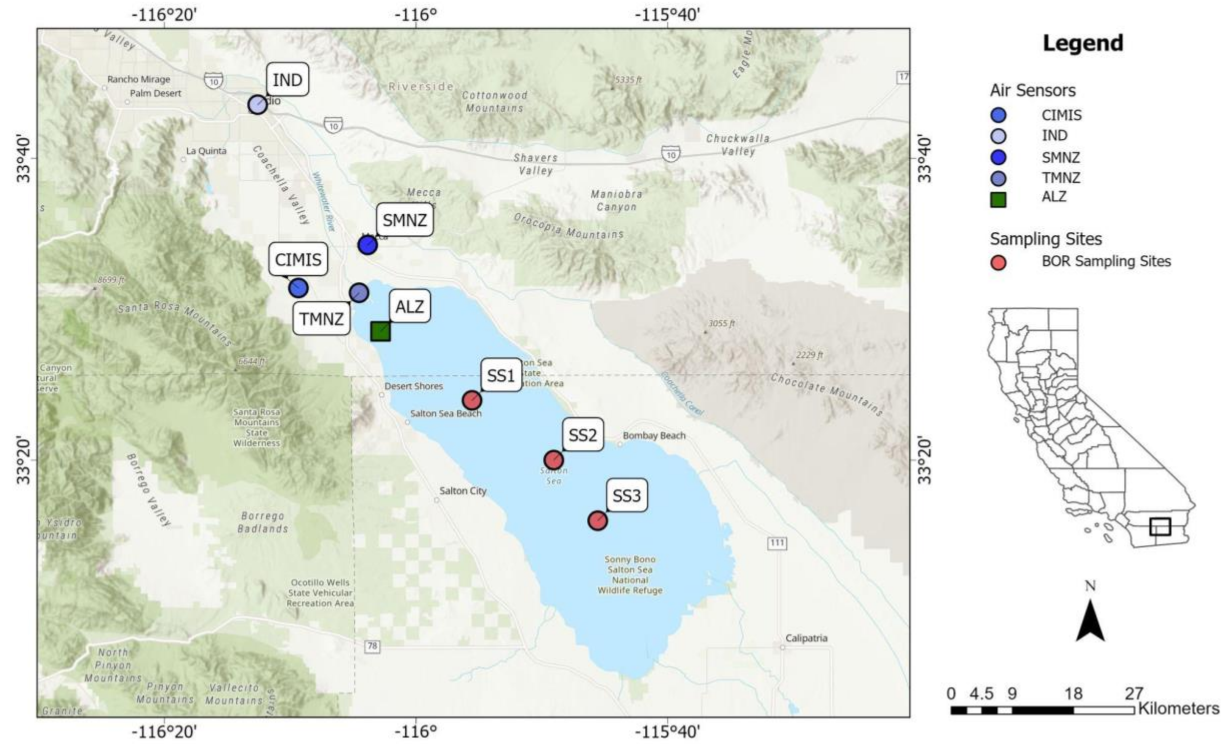

Figure 1 *Map of Salton Sea and Coachella (NW) and Imperial (SE) valleys with air sensor locations and sampling sites.*

Considered an endorheic basin (a basin that retains water and allows no outflow), the main inflow for the Sea is agricultural runoff from the highly productive agricultural lands surrounding the basin with a minor contribution from rainfall. Exacerbated water shortages in the Western United States, driven by climate change, local policies like the Quantification Settlement Agreement (QSA), and rising temperatures, have caused Salton Sea water levels to decline by 0.2 meters per year for nearly two decades resulting in a decrease in the lake depth of approximately 4 meters since 2003 (USGS, 2023; Figure 2). This has led to serious health impacts, including higher concentrations of dissolved substances (Frie, 2017) and increased exposure to dust from emissive playa (Parajuli et al., 2018). In order to provide actionable information about climate impacts on this desert community, we strive to more precisely establish the connection between the Salton Sea and the health of nearby communities.

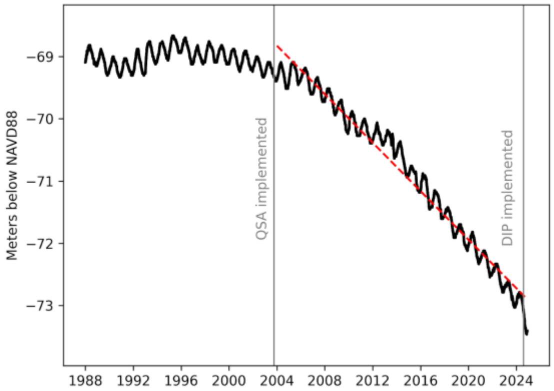

Figure 2 *Salton Sea water level relative to NAVD88, as recorded by the USGS Westmorland water gauge (station # 10254005). The vertical grey lines denote the enactment of the Quantification Settlement Agreement (QSA) and the Deficit Irrigation Program (DIP). The dashed red line represents the linear fit, with a slope of - 0.2 m/year.*

The communities surrounding the Salton Sea are largely Latinx and Torres Martinez Desert Cahuilla Indian, with over 23% living below the poverty line in the zipcode that straddles the north shore (U.S. Census Bureau, 2021). Many of the residents are farmworkers, working on the same fields that eventually run-off to the Salton Sea. Due to the demographic and socioeconomic make-up, as well as the high environmental pollution burden, these communities can be characterized as subject to environmental injustices (Raphael and Matsuoka, 2024).

Air quality is a particular concern for communities in the Salton Sea region. Excessively high asthma rates and pulmonary illness among the surrounding communities have been documented recently (Miao et al., 2022; CIRS, 2021; Sinclair et al., 2021; Farzan et al., 2019; Johnston et al., 2019; Sinclair et al., 2018). The high prevalence of respiratory issues are often attributed to dust from the dried lake bed (Biddle et al., 2022). However, recent studies (Biddle et al. 2021) have suggested that aerosolized particles from the Salton Sea seawater can induce an inflammatory lung response in an animal model, opening the possibility that a wide range of particles could have health impacts on local communities.

Another prominent air quality concern is malodors due to hydrogen sulfide (H_2S) emitted from the Sea. Some established sources of H_2S include oil and gas extraction and processing, agricultural activities — particularly manure — biomass recycling, geothermal power plant activity, and volcanoes. However, In the Coachella and Imperial Valleys, the Salton Sea itself is a source of H_2S emissions. It is already known that high nutrient loading, combined with strong summer stratification in the Salton Sea can lead to eutrophication, hypoxic conditions, and H_2S production by anaerobic sulfate-reducing bacteria in the Salton Sea bottom waters (Reese et al., 2008; Watts et al., 2001).

Studies conducted in similar environmental justice communities report adverse health effects such as headaches, irritability, fatigue, joint pain, nausea, respiratory illnesses, and sleep apnea from chronic low-level exposure to H_2S (1-1000 ppb) (Quist and Johnson, 2023; Lewis and Copley, 2015; Legator et al., 2001, Aatamila, 2011). While acute H_2S exposure indoors is a regulated environmental safety factor, much less is known about sources and impacts of chronic H_2S exposure (Banydeen et al., 2024; Lim et al., 2016).

Sulfur chemistry is mediated by microbial organisms and environmental conditions. While sulfate is reduced to sulfide in environments with low oxygen, when sulfide reaches the surface of the Sea it is prone to either oxidation, in which case it may precipitate as a sulfur mineral such as gypsum (calcium sulfate dihydrate) (Tiffany et al. 2007) or outgas as H_2S. Previous studies have identified gypsum precipitation events wherein gypsum crystals blanket the surface of the Salton Sea. While this has been observed to occur year-round, the largest gypsum area coverage (GAC) occurs during the summertime (Ma et al., 2020).

By leveraging data derived from air monitors and sensors, in-situ sampling, and remote sensing, this study aims to characterize the spatial and temporal variability of H_2S exposure in environmental justice communities in the Coachella and Imperial Valleys and its relationship to physical and chemical conditions in the Salton Sea. We find that wind patterns coupled with hydrological and physicochemical properties are both prerequisites for the outgassing of H_2S and transport from the Salton Sea into nearby communities. Section 2 details the underlying data origin and analysis methods while section 3 unfolds the results, and Section 4 elaborates on the implications of these results, particularly as they pertain to the environmental justice and health of the Coachella Valley community. Section 5 concludes this study and suggests future research directions.

2 Materials and Methods

The data used for this analysis consist of publicly available in-situ physicochemical and meteorological samples (Figure 1), as well as remote sensing measurements.

2.1 Physiochemical data

As part of their 2004–2020 monitoring program, the Bureau of Reclamation (BOR) collected a wide range of in-situ physicochemical data. For this study, we focus on a subset of these parameters: nitrogen (mg/L), dissolved oxygen (DO, mg/L), sulfate (mg/L), salinity (psu), and temperature (°C). Nitrogen concentrations were derived from a combination of nitrate and nitrite compounds (Lower Colorado Region BOR, 2020), with water samples collected approximately once per season at the surface and bottom of each of the BOR’s three sites (SS1, SS2, and SS3; Fig. 1). Although the exact depth of the water column varied intra- and inter-annually due to net evaporation, all bottom samples were collected from depths exceeding 10 meters.

Salinity and temperature contributions to density were accounted for by using a haline contraction (α) and thermal expansion coefficient (β) computed through the equation of state of seawater (TEOS-10). Stratification was approximated using the difference between surface and bottom density measurements, normalized by the water column depth.

2.2. Meteorological and H_2S data

Wind velocity and hydrogen sulfide concentrations were taken from the South Coast Air Quality Management District (SCAQMD; aqmd.gov) meteorological platforms and accessed using a public records request. The data are 1-hour averages, and their availability varies by instrument location, generally covering a 10-year time period between 2013 and 2024 (Table 1). The 3 SCAQMD meteorological platforms are situated on the northern end of the Salton Sea region (Figure 1). The Indio (IND; 33.708566, -116.215394) and Mecca (SMNZ; 33.571019, -116.063823) monitors are located within the Indio and Mecca communities in the Coachella Valley, respectively, while the Torres Martinez monitor (TMNZ; 33.518298, -116.075356) borders the contemporary northwest Salton Sea shore. These monitors provide wind speed, wind direction, and hydrogen sulfide (H_2S) concentrations. In 2023, as part of a community science initiative, Alianza Coachella Valley deployed an Aeroqual AQS-1 sensor above the northern Salton Sea (33.475697, -116.046867) to monitor real-time hydrogen sulfide (H_2S) levels and other pollutants (Fig. 1). This sensor continuously measures H_2S along with NO_2 and volatile organic compounds (VOCs). The real-time H_2S data collected by the sensor is publicly accessible on saltonseascience.org.

2.3 Remote Sensing

Satellite imagery was gathered for the years 2000-2023 from the MODIS (Moderate Resolution Imaging Spectroradiometer) Terra satellite. High-resolution data in multiple spectral bands was utilized to compute a gypsum Index (GI) and a Gypsum Area Coverage (GAC) parameter, following the methodology proposed by Ma et al. (2020). To address the impact of occasional cloud cover, our analysis is limited to days when at least 95% of the Salton Sea's surface was free of cloud coverage.

Table 1: Dataset Sources, Timeframes and Variables

Dataset Type	**Physicochemical**	**Meteorological**	**Remote Sensing**
Source	Bureau of Reclamation	SCAQMD[1], CIMIS[2], SSET[3]	MODIS TERRA
Years	2004-2020	2013-2024	2000-2023
Sites	SS1, SS2, SS3	Saul Martinez, Torres Martinez, Indio, Alianza	Salton Sea Area
Data	Dissolved Oxygen (mg/L), Sulfate (mg/L), Nitrite and Nitrate N (mg/L), Salinity (ppt), Temperature (^{o}C)	Wind speed (m/s), Wind direction (compass degrees), H_2S (ppb)	Gypsum Index

1. South Coast Air Quality Monitoring District
2. California Irrigation Management Information System
3. Salton Sea Environmental Timeseries

3 Results

3.1 H_2S Concentrations North of the Salton Sea Frequently Exceed California Standards

Monitors deployed by the South Coast Air Quality Monitoring District (SCAQMD), frequently show H_2S levels that exceed the California Air Resources Board (CARB) hourly exposure standard of 30 ppb (Fig. 3a) in communities within the Torres Martinez Reservation, as well as those in Mecca and Indio (Fig. 1). While the total number of hours exceeding this standard fluctuates from year to year (Fig. 3a), these exceedances are most commonly observed during the warmer months (June–September; Fig. 3b). To define seasons, we use an air temperature climatology derived from data collected between 2020 and 2024 at the CIMIS Oasis meteorological station (Fig. 1). Summer corresponds to months when the air temperature is climatologically 5°C above the annual mean (June–September), while winter includes months when the air temperature is climatologically 5°C below the annual mean.

Distance plays a key role in H_2S exposure, with communities farther from the Salton Sea experiencing fewer high H_2S events. The Torrez Martínez (TMNZ) site recorded the highest number of exceedances, followed by the Saul Martínez (SMNZ) site (Fig. 3). Limited data from the Indio (IND) site (2021-2022) prevents a definitive comparison, though during this period, IND recorded lower H_2S concentrations than both TMNZ and SMNZ.

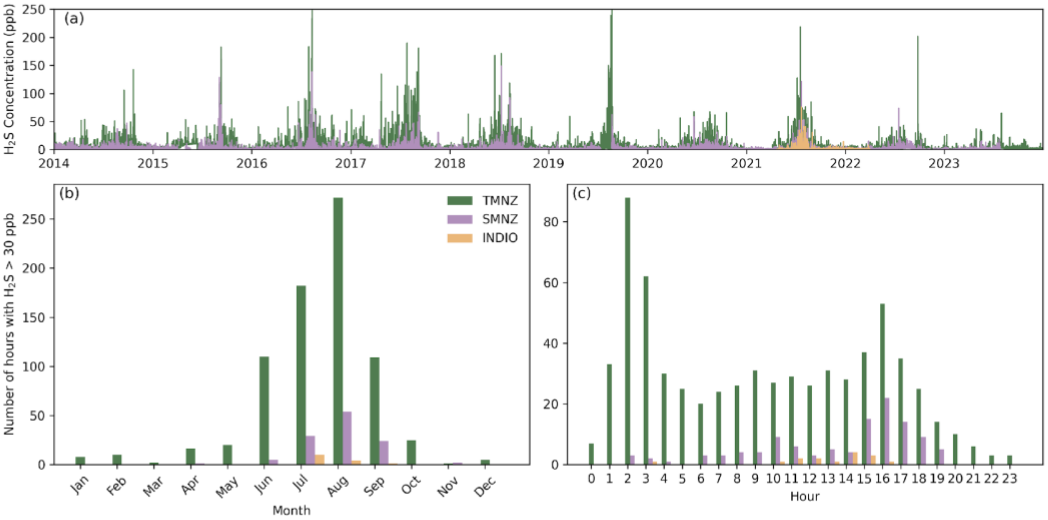

Figure 3: *(a) Hydrogen sulfide (H_2S) concentrations measured by the SCAQMD sensors, as shown in Fig. 1. (b) Monthly hydrogen sulfide hourly exceedances (above the CARB hourly exposure standard of 30 ppb) for the years depicted in (a). (c) Hourly hydrogen sulfide exceedances (above the CARB hourly exposure standard of 30 ppb) during the summer months for the years shown in (a).*

Although H_2S hourly exceedances have diurnal patterns, the details vary by season and site. During the summer (June-September) months at site TMNZ, exceedances were most often recorded from 02:00-03:00 (nighttime) and 15:00-17:00 (afternoon), whereas the SMNZ site presented a peak in exceedances in the afternoon but not in the nighttime (Fig. 3c and Fig S1). While fewer exceedances are observed during the winter (November-March) and transition (April, May, October) months, the available data (mostly from TMNZ) suggest that exceedances occur near midday in the winter and shortly after midnight in the spring (Fig. S1 a, d).

3.2 Wind Patterns Point to the Salton Sea as a Source of H_2S Exceedances

To identify the potential drivers of hydrogen sulfide peaks detected by monitors north of the Salton Sea, we examine the atmospheric conditions during periods of H_2S exceedances. Since most of the exceedances at sites SMNZ and TMNZ occur during the summer time, we focus on summer wind and pollution data for those sites for the years 2014-2023 and 2018-2020, when concurrent wind and H_2S data are available at SMNZ and TMNZ, respectively.

The Salton Sea region often experiences high wind due to the geography of the area. During the summer months, both northwesterly and southeasterly winds are observed at TMNZ and SMNZ with average speeds of 2-5 m/s (Fig. 4a,b). Similarly to the H2S emissions (Fig. 3), the wind direction exhibits consistent diurnal variability with westerly and northwesterly winds from 3 AM - 3 PM local time and easterly and southeasterly winds from 5 PM - 2 AM at the SMNZ and IND sites. The TMNZ site has a slightly different diurnal pattern with the wind being most frequently westerly and northwesterly from 8 PM - 6 AM and easterly and southeasterly from 11 AM - 6 PM.

Pollution roses for the same sites and periods were generated by plotting H_2S concentration as a function of wind direction during summer hours when H2S levels exceed the CARB standard at the respective monitor. Pollution roses (Fig. 4c,d) at both TMNZ and SMNZ show that H_2S exceedances are most frequently detected during episodes of southeasterly winds.

Although the SCAQMD monitors typically detect only sporadic H_2S exceedances outside of the summer months, exceedances at the TMNZ site occur year-round (Fig. S1), suggesting continuous, albeit variable, H_2S presence.

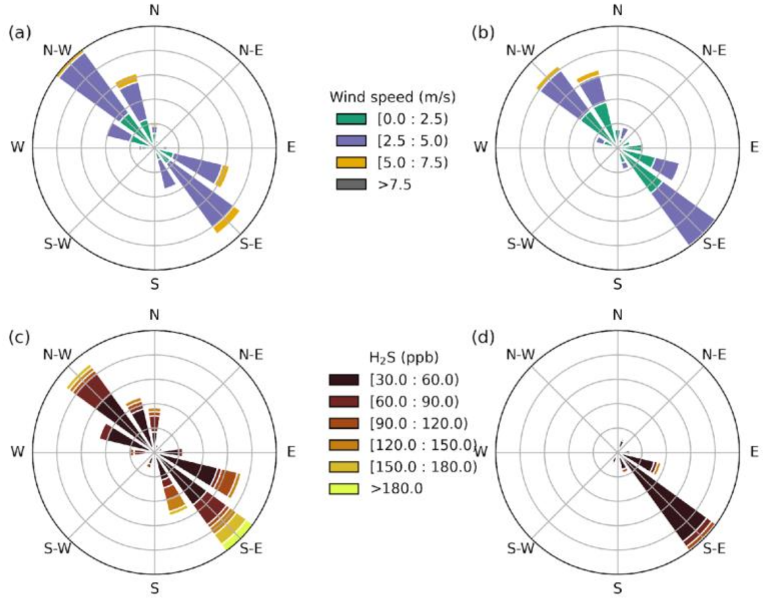

Figure 4 *Wind and pollution roses for Torres Martinez (TMNZ; panels a, c) and Saul Martinez (SMNZ; panels b, d), based on summer (June–August) wind and* H_2S *data from the South Coast Air Quality Management District (SCAQMD). Concurrent wind and* H_2S *data were available for TMNZ from 2018 to 2020 and for SMNZ from 2015 to 2022. The pollution roses (panels c, d) depict only periods when* H_2S *concentrations exceeded the 30 ppb California Air Resources Board (CARB) standard. Colors in the pollution roses indicate* H_2S *concentration levels, while the roses' directions correspond to wind direction.*

3.3 Historical H_2S Observations Fail to Capture True Emission Frequency

In early 2024, when both the TMNZ monitor (designated "near shore" by SCAQMD due to its proximity to the Sea) and the Alianza (ALZ) sensor were operational, a stark contrast in recorded H_2S exceedances emerged. For example, between May 1, 2024 and July 25, 2024, the ALZ sensor detected 177 hours of exceedances above the CARB threshold, while the TMNZ monitor recorded only four. This discrepancy is likely due to the ALZ sensor being positioned directly above the Sea, closer to the H_2S sources than the SCAQMD monitors, and therefore less influenced by wind advection and turbulent diffusion.

To further investigate this, we analyzed the relationship between wind direction and the discrepancies in exceedances from May to July 2024, a period of frequent H2S emissions when both sensors were active (Fig. 5). Wind data from a nearby California Irrigation Management Information System (CIMIS) station (Fig. 1), along with wind speed and differences in H_2S

concentrations between ALZ and TMNZ, support this conclusion. The largest discrepancies between the sensors occur when winds originate from the southwest, west, and northwest (Fig. 5). When the wind blows from these directions, H_2S is 17ppb higher at the ALZ location than at the TMNZ location (K-S test $p < 0.01$). Since TMNZ northwest of ALZ, these wind patterns suggest that emissions are being blown away from the SCAQMD monitors, causing them to underestimate the number of exceedances. While winds from the northeast might also contribute to such discrepancies, minimal H_2S is detected from that direction. By contrast, when the wind blows from the southeast, the TMNZ monitor and ALZ sensor measure the same H_2S levels within sensor uncertainty (K-S test $p < 0.01$).

Additionally, there is no clear relationship between wind speed and the amount of H_2S detected, or the observed discrepancies. These patterns highlight the critical distinction between emission and detection, emphasizing that sensor placement and wind direction play a crucial role in the accuracy of H_2S observations.

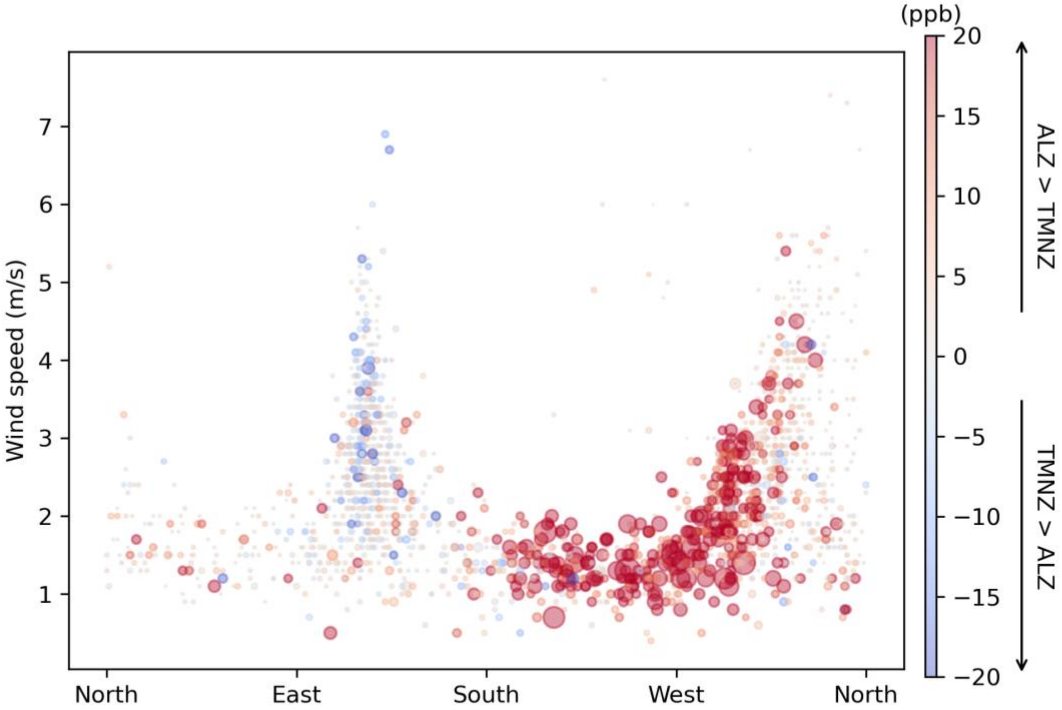

Figure 5 *Differences in H_2S concentrations (ppb) between the Alianza (ALZ) and SCAQMD Torres Martinez (TMNZ) sensors (color) as a function of wind direction and wind speed. Marker size indicates the average H_2S concentration measured by both sensors, with larger markers highlighting events with higher H_2S levels. Data spans May 1, 2024 through July 25, 2024, the latest SCAQMD data available at the time of writing.*

3.4 Water Column Characteristics Favor H_2S Production in the Salton Sea

Hydrogen sulfide (H_2S) is typically produced under anoxic, hypereutrophic conditions, which are common in the hypolimnion of stratified lakes (Thuy Do., et al, 2014). If the Salton Sea is generating H_2S, its bottom waters must exhibit these anoxic conditions. Hypoxiaxf is frequently observed in the dissolved oxygen (DO) profiles measured by the Bureau of Reclamation at each of their three sampling locations (Fig. 1). DO shows a distinct seasonal pattern, with hypoxic conditions (DO < 2 mg/L) most prevalent in the summer months (Fig. 6a). Notably, hypoxia is not restricted to the deep water column (Centeno et al., 2023).

Hyper-eutrophication is a potential precursor to the Salton Sea's hypoxic conditions (Hung et al. 2024). Seasonal averages of nitrate concentrations (NO_2-N + NO_3-N) can reach as high as 1.2 mg/L in the spring, reflecting the impact of exceedingly high nutrient runoff from the surrounding agricultural fields. Both the Alamo and New Rivers contribute to high nitrate levels, with seasonal averages exceeding 3.5 mg/L. Bottom-water nitrate concentrations also display a clear seasonal trend, mirroring the seasonal patterns in DO. Nitrate concentrations tend to be lowest in summer and highest in winter (Fig. 6b).

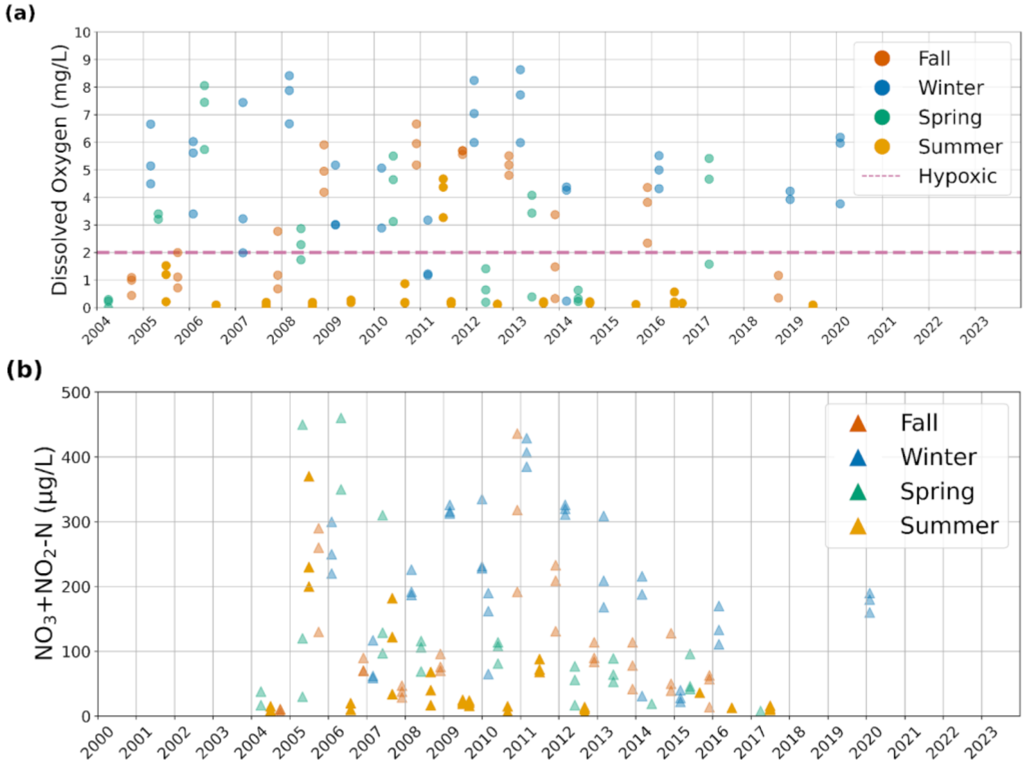

Figure 6 *(a) Bottom dissolved oxygen (DO) concentrations measured by the Bureau of Reclamation (BoR). In this context, 'bottom water' refers to the average of measurements taken at depths greater than 10 meters across the three BoR sites (SS1-SS3; Fig. 1). DO is similar across SS1-SS3 and is, therefore, plotted as an average of all sites. (b) Bottom Nitrate concentrations display near zero concentrations most often during the summer months. Here the seasons are defined based on BOR sampling and are Fall (SON), Winter (DJF), Spring (MAM), Summer (JJA).*

The formation of hypoxic conditions is exacerbated by the strong stratification in the Salton Sea. On average, the Salton Sea buoyancy stratification exhibits weak seasonality with an observed summertime peak of $O(10^{-4})$ and weaker values of $O(10^{-6})$ present throughout the year. Although the Salton Sea is stratified by both salinity and temperature, the Sea's stratification in the mid-lake site measured by BOR is consistently temperature dominated, with salinity playing a reinforcing role (Fig. S2). During the winter and fall months the Sea is occasionally observed to be predominantly salinity stratified with some observations of temperature inversions in the fall (Fig. S2).

Along with abundant nitrogen, the Salton Sea exhibits high sulfate concentrations, facilitating the formation of H_2S. Observations by the BoR reveal concurrent upwards, near-linear trends in both sulfate and salinity concentrations in the Salton Sea (Fig. 7). Sulfate is a major component of the salinity in the Salton Sea. Salinity and sulfate concentrations increased at a rate of ~ 1.4 ppt/year (2004 - 2020) and ~ 0.31 ppt/year (2004-2016), respectively. This represents a 33% increase in salinity and a 36% increase in sulfate by 2016 from 2004 levels. The collinearity of salinity and sulfate suggests common drivers, namely increased concentration due to net evaporation of freshwater and continuing inflow from agricultural canals and the rivers that flow into the Salton Sea. During the time period of these observations, the lake elevation declined at 0.2 meters/year (Fig. 2) and the total lake volume decreased. Moreover, the similarity between the percent increase of sulfate and total salinity suggests that any net loss of sulfate as H_2S is negligible compared with other sources and sinks of sulfate.

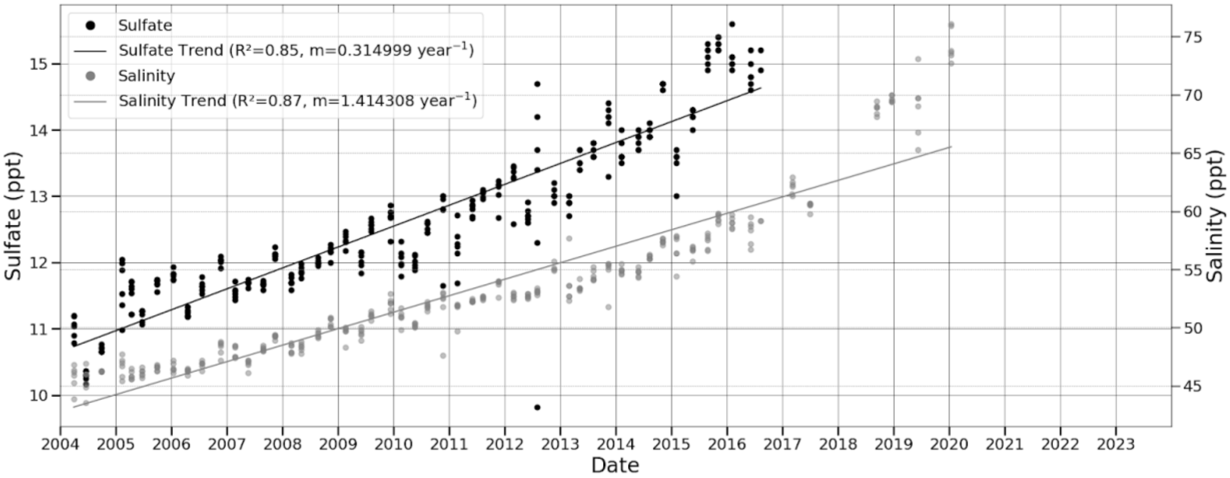

Figure 7 *Sulfate concentrations continue to increase in a linear fashion, salinity concentrations reinforce the sulfate increments.*

Another potential byproduct of high sulfate concentrations, in addition to hydrogen sulfide, is the formation of gypsum. Ma et al. (2020) noted that the Salton Sea exhibits seasonal gypsum precipitation events visible from satellite imagery. Following Ma et al. (2020), we looked at changes in the Gypsum Area Coverage (GAC) parameter across the years. While sulfate increases linearly across the years (Fig. 7), GAC shows no obvious trends (Fig. S3).

4 Discussion

Our findings suggest, first, that the Salton Sea is a major source of H_2S emissions in the Coachella Valley, and likely the Imperial Valley as well. Secondly, the concentration of these emissions may be vastly underestimated, highlighting the need for additional air quality monitoring around the Sea to fully evaluate the potential impacts. The lack of monitoring around such water bodies has been identified as an environmental justice issue (Díaz Vázquez et al., 2024), with limited precedent for management strategies to address this significant challenge.

Previous studies in the Salton Sea have identified wind-induced overturning, driven by high wind speeds, as a primary mechanism for mixing the water column and diffusing H_2S gas into the atmosphere (Reese et al., 2008; Tiffany et al., 2007). While wind speed is widely recognized as a critical factor, our findings suggest that this relationship may be more nuanced. We observed that H_2S is often detected at relatively low wind speeds, indicating that wind *direction* may play a more significant role in the detection of H_2S by the current sensor network—a result that may be biased due to the specific placement of sensors.

We find that the sensor over the water detects much higher H_2S concentrations than the sensors on land, particularly when the wind is southwesterly, westerly, and northwesterly. To the northwest of the ALZ sensor, which is the area between the TMNZ and ALZ sensors, we find mostly shallow water (approximately 1 m) and mudflats. The observed pattern implies that H_2S may potentially originate from shallower waters and mud flats (Azad et al., 2005) and not solely from deeper areas of the Salton Sea.

The prevailing paradigm in the literature has been that shallower lake regions accumulate less H_2S, while deeper areas produce higher concentrations (Zavialov et al., 2008; Wurtsbaugh & Marcarelli, 2004). However, our findings suggest that the Salton Sea is likely outgassing H_2S consistently from shallow near-shore areas. While this does not rule out the significant role of deeper anoxic layers in accumulating and releasing substantial H_2S concentrations, the extensive surface area of shallow waters, which are in close proximity to nearby communities, must be a key consideration in efforts to mitigate the health and well-being impacts of H_2S. This is particularly significant, as several proposed projects around the Salton Sea will accelerate its shrinkage (e.g. , thereby expanding mudflats (Imperial Irrigation District, 2024) or increasing the extent of shallow water areas (California Natural Resources Agency, 2018), both of which could exacerbate H_2S emissions. The impact of the declining water level on H_2S emissions should be quantified.

Our results also indicate that a significant portion of H_2S emissions remains unaccounted for, potentially being transported to communities without air monitoring stations. This is a particular concern in the southern basin which lacks hydrogen sulfide monitoring and where shallow waters are prone to complete mixing and H_2S diffusion (Reese et al, 2008) and in the unincorporated North Shore community that is to the east of the Salton Sea. Adding to this concern, most H_2S exceedances occur in the early morning hours when farmers are working in the fields without protection, highlighting stark environmental injustices.

Regardless of the precise source, stratification, dissolved oxygen (DO), sulfate, and nitrate are crucial factors in H_2S generation. Although earlier studies suggested that the Salton Sea's shallowness might limit temperature-dependent stratification by inducing periodic mixing throughout the year (Watts et al., 2001), more recent research proposes that stratification in shallow waters may actually exceed the wind energy required to disrupt it (Rueda and Schladow, 2009; Branco and Torgersen, 2008). Even if periodic mixing were occurring at a similar or increased rate, the documented presence of frequent hypoxia in shallower nearshore regions (<10 meters) (Centeno et al., 2023) suggests that mixing alone may not be sufficient to prevent year-round hydrogen sulfide (H_2S) emissions, albeit at varying frequencies.

The DO and nitrate concentrations in the Salton Sea display a marked seasonality and are both most often lowest during the summer, when hydrogen sulfide emissions are highest. Given the hypereutrophic conditions of the Salton Sea and the high observed nitrate concentrations, it is likely that both nitrate and sulfate reduction co-occur (Borceau et al., 2023). However, sulfate reduction is likely predominantly due to sulfate reducing bacteria in the Sea. In fact, a 2002 study by Wood and others recognized *Beggiaota* -a cyanobacteria capable of sulfate reduction- as a major biomass component of the Salton Sea’s microorganism ecology.

We do not observe long term trends in nitrate concentrations, stratification, or Gypsum Area Coverage. In contrast, sulfate and salinity are both increasing, with a long-term trend dominating over any seasonality. The observation that the fraction of the salinity that is sulfate has remained approximately constant suggests that sulfate and total salinity have similar net sources and sinks with evaporation and a reduction in lake volume due to reduced inflows being key factors in increasing concentrations of both. Any losses of sulfate to outgassing of hydrogen sulfide do not generate a net loss of sulfur in the Sea compared with other salinity constituents.

Additionally, inflow, including from agriculture, is a source of both salinity and sulfate, despite the relatively low concentrations compared with the Sea (SSET, 2023). Salinity continues to increase due to the shrinking lake volume, which is due to reduced inflows and evaporation.

While the high sulfate concentrations in the Salton Sea generate the potential for sulfate reduction and emission into the atmosphere as hydrogen sulfide, there is not a direct relationship between the sulfate concentration and detection of hydrogen sulfide. More complete understanding of the sulfur cycle in the Salton Sea may aid mechanistic descriptions of H_2S production. When reduced sulfur compounds (e.g. HS^{-1}) reach the surface of the Sea, they may oxidize to form gypsum. Previous studies have established a satellite algorithm to detect the signal of gypsum precipitation on the surface of the Salton Sea (Ma et al. 2020), which may be associated with upwelling of hydrosulfide from the bottom waters. However, no direct relationship has been established here between the area of the Salton Sea that is covered by the satellite-derived gypsum index, and H_2S on shore.

5.1 Study Limitations

Comprehensive understanding of the magnitude of the impacts of hypereutrophication of the Salton Sea are limited by the frequency of available observations. The Bureau of Reclamation began nutrient sampling in 2004 and discontinued their monitoring in 2020, despite the Salton Sea being California's largest lake. This lack of data poses challenges not only for understanding the dynamics of this distinct environment but also for implementing solutions (Díaz Vázquez et al, 2024, Vera 2024). Improved monitoring should include more air and water quality sensors, an accessible and routinely updated database, and yearly reports regarding significant findings.

Throughout this study we have reported hydrogen sulfide temporal dynamics relative to the threshold of 30 ppb (hourly average) established by CARB. The threshold approach is a limiting factor when assessing the harm H_2S imposes on a community because it risks minimizing the negative effects that the community experiences below the chosen threshold. This method fails to consider the experiences and concerns of communities directly affected by the pollutant (Liboiron 2021), thereby inadequately addressing the real-world impact on those living near the source of contamination. H_2S malodors, experienced at concentrations of just 2-3 ppb, can still have latent effects related to quality of life by restricting individuals to their homes during H_2S exceedances, increasing medical costs, and heightening stress. Internationally, the World Health Organization has established a guideline of 10.6 ppb over a 24 hour period to avoid health impacts and a significantly more stringent guideline of 5 ppb over a 30-minute period to avoid significant malodors. Other states have lower hourly standards, including New Mexico, New York, and Kentucky at 10 ppb. This range of standards emphasizes the importance of moving beyond a threshold approach to seek fundamental understanding. It is necessary to consider community-advised perspectives when defining success in mitigating pollution. In this case, the community-driven sampling in the areas near communities revealed the critical role that these areas play in community impacts.

5.2 Adverse health effects

Surrounding nearby communities are already vulnerable to the many documented health effects associated with the Salton Sea's water and air quality issues. Half a million individuals who inhabit the Coachella and Imperial valleys are at risk of adverse health effects (U.S. CDC). While the health effects from chronic H_2S exposure are less well-understood than those of acute exposure or other air pollution impacts, evidence from other communities suggest substantial adverse health effects. Research in Puna, Hawaii, revealed that more than 40% of individuals chronically exposed to hydrogen sulfide (H_2S) experienced symptoms such as fatigue, memory difficulties, sensory impairments, headaches, lethargy, shortness of breath, difficulty sleeping, numbness, and depression (Legator et al., 2001). Similarly, during a four-month period in Carson, California, residents endured comparable health effects as H_2S levels surpassed 30 ppb for a cumulative duration of over 490 hours (Quist and Johnston, 2023). Low levels of H_2S, below the CARB standard of 30 ppb have been associated with neurological effects and low levels in the range of 1 ppb have been associated with respiratory effects and impacts on eyes and nasal systems (Batterman et al., 2023). These symptoms overlap with known symptoms from asthma and respiratory illnesses, which have high incidences in the communities surrounding the Salton Sea (Miao et al., 2022; CIRS, 2021; Sinclair et al., 2021; Farzan et al., 2019; Johnston et al., 2019; Sinclair et al., 2018). Individuals chronically exposed to malodors and pollutants are often living on the fenceline of industry, residents in communities of color, and low-income (deSouza et al., 2024). These findings further reinforce the reality that these communities bear a disproportionate burden of malodors and other environmental hazards, highlighting the pervasive and systemic nature of environmental injustice.

Health impacts from H_2S are becoming a critical environmental justice issue. While fenceline communities near oil and gas extraction have long been exposed to H_2S (Vera 2024), exposure from other sources, such as hypereutrophic lakes, is less frequently discussed. This issue may be escalating due to the combined effects of cultural eutrophication and climate-induced droughts. The lack of attention to these sources means that the full spectrum of H_2S impacts—ranging from malodors to chronic physical and mental health issues, beyond just acute exposures—tends to be overlooked in advocacy, scientific research, and regulatory frameworks. A key challenge is bridging the gap between air and water quality research and regulation, as both are intricately linked in the context of lacustrine H_2S emissions.

These findings can help advance solutions to H_2S exposure through mitigation of the sources and short-term adaptation to reduce exposure. Mitigation requires definitive identification of the mechanisms of persistent H_2S emissions. This study suggests that shallow water and exposed sediments are a likely source. These sources hold potential for mitigation through aeration (Yamamoto et al., 2012). Short-term adaptation to reduce odor impacts could involve installing air filters that remove odors, in addition to dust, in homes.

5 Conclusions

Our findings highlight significant pollution exposure from the Salton Sea and outline a pathway for enhanced monitoring and assessment of environmental health in the region. We conclude that the Salton Sea is a major source of H_2S emissions, particularly during the summer months, when concentrations over the past decade frequently exceed the established CARB hourly standard. These elevated H_2S levels pose potential health risks to environmental justice communities in the Coachella and Imperial Valleys, contributing to respiratory issues, headaches, and fatigue. A critical factor in detecting these exceedances is the location of air quality sensors and the prevailing wind direction, emphasizing the distinction between measuring emissions and detecting them. While seasonal variations and wind-induced mixing likely contribute to H_2S outgassing, they do not fully account for the observed emissions. Many of these emissions, which may be underrepresented due to limited air quality monitoring coverage, could originate from shallow water areas or mudflats (Azad et al., 2005).

Although the Salton Sea presents a unique environmental case, other rapidly desiccating hypersaline lakes, such as the Great Salt Lake in the U.S. and the Aral Sea in Central Asia

(Kazakhstan/Uzbekistan), are experiencing similar physicochemical conditions and nutrient loading in other lakes contributes to hydrogen sulfide emissions (Achá et al. 2018). The lessons learned from the Salton Sea may provide valuable insights for managing these global environmental challenges.

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Open Research

The data used in this study are publicly available from the following sources: Bureau of Reclamation (https://www.usbr.gov/lc/region/programs/saltonsea.html), South Coast Air Quality Management District (via public records request), California Irrigation Management Information System (CIMIS Oasis station, https://cimis.water.ca.gov/), Salton Sea Environmental Timeseries H_2S Sensor, U.S. Geological Survey (USGS) Salton Sea NR Westmorland water level data (http://waterdata.usgs.gov/nwis/), and NASA MODIS L2 data. For ease of reproduction, the curated dataset is available at [DOI to be provided in final manuscript].

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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GeoHealth

Supporting Information for

Hypereutrophication, Hydrogen Sulfide, and Environmental Injustices: Mechanisms and Knowledge Gaps at the Salton Sea

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Contents of this file

Figures S1 to S3

Introduction

This document includes Figures S1 to S3, which provide additional context and support to the main findings presented in the manuscript. While these figures are not central to the primary message, they enhance the overall understanding of the study. The data used to create these figures are detailed in Section 2 (Materials and Methods) of the main manuscript.

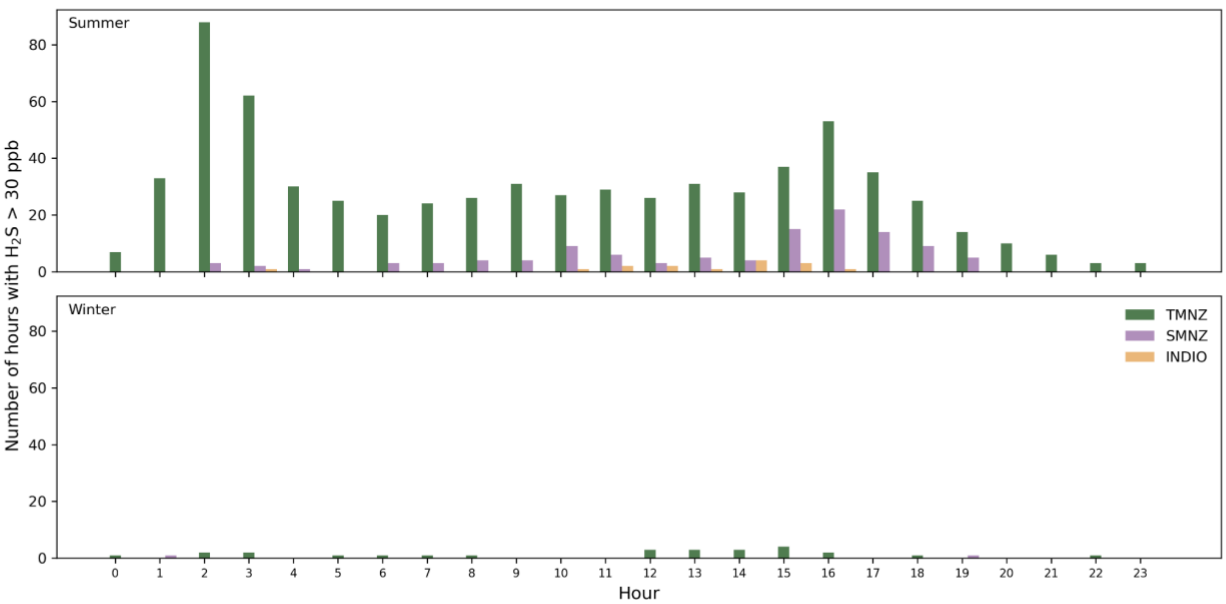

Figure S1. Hourly hydrogen sulfide exceedances (above the CARB hourly exposure standard of 30 ppb) for summer and winter for the years shown in Fig. 3a of the manuscript.

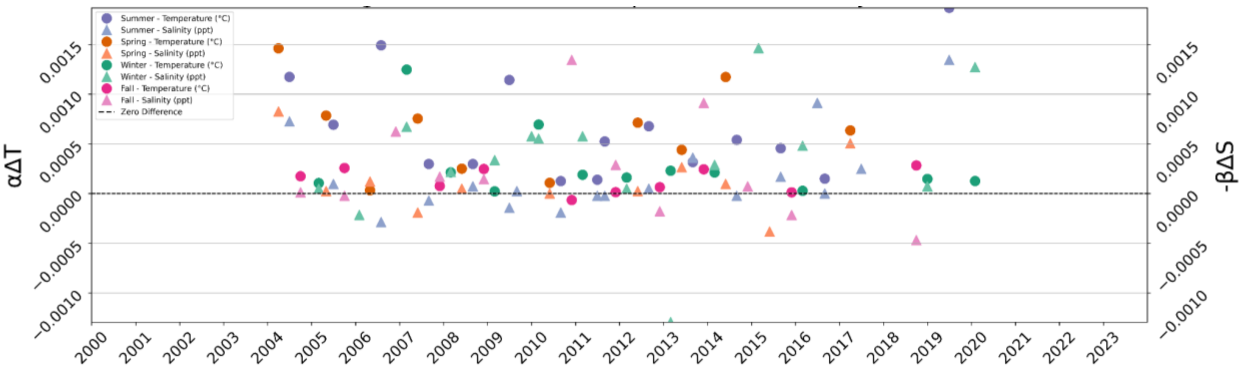

Figure S2. The relative contributions of temperature and salinity to density are calculated by scaling changes in each by their respective thermal expansion and haline contraction coefficients. The differences in temperature and salinity are determined by comparing surface and bottom values. Given the similarity in salinity and temperature across sites SS1-SS3, an average of all sites is plotted.

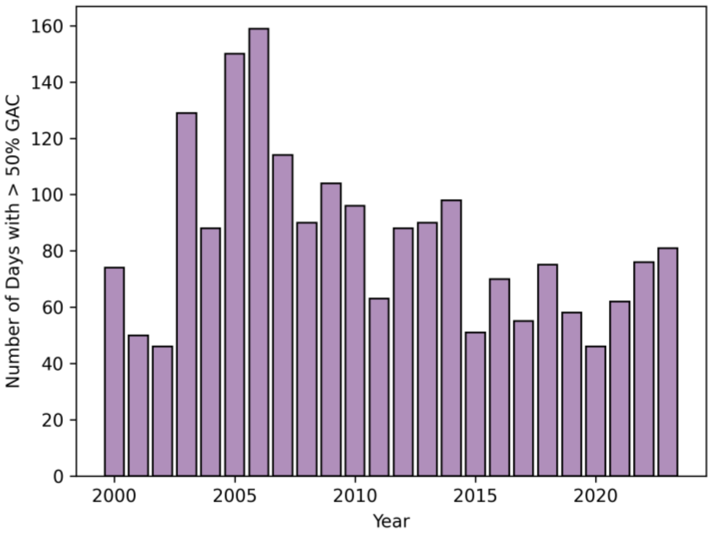

Figure S3. Total number of days in which the Salton Sea has greater than 50% of its area covered by gypsum, as defined by Ma et al. (2020).