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Air Quality

Particulate Matter, Pollutant Gases and Atmospheric Transport at the Salton Sea

Roya Bahreini[1], **William C. Porter**[1] and **Emma Aronson**[2]

[1]Department of Environmental Sciences

[2]Department of Microbiology and Plant Pathology

University of California, Riverside, CA 92521

HIGHLIGHTS

- **The state of the Salton Sea is tied intrinsically to air quality in the surrounding communities through the emission of particulate pollutants, toxic gas and gas-phase pollutant precursors.**
- **A large fraction of coarse particulate matter at sites closest to the shore of the Salton Sea is associated with emissions from the lakebed and sea spray.**
- **Airborne dust fluxes at sites close to the Sea are already in the high range of values observed at Owens Lake, Calif., before mitigation efforts began there.**

Air quality around the Salton Sea, located between the Imperial and Coachella valleys of southern California, is impacted by emissions from the surrounding arid lands, urban and other anthropogenic emissions upwind, emissions from the dry lakebed, or playa, and direct emissions from the Sea itself. Atmospheric emissions of pollutants can be categorized into particulate matter (PM) and gaseous pollutants, with PM having gained most attention in recent years given that its concentration has regularly exceeded the national and state ambient air quality standards. Air quality standards for PM, which refers to solid and liquid particles suspended in the air at sizes in the range of a few nanometers to tens of microns (μm), are set for mass concentrations of particles up to 2.5 μm in aerodynamic size ($PM_{2.5}$) or up to 10 μm

DUST BERMS constructed to reduce windblown dust along the exposed southern shore of the Salton Sea. Jonathan Nye

in aerodynamic size (PM_{10}). PM is known to have adverse effects on the pulmonary and cardiac systems (Pope, 2000). One of the mechanisms for these effects is through oxidative stress and inflammation caused by certain components of PM, e.g., redox active metals, quinones and other oxidized organic components (Lakey et al., 2016). In addition to their chemical composition, the size of airborne particles has a major influence on the extent of negative impacts on pulmonary health since smaller PM (e.g., $PM_{2.5}$) can penetrate deeper into the lungs.

PM can be emitted directly into the atmosphere by mechanical processes (e.g., wind blowing over dry deserts or large bodies of water or breaking waves), forming "primary PM," and can also form in the atmosphere through oxidation reactions of gaseous pollutants, leading to "secondary PM." Not all gaseous pollutants are reactive and immediately harmful, however. For example, greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2) are long-lived pollutants that, once emitted, can remain in the atmosphere for decades, posing impacts on the earth's radiative balance as they accumulate over time. Given the recent environmental changes at Salton Sea, it is necessary to investigate how environmental changes at the Sea impact air quality under current and possible future management scenarios. In the worst case scenario, the ongoing decline of lake levels will expose greater than 400 km^2 by 2038 (assuming lake water level is -255 ft or less), exacerbating the creation of all major classes of atmospheric pollutants: PM emissions from the playa and the Sea, reactive gases that can form secondary PM, and greenhouse gases.

Atmospheric Pollutants

WHEN CONSIDERING LOCAL AIR QUALITY in the Salton Sea region, it is critical and non-trivial to identify the different types and sources of atmospheric pollutants that are at play. The major pathways to produce atmospheric pollutants from the Salton Sea include

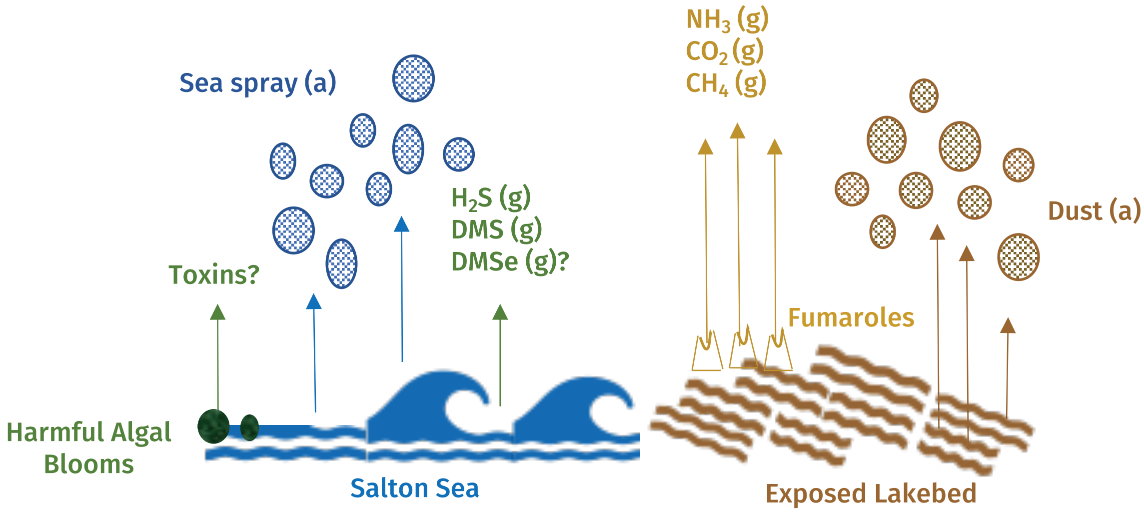


Figure 4.1 Major sources of gas-phase (g) and aerosol-phase (a) pollutants at the Salton Sea.
Credit: Roya Bahreini.

direct emissions of PM (i.e., sea spray and dust aerosols); emissions of reactive trace gases that may lead to formation of secondary PM (e.g., dimethyl sulfide [DMS], dimethyl selenide [DMSe], and ammonia [NH_3]); and emissions of unreactive, greenhouse gases (e.g., carbon dioxide [CO_2] and methane [CH_4]) (Figure 4.1).

Direct Particulate Matter

THE MAJOR FACTORS controlling the extent of direct emissions of PM from arid lands are soil crust type, which depends partly on soil composition and soil moisture; soil aggregate size distribution; surface roughness; and atmospheric wind strength (Alfaro et al., 2004). The possibility of increased PM emissions are of concern given the already high concentrations of PM_{10} in the region. Although hourly concentrations of PM_{10} have been measured at several air quality monitoring stations around the Salton Sea (IID et al., 2017), until recently the composition of PM was unknown, and the contribution of different sources to PM loading in the region was unclear.

In a 2015 study, size-dependent aerosol samples were collected at Salton City and Bombay Beach during short periods of time in the summer and winter to investigate sources of atmospheric dust by comparing concentration ratios (i.e., enrichment factor or EF) of elements in the atmospheric dust samples with those of local arid crustal surfaces and playa (lakebed) samples (Frie et al., 2017). For elements with a significant non-crustal source—for example, those with an anthropogenic source such as cadmium—the EF is higher than 1, meaning that there was considerably more of these chemicals in the dust than there should have been if the source had not been influenced by human activities (Box 4A).

Conversely, for elements that predominantly stem from arid crustal surfaces the EF value approaches 1. Figure 4.2 shows the enrichment factors for various elements in the PM filter and soil samples collected from different playas as well as the arid lands around Salton Sea (Frie et al., 2017). For sodium (Na), calcium (Ca) and selenium (Se), playa EF is significantly higher than that of the arid soils around the Salton Sea. This observation suggests that these elements are good indicators of playa influence on PM samples. Additionally, for sodium and calcium, PM EF lie in between the playa and soil ranges, suggesting mixing of two different sources for these elements. PM EF of selenium, however, is significantly higher than either playa or soil samples, indicating an additional source is responsible for concentrating selenium on PM.

Size-dependent elemental composition corroborated the mixed contribution of arid-crustal surfaces and non-desert sources to the observed PM since concentrations of elements thought to be associated with dust from terrestrial sources (e.g., Ca, aluminum [Al], Na, iron [Fe], titanium [Ti]) were enriched on particles larger than a micron (supermicron), while those from non-desert sources (chromium [Cr], nickel [Ni], cadmium [Cd], and Se) were concentrated more uniformly among the submicron particles (Figure 4.3). This result is expected: mechanical processes that form pri-

Composition and Size of Dust Particles

BOX 4A

ABSENCE OF KNOWLEDGE on the chemical composition or size distribution of the dust in the Salton Sea region has limited our understanding of the human health impacts of dust until recently. Researchers at UC Riverside conducted studies in 2015 that indicate at least 9% of the coarse particulate matter (PM_{10}) in regional dust samples comes directly from the dried lakebed, or playa. For some elements, such as sodium (Na), the playa is the source for 40–70% of the total (Figure 4.2). Sorting the size of dust particles by element further indicated that a gas-phase form of selenium (Se) may be coming from the playa or sea spray (Figure 4.3). Like many metals, selenium is an essential nutrient in small doses but toxic at larges doses.

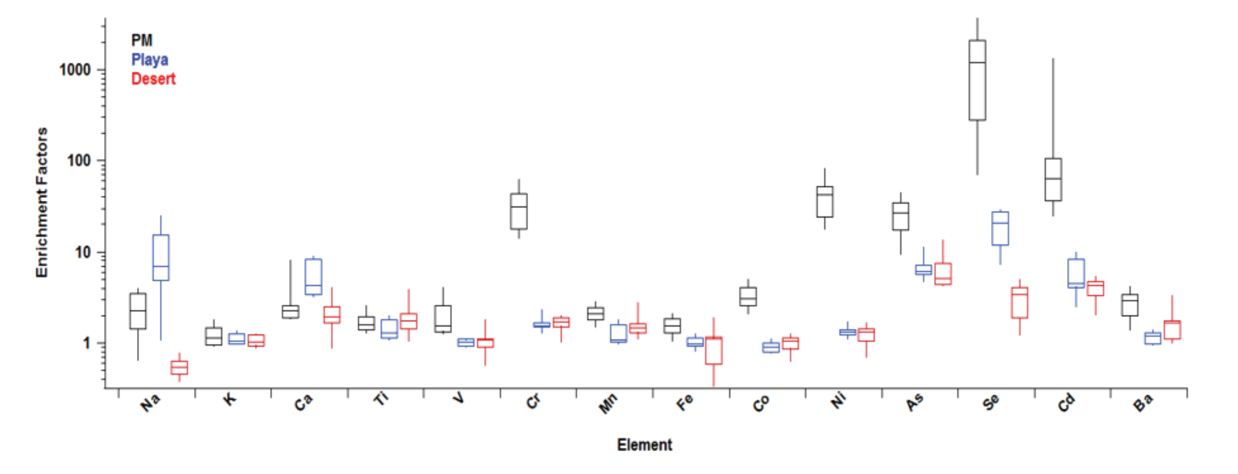


Figure 4.2 Elemental enrichment factors determined for particulate matter, playa, and arid desert lands. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values, the horizontal lines show the median. Credit: Frie et al. (2017).

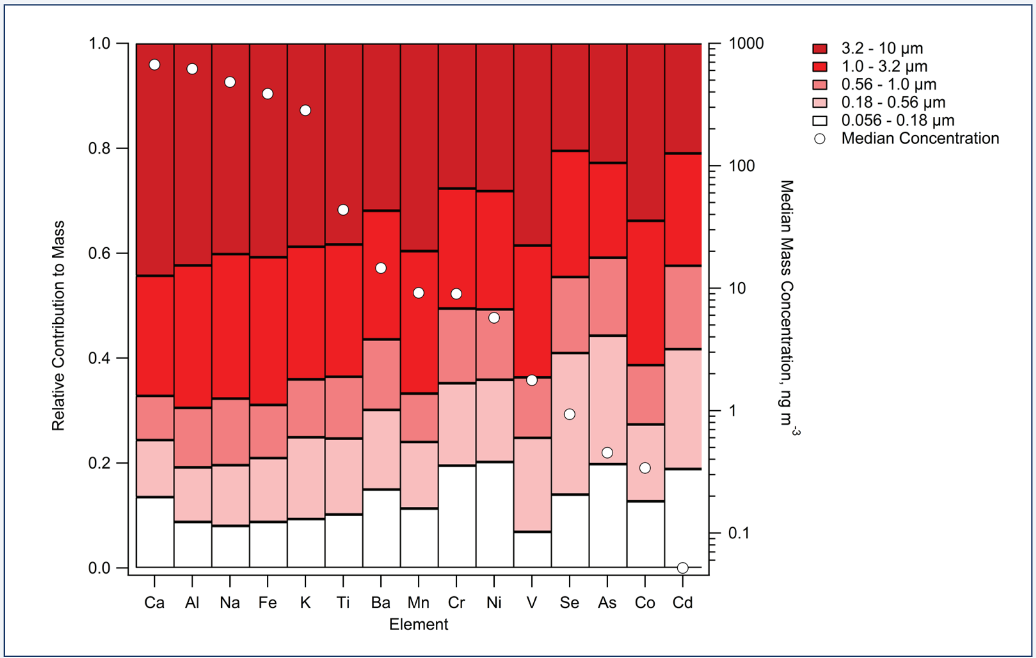


Figure 4.3 Size segregated elemental composition of particulate matter. Credit: Frie et al. (2017).

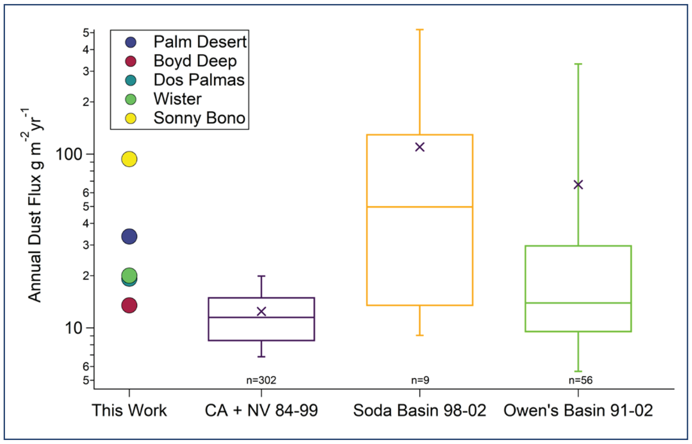


Figure 4.4 Estimates of annual dust flux at several sites around the Salton Sea as well as several historic records in the US Southwest. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values; horizontal lines show the median; crosses show the mean. Credit: Frie et al. (2019).

mary PM generate larger particles, whereas secondary atmospheric oxidation processes concentrate the condensing components on submicron particles. Because Se was more equally distributed between submicron and supermicron sizes (Figure 4.3), it is likely that a gas-phase source of Se exists in the region.

There are also elements (e.g., Cr, cobalt [Co], Ni, Cd) whose PM EF is significantly higher than either playa or arid soil EF while playa and arid soil EFs are in a similar range. This observation confirms a strong contribution of atmospheric anthropogenic sources to these elements. Using a source apportionment technique (EPA's PMF 5.0), combined with total PM_{10} concentrations measured close by, and the composition of playa sampled by Buck et al. (Buck et al., 2011), it was estimated that during this sampling period, the arid and desert lands contributed to ~45% of PM_{10} (Frie et al., 2017) while the playa sources contributed by up to ~10% to PM_{10} concentrations. The contribution of playa sources to Na concentration of PM_{10} was significant at 40-70% (Frie et al., 2017).

A follow up study in 2017–2018 placed monthly samplers at a control site (University of California's Natural Reserve at Boyd Deep Canyon), an urban location (Palm Desert), on the lakebed (Sonny Bono National Wildlife Refuge and Wister), and open desert with moderate distance from the shoreline (Dos Palmas). The estimated deposition mass flux show that even with only ~60 km^2 of playa being exposed, dust fluxes were higher than the historical median values in the US Southwest. Even at Owens Lake before mitigation when ~260 km^2 of the lakebed was exposed, fluxes were lower than those measured in the Salton Sea region (Figure 4.4) (Frie et al., 2019). Owens Lake, a closed-basin, saline lake on the eastern side of the Sierra Nevada in California, has gone through a similar desiccation processes in the 20th century due to water diversion to Los Angeles, creating a brine pool in its center surrounded by the dried lakebed. In 1987, the southern Owens Valley exceeded the 24-hr average national ambient air quality standard for PM_{10}, prompting the local air pollution control district to establish a monitoring network of PM_{10} surrounding the lake. In the following years and after establishing the State Implementation Plans, the California Department of Water Resources was ordered to mitigate dust emissions by implementing a variety of dust control measures on ~127 km^2 of the emissive lakebed. In 2019, when ~43% of the lakebed was under dust control measures, the number of exceedance days were reduced to four from 37 back in 2000 before start of mitigations. After dust control measures were put in place, the average PM_{10} exceedance value in 2019 was at 280 micro-g/m^3, substantially reduced from 1,087 micro-g/m^3 in 2000 (Allen et al., 2020).

It is worth noting that the brine at Owens lake is dominated by sodium carbonate and sodium sulfate (Mihevc et al., 1997), which form fragile and erodible crusts. At the Salton Sea, sodium chloride, calcium sulfate and magnesium sulfate have been observed as the principal evaporite minerals. Sodium chloride is expected to form a stable crust, but the two sulfate-based salts are not (Frie et al., 2019). Such playa emissions are seasonal and their influence at the sites closest to the Sea was most significant during late spring/early summer. Factors enriched in elements related to the playa and Salton Sea were identified only at the Sonny Bono National Wildlife Refuge and Wister sites, while the factor representing the Colorado river sediments had the highest contribution at Dos Palmas and Wister sites (Frie et al., 2019). Another factor characterizing the local soils contributed more uniformly to the collected mass at all locations.

Although these studies have been highly valuable in understanding the current influence of playa emissions on local PM and the potential impacts on human health, ongoing measurements are needed to examine how dust concentrations, composition, and size change with time because the exposed lakebed in the future may not have the same physical and chemical characteristic as currently exposed areas. Once the salt crust erodes, the potential increases for generating dust from the underlying sediments, which may have very different composition and higher concentrations of toxic elements (Vogel & Henry, 2002) (Chapter 3).

Additionally, dust events are sporadic and episodic (Box 4B); therefore, their signature in the month-long samples at locations farther from the source might have gone unnoticed in the previous studies. None of the studies completed thus far have investigated detailed organic matter content of PM, which potentially could be laden with pesticides and herbicides. The high input of agricultural runoff to the Sea during the last several decades and the high toxicity associated with certain organic pesticide and herbicide residues causes additional concern, as do various bioaerosols (Box 4C). These compounds can also be suspended in air through production of sea spray from the Sea or dust from the playa. Future studies aiming at a more comprehensive chemical analysis of PM would be highly valuable and critical to fully understand the potential health impacts of atmospheric PM.

Reactive Trace Gases

PREVIOUS STUDIES have shown variable, but at times significant, emissions of sulfur containing gases, e.g., hydrogen sulfide (H_2S) and dimethyl sulfide (DMS), from the Sea. Depending on water temperature and stratification levels in the Sea as well as atmospheric wind speeds, hydrogen sulfide produced deep in the Sea can be brought up to the surface, where it can partially degas into the atmosphere. Under the right conditions, up to 25% of sulfide produced in the Sea can end up in the atmosphere (Reese et al., 2008). Once in the air, H_2S has a daytime atmospheric oxidation lifetime of ~10 hr, leading to the production of sulfur dioxide, another toxic gas. Further, another reduced sulfur species that is typically measured in the air over the oceans is the methylated form of hydrogen sulfide, namely DMS. Reese and Anderson (2009) measured very high concentrations of DMS in surface waters from 0–2 m depth. These high concentrations of DMS are correlated to chlorophyll-a and dimethylsulfoniopropionate (DMSP) that are chemical markers of algae activity. They result in high rates of transfer of gaseous DMS to the atmosphere—rates up to two orders of magnitude higher than the DMS emission rates from other lakes or the open ocean (Lana et al., 2011; Reese & Anderson, 2009). Similar to hydrogen sulfide, DMS has a daytime lifetime of ~10 hr before it reacts to form other compounds.

The Colorado River and the sediments it carries are

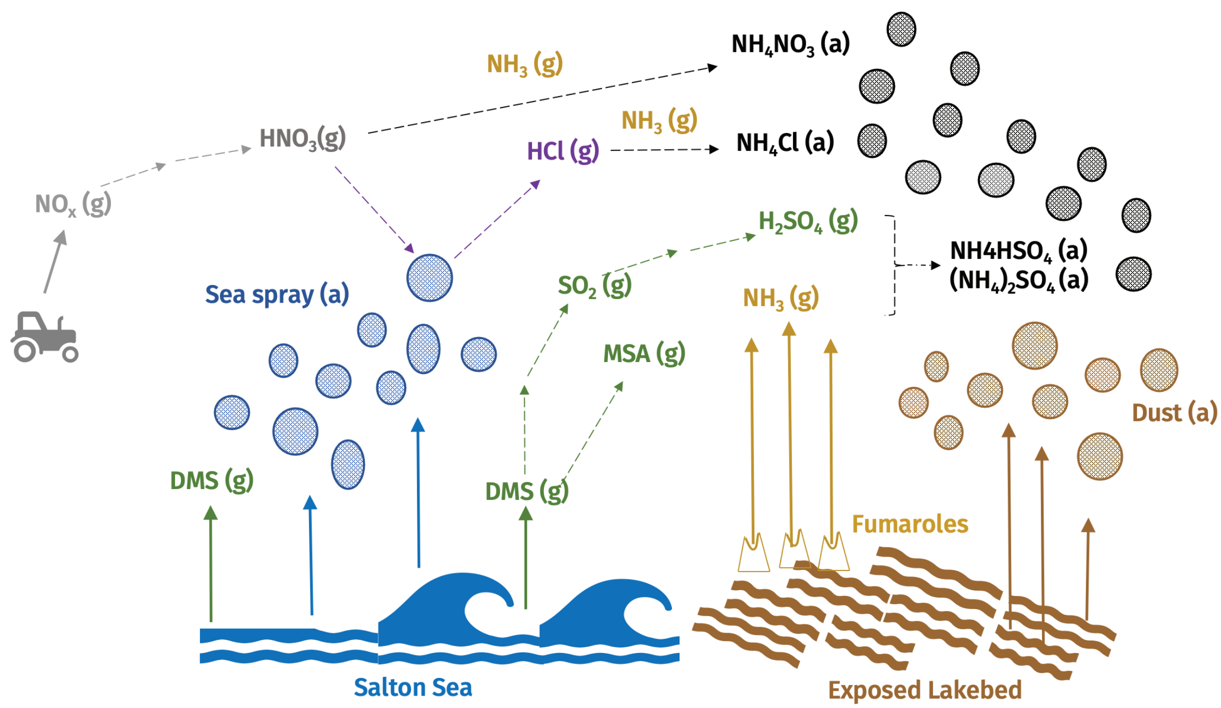


Figure 4.5. Diagram depicting chemical interactions of various reactive gas-phase (g) and aerosol-phase (a) pollutants at Salton Sea. Solid arrows show emissions; dashed arrows show chemical reactions. Credit: Roya Bahreini.

known to be high in Se. Because of the decades-long input of water from the Colorado River to the Salton Sea, Se concentration in the Salton Sea and its sediments are also relatively high (Xu et al., 2016). Microbial activity in water, soils, and sediments can convert selenium to solid elemental Se, metal selenide, or gaseous methylated selenium (e.g., dimethyl selenide, DMSe) (Kausch & Pallud, 2013; Vriens et al., 2014; Winkel et al., 2015). Methylated selenium species are volatile and can enter the atmosphere. Once in the air, these compounds oxidize and form secondary PM, as demonstrated in a recent laboratory-based study (Ahmed et al., 2019). Secondary selenium aerosol components have not been directly measured in the PM collected around Salton Sea. The relatively high EF of Se in PM samples, however, as well as the more uniform distribution of Se on submicron PM, suggests that Se on PM is likely derived from oxidation of methylated Se species and the resulting products containing Se. Unlike sulfate, DMSe-derived oxidation products forming secondary PM may lead to elevated toxicity linked to oxidative DNA damage and a negative immune system response to airway inflammation in human epithelial lung cells (Ahmed et al., 2019). It is unknown how concentrations of H_2S, DMS, and methylated Se in the water and air or the concentration of their oxidation products in PM will evolve due to changes in the biological activities and physical conditions of the water column under future scenarios.

In addition to gaseous species directly emitted from the Salton Sea or its playa, ammonia gas is emitted from the fumarolic vents on the geothermal fields located at the southern edge of the Salton Sea (Tratt et al., 2011). Ammonia flux from these vents is estimated to be up to 25% of the total regional flux (Tratt et al., 2011). Ammonia is a common base that reacts with the acidic components of submicron PM (typically, nitrate, sulfate, bisulfate, or chloride) and is also recognized as a facilitator for new particle formation (Figure 4.5). Such emissions are therefore indirectly critical in controlling the local and regional levels of submicron PM.

Greenhouse Gases

PREVIOUS STUDIES have examined release of concentrated plumes and diffuse seepage of CO_2 and CH_4 from the main seep field of the Salton Sea geothermal system, namely the Davis-Schrimpf field, at the south-

Atmospheric Transport Patterns

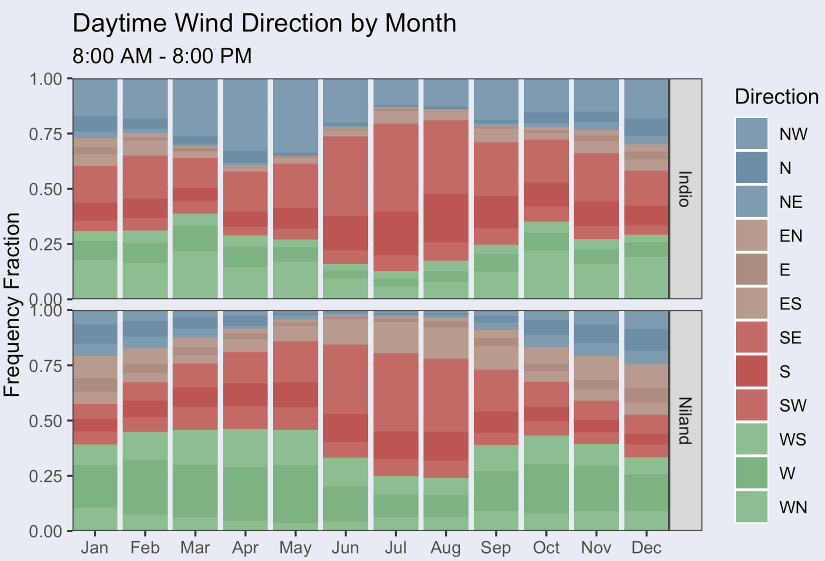
WITH INCREASING CONCERN over pollutants originating from the Salton Sea and its surrounding dry lakebed, transport patterns derived from local surface wind data are useful tools for understanding historic and future exposure to pollution from these sources. Based on 10-meter wind measurements taken from long term monitoring sites (US EPA) in the Coachella and Imperial Valleys, monthly wind direction patterns can be analyzed to reveal seasonal patterns in exposure risk for communities throughout the Salton Sea basin.

At the Indio station in the Coachella Valley (Figure 4.6, top), winds are predominantly from the north and west (blue and green fills, respectively) during much of the year. However, southerly winds are not uncommon, and become increasingly frequent during summer months, at times due to strong pressure gradients related to the North American monsoon driving winds originating from the Gulf of California—so-called "gulf surges" (Adams and Comrie, 1997). Interannual variability in wind direction outside of the summer months may also be a result of synoptic events including Santa Ana winds, characterized by easterly winds driven to the California coast by high pressure systems over deserts on the far side of the Sierra Nevada mountains (Raphael, 2003). Regardless of the cause, these types of events likely contribute to the variability apparent in the observed surface wind direction shown here. Imperial Valley wind dynamics, represented by measurements taken at the Niland station off the southeast coast of the Salton Sea likewise see a summertime shift towards more frequent daytime southerly winds, on average (Figure 4.6, bottom).

Diurnal patterns measured at local stations further demonstrate the significance of wind variability observed across the Coachella and Imperial Valleys. Filtering hourly wind-speed data to include only regional dust event days, defined as those days during which multiple air quality monitoring stations reported daily PM_{10} concentrations that were at least one standard deviation above the station

BOX 4B

mean, shows that a large fraction of those regional dust event days have historically included midday winds blowing from the south (Figure 4.7, top). Based on these observations, exposure to PM_{10} during these types of Coachella Valley dust events would be expected to disproportionately include dust originating from the Salton Sea or the surrounding dry lakebed, making the physical and chemical properties of this growing dust source an important knowledge gap. These patterns are not constant or uniform across the region, reflecting key differences in local topography and resulting upslope and downslope wind patterns. A similar analysis of winds measured at the Niland station during Imperial Valley dust events shows frequent early morning winds from the east, with afternoon and evening winds dominated by winds from the west. The seasonal and diurnal variability in transport patterns observed at stations across the valley points to the importance of understanding the timing, quantity, and composition of emissions generated during high-wind dust events in order to most effectively understand and mitigate any health impacts caused by potentially contaminated particulates.



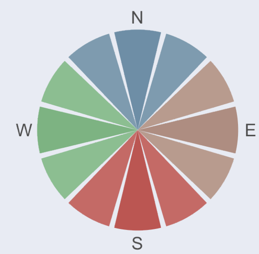


Figure 4.6 Frequencies of hourly daytime wind direction at Indio (Coachella Valley) and Niland (Imperial Valley) stations. Credit: William Porter. Source: EPA Air Quality System (EPA AQS) network.

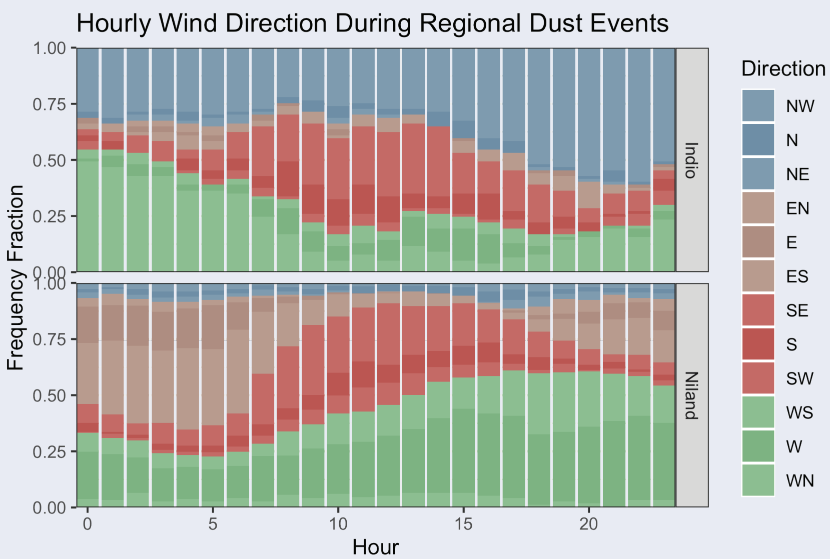


Figure 4.7 Hourly wind speed frequencies for regional dust event days, defined as days during which multiple local stations (in the Coachella Valley or Imperial Valley for the Indio and Niland stations, respectively) exhibit daily PM_{10} values exceeding the station mean by at least one standard deviation. Credit: William Porter. Source: EPA Air Quality System (EPA AQS) network.

Dust storm along Highway 111 on May 11, 2018. Jonathan Nye

eastern edge of the Salton Sea (Mazzini et al., 2011). Based on measurements from 91 vents and 81 soil degassing stations on a 20,000 m^2 area, daily emission rates of CO_2 and CH_4 were estimated to be 9,410 kg CO_2/day and 44.5 kg CH_4/day, respectively, with only 25% of the emissions originating from the vents (Mazzini et al., 2011). These emission rates translate to 3841 MT CO_2/yr (i.e., metric ton of equivalent CO_2, assuming global warming potential of 25 for CH_4), which is equivalent to CO_2 emitted from ~835 typical passenger vehicles in a year (assuming 11,500 miles driven per year and 22 MPG fuel efficiency) (EPA, 2018). Compared to regional anthropogenic sources, these emission estimates are not significant. It is worth noting though that total emission rates of CO_2 and CH_4 from the Salton Sea geothermal system are likely higher than the current estimates since additional emissions of CO_2 and CH_4 are expected from areas outside the Davis-Schrimpf field site and along the Salton Trough.

Future Air Quality

THE TRENDS in the amounts and composition of atmospheric emissions in the future depends on the extent of the lakebed being exposed, the type and composition of the exposed area, as well as the quantity and quality of the water in the Salton Sea under each scenario presented in Chapter 1. Under scenario 1, it is expected that more than 400 km^2 of the lakebed will be exposed by 2038. This scenario will bring out the worst air quality as far as direct PM emissions are concerned and has the potential to also suspend more toxic elements from the heavy-metal-enriched sediments that are located in the deepest areas of the Salton Sea lakebed. Depending on the quality of water in the remaining parts of the Salton Sea, conditions may favor more frequent production of plankton and harmful algal or cyanobacterial blooms, thus increasing the chance of trace gas volatilization and airborne mobilization of algal toxins, as well as the mobilization of potentially toxin-producing bacteria. Under this scenario, currently submerged fumaroles will also get exposed, contributing to direct emissions of reactive and non-reactive gases to the atmosphere.

Under the stabilization scenario, many of the same atmospheric emission implications apply. The only significant difference would be if enough water were directed to the Sea to halt the shoreline retreat before the most toxic sediments beneath the center of the lake are

Microbial Emissions

BOX 4C

AN EMERGING AREA of research worldwide is called aerobiology, or the study of the movement in air of "bioaerosols," which include bacteria, fungal spores, pollen grains and viruses. Often these bioaerosols also include non-living matter to which the biological particles are attached, including soil or mineral particles and water droplets.

Researchers in the UC Riverside Department of Microbiology and Plant Pathology study the bioaerosols that make up some fraction of the aerosol phase emissions of sea spray from the Salton Sea and the dust emissions from the exposed playa. Compounds produced by microorganisms—during harmful algal blooms, for example—can also be picked up and transported as aerosols (Figure 4.5). The potential for microbial toxins to become airborne is of particular interest, as harmful algal blooms will likely become more frequent as lake volume decreases and the concentration of nutrients grows.

As the Salton Sea becomes smaller and more saline, which is predicted in all scenarios, the environment and ecosystems in and around the Sea will experience changes. The microbiology of the Sea and playa will in turn shift the microbial communities that are picked up as bioaerosols. Microbial responses to these environmental fluctuations may differ by the sensitivity of the particular microbial group (Allison & Martiny, 2008), coupled with the dynamic features of the abiotic environment. Clarifying how these disturbances impact microbial assemblages and ecosystem performance across systems (Biggs et al., 2012) within the Salton Sea Basin is crucial to its long-term sustainability, and will provide valuable information to augment successful management strategies.

exposed, thereby avoiding the hazard related to dust emissions from these sediments.

The best outcome for air quality is expected under scenario 3, where sufficient water is imported to the Sea to recover some of the lost lake volume and re-wet dry lakebed. Depending on the extent of the exposed lakebed, significant reduction in PM and associated microbial emissions could be achieved under this scenario. Of concern is the maintenance of water quality (e.g., salinity and oxygen content) under this scenario, which will still have impacts on emissions of trace gases by volatilization and potentially toxins through sea spray generation. Additionally, if water levels are high enough to allow fumaroles to remain submerged, ammonia and greenhouse gas emissions from these sources will be limited.

Research Needs

UNDERSTANDING THE CURRENT IMPACTS of the Salton Sea emissions and reliable prediction of atmospheric emissions from the Salton Sea in the future requires detailed, process-level understanding of several key elements and continuous research to reassess these elements given the rapidly changing dynamics of the system. These elements are highlighted as follows:

- Thorough chemical finger-printing, including that of the trace organic constituents (e.g., pesticides), of dust sources is needed for successful and complete PM source apportionment efforts.
- Size-dependent composition—including specific elements such as selenium, chemical ionic species, and organic compounds—of PM needs to be measured on a regular basis.
- Gaseous emissions from the Sea need to be characterized, and the extent of their influence on $PM_{2.5}$ formation should be investigated.
- Seasonal emission potential of different lakebed types needs to be investigated under atmospherically relevant conditions (e.g., hot and dry) and in relation to physical and chemical characteristics of the lakebed and its moisture content.
- Relationships between gaseous emissions from the Sea and the chemical and biological state of the Sea need to be investigated to better understand future emissions of these species given the different management scenarios.

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