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Theme

Saline Lakes

Publications from the Seventh International Conference on Salt Lakes, held in Death Valley National Park, California, U.S.A., September 1999

Guest Editors

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Thermal, mixing, and oxygen regimes of the Salton Sea, California, 1997–1999

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Key words: saline lake, polymixis, stratification, wind, sulfide, anoxia, eutrophication

Abstract

The Salton Sea is a shallow (mean depth = 8 m; maximum depth = 15 m), saline (41–45 g l^{-1}), intermittently mixing, 57 km long, 980 km^2 lake located in the arid southwestern United States. The Sea is a wind driven system, with predominant winds paralleling the long axis of the lake, being strongest in spring and weakest in summer and fall. The Sea mixed daily or nearly daily between September and January. During this cooling period, moderate to high levels of dissolved oxygen (3–11 mg l^{-1}) were found throughout the water column. Mean water column temperature ranged from a minimum of 13–14 °C in early January to a maximum of 30–34 °C in July–September. During most of this warming period, the Sea was thermally stratified but subject to periodic wind driven mixing events. Winds were stronger in spring 1998 than in 1997 or 1999, causing more rapid heating of the lake that year and also delaying onset of anoxic conditions in bottom waters. During summer months, mid-lake surface waters were sometimes supersatured with oxygen, and bottom waters were hypoxic or anoxic with sulfide concentrations > 5 mg l^{-1}. Oxic conditions (> 1 mg O_2 l^{-1}) often extended a few meters deeper nearshore than they did well offshore as a consequence of greater mixing nearshore. Mixing events in late summer deoxygenated the entire water column for a period of days. Consumption of oxygen by sulfide oxidation likely was the principal mechanism for these deoxygenation events. Sulfide concentrations in surface waters were 0.5–1 mg l^{-1} approximately 3 days after one mixing event in mid-August 1999. These mixing events were associated with population crashes of phytoplankters and zooplankters and with large fish kills. In the southern basin, freshwater inflows tended to move out over the surface of the Sea mixing with saline lake water as a function of wind conditions. Salinity gradients often contributed more to water column stability than did thermal gradients in the southeasternmost portion of the lake.

Introduction

The Salton Sea is a shallow, discontinuous warm polymictic (sensu Lewis, 1983), eutrophic lake located in the arid California desert (Fig. 1). It formed in 1905–1906 as a result of an engineering accident and was initially a freshwater lake. Since then, the Sea has changed dramatically in size, salinity and biology (Walker, 1961; Parson, 1986; Bain et al., 1970; Cohen et al., 1999). Agricultural and municipal wastewaters supply 88% of the inflow, at present, to the Sea via three inflows: the New, Alamo, and Whitewater rivers (Cohen et al., 1999; Fig. 1). At present, the Sea is a closed-basin lake with salinity at 41–45 g l^{-1} and increasing at 0.3–0.4 g l^{-1} per year (Tostrud, 1997; Hurlbert & Detwiler, unpub. data). Seasonal variation in evaporation and inflow rates causes seasonal variation in lake level of ca. 0.3 m and in salinity of 1–2.5 g l^{-1} (Hely et al., 1966; Fig. 2D). As with other closed basin lakes of the western United States (Galat et al., 1981; Cooper & Koch, 1984; Jellison & Melack, 1993b; Romero & Melack, 1996), water diversion, conservation and reallocation projects may reduce inflows to the Sea. This would be expected to both lower lake level and increase salinity.

During the 1950s and 1960s, studies were carried out on aspects of the lake's physical,, chemical and biological limnology (Carpelan, 1958; Arnal, 1961), water budget and salinity (Hely et al., 1966), evaporation (Blaney, 1955), fish biology and sport fishery

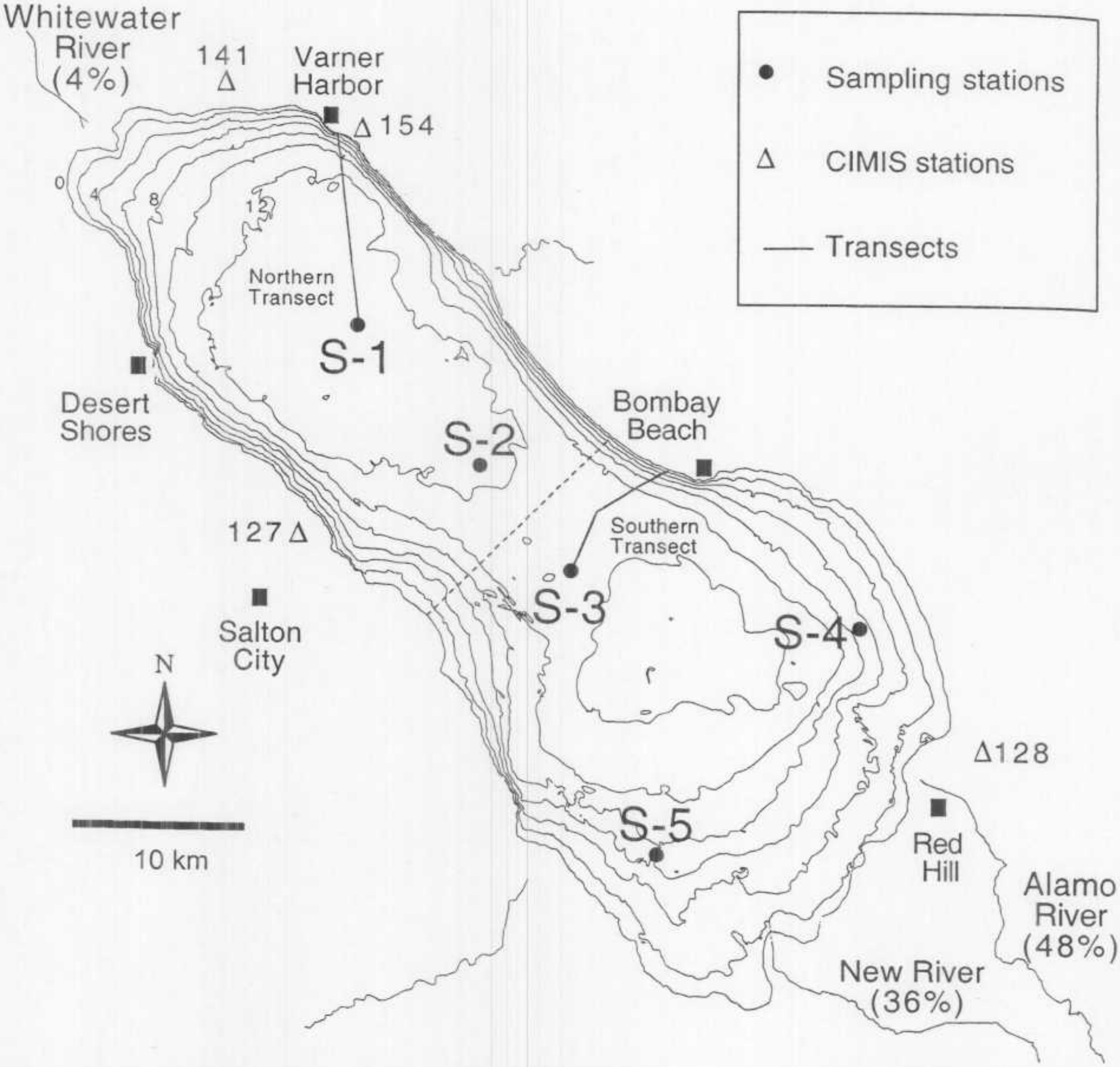

Figure 1. Bathymetric map of the Salton Sea, California showing sampling stations, transects and meteorological stations. Isobaths are at 2 m intervals, with lake elevation at −69 m below sea level. Percent contributions to the 1997 inflow of 1.4×10^9 m^3 are indicated for the three major rivers. An approximate divider of the north and south basin has been added.

(Walker, 1961), eutrophication (Bain et al., 1970) and effects of water conservation measures (Parsons, 1986). Carpelan (1958, 1961) and Arnal (1961) gave general descriptions of the thermal, mixing and dissolved oxygen regimes. Carpelan monitored temperature and dissolved oxygen profiles at two mid-lake stations and two nearshore stations for a period of 24 months. Arnal (1961) surveyed water and sediment conditions at 93 sites throughout the Sea. They found maximum water temperature was reached in August and the minimum water temperature in January. When the Sea stratified in summer months, the bottom waters were often anoxic. They also documented a wind-driven double gyre circular pattern, polymixis, vertical salinity gradients near inflows and anoxia and the presence of sulfide in bottom waters during periods of stratification.

A study in 1968–1969 monitored temperature, oxygen and nutrient conditions (Bain et al., 1970). In summer, bottom waters had low concentrations of

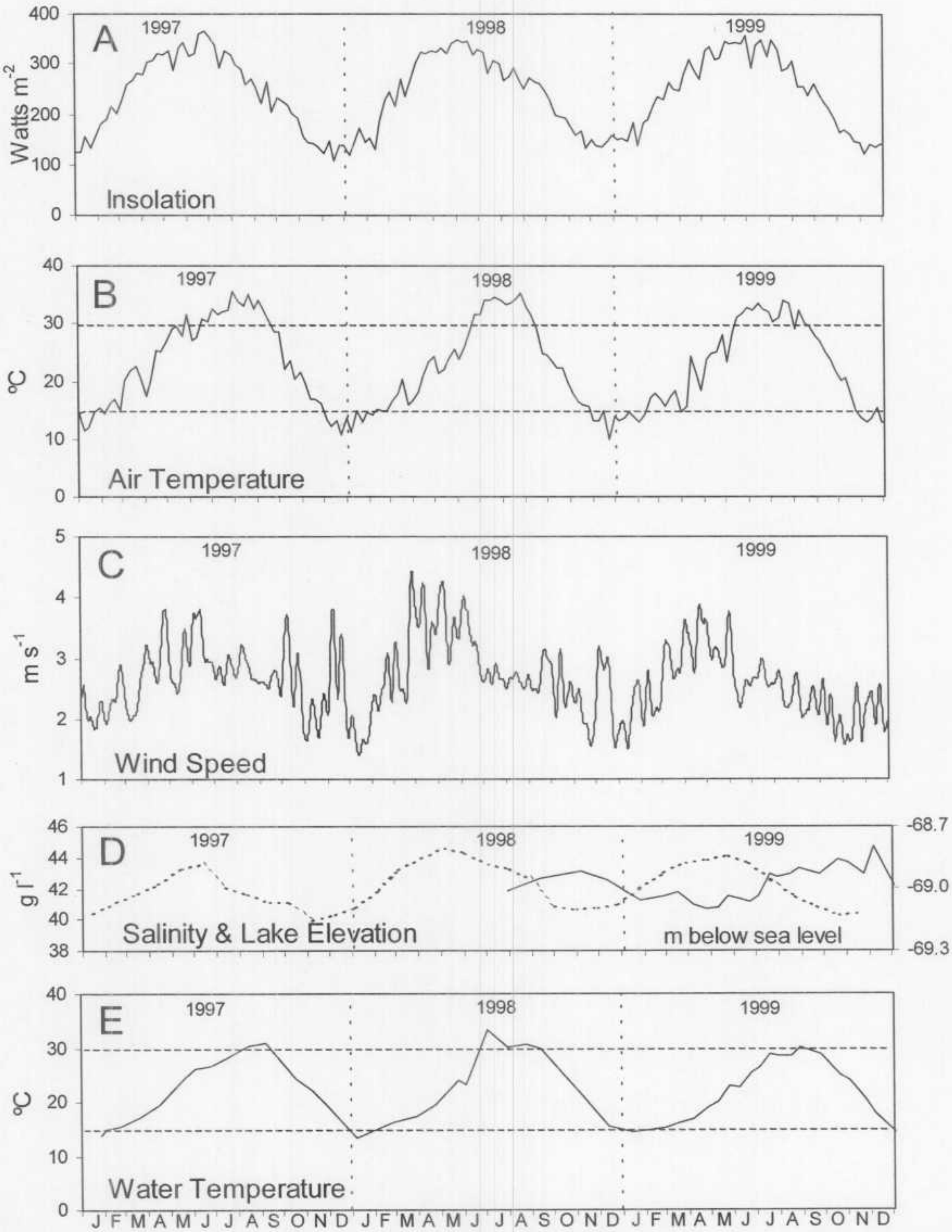

Figure 2. Salton Sea physical environment, 1997–1999. (A) Mean daily solar radiation. (B) Mean weekly air temperature. (C) Seven day running average wind speed. (D) Salinity (solid line) and lake level from the Imperial Irrigation District (dashed line). (E) Mean water temperature calculated for the 0–12 m water column, averaged over stations S-1, S-2, and S-3.

Table 1. Location and attributes of Salton Sea sampling stations

Station	Depth (m)	Distance to shore (km)	Geographic coordinates (N latitude; W longitude)
Primary sampling stations			
S-1	14	6.7	33° 25′ 00″; 115° 55′ 00″
S-2	12	6.1	33° 21′ 00″; 115° 51′ 00″
S-3	12	7.6	33° 18′ 00″; 115° 48′ 00″
S-4	7	3.5	33° 16′ 30″; 115° 38′ 50″
S-5	7	4.5	33° 10′ 00″; 115° 45′ 30″
Northern transect stations			
T-1	6	0.1	33° 30′ 16″; 115° 55′ 11″
T-2	6	0.15	33° 30′ 13″; 115° 55′ 13″
T-3	8	0.3	33° 30′ 00″; 115° 55′ 18″
T-4	10	2.0	33° 29′ 74″; 115° 55′ 20″
T-5	12	4.0	33° 29′ 17″; 115° 55′ 10″
S-1	14	6.7	33° 25′ 00″; 115° 55′ 00″
Southern transect stations			
T-6	2	0.2	33° 21′ 13″; 115° 44′ 92″
T-7	4	0.4	33° 21′ 00″; 115° 45′ 03″
T-8	6	0.45	33° 20′ 96″; 115° 45′ 17″
T-9	8	0.8	33° 20′ 85″; 115° 45′ 34″
T-10	10	3.6	33° 20′ 66″; 115° 45′ 72″
T-11	11	4.4	33° 19′ 99″; 115° 47′ 00″
S-3	12	7.6	33° 18′ 00″; 115° 48′ 00″

dissolved oxygen and were often hypoxic or anoxic. Surface waters were generally well oxygenated and even supersaturated. Low dissolved oxygen and sulfide were thought possibly responsible for fish kills, but the possibility of ammonia toxicity or toxic algae was not ruled out.

We initiated a long-term study in January 1997 to investigate various aspects of the physics, chemistry and biology of the Salton Sea. In this article, mixing, thermal and dissolved oxygen regimes, along with climatic data are described and analyzed for the 3-year period 1997–1999. The plankton, benthos, fish and aquatic birds of the Sea are affected in numerous direct and indirect ways by the physical and chemical behavior of the system. This study provides a foundation for forthcoming analyses of those populations (Detwiler et al., 2001; Riedel et al., 2002; Tiffany et al., 2002).

Methods

Monitoring regime

Monitoring of physical and chemical conditions was conducted at three mid-lake stations (S-1, S-2 and S-3) beginning in January 1997, and at two near shore stations (S-4 and S-5) beginning in January 1999 (Fig. 1, Table 1). The first three stations were chosen to represent the main water mass of the Sea. The two additional ones were added to better sample the southern basin, monitor nearshore areas, and to document the influence of freshwater inflows. Due to the counter-clockwise current system in the southern part of the Sea, station S-4 was 'upstream' and station S-5 was 'downstream' from the mouths of the two main freshwater inflows.

Monitoring was conducted at 2–5 week intervals, although in 1997–1998 some stations were not visited on all dates due to logistical problems or storms. Sampling dates were, for 1997: 21 January (2,3), 3 February (3), 22 February (2,3), 19 March (2,3), 16 April (3), 20 May (3), 3 June (3), 24 June, 18 July (2,3), 13 August (2), 6 September (2,3), 17 October, 7 November, 25 November; for 1998: 6 January (2,3), 6 February (2,3), 27 February (3), 30 March, 24 April (2,3), 22 May, 4 June, 3 July, 16 July, 30 July, 24 August (2,3), 12 September (2,3), 7 November (2,3), 12 December; and for 1999: 25 January, 28 February, 16 March, 7 April, 25 April, 10 May, 25 May, 8 June, 23 June, 5 July, 19 July, 30 July, 16 August, 28 August, 25 September, 19 October, 2 November, 23 November, 7 December, 6; and for 2000: January 6. Numbers in parentheses in this list indicate the specific stations that were not visited on a given date. Stations were visited, usually in numerical order, between 0800 and 1500 h.

Measurements of temperature, dissolved oxygen and specific conductance were made at each station from surface (actually 15 cm below the surface) to bottom at 1 m intervals using a thermistor (accurate to 0.05±0.01 °C), rapid pulse oxygen probe (accurate to 0.2±0.01 mg l^{-1}), and a 4 electrode specific conductance probe (accurate to 0.01±0.01 mS cm^{-1}) housed in a YSI 45 or a YSI 6000UPG sonde. At each station phytoplankton, zooplankton, nitrogen, phosphorus and silica concentrations, pH, oxidation-reduction potential, light attenuation and Secchi depth were also sampled or measured. Those variables are reported and analyzed in other reports (Tiffany et al., 2002). Specific conductance was measured starting 16 July 1998.

As the Salton Sea is located below sea level, measurements of dissolved oxygen must account for the increased atmospheric pressure. Prior to July 1998, dissolved oxygen probes were calibrated daily in air at 100 percent humidity, correcting for probe temperature and for atmospheric pressure using altitude (69 m below sea level). This method did not take into account variations in atmospheric pressure at different sampling dates due to meteorological conditions (source of 2–4% variation). After July 1998, a temperature corrected surveying barometer (Taylor SMT-5-51) was used to calibrate dissolved oxygen concentrations daily in air at 100% humidity, correcting for atmospheric pressure directly. The barometer itself was calibrated using a constant temperature mercury barometer (22 °C) located at San Diego State University. The specific conductance probe was calibrated at 3 month intervals. A two point calibration was performed at temperatures close to 25 °C using standards that covered the expected range of values encountered of ~10 and 65 mS. The temperature thermistor was factory calibrated and did not require calibration during this study.

Observations on a sonar depth sounder suggested that fish vacated the center of the lake in early summer, later confirmed by gill-netting (Riedel et al., 2002), and led us to examine variation in dissolved oxygen concentrations as a function of distance from shore. Temperature and dissolved oxygen profiles were taken at five stations along each of two onshore-offshore transects on 17 June and 29 August 1999 and 6 January 2000 (Fig. 1). A northern transect covered a depth range of 4–14 m and extended from Varner Harbor to mid-lake station S-1. A southern transect covered a depth range of 2–12 m and extended from Bombay Beach to mid-lake station S-3 (Fig. 1, Table 1). Measurement procedures and depth intervals were the same as for the monitoring of mid-lake stations.

We measured sulfide in the water column on two dates (31 July and 16 August 1999) at all five mid-lake sampling stations after sulfide was detected in the air during mixing events. Measurements were made at 2 m intervals from surface to bottom using a lead acetate paper (accurate to 0.1 ± 0.5 mg l^{-1}; APHA, 1998). These two dates represented a stratified and a mixed condition, respectively.

Lake elevation data were obtained from the Imperial Irrigation District. These data were taken on the first of every month from January 1997 to December 1999.

Analysis of limnological data

Analysis of data considers that we have data for the whole 1997–1999 period only for the three mid-lake stations. Only for 1999 do we have the additional information on spatial variation provided by stations S-4 and S-5. Mean water temperatures were calculated using data from 0-12 m depths at stations S-1, S-2 and S-3. For this purpose, temperatures at 0 and 1 m were set equal to the temperature at 2 m to reduce noise caused by diel warming and cooling of surface waters.

Mean oxygen profiles for overlying water of stations S-1, S-2 and S-3 and Salton Sea bathymetric data (Ferrari & Weghorst, 1997) were used to calculate the percentage of lake bottom exposed to different dissolved oxygen concentrations: < 1 mg l^{-1}, 1–2 mg l^{-1}, 2–4 mg l^{-1}, and > 4 mg l^{-1} (Fig. 3C). This calculation assumed a maximum depth of 15 m, that oxygen levels below 14 m were the same as those at 14 m, and that dissolved oxygen concentration at a given depth nearshore was the same as the mean oxygen concentration of water at the same depth at the mid-lake stations.

Sulfide oxidation has potential for deoxygenating the water column during mixing events following stratification. We quantified this using oxygen and sulfide profiles for 31 July and 16 August 1999, a mixing and deoxygenation event apparently having occurred between the two dates. pH on these dates was 7.6 – 8.3, and in this range sulfide is found primarily as sulfide ion (HS^-) (~80%, pKA 6.88 for 35 g l^{-1}) with hydrogen sulfide (H_2S) making up ~20% and S^{2-} making up less than 1% (Snoeyink & Jenkins, 1980; Millero, 1986). Proposed reactions of the oxidation of sulfide have three products; thiosulfate, sulfite and sulfate. With time, both thiosulfate and sulfite are converted to sulfate. In addition, experimental data has shown that when oxygen is the limiting reagent in the sulfide oxidation reaction , as in the Sea on the dates sulfide was measured, greater than 50% of the reaction products of sulfide oxidation are sulfate (Cline & Richards, 1969). Therefore, consumption of dissolved oxygen in the lake by oxidation of sulfide was calculated using the reaction:

$HS^- + 2O_2 \rightarrow SO_4^{2-} + H^+$ (Chen & Morris, 1972)

Three assumptions were made in this calculation. First, that hydrogen sulfide is converted to sulfide ion before oxidization during a mixing event. This assumption makes our estimate of oxygen consumption conservative as more dissolved oxygen is consumed in the oxidation of hydrogen sulfide than in the oxidation of sulfide ion. Second, that all sulfide is oxidized to sulfate. Third, that the dissolved oxygen and sulfide profiles prior to the mixing event were similar to those of 31 July.

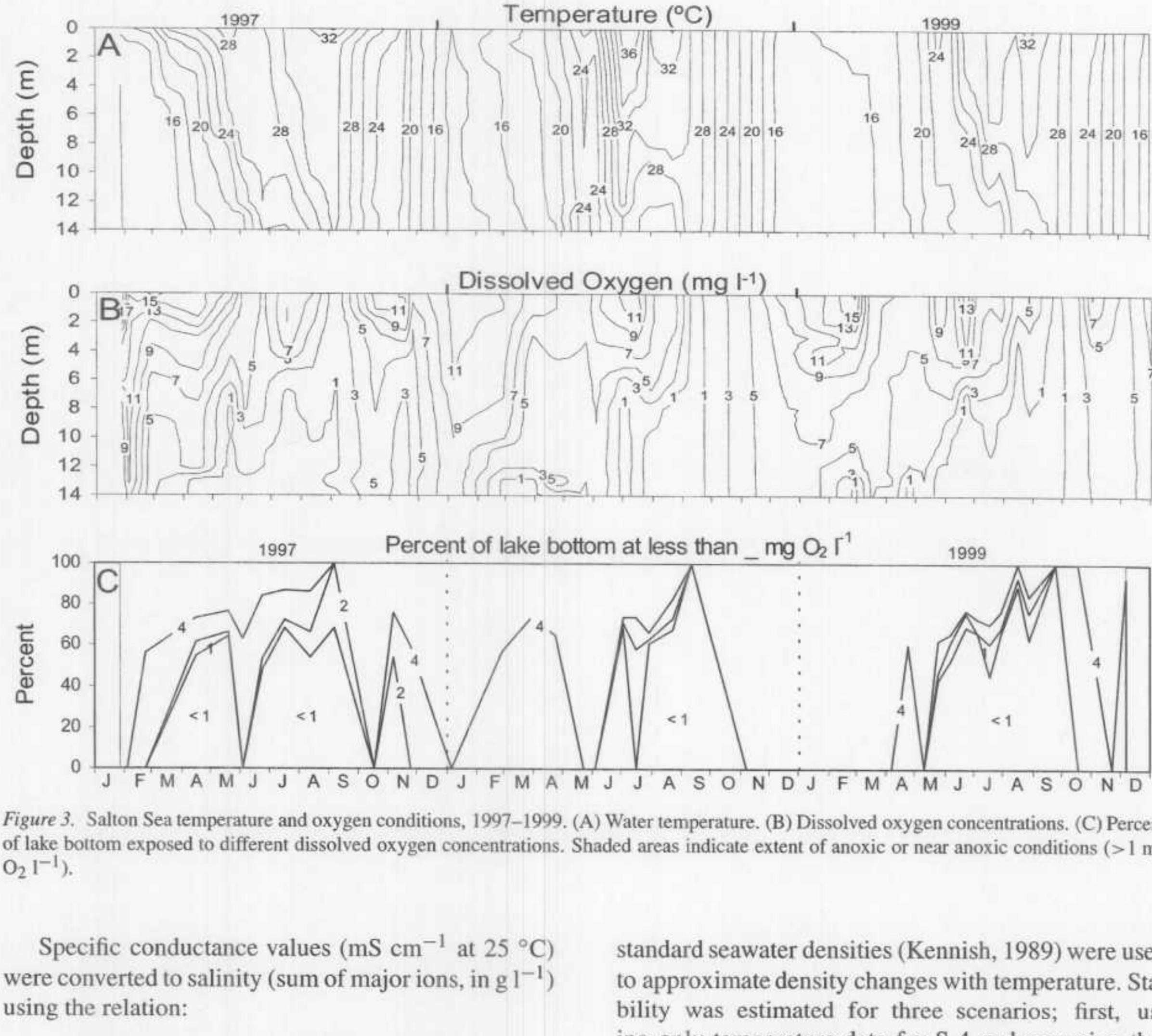

Figure 3. Salton Sea temperature and oxygen conditions, 1997–1999. (A) Water temperature. (B) Dissolved oxygen concentrations. (C) Percent of lake bottom exposed to different dissolved oxygen concentrations. Shaded areas indicate extent of anoxic or near anoxic conditions (>1 mg O_2 l^{-1}).

Specific conductance values (mS cm^{-1} at 25 °C) were converted to salinity (sum of major ions, in g l^{-1}) using the relation:

$$S = 17.102 - 0.233K + 0.013K^2$$

This empirical relation was determined using specific conductance and major ion data for 24 samples from the Sea that ranged in salinity from 20 to 42 g l^{-1} (Setmire et al., 1993; Hurlbert & Detwiler, unpubl. data).

Water column stability is determined by both salinity and temperature gradients. Calculations were performed for S-4 on 23 June 1999 to compare the contribution of the temperature gradient and the salinity gradient to stratification stability on this date. Stability calculations used the equation developed by Schmidt as modified by Idso (1973) and assumed eight 1m thick strata, each isothermal. Density–temperature-conductivity relations have not been developed for Salton Sea water. To perform stability calculations, standard seawater densities (Kennish, 1989) were used to approximate density changes with temperature. Stability was estimated for three scenarios; first, using only temperature data for S-4 and assuming that salinity was invariate with depth (observed thermal gradient only); second, using an extreme hypothetical situation (35 °C at 0–4 m, 12 °C at 4 – 6 m) and assuming salinity was invariate with depth (hypothetical high thermal gradient only); and third using the observed salinity profiles for S-4 and assuming an isothermal water column (observed salinity gradient only). The second scenario provides a point of reference to illustrate the dominant role of salinity gradients when present; 35 °C approximates the lakes maximum summer temperature and 12 °C its minimum winter temperature

Analysis of meteorological data

Measurements of solar insolation, air temperature, wind speed and direction for 1997–1999 were ob-

Table 2. Location of California Irrigation Management Information System (CIMIS) weather stations

Station	Approximate location	Elevation (m)	Distance to nearest shoreline (km)	Geographic coordinates (N latitude; W longitude)
127	Salton City	−68	2	33° 19′ 38″; 115° 57′ 00″
128	Wister	−68	0.5	33° 13′ 12″; 115° 34′ 48″
141	Mecca	−55	5	33° 32′ 17″; 115° 59′ 30″
154	North Shore	−61	0	33° 32′ 56″; 115° 54′ 58″

tained from four California Irrigation Management Information System (CIMIS) meteorological stations located on the perimeter the Salton Sea (Fig. 1, Table 2). These stations are maintained by the Department of Water Resources (DWR) and record meteorological data each minute using an onsite datalogger. Hourly means are calculated onsite and transmitted to a CIMIS public database for long-term storage and public access. Wind speed was measured using an anemometer (accurate to 0.4 ± 0.1 m s^{-1}), mean daily air temperature (thermistor accurate to 0.1 °C), and daily solar insolation (pyranometer accurate to 20 ± 4 Watts m^{-2}). These measurements, averaged over the four stations, are presented. In the case of wind speed, we present seven-day running means calculated from the daily four station means.

Results

Climate and weather

Local climatic conditions, especially wind, air temperature and solar insolation, were important factors that determined mixing and water temperature (Fig. 2A, B, C, E). The region experienced large seasonal differences in air temperature with a monthly mean air temperature of 13.5 °C in January and of 33.5 °C occurring in June or August (Fig. 2B). Solar insolation followed a similar pattern with a maximum occurring one month earlier than the maximum air temperature (Fig. 2A, B).

Prevailing winds in the Salton Sea basin were from the north (300°–360°), roughly paralleling the long axis of the lake. Infrequent wind events originated in the opposite direction (120°–180°), also along the long axis of the lake. Spring consistently had the highest 7-day running mean wind speeds (Fig. 2C). Although winter and fall generally had lower 7-day running mean wind speeds, storm events did occur. Lowest mean wind speed occurred in summer (June–September) in 1997 and 1998 and in fall in 1999.

Notable differences in wind speed and air temperature were measured among the three years of the study. Spring (March–May) 1998 had higher 7-day running mean wind speeds than did spring of 1997 or 1999 (Fig. 2C). Between April and June 1998, 7-day running mean wind speed never dropped below 2.8 m s^{-1} and had the highest values during the study (4.3 m s^{-1}). In summer 1998 (June–August), 7-day running mean wind speeds were always lower than 3 m s^{-1}, whereas both 1997 and 1999 had summer 7-day running mean wind speeds above 3 m s^{-1}. Mean spring air temperature (March–June) in 1997 was 3 °C higher than in 1998 and 2 °C higher than in 1999 (Fig. 2B). Maximum mean air temperature was reached on 3 July in 1998, but not until 6 September in 1997 and 18 August in 1999.

Salinity and lake elevation

Salinity and lake elevation varied seasonally and were inversely related. Salinity ranged between 41.0 and 44.7 g l^{-1} with the maximum values occurring in November 1998 and December 1999 (Fig. 2D). Maximum salinity coincided with lake elevation minima in November of each year. Lake elevation varied between −68.8 and −69.2 m below sea level, with a mean of −69.0 m (Fig. 2D). Highest lake elevation occurred in early summer. Evaporation in the region is high then (Blaney, 1955; Hely et al., 1966), but inflows of agricultural wastewaters to the Sea are highest during the preceding spring months (April–June).

Thermal and mixing regimes

As the Salton Sea warmed from January to August, periods of stratification were sporadically interrupted by mixing that increased bottom water temperature throughout the warming period (Fig. 3A) and also distributed oxygen downward to bottom waters (Fig. 3B).

Maximum water temperature was reached two months earlier in 1998 than in 1997 or 1999. Maximum mean water column temperatures were 30.8 °C on 9 September 1997, 32.8 °C on 3 July 1998, and 30.1 °C on 28 August 1999 (Fig. 2E). Higher wind speeds in 1998 relative to 1997 or 1999 probably were responsible for the accelerated heating during May–June 1998 even though, with respect to air temperature, it was the coolest spring of the triennium

(Fig. 2C, E). By mixing downward of heat taken up by surface waters, wind-generated turbulence can diminish heat loss via backradiation and increase heat gain via conduction.

The Sea cooled from September to January (Fig. 3A). Except for daily surface (0–2 m) warming (Fig. 3A), the midlake water column tended to be isothermal during this period. It presumably mixed daily or nearly daily due to convectional circulation driven by conductive and evaporative cooling of surface waters and by periodic windy conditions (Fig. 2E). Seasonal lows for mean water column temperature always occurred in January and were 13.9 °C on 27 January 1997, 13.2 °C on 6 January 1998 and 13.8 °C on 25 January 1999.

Dissolved oxygen regime

Dissolved oxygen concentrations ranged from 0 to >20 mg l^{-1} with surface waters typically containing >4 mg O_2 l^{-1} during the day (Fig. 3B). When the Sea was stratified in spring and summer, an oxygen gradient existed between surface (6–>20 mg l^{-1}) and bottom waters (0–3 mg l^{-1}) (Fig. 3B). Anoxic conditions developed rapidly in bottom waters during periods of stratification. From September to January the entire water column usually had >3 mg O_2 l^{-1}.

The entire water column occasionally became anoxic, or nearly so, in late summer. We observed this on 12 September 1998 and 16 August and 25 September 1999 (Fig. 3B). It may also have occurred just prior to September 6 1997. These events occurred during or just after a wind-driven mixing event following a period of stratification. Mixing during the September events was most likely facilitated by reduced stability and increased circulation following cooling of surface waters (Fig. 2B, E). The September 1998 mixing event probably occurred during windy conditions on 9 September 1998, 3 days prior to sampling (mean daily wind speed of 3.6 m s^{-1} and maximum mean hourly wind speed of 8 m s^{-1}, 6 September). In August 1999, a wind event occurred two days (mean = 3 m s^{-1}, max = 7.6 m s^{-1}, 14 August) and in September 1999 3 days prior to detection of the hypoxic water column (mean = 3.6 m s^{-1}, max = 5.3 m s^{-1}, 22 September).

Following these events, photosynthesis and shallow mixing replenished dissolved oxygen in surface waters (Fig. 3B). Dissolved oxygen injected into bottom waters was rapidly consumed and following most spring and summer mixing events, the deeper portions of the lake bottom remained anoxic (Fig. 3B). In fact, large portions (60–100%) of the water column and lake bottom were anoxic or nearly so on most sampling dates in spring and summer of all years (Fig. 3B, C). Extensive hypoxia or anoxia of the lake bottom was observed as early in the year as March (1997) and persisted until early October of all 3 years. In 1998, a windy year, it developed three months later than it did in 1997 and 2 months later than it did in 1999.

Sulfide

Sulfide presumably was usually present in anoxic waters when the Salton Sea was stratified. On 31 July 1999, sulfide concentration was 1.0–3.0 mg l^{-1} at 8–10 m depth and >5 mg l^{-1} at 10–14 m depth. On 16 August 1999, it was 0.5–1.0 mg l^{-1} at 0–6 m depth and 3–5 mg l^{-1} at 6–14 m depth. These sulfide concentrations were high enough to deoxygenate the entire water column during a mixing event, at least over the greater part of the lake, where depth >8–10 m.

At station S-1 on 31 July, we calculated 3.8 mg O_2 l^{-1} would be consumed by complete oxidation of 1.9 mg HS^- l^{-1}, the mean sulfide concentration averaged over the 0–14 m water column. On this date the mean oxygen concentration was 2.8 mg O_2 l^{-1}. This would have been enough to oxidize 1.4 mg HS^- l^{-1} and to leave a final mean concentraion of 0.50 mg HS^- l^{-1} in the water column. On 16 August 1999, mean dissolved oxygen was 0.1 mg l^{-1} and mean sulfide concentration was 1.3 mg l^{-1}. Even in surface waters, oxygen concentration was low (mean of 0.2 mg O_2 l^{-1} for 0–3 m) on 16 August. Since the mixing event that initiated this condition occurred at least two days prior to 16 August (see above), the residual levels of sulfide in surface waters on 16 August seemed high.

Mid-lake horizontal variations

In general, temperature and dissolved oxygen profiles were similar among S-1, S-2 and S-3 during the 3-year sampling period. However, large differences among stations in temperature and dissolved oxygen profiles were found on a few dates (Fig. 4A, B, D, F, G, I). On 3 July 1998, the northern basin apparently had mixed more recently than the southern basin (Fig. 4B, G). On this date S-1 was nearly isothermal below 2 m, whereas S-2 and S-3 were stratified with a difference of 3 °C between 2 m and 12 m (Fig. 4B). All three stations were anoxic below 6 or 8 m (Fig. 4G).

The southern basin may have mixed more recently than the northern basin just prior to 19 July 1999. All five stations were thermally stratified on that date (Fig. 4D). However, the water below 6 m was 2–6 °C colder

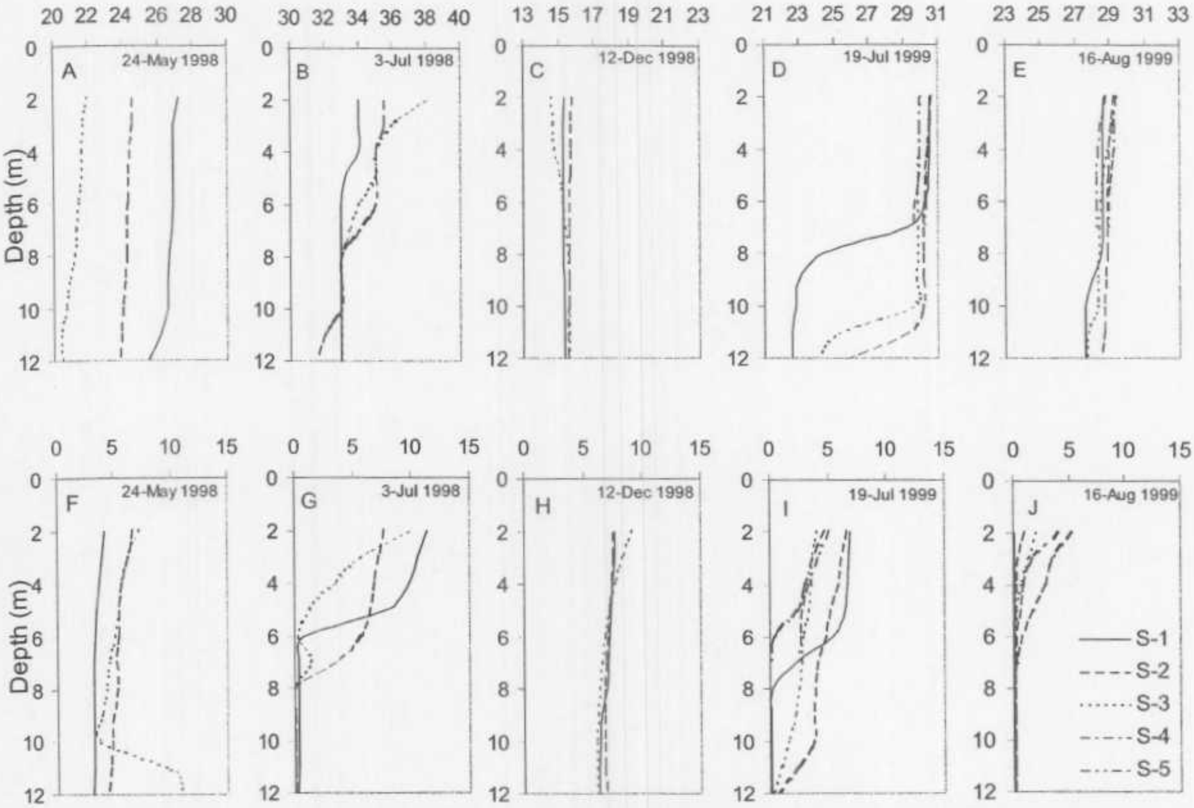

Figure 4. Temperature and dissolved oxygen profiles for the midlake sampling stations on five dates in 1997–1999. Temperatures for top 2 m of the water column are not shown as they were strongly influenced by time of day and the sequence in which stations were visited. Temperature ranges shown differ, but each spans 10 °C.

at S-1 than at S-2 and S-3, indicating that the latter two stations had mixed more completely or recently than had S-1. Between 3 July and 19 July, bottom water (>7 m) temperature showed no increase at S-1 but a ~3 °C increase at S-2 and S-3. Dissolved oxygen profiles also support this conclusion as S-2 and S-3 had measurable dissolved oxygen near the lake bottom while station S-1 was anoxic below 8 m (Fig. 4I)

An unusual unstable condition was observed on 24 May 1998. The water column was almost isothermal at S-1, S-2 and S-3 with a 1–2 °C difference between 2 and 12 m at each station (Fig. 4A). At all depths, however, the northernmost station (S-1) was 2–3 °C warmer than the middle station (S-2), and that in turn was 2–3 °C warmer than the southern station (S-3). That the three stations had mixed recently to a depth of 10 m was suggested by the dissolved oxygen concentrations at depth (Fig. 4F). This unusual situation may have resulted from a combination of greater windiness and downward mixing of surface waters in the southern part of the lake, and from warmed surface waters being advected southward by winds. Wind speeds were higher at the southernmost meteorological station prior to 24 May 1998. During 10–24 May 1998, the northernmost two stations (CIMIS 141 and CIMIS 154), and the eastern station (CIMIS 127) had an average wind speed of 3.0–3.3 m s^{-1}. For this same period, the southeastern station (CIMIS 128) had an average wind speed of 4.2 m s^{-1}. Winds were predominantly from the north and northwest (300°–360°) during this period.

Variations with distance from shore

Nearshore areas differed from offshore areas in their oxygen profiles during summer. On 17 June and 29 August 1999, the stratum of water containing >1 mg O_2 l^{-1} thickened from lake center toward shore (Fig. 5A, B, D). In other words, the isopleth for 1 mg O_2 l^{-1} lay deeper nearshore than in lake center. An hypoxic stratum (<1 mg O_2 l^{-1}) was not detected in areas shallower than approximately 8 m.

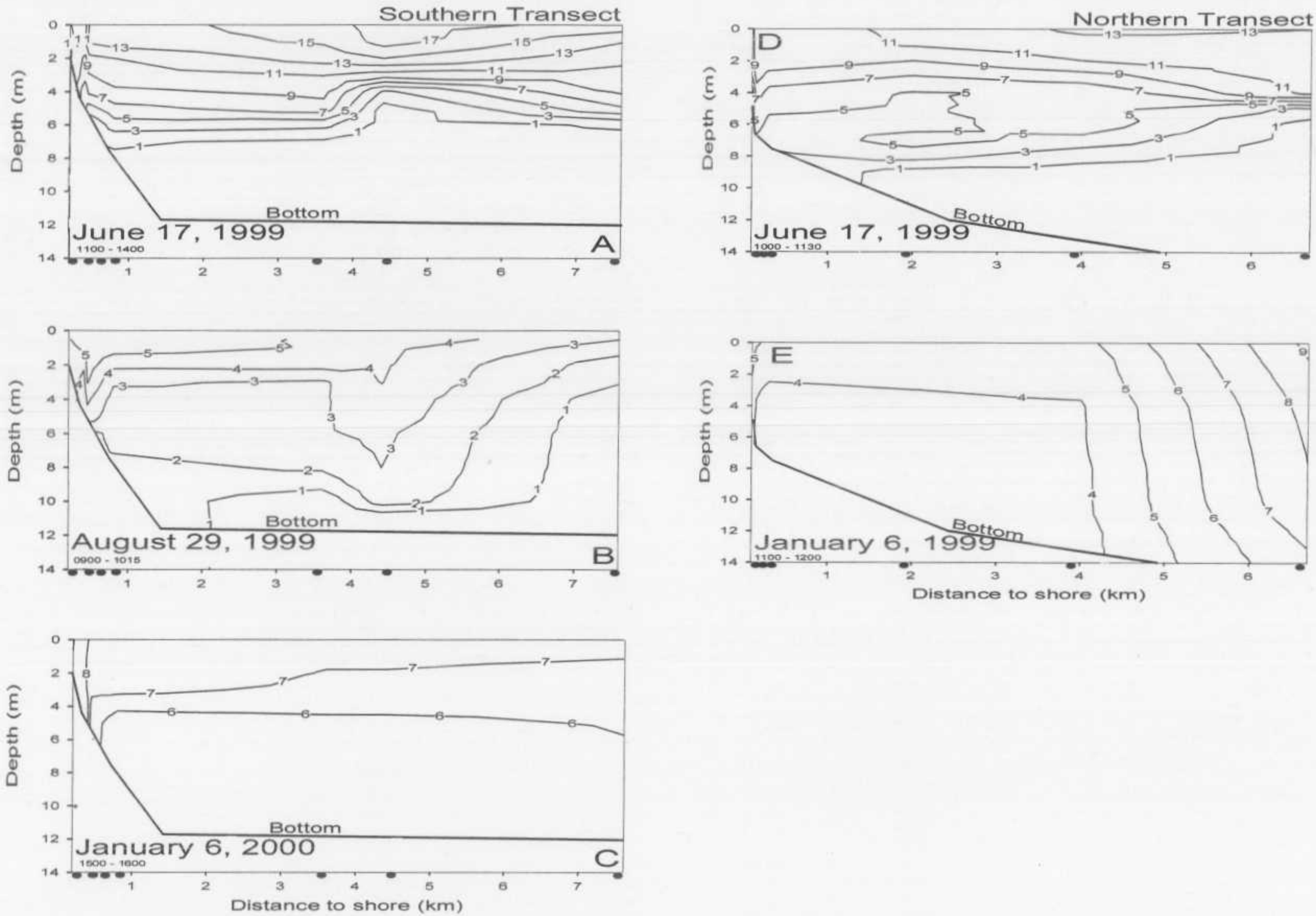

Figure 5. Oxygen profile variations along the northern (A,B,C) and southern (D,E) transects on three dates in 1999 and 2000. Sampling stations are indicated by dots on the X-axis.

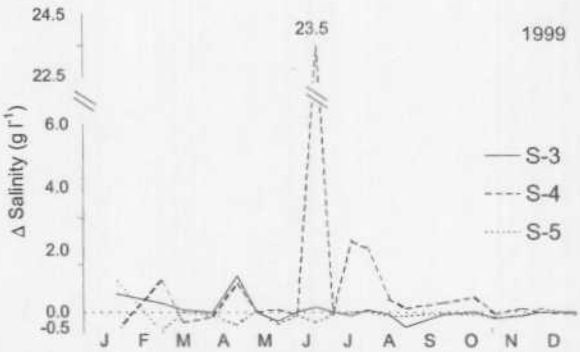

Figure 6. Salinity differential between surface (0.15 m) and 1 m depth for three stations (S-3, S-4, and S-5) located in southern basin, 1999.

In June on both transects, the top 2 m of the water column located <1 km from shore contained lower dissolved oxygen concentrations than mid-lake surface waters by 1–6 mg O_2 l^{-1} (Fig. 5A, D). The 29 August 1999 oxygen profiles do not show this pattern, perhaps because of a deoxygenation event that, based on wind records, most likely occurred on 24 August 1999.

Hypoxic strata were not detected on 6 January 1999, and at all depths nearshore and mid-lake waters contained >3 mg O_2 l^{-1} (Fig. 5C, E). On the southern transect, nearshore water contained higher dissolved oxygen concentrations (by 1–2 mg l^{-1}) than did mid-lake. On the northern transect, the nearshore water contained 2–4 mg O_2 l^{-1}less than did mid-lake.

We do not present here the temperature profiles along the transects. Those profiles show little variation and do not aid understanding of the oxygen concentration variations. On all three sampling dates, water temperature at any given depth varied only 1–2 °C between nearshore and offshore waters.

Effect of inflows on vertical surface salinity gradients and stability

Vertical salinity gradients were detected in the southern part of the lake. On 23 June 1999 after a windless period of 10 days, a salinity gradient was observed in surface waters at S-4, the station located 10 km to the north northwest of the mouth of the Alamo River (Fig. 6). Salinity was 17 g l^{-1} at the surface and 41 g l^{-1} at 1 m and deeper; temperatures were 30.1 °C at 0.15 m, 29.4 °C at 1 m, 28.4 °C at 2 m, 28.2 °C at 3 m, 28.2 °C at 4 m, 28.0 °C at 5 m, 27.9 °C at 6 m, and 24.7 °C at 7 m. No salinity gradients were observed on this date at any of the other four sampling stations. On other dates after windless periods, salinity differences between 0.15 m and 1 m ranging from 0.6 to 2.3 g l^{-1} were observed at station S-4.

Table 3. Water column stability attributable to temperature and salinity gradients at S-4 on 23 June 1999

Condition	Stability (g-cm cm^{-2})
Thermal gradient only	0.0055
High thermal gradient only	0.0330
Salinity gradient only	0.0759

The potential import of such salinity gradients is reflected in some simple calculations of stability, the amount of work that would be required to eliminate the density gradient (Table 3). Salinity differences between the 0.15 m and 1 m contributed to stability more than did the thermal gradient on 23 June 1999 at S-4. Salinity stability was 14 times greater than stability due to the temperature gradient (Table 3). When thermal stability was calculated for the hypothetical condition of 35 °C at 0–4 m and 12 °C at 4–6 m, it was still only 43% that of salinity stability.

Discussion

Wind regime as major driver

Throughout the year, wind events are important for mixing of the Sea. Wind also drives the currents of the Sea that distribute the nutrient rich, low salinity waters flowing into it via the New, Alamo and Whitewater rivers. The frequency, strength and duration of wind events affects currents, temperature, dissolved oxygen, sulfide, nutrient cycling and the distribution and abundance of biota, as in other polymictic lakes (Mitteilung, 1988; MacIntyre, 1993; MacKinnon & Herbert, 1996). Differences among years in spring and summer wind patterns can cause significant variation in lake dynamics among years, making many processes and phenomena very unpredictable in their timing and magnitude.

Frequent and strong wind events, as in spring 1998, can repeatedly break down incipient thermal stratification throughout the spring and delay the onset of anoxia and sulfide accumulation in bottom waters. Conversely, when spring wind events are infrequent or weak, thermal stratification and anoxia develop sooner in the year and persist for longer intervals.

Convection due to heat loss from surface waters likely causes much of the water column to mix on a daily or near daily basis in fall and winter and surface waters in spring and summer. Heat loss results from conduction and evaporation (Imberger, 1985). As the Salton Sea is isothermal or nearly so from October to January, even low wind speeds can contribute directly to mixing. Heat loss occurs in surface waters even during spring and summer as a result of both high evaporation rates and large day-night air temperature differentials.

Differential mixing due to differences in wind conditions and bathymetry of the northern and southern basins probably accounts for differences in their temperature and dissolved oxygen regimes (Fig. 4). Evidence of differential mixing among stations was found almost exclusively during the spring and summer when wind drives mixing, as on 24 May 1998 (Fig. 4A, F). Mean daily wind speed for the 10 days previous to this date were 1–4.5 m s^{-1} higher at the southeastern meteorological station than the northern and eastern stations and may have generated the 4–6 °C temperature gradient that existed along the lake's main axis. Differential mixing would be increased due to bathymetric differences between the two basins. No sharp boundary exists between the northern and southern basins, but a convenient dividing line can be drawn based on circulation data (Arnal, 1961; Cook & Orlob, 1997) (Fig. 1). Although lengths (fetches) of the two basins are roughly equal, the southern basin is wider, with a maximum width of ~25 km as opposed to 16.5 km for the northern basin. In addition, the northern basin has a greater maximum depth (14 m, as opposed to 12 m) and a greater mean depth (Arnal, 1961; Ferrari & Weghorst, 1997). Because the southern basin is shallower and has a greater surface area, lower wind speeds may result in more complete mixing of the southern basin during spring and summer. This would produce differences between the two basins in their thermal, dissolved oxygen and sulfide dynamics and in the impacts on biota during spring and summer months. Differences between basins would disappear due to horizontal advection during periods high wind speeds. The greater extent of well-mixed water in the southern basin probably makes it an important refuge from hypoxia and anoxia for fish and benthic macroinvertebrates from May to September.

Arnal's (1961) analysis of wind patterns suggested that prevailing west to northwest winds in the northern basin and west to southwest winds in the southern basin drove circulation patterns of the Sea. During our study, winds in the southern basin (CIMIS 128) usually originated from the northwest and rarely originated from the west or southwest, and when they did, they were of short duration and low velocity. The discrepancy between this finding and that of Arnal is most likely due to Arnal's wind data coming from a weather station in the city of El Centro, ~40 km to the south of the Sea.

Currents and salinity gradients

During windless and to some extent even windy periods, the fresher water (2.5–5 g l^{-1}) entering the Sea from the New and Alamo rivers flows over the surface of the southernmost portion of the Salton Sea creating a surface layer of less saline, less dense water. We detected salinity gradients only at one station (S-4). These scant data combined with salinity and current data from other studies (Arnal, 1961; Parsons 1986) suggest that salinity gradients may inhibit mixing over portions of the southern basin. The phenomenon does not appear significant in the northern basin. Salinity gradients of 0.2–2 g l^{-1} extending 11 km from the Whitewater River in the north were found by Arnal (1961), however. Such gradients were not observed at the northern stations monitored by Parsons (1986) or ourselves.

Distribution of salinity gradients in the southern basin is determined primarily by wind and currents. Salinity at the surface of station S-4 was often 2 g l^{-1} less than mean Sea salinity and occasionally substantially lower, as on 23 June 1999 (Fig. 6). Under windy conditions, the current pattern in the southern basin is a counter clockwise gyre that causes freshwater to flow northeast along the southeast shoreline and then northwest along the eastern shoreline (Arnal, 1961; Cook & Orlab, 1997). Vertical salinity gradients of >1–2 g l^{-1} are then created along a 2–8 km wide strip along these shorelines. Strong winds would accelerate mixing and minimize the spatial extent of areas with lowered surface water salinity. Current strength will be at a minimum during low wind periods when strong vertical salinity gradients are likely to extend well out from the delta areas of the New and Alamo rivers.

Wherever they occur, salinity gradients arising from these inflows will inhibit mixing of surface and bottom waters and the movement of heat and oxygen from surface to bottom waters. The water column stability caused by these salinity gradients is usually much greater than that caused by thermal stratification. It may counter the tendency for the shallower southern basin to mix more readily at lower wind speeds than does the deeper northern basin. The impact of inflows on mixing is increased by the fact that the majority of water entering the Sea enters from these two rivers and their mouths are only 12.5 km from each other on a ~150 km shoreline.

Sulfide and deoxygenation of the mid-lake

The deoxygenation events consistently occurred during the time of maximum water temperatures (July–September), most notably in September of all three years. These were a result of bottom waters low in oxygen and rich in sulfide, and presumably organic matter (dissolved and particulate) and microbial heterotrophs, mixing with surface waters.

The chemistry and kinetics of sulfide production and oxidation are complex and important in understanding development of these deoxygenation events. In the absence of oxygen, bacteria may use nitrate, metal oxides, carbon dioxide, or sulfate as a terminal electron acceptor to decompose organic matter (Jørgenson, 1982). In the Salton Sea, high concentrations of sulfate (9.1 g l^{-1}) make it likely to be the predominant electron receptor used by bacteria for anaerobic decomposition (Goldhaber & Kaplan, 1974). The reduction of sulfate coupled with organic matter decomposition generates sulfide in the anoxic bottom waters. In some systems, photosynthetic bacteria oxidize any sulfide produced by decomposition (Huxtable, 1986). However, in the Salton Sea, anoxic bottom waters usually are found below the euphotic zone (top 4–5 m) so sulfide is not oxidized by this mechanism. Therefore, sulfide accumulates in the bottom waters, as it does in most aquatic systems with high organic matter loading to bottom waters during thermal stratification, e.g. Baltic Sea (Ehrhardt & Wenck, 1983) and Lake Kinneret (Eckert & Hambright, 1996). In the Sea, enough sulfide is present in bottom waters that mixing events may leave surface waters hypoxic and laden with sulfide.

The length of time that sulfide is present may be as important for biota as the absolute concentrations present after a mixing event (Theede et al., 1969). Sulfide oxidation is not instantaneous and although the reaction half-life has not been directly measured at the Salton Sea, it has been estimated at 10 – 50 h in the laboratory (Cline & Richards, 1969; Almgren & Hagström, 1974). If the reaction half-life is conservatively assumed to be 24 h and initial concentrations are 2.8 mg HS l^{-1} (as on 31 July 1999), sulfide concentrations may still be 0.4 mg l^{-1} after 3 days. Such levels can be toxic for fish and invertebrates (Bagarinao & Vetter, 1989; Hagerman & Vismann, 1995). To persist, mid-lake fish and metazoan populations must exist in hypoxic, sulfide-rich conditions for a period of days.

Changes in sulfide levels since 1950s

Sulfide concentrations seem to have increased in the Salton Sea over the last half century. Carpelan (1958) found maximum sulfide concentrations of only 0.085 mg l^{-1} (and average concentrations of approximately 0.02 mg l^{-1}) in anoxic bottom waters 7 km to the west-southwest of S-1 during biweekly monitoring in 1956. This compares with sulfide concentrations measured in this study of >5 mg l^{-1}, and we measured sulfide only on two dates. The increased sulfide concentrations could be a consequence of an increase in sulfate concentrations from 6.8 in 1956 to 9.1 g l^{-1} in 1999 and an increase in biomass in the Sea (Carpelan, 1961; Hurlbert & Detwiler, unpubl. data; Riedel et al., 2002; Tiffany et al., 2002; unpubl. data). The increased organic matter in the Sea may be in the form of both phytoplankton and tilapia (*Oreochromis mossambicus* Peters) biomass and fecal matter. Tilapia, an exotic fish that invaded the Sea in the 1960s, is now the most abundant fish present, and periodically suffers massive moralities, along with other fish, during some mixing events.

Carpelan (1958, 1961) noted a single deoxygenation of the mid-lake water column in 1955. It followed a windstorm that lowered surface dissolved oxygen concentration to 0.8 mg l^{-1} on 16 September 1955. Although sulfide oxidation and simple dilution by anoxic bottom waters most likely the caused this deoxygenation event, sulfide was not monitored in the water column until 1956. The deoxygenation event only lasted 1 day (Carpelan, 1958), perhaps because sulfide concentrations were lower in 1955 than in 1997–1999. Later studies also noted the odor of sulfide in the air following wind driven summer mixing events, but did not measure sulfide concentrations in the lake (Bain et al., 1970).

Changes in oxygen levels since 1950s

Since 1954–1956, when Carpelan investigated the oxygen regime of the Sea, notable changes have occurred in the system that led us to suspect that dissolved oxygen concentrations would be generally lower during this study. Salinity increased from ~33 to ~42 g l^{-1}, lowering oxygen solubility. Fish biomass

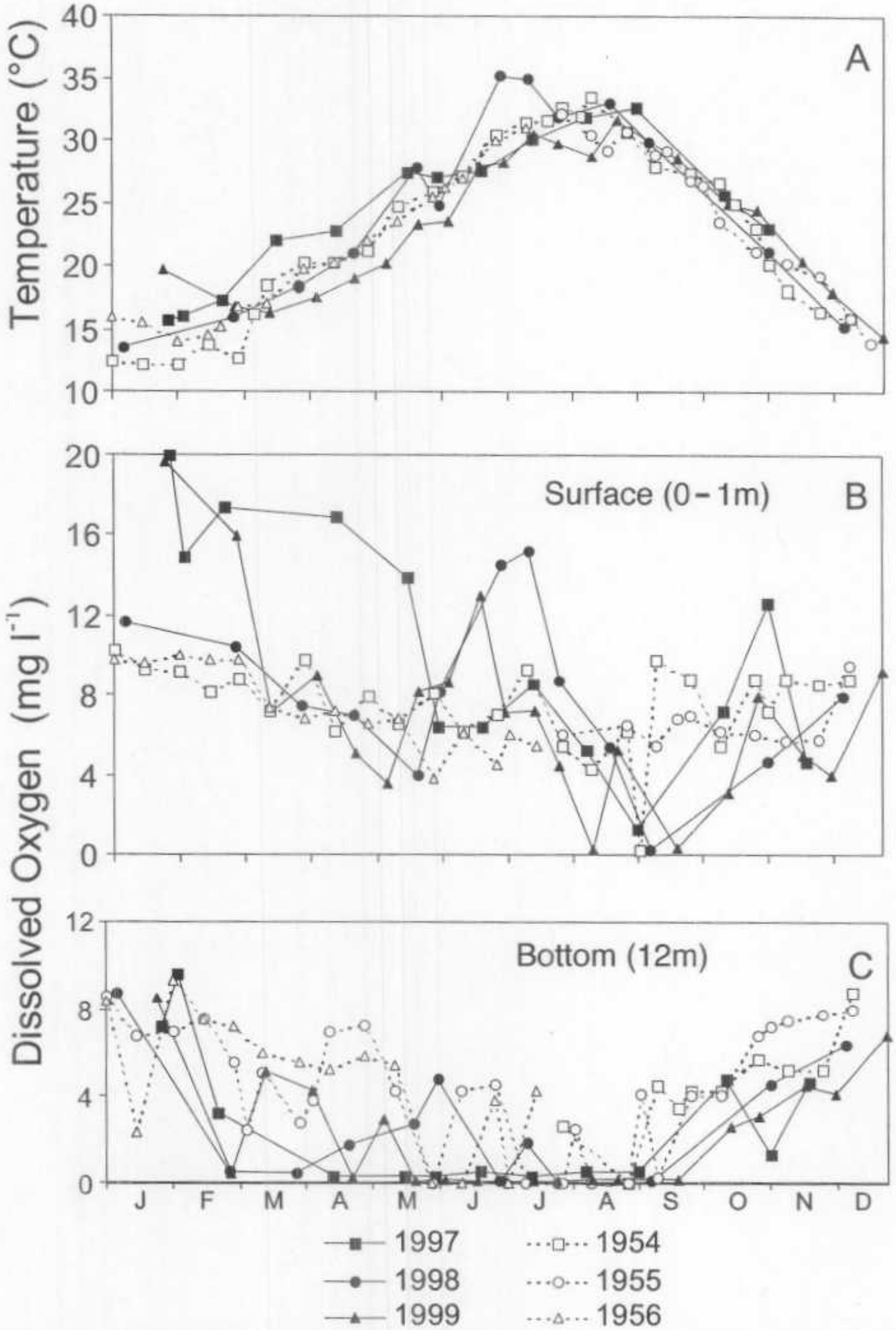

Figure 7. Salton Sea temperature and dissolved oxygen comparison of conditions between 1954–1956 and 1997–1999. (A) Surface temperature (0–1 m). (B) Dissolved oxygen in surface waters. (C) Dissolved oxygen in bottom waters. Measurements for 1954–1956 were taken biweekly at a sampling station 7 km west-southwest of S-1 from August 1954 to July 1956. Those for 1997–1999 were taken at S-1 (Fig. 1).

has increased, mainly due to the introduction of tilapia to the Sea, thereby increasing respiration and, presumably, decomposition rates in the Sea. Temperature affects dissolved oxygen, but the thermal regime has not changed notably since 1954–1956 (Fig. 7A). But to our surprise, a pattern of generally lower oxygen levels in 1997–1999 was not observed.

In surface waters, mid-day dissolved oxygen concentrations were, however, more variable during 1997–1999 when compared to 1954–1956 (Fig. 7B). Little inter-annual variation and only small seasonal differences were found in 1954–1956 whereas large variation was found among years and seasons in 1997–1999. In 1954–1956, surface waters were well oxygenated at all seasons (5–11 mg O_2 l^{-1}) except for one notable date in September 1955 when surface waters were hypoxic (0.8 mg O_2 l^{-1}). In contrast, surface waters in 1997–1999 were supersaturated at times during January–July (10–20 mg O_2 l^{-1}) and then hypoxic or anoxic at times in August and September. During the cooling period when the Sea was mixing daily or nearly daily, oxygen concentrations of surface waters were similar among all six years.

Bottom waters in 1954–1956 were usually oxic, with periods of hypoxia or anoxia developing during June–August for only a few days at a time (Fig. 7C). During 1997–1999, hypoxic or anoxic conditions began occurring as early as February and persisted for longer periods than in 1954–1956.

These changes in oxygen dynamics are most likely a result of increases since 1954–1956 in rates of primary production, fish production, decomposition, and sulfide production. Higher phytoplankton densities (M.A. Tiffany, unpubl. data) lead to increased photosynthetic rates and, therefore, a greater tendency for surface waters to be supersaturated during spring and summer when the Sea is stratified. Increased primary production supports higher densities of other organisms in the Sea and, therefore, higher rates of decomposition and sulfide production in bottom waters throughout the year. Sulfide production may also have been enhanced by the 34% increase in sulfate concentrations in the Sea since the 1954–1956. These higher sulfide concentrations can now reduce more dissolved oxygen in the water column during a mixing event. During fall and winter, when the Sea is well-mixed, processes favoring supersaturation and deoxygenation are inhibited and dissolved oxygen concentrations in 1997–1999 are comparable to 1954–1956.

Thickening of oxic stratum nearshore

The greater thickness of the oxic stratum in nearshore waters seems likely to be a general phenomenon during the warmer part of the year. Though our own data are limited, we suspect it is attributable to two principal factors: greater turbulence of surface waters nearshore than offshore, and less frequent and intensive mixing of oxygen poor bottom waters into surface waters nearshore. The potential biological significance of the thickened oxic stratum nearshore region is great, as the oxic nearshore acts as a refuge from hypoxic or anoxic conditions for fish and benthic macroinvertebrates, even during major deoxygenation events.

Breaking waves at the shoreline, friction at water-sediment interface generated by wind driven surface currents, and convection driven by greater nocturnal cooling of shallow waters all probably contribute to the greater oxygenation and mixing of the nearshore waters. These mechanisms were not directly investigated in this study, but would be expected to result in a thicker oxic stratum and less opportunity for build-up of sulfide concentrations close to shore.

Strong wind events that mix the Sea occur sporadically throughout spring and summer at mid-lake. These reduce oxygen concentrations in surface waters by mixing into them, to a greater or lesser degree, oxygen poor, sulfide-rich bottom waters. These mid-lake surface waters then gradually reoxygenate. In shallower nearshore areas, however, these low quality bottom waters are either absent or occupy a smaller percentage of the water column. Thus a mixing event that reduces oxygen levels in mid-lake surface waters by 50, or 90, or 99% may have negligible effects on oxygen levels in nearshore surface waters. Under the right conditions, however, currents can carry oxygen poor mid-lake surface waters toward shore.

The thickening of the oxic stratum nearshore affects estimates of lake bottom exposed to various dissolved oxygen concentrations (Fig. 3C). Plotted values slightly overestimate the areal extent of low dissolved oxygen conditions. Only oxygen values at the mid-lake stations were used for calculating these percentages. Overestimates only occur during periods of stratification and are on the order of ~5% when conditions mimic those found on 17 June 1999 (Fig. 5A), somewhat greater under conditions such as those found on 29 August 1999 (Fig. 5B).

Consequences for biota

Sulfide and oxygen regimes, themselves driven largely by wind and temperature regimes, have an influence on plankton, benthos and fish populations in the lake. Anoxia and sulfide have well documented adverse effects on aquatic organisms, especially metazoans (Bagarinao, 1992; Hagerman & Vismann, 1995). As the two factors usually coincide in the Salton Sea, their separate effects were not distinguishable in this study, and, for convenience, are sometimes both subsumed under phrases such as 'deoxygenation effects'. Major direct effects of deoxygenation are abandonment of the lake center by fish and benthic macroinvertebrates during May–September and abrupt plankton and fish die-offs in August and September.

A recent gillnet survey of fish distribution found that during summer few fish are found in the mid-lake (Riedel et al., 2002); and observations with a depth/fish sonar unit mounted on the sampling vessel show that when fish are found mid-lake, they are only found in the top 6 m of the water column. In spring, fish migrate to nearshore waters. This movement may be in response to the first injections of hypoxic and sulfide-bearing bottom waters into surface waters during wind events after early stratification periods in April and May. Reduction of mid-lake fish abundance likely affects mid-lake plankton populations (Tiffany et al., 2002, unpubl. data). Movement of fish to nearshore occurs when tilapia is reproductively active (Riedel et al., 2002). Tilapia are mouth brooders that build nests on the lake bottom in the form of depressions a few decimeters in diameter. High densities of their nests have been documented by sonar imaging in offshore areas at depths down to 12 m. It is not known at what time of year these nests were created. Clearly it would have been prior to strong thermal stratification, during which nesting would be restricted to shallow (<6 m deep) areas. The reduced area habitable by fish may also affect the growth rate of the fish and reduce rates of reproduction (L. Helvenston, pers. comm.).

In April and May, a vacating of the lake bottom below 4 m by benthic macroinvertebrates begins, via either mortality or migration to nearshore areas (Detwiler et al., 2002). By July, the lake bottom below 4 m depth is devoid of benthic macroinvertebrates. Anoxia and sulfide in bottom waters and sediments are the likely cause. Benthic macroinvertebrates are often tolerant of hypoxic or anoxic bottom waters (Llanso, 1991), but measured concentrations of sulfide in mid-lake areas (1–>5 mg $HS^- l^{-1}$) are in the lethal range for many aquatic organisms (Smith et al., 1976; Bagarinao, 1992). Nearshore areas provide refugia for metazoan benthic macroinvertebrates during summer. Their densities are low even here in summer, however, which represents a further reduction in fish food supplies. The beginning of strong and deep convectional circulation, usually in September, signals when effective recolonization of deep sediments by benthic macroinvertebrates can begin (Detwiler et al., 2002).

The deoxygenation events in August and September cause mortality of fish and plankton. These events in 1997, 1998 and 1999 were accompanied by crashes in populations of the dominant metazoan zooplankters (*Apocyclops dengizicus* Müller and *Brachionus rotundiformis* Lepeschkin), reduction in phytoplankton densities (dominated by diatoms, dinoflagellates and a raphidophyte), and increases in anoxia-tolerant ciliates (Tiffany et al., 2002, unpubl. data). Moribund and freshly dead fish were observed on the lake surface in large numbers following deoxygenation events. Large fish mortalities events are common at the Sea. One fish die-off in August 1999 was estimated to involve 7.6 million tilapia. A deoxygenation event in September 1955 resulted in mortality of bairdiella (*Bairdiella icistia* Jordan and Gilbert), the most abundant fish in the Sea at the time (Carpelan, 1958). Not all mortality events are associated with deoxygenation events. Mortalities of tilapia that sometimes occur during winter months have been attributed to low water temperatures (<12 °C) (Black, 1988).

In addition to fish kills and zooplankton crashes, the deoxygenation events in spring and summer are associated with bright, milky green-colored water described as 'green tides'. Previously, these 'green tides' were thought to be caused by phytoplankton blooms created by the mixing of nutrient rich water with surface waters after prolonged periods of stratification. In fact, green water has reduced abundance of phytoplankton (K. M. Reifel & M. A. Tiffany, unpubl. data.). Mention of these 'green tides' can be found in daily records kept at the Salton Sea State Recreation Area as early as the 1960s. The green color is an optical effect of gypsum crystals that precipitate as sulfide is oxidized to sulfate, already at saturation with calcium in the water column (Hurlbert et al., unpubl. data). These 'green tides' only occur in spring or summer and are associated with a strong wind event following a period of stratification, the odor of sulfide in the air and fish kills. The term 'green tides' has also been used' to describe surface blooms of the phytoplankter *Pleurochrysis pseudoroscoffensis* Gayral et Fresnel that occur at the Sea (Reifel et al., 2001).

Consequences of future changes

Inflow to the Salton Sea may be reduced in the coming years as a result of water conservation and water transfers to coastal California. The predicted reduction ranges from 25 to 43% depending on legislative and other decisions (Tetratech, 2000). In addition, engineering projects to stop the increase of salinity in the Sea may involve the creation of evaporation ponds using diked-off sections of the existing Sea. Under the various alternatives to 'fix' the Sea over the next 30 years, its level may drop 2–6 m, its area may be reduced from 980 km^2 to 675–834 km^2, and its salinity may increase and then drop as low as 38 g l^{-1} (Tetratech, 2000). The extent and timing of these modifications depend on numerous political and engineering decisions. These should take into account how modifications of the complex mixing, thermal, and dissolved oxygen regimes of the Sea will affect its future value to people and wildlife. Lakes of such large size do not exist in hot endorrheic regions such as the Salton Sink without a large water supply. For the past century, agricultural wastewaters have been the main source of water for the Salton Sea. If this supply cannot be guaranteed for the future, the ecological dynamics of this lake become, of course, irrelevant.

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