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Hydrography, nutrients and chlorophyll during El Niño and La Niña 1997–99 winters in the Gulf of the Farallones, California

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Abstract

Nutrient and chlorophyll concentrations were measured in January 1997, 1998 and 1999 in the Gulf of the Farallones, CA at locations stretching north/south from Point Reyes to Half Moon Bay, and seaward from the Golden Gate to the Farallon Islands. The cruises were all carried out during periods of high river flow, but under different climatological conditions with 1997 conditions described as relatively typical or 'neutral/normal', compared to the El Niño warmer water temperatures in 1998, and the cooler La Niña conditions in 1999. Near-shore sea-surface temperatures ranged from cold (9.5–10.5°C) during La Niña 1999, to average (11–13°C) during 1997 to warm (13.5–15°C) during El Niño 1998. Nutrients are supplied to the Gulf of the Farallones both from San Francisco Bay (SFB) and from oceanic sources, e.g. coastal upwelling near Point Reyes. Nutrient supplies are strongly influenced by the seasonal cycle of fall calms, with storms (commencing in January), and the spring transition to high pressure and northerly upwelling favorable winds. The major effect of El Niño and La Niña climatic conditions was to modulate the relative contribution of SFB to nutrient concentrations in the coastal waters of the Gulf of the Farallones; this was intensified during the El Niño winter and reduced during La Niña. During January 1998 (El Niño) the oceanic water was warm and had low or undetectable nitrate, that did not reach the coast. Instead, SFB dominated the supply of nutrients to the coastal waters. Additionally, these data indicate that silicate may be a good tracker of SFB water. In January, delta outflow into SFB produces low salinity, high silicate, high nitrate water that exits the bay at the Golden Gate and is advected northward along the coast. This occurred in both 1997 and 1998. However during January 1999, a La Niña, this SFB feature was reduced and the near-shore water was more characteristic of high salinity oceanic water penetrated all the way to the coast and was cold (10°C) and nutrient rich (16 μM NO_3, 30 μM $Si(OH)_4$). January chlorophyll concentrations ranged from 1–1.5 $\mu g\ l^{-1}$ in all years with the highest values measured in 1999 (2.5–3 $\mu g\ l^{-1}$) as a result of elevated nutrients in the area. The impact of climatic conditions on chlorophyll concentrations was not as pronounced as might be expected from the high temperatures and low nutrient concentrations measured offshore during El Niño due to the sustained supply of nutrients from the Bay supporting continued primary production. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: USA; California; Gulf of Farallones; San Francisco Bay; El Niño; La Niña

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1. Introduction

The Gulf of the Farallones refers to the continental shelf area ($<$ 200 m depth) off central California between Point Reyes (38°N) to the north and Point Montara (37.5°N) to the south and extends 80 km offshore (Steger et al., 1998). The coastline and bathymetry are generally oriented in a northwest/southeast direction. The bathymetry is complex with a narrow continental shelf (6–8 km) widening to 50 km off the Golden Gate. Near the shelf break are the Farallon Islands, rich breeding grounds for marine mammals (e.g. Allen, Huber, Ribie, & Ainley, 1989) and seabirds (e.g. Sydeman, Nur, McLaren, & McChesney, 1998). The Gulf was designated as a National Marine Sanctuary in 1981 and has abundant dolphins and sharks (Anderson & Goldman, 1996). These waters are used for a wide range of fishing, commercial and recreational activities. The nutrient supply for this rich ecosystem is provided both by seasonal coastal upwelling near Point Reyes and by the outflows of eutrophic estuarine waters issuing from San Francisco Bay (SFB) at the Golden Gate. The relative contribution of each nutrient source to the Gulf during the year is unclear, since the hydrography and chemical oceanography of the area has received little scientific attention in recent years (e.g. Van Geen & Luoma, 1993) and most studies have been directed towards collecting other types of data. Studies designed to measure distributions of birds, rockfish, sand dabs (e.g. Ainley, Veit, Allen, Spear, & Pyle, 1995; Ainley, Spear, & Allen, 1996; Larson, Lenarz, & Ralston, 1994; Sakuma & Larson, 1995) and meroplankton larval settlement (e.g. Wing, Botsford, Largier, & Morgan, 1995a; Wing, Largier, Botsford, & Quinn, 1995b) in the area have reported temperature and salinity (water mass) data. However, the nutrient data available for this region is sparse and has typically been collected during the summer and no published nutrient climatology is available.

This area lies within the California Current system with generally meandering equatorward flow. In winter the Davidson Current flows northward and close to the coast (Johnson, Botsford, Methot, & Wainwright, 1986). Over the continental shelf the ploeward undercurrent flows northward, except when strong northwesterly winds are prevalent during spring and summer (Strub, Allen, Huyer, Smith, & Beardsley, 1987). The structure and regional circulation of the Gulf is very dynamic and three-dimensional in nature, and it is a center for active mixing and exhange between the coastal and California current waters (e.g. Noble, Beardsley, Gardner, & Smith, 1987; Noble & Gelfenbaum, 1990; Largier, Magnell, & Winant, 1993; Noble & Ramp, 2000) have studied the Gulf's circulation and structure. Steger et al. (2000) summarized the more important upper-ocean circulation features as: (1) a poleward (upper 300 m) Slope Countercurrent

(SCC); (2) variable shelf circulation; and (3) submesoscale eddy-like features. AVHRR imagery provides indications of cyclonic flow in the Gulf that is consistent with the separation of an equatorward jet from the shore boundary at Point Reyes (Wing et al., 1995b). Throughout the year a positive wind stress curl lies over the Farallones in the lee of Point Reyes (Dorman & Winant, 1995) and this may help to set up the slope countercurrent (Hickey, 1979). There is always a strong poleward flow over the shelf in the SCC, 1.3 Sv enters from the south, about a third of which exits offshore and the rest moves on northwards (Steger et al., 2000). Shelf circulation is more variable than the SCC and responds to synoptic wind forcing, consistent with Ekman dynamics (Noble & Ramp, 2000; Steger et al., 2000). Sub-meso-scale eddies often dominate the flow field. These eddies have a distinct water type associated with either the SCC or the California Current, and are probably generated by frictional torque associated with current interactions with topography (Garfield, Collins, Paquette, & Carter, 1999). Freshwater flows into the Gulf from SFB through the Golden Gate and the influence of the strong tidal jet at the Golden Gate (Largier, 1996; Petzrick, Collins, & Boicourt, 1996) may extend seaward as far as 50 km (Steger et al., 1998).

According to Schwing, Husby, Garfield and Tracey (1991) and summarized in Wing, Botsford, Ralston and Largier (1998), there are at least four water types making up the waters of the Gulf of Farallones. These have been described as: (1) newly upwelled water (typically 8–10°C); (2) offshore oceanic water; (3) SFB outflow; and (4) Gulf water. Gulf water is a mixture of the first three types that tends to be retained near the coast and then heated. Consequently it is warmer than upwelled water but has no specific thermohaline definition (Schwing et al., 1991). When the winds are light, this warm water propagates polewards in the north of the Gulf, as a rotating buoyancy current (Send, Beardsley & Winant, 1987; Wing et al., 1995a, b). The region is very dynamic with the proportions of the various water masses varying as a result of local wind forcing of the thermocline depth and climatic events such as El Niño, and La Niña.

The effects of inter-annual climatic factors, such as the El Niño, La Niña phenomenon, on the distribution and relative contributions of the different water types have not been described specifically. Although the El Niño Southern Oscillation is initiated in the equatorial region, the El Niño signal does reach the Farallones (Ramp, McClean, Collins, Semtner, & Hays, 1997) and some data have been collected during El Niño years, that illustrate the contrasting conditions between these and more ‘neutral’ or ‘normal’ years. For example, Steger et al. (2000) described circulation patterns during 1991 and 1992. They found poleward transport was stronger along the shelf and slope with greater outflow to the north and warmer surface temperatures during February 1992 (El Niño conditions) than in 1991, which they labeled as a more ‘neutral or normal’ year. The negative impact of El Niño on animals near the apex of the food web, such as California sea lions (Sydeman & Allen, 1999) and seabirds (Ainley, Sydeman, & Norton, 1995) has been described, but there is little information on lower trophic levels. The published information regarding nutrient and chlorophyll distributions for this area and their responses to climatic phenomena such as El Niño, is sparse. We were fortunate enough to collect data in the Gulf of Farallones during a single month (January) during three successive years that encompassed relatively a ‘neutral/normal’ year — 1997, an El Niño year — 1998, and a La Niña year — 1999, as determined from temperature conditions compared to the climatic mean. These cruises were opportunistic and designed for other purposes, which meant we were unable to select the time of study and were restricted to the month of January. However, January is a month that provides extremes in the physical and chemical nature of the region (Steger et al., 2000). Typically it is the month when the impact of the SFB outflow on the Gulf of the Farallones should be high as rainfall is high boosting the delta outflow. The contribution of upwelling is expected to be low as the upwelling favorable winds tend to dominate in the summer months (Wing et al., 1998). We will compare the hydrographic, nutrient and chlorophyll data collected over these three winters to evaluate the different climatic conditions particularly on the contribution of SFB water to nutrient concentrations in the Gulf of the Farallones.

2. Methods

2.1. Sampling

Sampling was conducted aboard the R/V Point Sur in the Gulf of Farallones (Fig. 1a,b,c) in January 1997 (1/26–1/29), 1998 (1/25–1/28) and 1999 (1/29–2/2). These were part of approximately one-week cruises undertaken by the Naval Postgraduate School (NPS) as training cruises (OC3570) designed to collect physical oceanographic data and measure exchange at the Golden Gate Bridge and the near-shore region outside SFB (unpublished data). Nutrient, chlorophyll, biogenic silica and nitrogen uptake measurements were made in conjunction with the hydrography and physical measurements being made by NPS. Here we report on the CTD, nutrient and chlorophyll data. Discrete water samples were collected from five depths (surface, 5 m, 10 m, 25 m and near-bottom) using acid-cleaned 10-L PVC Nisken bottles equipped with Teflon coated springs and fittings and silicone tubing mounted on an instrumented rosette sampler with a Seabird CTD. Salinity is reported as practical salinity scale (Millero, 1993). Surface data are mostly provided in this paper, but the entire data-set is available from the first author.

2.2. Nutrient and chlorophyll analyses

Water samples for NO_3, $Si(OH)_4$ and PO_4 analyses were frozen in 20 ml polycarbonate scintillation vials until they could be analysed using a Technicon AutoAnalyzer II according to the procedures of Whitledge, Malloy, Patton, and Wirick (1981). Combined NO_3 and NO_2 concentrations are reported as NO_3.

Water samples (100–280 ml) were filtered onto 25 mm GF/F glass fiber filters and assayed for chlorophyll a using the fluorometric technique (Holm-Hansen, Lorenzen, Holmes, & Strickland, 1965), with a 24–30 h extraction in 90% acetone at $-20°C$ (Venrick & Hayward, 1984). Chlorophyll a was calculated from data obtained using a Turner Designs model 10 fluorometer calibrated (Parsons, Maita, & Lalli, 1984) with chlorophyll *a* (Sigma Chemical Co.).

3. Results

3.1. January 1997, a neutral year

Surface temperature plots (Fig. 2a) show the water in the Gulf of Farallones was warmer than the water inside SFB, and ranged from 11 to 13°C. Temperatures in the estuary were cooler at 9.5–10°C. The salinity contours (Fig. 3a) show the same along-shore pattern as the temperature, but with two small near-shore cool, low salinity features, one just to the north of Point Reyes and a similar feature midway between Point Reyes and the Golden Gate. Offshore, the Farallon Islands were bathed in typical Pacific water ($>$ 32). Near the coast, the surface water were cooler (11.5–12°C) and less saline (24–30) (Fig. 3a), indicating the influence of outflow from the Golden Gate of SFB water (i.e. cold and fresh). Surface water within SFB was low in salinity (12–18) probably as a result of the typical heavy January rainfall, the maps for the deeper water of SFB (not shown) show that the salinity increases with depth, reaching 28–30 at 25 m. The surface nutrient concentrations (Figs. 4a and 5a) showed similar spatial patterns to temperature and salinity, with higher concentrations in SFB (NO_3=18–26 μM, $Si(OH)_4$=30–130 μM) than in the coastal nearshore water (NO_3=12–18 μM, $Si(OH)_4$=30–60 μM). Offshore in the higher salinity warmer water, nutrients were much lower (NO_3=2–8 μM, $Si(OH)_4$ up to 10 μM). Surface chlorophyll concentrations were higher ($>$ 1.5 $\mu g\ l^{-1}$) in the areas of higher nutrients, at the Golden Gate and along-shore up to Point Reyes (Fig. 6a). The warmer offshore water with high salinity, but lower nutrient, did contain some chlorophyll (1–1.5 $\mu g\ l^{-1}$).

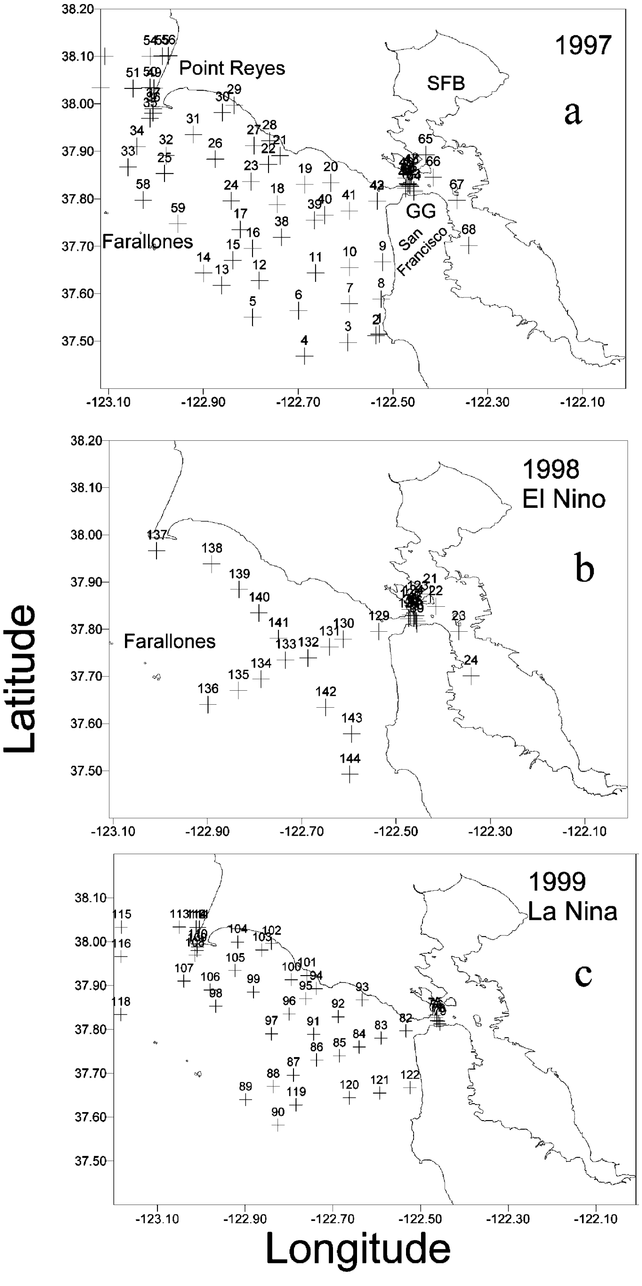

Fig. 1. Location of stations in the Gulf of Farallones and SFB, occupied during this study: (a) 1997, (b) 1998 and (c) 1999. GG shows location of Golden Gate Bridge.

3.2. January 1998 — an El Niño year

This cruise took place at the peak of the 1997–1998 El Niño warming event. The surface temperatures and salinities show along-shore patterns (Figs. 2b and 3b) similar to those seen in 1997, with the similar

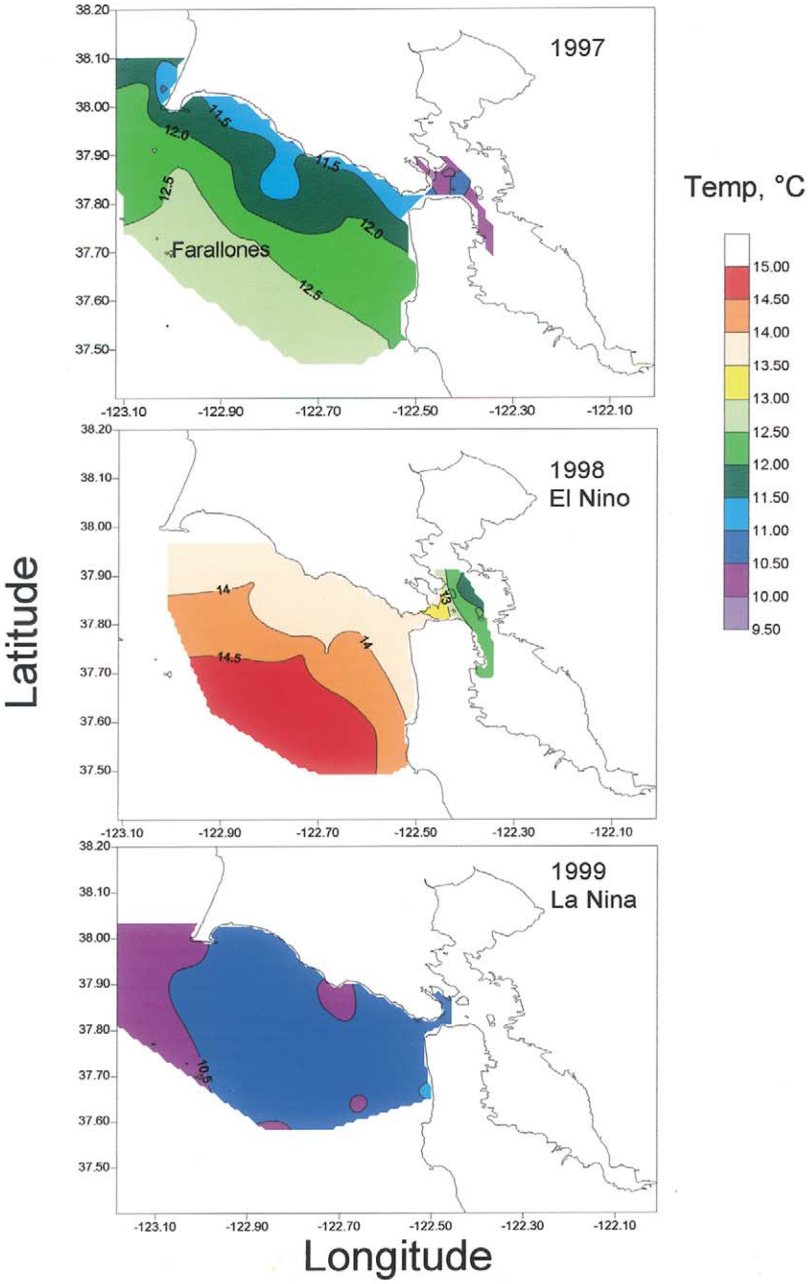

Fig. 2. Surface distributions of temperature (°C) in the Gulf of Farallones during January (a) 1997 (neutral/normal), (b) 1998 El Niño and (c) 1999 La Niña.

bulge in fresh water along the coastline, but temperatures were much warmer (13.5–15°C, compared to 11–13°C) and salinities were fresher (16–28 compared to 24–30) than in January 1997. The lower salinity water had spread further offshore in January 1998 than in January 1997 and the oceanic high salinity water (> 32 pss) was confined to a smaller offshore area compared to 1997. Although the surface water in SFB

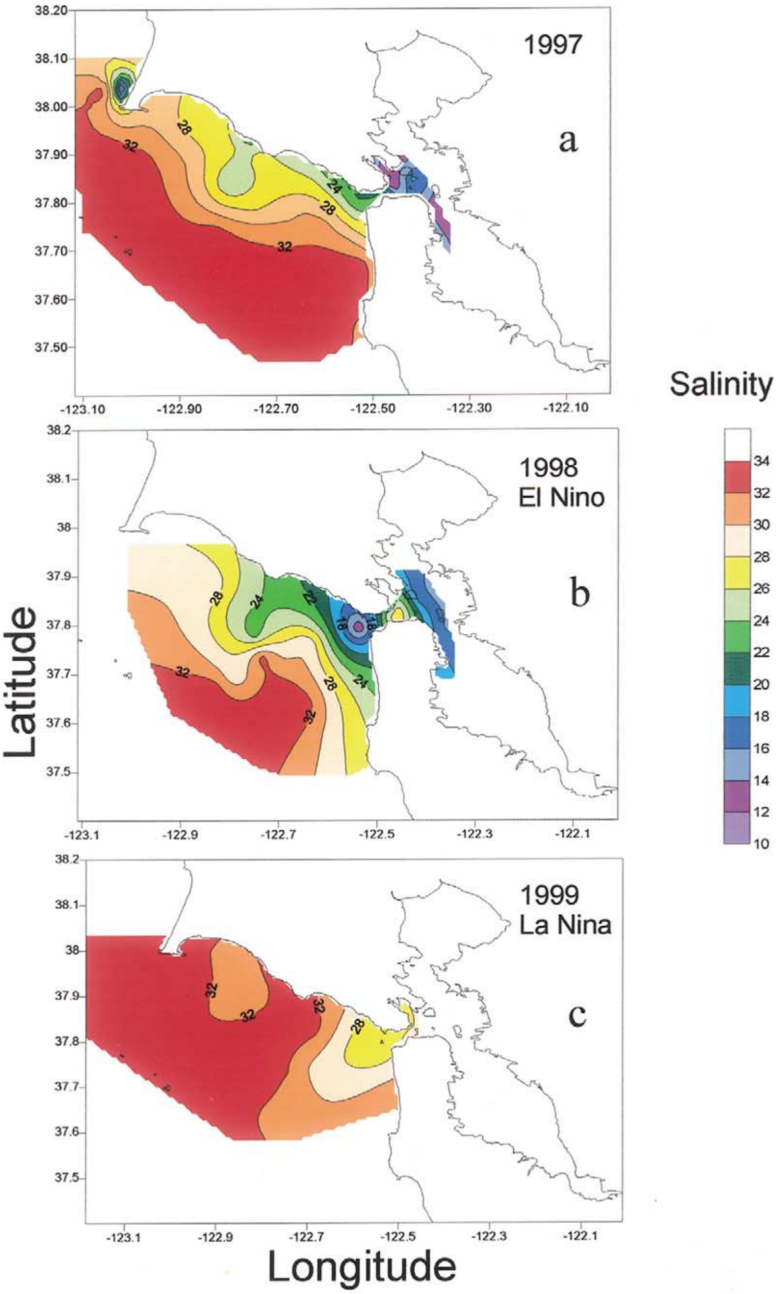

Fig. 3. Surface distributions of salinity (pss) in the Gulf of Farallones during January (a) 1997 (neutral/normal), (b) 1998 El Niño and (c) 1999 La Niña.

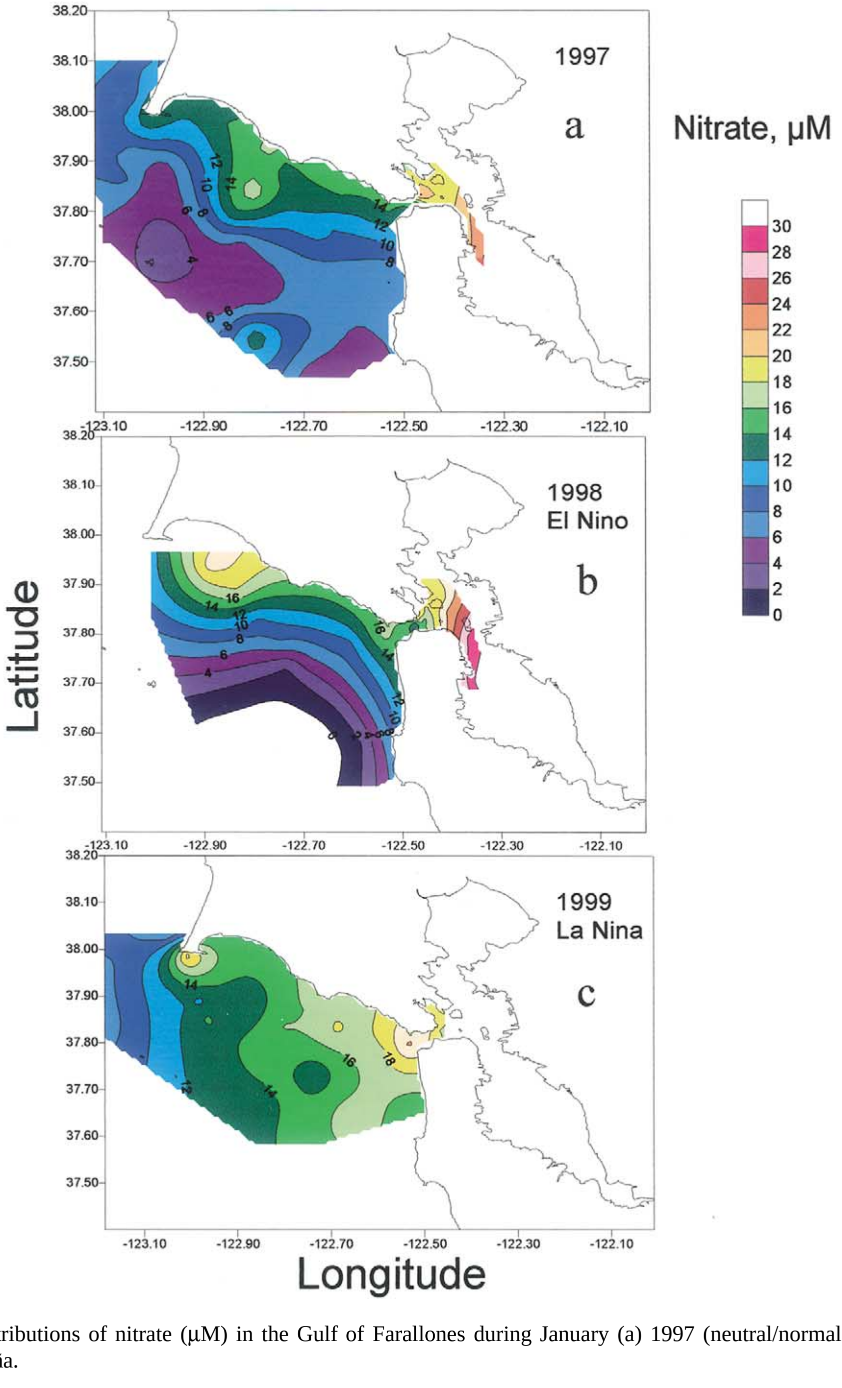

Fig. 4. Surface distributions of nitrate (µM) in the Gulf of Farallones during January (a) 1997 (neutral/normal), (b) 1998 El Niño and (c) 1999 La Niña.

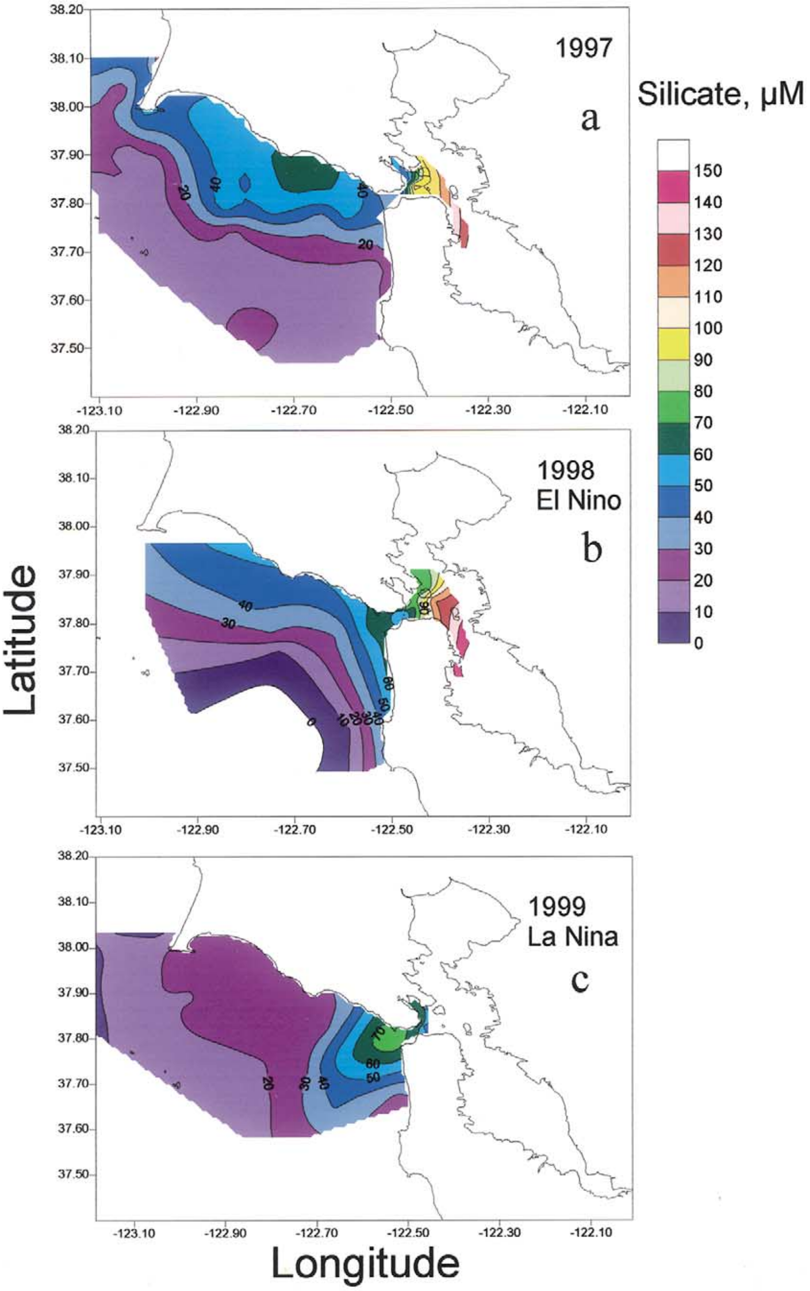

Fig. 5. Surface distributions of silicate (µM) in the Gulf of Farallones during January (a) 1997 (neutral/normal), (b) 1998 El Niño and (c) 1999 La Niña.

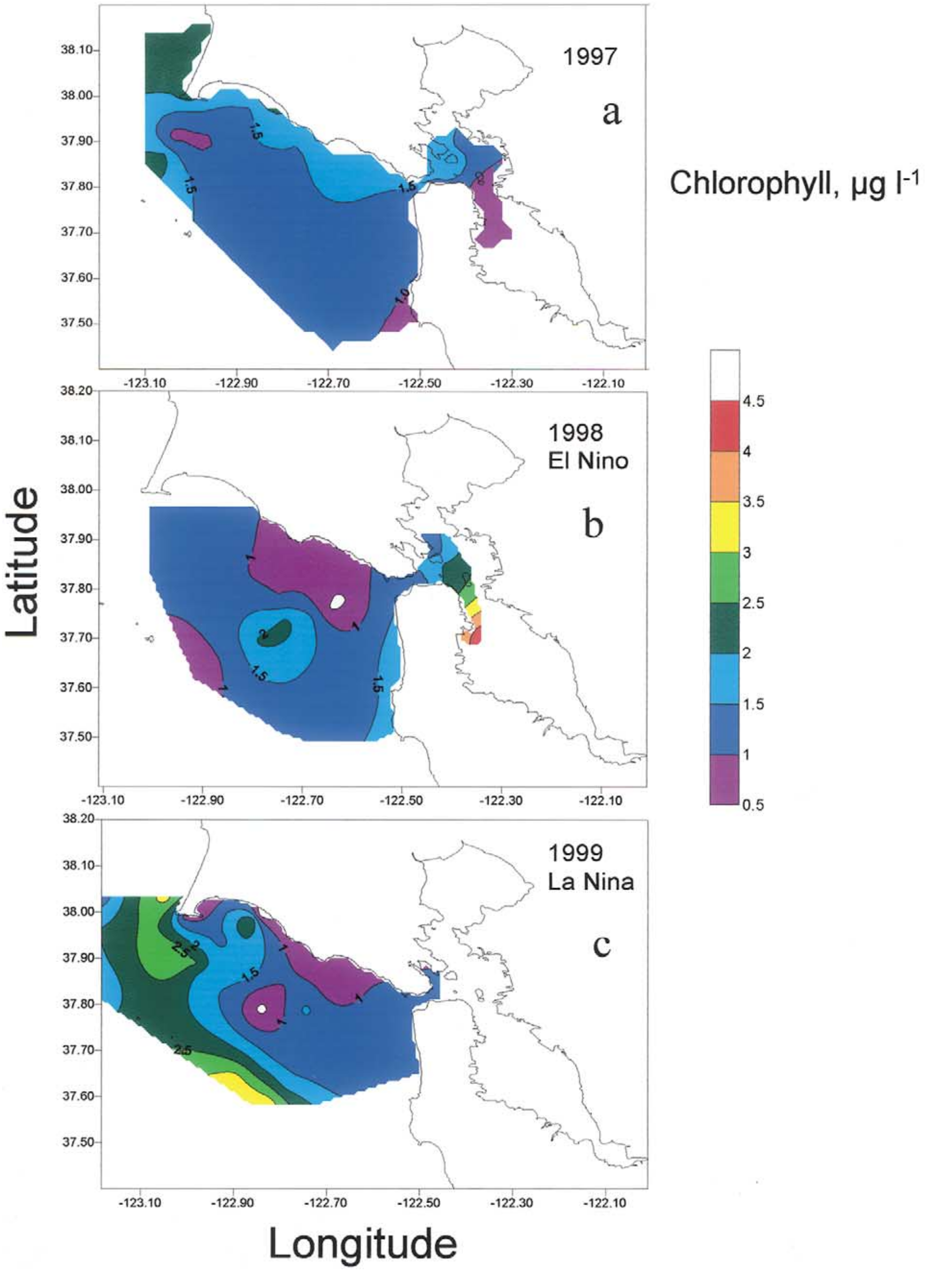

Fig. 6. Surface distributions of chlorophyll-a (µg l^{-1}) in the Gulf of Farallones January (a) 1997 (neutral/normal), (b) 1998 El Niño and (c) 1999 La Niña.

was cooler (11.5–14°C) than offshore, it was still warmer than in 1997 (9.5–10°C). It was also saltier than in 1997 (14–28, compared to 12–18 in 1997). Nutrient concentrations in 1998 (Figs. 4b and 5b) again tracked the salinity contours and so showed similar patterns to those of 1997, although offshore values were lower, and along the coast concentrations were higher. In SFB surface nitrate peaked with concentrations ranging from 18 to30 μM (similar to 1997) and concentrations decreased going offshore from the Golden Gate, down to subdetection levels (indicated as 0 μM) in the California Current region. In the Gulf, there was a small surface peak in nitrate (18–22 μM) just south of Point Reyes (Fig. 4b). At the surface in SFB, silicate concentrations ranged from 70 to 150 μM (Fig. 5b) with concentrations decreasing moving out through Golden Gate and offshore. At 25 m depth silicate concentrations were similar both inside and outside of SFB (data not shown) and ranged between 0 and 40 μM. The source of the higher silicate concentrations that occur at the surface in the Gulf of Farallones, along both the Point Reyes and SF Peninsula coastlines is silicate-rich estuarine waters of SFB. Nitrate is also supplied from this source but concentrations are lower than silicate. Nutrients may also have been provided by coastal upwelling at Point Reyes and then held there by a small eddy, thus creating the feature seen in the nitrate pattern. Nitrate and silicate concentrations tended to be higher at the surface during the El Niño winter (1998), both in SFB and Gulf of Farallones but they were lower in subsurface waters (not shown). Surface chlorophyll (Fig. 6b) in SFB occurred at higher maximum concentrations in 1998 (up to 4.5 μg l^{-1}) than in 1997, but along the coast and in the Gulf concentrations were generally lower (0 to 1.5 μg l^{-1}) than in 1997, except at the two central stations where chlorophyll concentration reached 2 μg l^{-1}.

3.3. January 1999 — a La Niña year

This cruise sampled during the cooler La Niña event that following El Niño 1997/8. This is clear in the temperature map (Fig. 2c), which shows that surface temperatures in the Gulf of Farallones only reached 11°C compared to the maxima of 13°C in 1997 (Fig. 1a) and 15°C in the previous January 1998 (Fig. 1b). Unfortunately this cruise did not sample in SFB. Throughout the Gulf salinities were saltier (Fig. 3c) > 26, than in either 1998 (> 14) or 1997 (> 20). The surface bulge seen both in 1997 and 1998 in both the temperature and salinity isolines along the Point Reyes–Golden Gate shoreline was still evident. The influence of the surface outflow from the Golden Gate in reducing salinity along the adjacent coastline was much weaker in 1999 than in the other years. During January 1999 (Fig. 4c) surface nitrate concentrations in the Gulf were higher (mostly > 12 μM) than 1997 and 1998 (ranging from 0–2 μM upward). The two regions of higher nitrate concentrations in the outflow plume from Golden Gate were again evident as in 1997 and 1998, but there was an additional area of high concentration just south of Point Reyes, where surface temperatures suggested this to have been a result of upwelling. The silicate map (Fig. 5c) shows one area of high silicate concentration, at the Golden Gate outflow. The silicate seen at the surface along the Point Reyes coast may well have come from upwelling to the north. Silicate concentrations in the Gulf in January 1999 tended to be lower than in either of the previous two years, which was probably because of the reduced delta outflow in January 1999 and lower silicate in the SFB water. Just inside the Golden Gate the surface silicate maximum was only 70–80 μM compared to 80–90 μM in 1997 and 90–100 μM in 1998. Chlorophyll in the Gulf reached higher values in January 1999 (up to 3.5μg l^{-1}) compared to the other years (typically around 1.5 μg l^{-1}) with the highest concentrations extending from the north (Fig. 6c). In 1998 this region was not sampled.

3.4. Temperature versus salinity relationships

The plot of all the available temperature and salinity data (Fig. 7) from the Gulf of the Farallones (for all depths to 50 m) clearly shows the presence of warmer waters (13.5 and 15°C) during the 1998 El Niño and cooler water (9.5 to just over 11°C) during the 1999 La Niña. During the neutral winter of 1997 water temperatures were intermediate (11–13°C). In both 1997 and 1998 temperatures decreased with salinity, albeit with some scatter in 1998. Mixing between warmer saltier oceanic water and the colder, fresher water discharging from SF Bay water is evident during the first two years but in the La Niña data where similar (cool) temperatures occurred both offshore and in the plume issuing from SFB. The slight negative

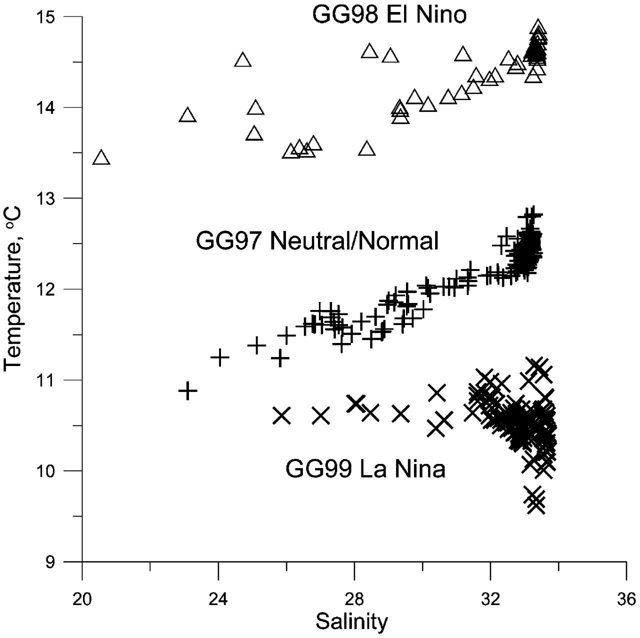

Fig. 7. Temperature versus salinity plots for Gulf of Farallones (data from depths <50 m), for 1997 (neutral/normal), 1998 El Niño and 1999 La Niña cruises.

slope during the La Niña (1999) when salinities were >32 is indicative of upwelling, generating a very different *T*/*S* relationship to the positive one observed in 1997 and 1998.

3.5. Silicate versus nitrate relationships

Plotting silicate versus nitrate for the Gulf of Farallones data from the upper 50 m revealed different mixing lines, indicating different water masses. The 1997 data (Fig. 8a) shows two mixing lines: (a) a steep line with higher silicate concentrations and low salinities contributed by SFB water; and (b) a less steep mixing line (slope close to 1:1) that is oceanic water with salinities >33 and lower silicate:nitrate ratios than in the SFB mixing line. In the El Niño year (1998) the lower mixing line (with near 1:1 silicate:nitrate) is not evident (Fig. 8b) and only the steep SFB mixing line is apparent as the Gulf was being supplied primarily by nutrients from SFB. Water in SFB was high in silicate and consequently silicate:nitrate ratios throughout the Gulf were higher than in 1997. The high salinity oceanic water was low in nutrients and its data appears compressed at the bottom of the mixing line near the origin of the axes. In January 1999 (La Niña, Fig. 8c), both mixing lines are observed as in 1997. However in 1999 most of the data lies on the lower oceanic mixing line, although some of the stations fit the SFB mixing line with $Si(OH)_4 > 40$ μM and lower salinities. The oceanic slope is not 1:1 silicate:nitrate as in 1997 but a little higher.

To illustrate the mixing between oceanic and estuarine waters that result in the variations in nutrient (NO_3 and $Si(OH)_4$) that can occur in the Gulf of the Farallones, $Si(OH)_4$ and NO_3 concentrations measured at Angel Island (a station just inside the Golden Gate) for January 1997, 1998 and 1999 are plotted in Fig. 8d, together with the same pairs of nutrient data for offshore Gulf of Farallones stations from 50 m depth, which more or less represent the maximum oceanic concentrations available for mixing. It is immediately apparent that the estuary water has a high silicate:nitrate ($Si(OH)_4$:NO_3) ratio and its variability results

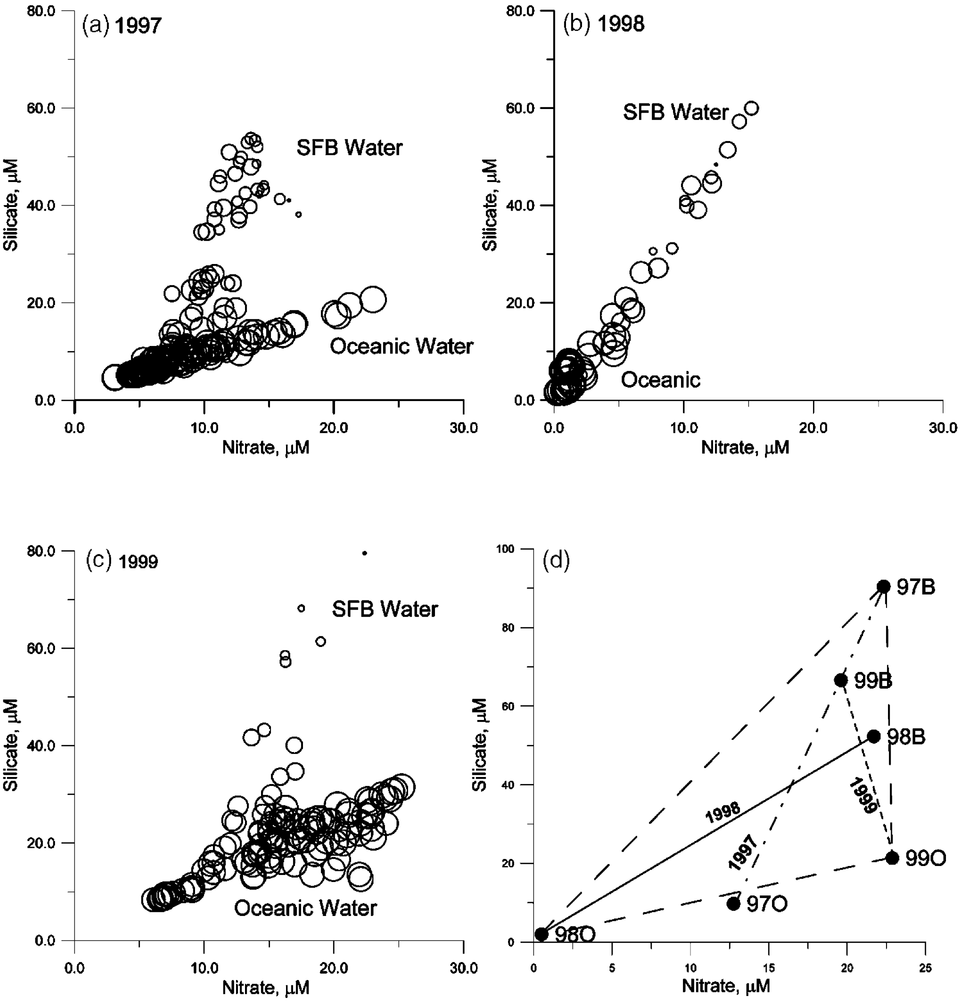

Fig. 8. Silicate versus nitrate for Gulf of Farallones (depth <50 m), (a) January 1997 (neutral/normal), (b) January 1998 El Niño and (c) January 1999 La Niña. Size of circles indicate salinity values, (d) Silicate versus nitrate from stations in the outer Gulf of Farallones (97O, 98O and 99O) and Angel Island, inside the SFB (97B, 98B, 99B) measured during January 1997, 1998 1999, connected by potential mixing lines.

primarily from changes in silicate rather than nitrate. The $Si(OH)_4$:NO_3 ratio in the oceanic water is relatively constant (nearly 1:1) making a straight line between the points for the three years (98O, 97O and 99O in Fig. 8). Mixing can take place between any point in the $Si(OH)_4$:NO_3 space of the estuarine water (97B,98B and 99B in Fig. 8) to any location on the oceanic $Si(OH)_4$:NO_3 line: i.e. a web of lines can be expected within the outlines of the triangle formed by low oceanic (98O), high oceanic (99O) and high estuarine (97B) data points. The 1997 mixing diagram (Fig. 8a), corresponds to features in Fig. 8d, e.g. the oceanic line at the bottom and the mixing line with SFB bay water extending to the high $Si(OH)_4$:NO_3 point, with an intersection of the two lines occurring with oceanic water having about 8 µM of both $Si(OH)_4$ and NO_3. The water formed by this process has both enhanced $Si(OH)_4$ and NO_3 from SFB, with much more enrichment in $Si(OH)_4$ than NO_3 (see steep slope of 97O to 97B in Fig. 8d). The 1998 El Niño diagram (Fig. 8b) illustrates the mode in which almost the entire nutrient enrichment of the Gulf occurs from the entrainment of SFB water (line 98O to 98B in Fig. 8d) and the oceanic line is missing, as oceanic water above 50 m depth is very low in both silicate and nitrate. The mixing diagram for La Niña 1999 shows a strong oceanic line (Fig. 8c) reflecting the high nutrient conditions of the oceanic water in that year, when mixing with SFB water only increased silicate concentrations in the Gulf Water. This was because nitrate concentrations in SFB were similar to the oceanic source water, so the resultant mixing line was about vertical, (99O–99B in Fig. 8d); the SFB-oceanic line has a slight reverse slope because of the high nitrate concentrations in the oceanic region.

In summary, for the month of January, the estuary (SFB) contributed both silicate and nitrate to the Gulf in the ‘neutral/normal’ year (1997), was the major source of these two nutrients in the El Niño (1998) year but influenced the Gulf nutrient conditions relatively little in the La Niña year, 1999. In any year, the nutrient that shows the most dramatic changes in the Gulf as a result of climatic variations is silicate, reflecting the relative contribution by SFB water to the Gulf of the Farallones water.

4. Discussion

The temperature data clearly support the occurrence of anomalously warm classical El Niño conditions in January 1998 and cold La Niña conditions in January 1999. The climatology (www.ndbc.noaa.gov/data/climatic) of mean sea-surface temperature for January measured at the NOAA Gulf of the Farallones buoy (#46026) using data from 1982 to 1993 is 11.4±0.94°C (s.d., $n = 6372$). A minimum temperature of 8.7°C was recorded in January 1991 and a maximum of 14.2°C in January 1983 during a strong El Niño event. Mean surface temperatures in our data sets showed that in 1997 they were close to the climatological mean at 11.6±0.84 ($n = 69$), and roughly in agreement with 1991 near-shore Gulf values (*ca*. 11.2°C) reported by Steger et al. (2000) for a neutral year. This is in contrast to the warm mean SST observed in January 1998 of 13.6±0.8 ($n = 29$). In February 1992, another El Niño period, mean SST was reported to be ~13.2°C in the near-shore Gulf study of Steger et al. (2000). The maximum temperature recorded in January 1998 was 14.9°C at station 136 which was near to the buoy location. Mean temperature for the 1999 cruise was 10.6±0.2 ($n = 45$), which was cooler than the climatological mean buoy temperature.

It is difficult to compare our January nutrient data with other available hydrographic data, e.g. Wing et al. (1998) and Schwing et al. (1991) that were collected in May/June. However, three of the four different water types described by Schwing et al. (1991) were clearly evident in January. Water types that we observed on all three cruises were: (a) offshore oceanic water—typically with $S>32$ and $T>12.5$°C; (b) SF Bay outflow with low salinity, which was described by Wing et al., (1995b) as being warmer but in January it was typically colder than the oceanic water (cf. Largier, 1996); and (c) mixtures of the two previous water types that make up Gulf water. This is water with characteristics that are intermediate between the oceanic and the bay waters; typically it is retained close to the coast where it is warmed (Wing et al., 1995b). This can be seen clearly in the salinity contours for January 1997 and 1998 but not in 1999 when the oceanic water dominated the region and Gulf water was not easy to identify. *T/S* and nitrate versus silicate plots (Figs. 7 and 8) also indicate that oceanic water dominated the Gulf during January 1999 and most of the data fell along the high salinity mixing line. The fourth water type described by Schwing et al. (1991) — recently upwelled water — was seen in 1999 an 1997. In 1999 a patch of upwelled water was observed to the north of Point Reyes, and we have tentatively attributed the negative slope of the temperature versus salinity relationship as an upwelling signal. In 1997 cold, nutrient rich water was again present just north of Point Reyes.

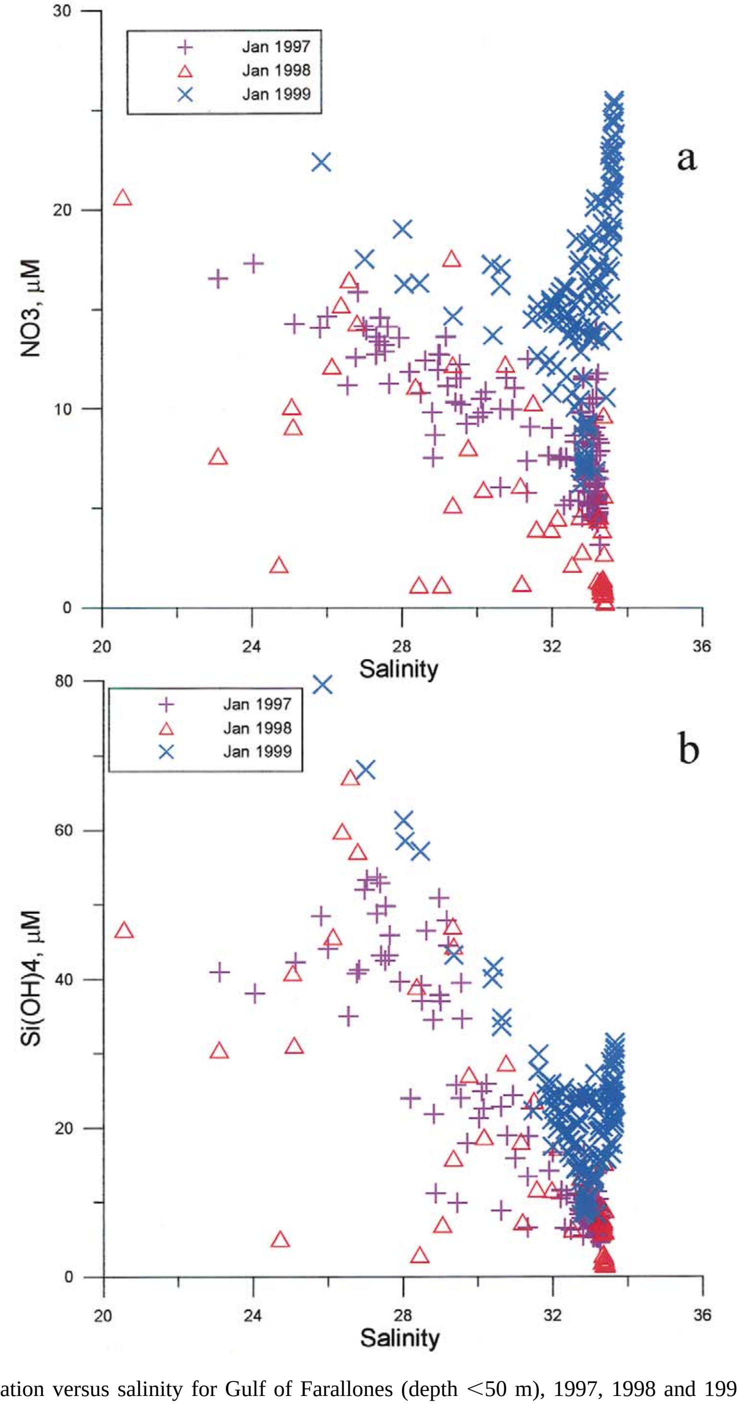

Fig. 9. Nutrient concentration versus salinity for Gulf of Farallones (depth <50 m), 1997, 1998 and 1999, (a) nitrate, (b) silicate.

The SFB is clearly a major source of nutrients in the Gulf during most winters, although its importance diminished during the La Niña event (1999). This source for nitrate to the Gulf was also described by Van Geen and Luoma (1993). When nitrate is plotted versus salinity for our entire data set (Fig. 9a) the lower salinity water (<28 i.e. from the SFB can be seen) dominant nitrate source in 1997 and 1998, whereas in 1999 the contribution by high salinity oceanic waters (>32) was greater. The upwelling center source concentrations were ~26 μM at 25 m in 1999 (data not shown) whereas the surface supply from SFB reached 20–22 μM (1997 and 1999 data). Silicate is usually supplied from both sources, but the major source of silicate for the Gulf is from the SFB, as a result of the very high concentrations that enter the delta of SFB. Silicate is also provided to the Gulf by upwelling but the very high concentrations in SFB masked any peaks in silicate that may have come from upwelling. Typically SFB water flowing out of the Golden Gate contains silicate at 70–80 μM in January, whereas that from upwelling will be closer to 30 μM. The silicate versus salinity plot using the entire data set (Fig. 9b) shows the significant contribution of silicate to the Gulf by lower salinity water, with silicate concentrations of >30 μM only in water with salinity <30.

In conclusion, the estuary (SFB) is a source of silicate to the Gulf in all three climatic conditions represented by the data from January 1997, 1998 and 1999, because of the characteristic very high concentrations in SFB water, aided by the high exchange through the Golden Gate during January (Largier, 1996, his Fig. 10). January is when surface current velocities reach their maximum (>60 cm s^{-1}) compared with the rest of the year (April–July and August–November) (Largier, 1996). The relative importance of the contribution of nitrate from the estuary to the Gulf depends on the gradient between the oceanic water and the estuarine water. This gradient was high during El Niño conditions, but low during La Niña and intermediate during the neutral/normal conditions of 1997. The overall effect of the bay outflow is to impart a measure of stability to the winter Gulf nutrient supply over a wide range of climatic variability, ensuring the availability of nutrients to the winter productivity period. The supply of silicate above the usual ratio of $Si(OH)_4$:NO_3 of 1:1 typical of oceanic upwelled water is another result of the export of Bay water to the Gulf of the Farallones. Since nutrients were supplied in abundance from SFB to the Gulf during the El Niño in January it is likely that any potential negative impact of El Niño on productivity as typical in California coastal waters was ameliorated in the Gulf by the increased supply of nutrients from SFB. The surface chlorophyll data (Fig. 6) supports this with chlorophyll during January 1998 only slightly less than in 1997. Another important climatic condition to impact the Gulf ecosystem in terms of chlorophyll was La Niña when the balance of nutrient sources was altered and the highest values for January were measured (2.5–3 μg l^{-1}) as a result of elevated nutrients in the area.

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