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El Nino effects on hydrogen ion concentration of a California reservoir

JOHN G. McCOLL
Department of Soil Science, 108 Hilgard Hall, University of California, Berkeley, California 94720, USA

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Abstract. Hydrogen ion concentration, $[H^+]$, of discharge water from Pardee reservoir in the central Sierra Nevada, California was greater than expected in years of El Nino occurrence over the period 1954–86. This pattern is in addition to the general increase in $[H^+]$ over the same period attributed to acidic atmospheric deposition. Monthly means of $[H^+]$ also show differences between El Nino and non-El Nino years. Total annual runoff does not seem to be a controlling factor; the source and timing of storms are probably more important. Storms are usually from the west or northwest, but during El Nino years tropical-like storms from a more-southerly direction appear to carry acidic pollutants to the central Sierra Nevada.

This report examines yearly and monthly variation in the hydrogen ion concentration of discharge water from Pardee, which is a large reservoir in the central Sierra Nevada of California, with the occurrence of El Nino events.

El Nino is part of a complex system of fluctuations referred to as the El Nino/Southern Oscillation (ENSO) which is the dominant index of global climatic changes over time periods of months to a few years (Graham & White 1988; Rasmussen 1984). ENSO anomalies generally result in unusual winter conditions to mid-latitudes, as well as causing major changes in tropical rainfall patterns associated with severe drought conditions or torrential rains in other places of the globe (Rasmussen 1984). The recent 1982–83 ENSO event was an outstanding example of anomalous variations in climate which were associated with various biological and chemical changes, and its classical effects have heightened intensity of multidisciplinary workshops and research (Mooers et al. 1986; Reinecker & Mooers 1986).

Caution must be exercised in attributing causes of anomalous biological processes to climatic forcing by ENSO events (Namias & Cayan 1984). However, there is growing evidence that good correlations (if not cause and effect relationships) exist even for processes in terrestrial ecosystems, although most studies have focused on oceanic and coastal environments. In the western U.S., climatic forcing is related to thermal properties of a small temperate lake in northern California (Strub et al. 1985), and contributes to the control of the physical, chemical and biological properties of the San Francisco Bay estuary in California (Cloern & Nicholas 1985; Peterson et al. 1985).

An important characteristic of the discharge water from the two main reservoirs in the Sierra Nevada that supply the San Francisco Bay metropolitan area is the increase in $[H^+]$ over the period of 1954–79; a parallel decrease in alkalinity has also been documented at one reservoir (McColl 1981). The cause is probably acidic atmospheric deposition, primarily from emission of NOx from the San Francisco Bay area; these emissions are four times greater than those of SO_2 (McColl 1981). The general increasing trend for $[H^+]$ has continued (Fig. 1A, $r = 0.70$, $p < 0.001$), at least for Pardee reservoir, which has been examined through 1986 (McColl 1988). Apart from the $[H^+]$ increase over this relatively long time period, it is the variation in $[H^+]$ from year to year and seasonally that is examined in this report with particular reference to the occurrence of El Nino events. The reservoir data of $[H^+]$ dating back to 1954 provide a unique opportunity to examine historical trends that may be related to El Nino events, as other desirable data are lacking. For example, data from monitoring of air-pollution emissions, atmospheric deposition or river-water chemistry are only available for the last few years, and therefore have little value in tracing historical trends (McColl 1982; McColl et al. 1982).

Field site and data collection and analysis

A full description of the reservoir and its drainage basin and data collection has been given earlier (McColl 1981, 1988), and is summarised as follows:

Pardee reservoir is located on the Mokelumne River in the central Sierra Nevada, California, and supplies over 90% of the water used by east San Francisco Bay communities including the cities of Berkeley and Oakland. The dam is at 173 m elevation, and the reservoir has a surface area of about 913 ha, holding 259×10^6 m^3 at spillway elevation. The large drainage basin (1,490 km^2) is underlain primarily by Mesozoic granite and granodiorite and encompasses a wide range of ecosystems that vary with elevation, to a maximum of 3,462 m. From about November to April, most streamflow is runoff from rainfall at lower elevations, although heavy snowfall also accumulates at higher elevations. Streamflow is primarily from snowmelt which usually begins in April, peaks in May and is comparatively low from July through October when there is very little precipitation.

Data of untreated reservoir discharge water were obtained from weekly records of East Bay Municipal Utilities District. Samples were collected at the outlet tower of Pardee Reservoir at a depth of 3–10 m in the epilimnion. Hydrogen ion activity, $[H^+]$, was calculated from potentiometric measurements of pH made at the site immediately following collection. (Unfortunately there are not consistent records for other ionic analyses.) Monthly and yearly means (July–June basis) were calculated. Years of occurrence of El Nino events listed in Table 1 are those designated by Rasmussen (1984). Regression analyses were performed using standard statistical methods (Snedecor & Cochran 1967).

Results and discussion

Yearly means of $[H^+]$ of reservoir discharge water are plotted over time (Fig. 1A). Separate linear regressions are fitted for El Nino and non-El Nino years (Fig. 1B); Spearman's rank correlation coefficients were 0.84 and 0.85 ($p < 0.001$) respectively. There is no difference ($p > 0.05$) between the rates of $[H^+]$ increase, but the El Nino regression line is significantly elevated above the non-El Nino line ($p < 0.05$). Distribution of $[H^+]$ data above and below the El Nino regression line (Fig. 1B) occurs irrespective of the "intensity" of El Nino events, as defined by Rasmussen (1984) (Table 1). There were two years (1972–73 and 1973–74) where observed values were well below the regression line (Fig. 1B). There is no obvious reason for this, although the consecutive years in which they occurred are designated as having "strong" El Nino events without separate onsets (Rasmussen 1984).

Changes in $[H^+]$ of reservoir discharge water throughout the year were also examined; mean monthly values of $[H^+]$ were calculated from data over the period 1954 through 1986, for both El Nino and non-El Nino years (Fig. 2). There is a tendency for monthly $[H^+]$ to be elevated in El Nino years. Greatest differences would be expected during the periods of spring snowmelt and fall rains when runoff water has least contact with soil and when the chemistry of runoff largely reflects atmospheric inputs (McColl 1981 1988). In the period February through April, differences between El Nino and non-El Nino years are negligible (Fig. 2); runoff in this period is mainly from rainfall at lower elevations in the drainage basin, and its chemical characteristics are modified by intimate contact with soil (McColl 1988).

El Nino years often have intense autumn and winter storms with abnormally high precipitation and strong winds along the west coast, as illustrated

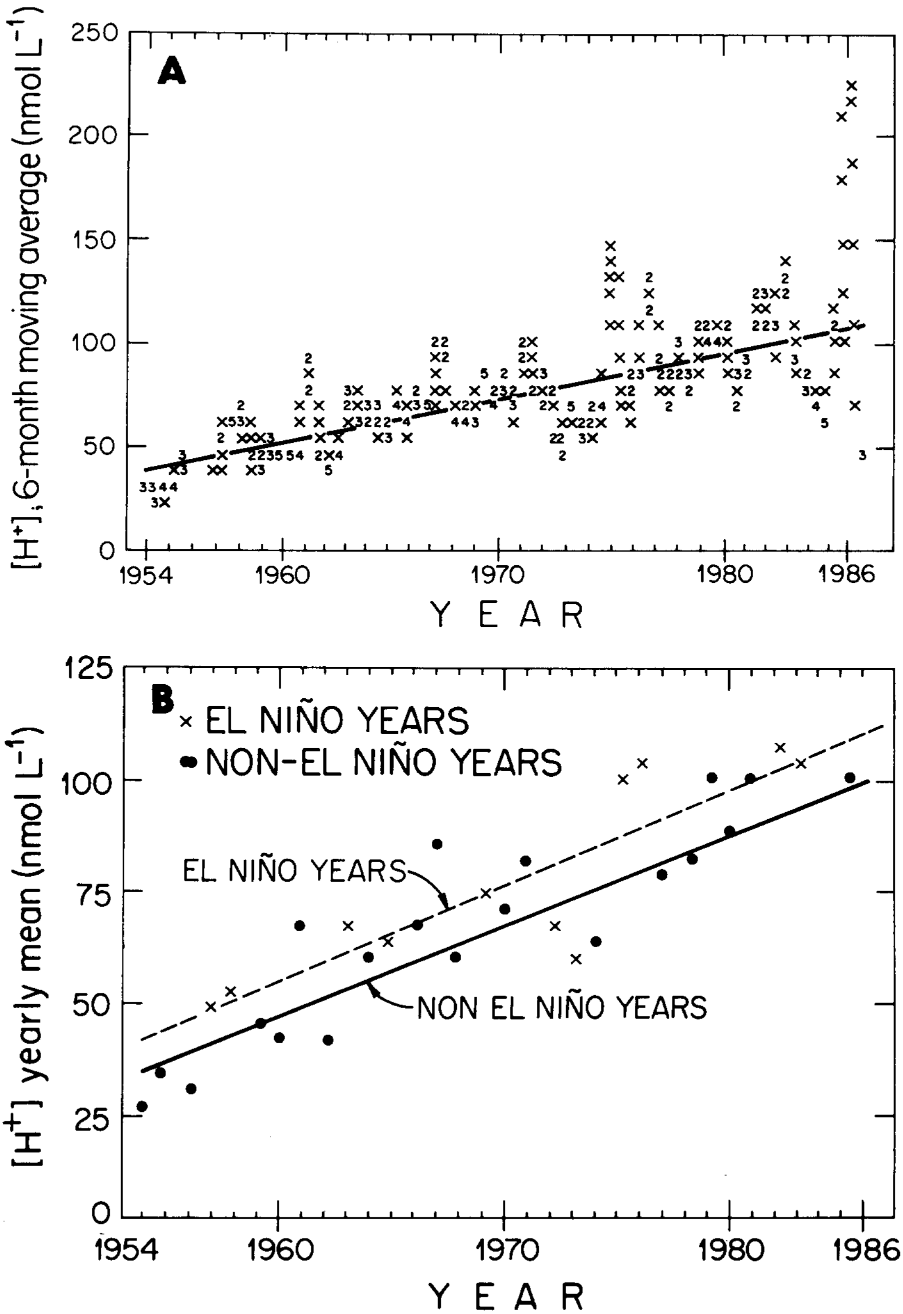

Fig. 1. The hydrogen ion concentration, $[H^+]$, of discharge water from Pardee reservoir, 1954–86. (A) 6-month moving averages with linear regression ($r = 0.70, p < 0.001$); numbers indicate more than one data point. (B) Yearly means with linear regressions for El Nino years ($r = 0.84$, $p < 0.001$) and non-El Nino years ($r = 0.85$, $p < 0.001$).

Table 1. Years of occurrence and intensity of El Nino events.

Hydrologic year	Intensity[a]
57–58	4
58–59	4
63–64	1
65–66	3
69–70	2
72–73	4
73–74	4
75–76	1
76–77	3
82–83	4
83–84	4

[a] 1 = weakest, 4 = strongest (see Rasmussen 1984).

during the outstanding ENSO event of 1982–83 (Mooers & Peterson 1986; Reinecker & Mooers 1986). However the correlation between rainfall in California and indices of ENSO events is not always strong (Rasmussen & Wallace 1983). The total annual reservoir discharge during El Nino years

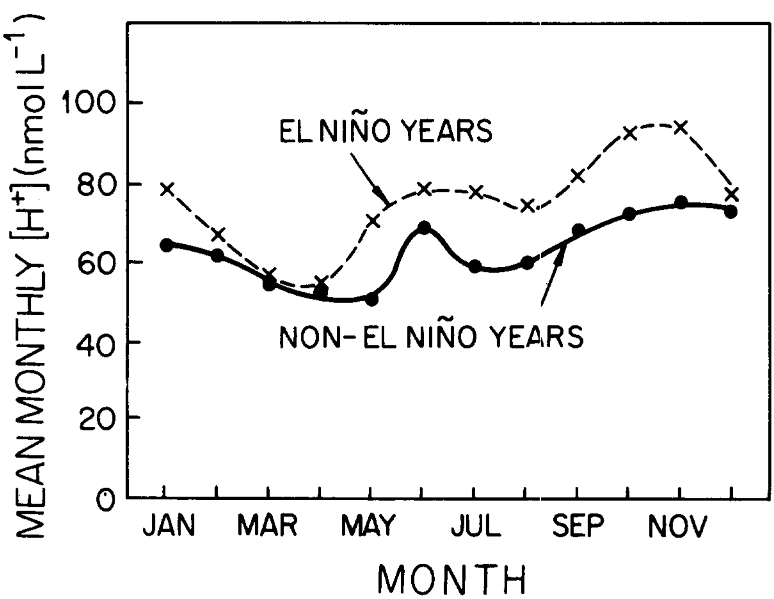

Fig. 2. The mean monthly hydrogen ion concentration, [H^+], of discharge water from Pardee reservoir, 1954–86, for El Nino and non-El Nino years.

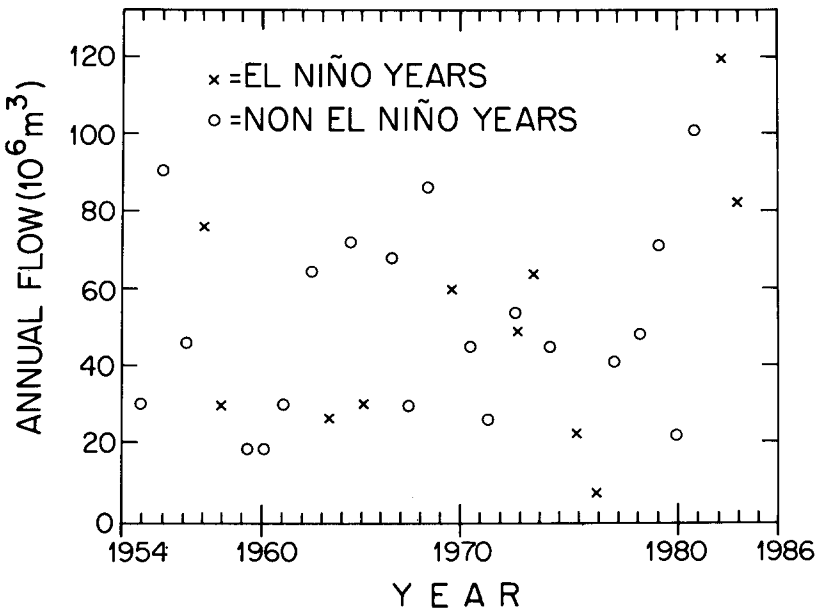

Fig. 3. The annual water flow past Pardee dam over the period 1954–86, showing no distinction between El Nino and non-El Nino years.

might therefore be expected to be higher than that during non-El Nino years, but this does not appear to be the case (Fig. 3); for El Nino years, $r = 0.37$ ($p > 0.05$), and for non-El Nino years, $r = 0.17$ ($p > 0.05$). Also, there were no significant correlations between annual flow and $[H^+]$ of reservoir discharge water either for El Nino or non-El Nino years ($r < 0.15$, $p > 0.05$ in both cases). Strub et al. (1985) found that yearly variation in the maximum heat content of Castle Lake, a small lake in northern California, was influenced by climatic forcing. However, they had no explanation of why El Nino conditions triggered both light and heavy snowfall which resulted in small and large thermal storage, respectively. In this regard our results were similar, as peak reservoir discharge, which is highly correlated with melting of the snowpack (McColl 1988), seems unrelated to El Nino events (Fig. 3).

Characteristics of precipitation other than yearly total amount, such as storm origin and timing, may be controlling factors of $[H^+]$ of reservoir discharge water. The typical dominant surface airflow for all seasons is from the west to northwest (California Air Resources Board 1977), and typical storms appear to carry acidic air pollutants from the San Francisco area and Sacramento Valley to the Sierra Nevada (McColl 1981). Storms during El

Nino years, associated with pronounced intensification and southward displacement of the normal westerly jet stream (Rasmussen & Wallace 1983), appear to carry acidic pollutants originating in southern California or even further south, to the central and northern Sierra Nevada. Processes within the reservoir and catchment, such as those discussed by McColl (1981, 1988), may also be linked to El Nino events, but no data are available that would elucidate such relationships.

Although the reasons for the observed results are not fully known, results presented here and those of others (e.g., Strub et al. 1985) suggest that there are important effects of El Nino events in temperature latitudes in terrestrial environments, as well as in the ocean or on the coast where most previous studies have been conducted.

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