lithologic boundaries in the Searles Lake sequence, and five stage boundaries (3/4, 4/5, 6/7, 7/8, and 8/9) do not (Fig. 2).

The similarity between the ages of both the 1/2 and 2/3 boundaries and the two ^{14}C-dated episodes of desiccation in Searles Lake has been noted (*4*). That study also noted the apparent correlation of the 5/6 isotope stage boundary at 127×10^3 years (*8*) and the estimated age of the contact between the mixed layer and the bottom mud (Fig. 2), but the age of that horizon was then too speculative to allow significant conclusions. The 5/6 stage boundary reflects a rapid change from glaciation to the beginning of the Sangamon interglaciation. At Searles Lake, the stratigraphic boundary represents a shift from an estimated 180×10^3 year period when lakes had intermediate depths and moderate salinities to a 100×10^3 year period when most lakes had great depths and low salinities (*2*). The new dates, therefore, confirm that the climatic changes seen in the marine and lacustrine records occurred very close to the same time. However, the nature of the indicated climate change was opposite to that occurring at the analogous 1/2 stage boundary when Searles Lake rapidly changed from a deep lake to a salt flat (*2, 4*).

The 3/4 and 4/5 isotope stage boundaries are equivalent in age to two horizons within the bottom mud. The lithology of the bottom mud, a dark green to black marl, indicates deposition in a series of mostly deep perennial lakes (*2*). Searles Lake sediments correlative with the 3/4 boundary (61×10^3 years) are bracketed by two dates within the bottom mud (samples 2 and 3). The 4/5 boundary at 73×10^3 years is equivalent in age to a horizon about 6 m below the top of the bottom mud, just below sample 4 (Fig. 2). No change in lake depth or sedimentation is evident during the time either horizon of the unit was deposited. Thus the lower 80 percent of the bottom mud is correlative with a time indicated by marine data as an interglacial period (Sangamon), and the upper 20 percent is correlative with the first half of the last glacial period (Wisconsin).

In core LDW-8, unit A + B of the underlying mixed layer is a sequence of about 30 monomineralic saline layers (mean thickness, 0.5 m) separated by brown- to olive-colored marl beds (mean, 0.7 m). The salines are predominantly trona or nahcolite which formed in a moderately saline lake that cooled seasonally. Marls indicate lake expansion, but the thinness of both the marl and the salt beds shows that the lake neither expanded nor precipitated salts for long periods (*3*). Horizons equivalent in age to the 6/7, 7/8, and 8/9 isotope stage boundaries, approximately 190×10^3, 247×10^3, and 276×10^3 years, lie within unit A + B of the mixed layer but do not correspond with any lithologic subdivisions (*3*). The youngest of these horizons is very close to sample 9. The two older horizons lie between samples 11 and 13, which precludes correlation of either stage boundary with the underlying contact between unit A + B and unit C of the mixed layer.

The new dates presented here confirm an earlier proposal (*4*) that there is an inconsistent relation between the marine isotope record of high-latitude glaciation and this record of mid-latitude hydrologic regimes. Is this hydrologic record a function solely of climate? Abrupt changes in water depths in Searles Lake could have been produced by nonclimatic processes such as faulting, stream piracy, or volcanism, and gradual change might have resulted from the topographic evolution of one or more basins and uplift of the Sierra Nevada. None of these processes, however, appears capable of causing repeated changes in the lake's inflow volumes that reached both low and high extremes several times. Furthermore, several direct lines of evidence indicate that the tributary region of Searles Lake over the past 300×10^3 years remained constant into the late Pleistocene (*3*). Except for the volcanic event that appears to have been responsible for the first lake in Searles Valley 3200×10^3 years ago (*3*), no eruptions appear to have had more than a temporary effect on the throughgoing drainage (*10*), and several lines of evidence suggest that the late Quaternary succession of basins resembled the middle Pliocene succession when the first lake formed.

We therefore interpret the lithologic changes observed in the cores and outcrops from Searles Valley as climatic in origin. Furthermore, there is circumstantial evidence from that record that glacial cycles did affect mid-latitude climates. The new dates, however, confirm the fact that those cycles had less impact on the intensity of local hydrologic regimes than other phenomena, and the suggestion (*4*) that the dominant factor was the 413,000-year orbital eccentricity cycle remains viable.

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Gas Exchange–Wind Speed Relation Measured with Sulfur Hexafluoride on a Lake

Abstract. *Gas-exchange processes control the uptake and release of various gases in natural systems such as oceans, rivers, and lakes. Not much is known about the effect of wind speed on gas exchange in such systems. In the experiment described here, sulfur hexafluoride was dissolved in lake water, and the rate of escape of the gas with wind speed (at wind speeds up to 6 meters per second) was determined over a 1-month period. A sharp change in the wind speed dependence of the gas-exchange coefficient was found at wind speeds of about 2.4 meters per second, in agreement with the results of wind-tunnel studies. However, the gas-exchange coefficients at wind speeds above 3 meters per second were smaller than those observed in wind tunnels and are in agreement with earlier lake and ocean results.*

Gas exchange across the air-water interface has received much attention (*1*) because it determines the degree of reaeration and the uptake and release of volatile pollutants in aquatic systems and because the oceans are a major sink for anthropogenic CO_2 (*2*). Gas-exchange processes have been studied in wind tunnels and in laboratory setups (*3*), and average oceanic gas-exchange coeffi-

cients have been determined by the ^{14}C method and the ^{222}Rn deficit method (*2*).

For moderately or slightly soluble gases, gas exchange is controlled by turbulence in the water (*4*). The major sources of turbulence at the interface are gravity flow (in rivers and tidal estuaries) and wind stress. The effect of wind speed on gas exchange in natural systems is very uncertain (*5*). We have measured this effect for a lake by injecting SF_6 into Rockland Lake in New York State (41°08′N, 73°56′W) and monitoring the gas concentration in the lake for 1 month as the gas escaped to the atmosphere. This gas is an excellent tracer for the aquatic environment because it is a chemically and biologically nonreactive gas (*6*) present in background concentrations of less than 10^{-15} mol/liter in natural waters. Quantities of less than 10^{-16} mol are detectable with a gas chromatograph equipped with an electron-capture detector.

Rockland Lake is roughly elliptical with a long axis of 1.4 km, a short axis of 1.0 km, a surface area of 1.0×10^6 m^2, and an average depth of 6 m. Since the residence time of the water in the lake is long (>1 year) compared to the degassing time found in the experiment and since SF_6 did not partition onto the sediments, the only important sink was the atmosphere. The experiment was conducted after the fall overturn of the lake, and, except for weak diurnal effects, the lake remained unstratified. The wind was monitored 1 m above the surface near the middle of the lake from a buoy equipped with an anemometer, which recorded histograms of the wind speed by tallying 1-minute averages in intervals of 1 m/sec during the entire experiment.

We spiked the lake by bubbling several liters of SF_6 through a diffuser at a depth of 4 m while rowing around the lake. Concentrations measured the next day varied over a factor of 2 from sample to sample and indicated that about 2.5 liters (standard temperature and pressure) had been dissolved. No horizontal or vertical variations in concentration were observed after 1 week, and gas-exchange measurements then commenced.

The lake was sampled 19 times over a period of 30 days. Samples were drawn into 50-ml glass syringes by hand from a few centimeters below the surface and by peristaltic pump from depth. Copper tubing was used in all parts of the sampling system, except for Tygon tubing in the pumphead, to minimize diffusive losses. During the first 2 weeks the samples were taken at four different depths (surface, 0.3 m, 1.5 m, and 2.7 m) at four locations around the lake. Subsequently, as no systematic variation in concentration with location or depth was found, three sets of samples were taken at the middle of the lake at five different depths (surface, 0.3 m, 1.5 m, 2.7 m, and 7.3 m) and returned to Lamont-Doherty Geological Observatory for analysis (*7*).

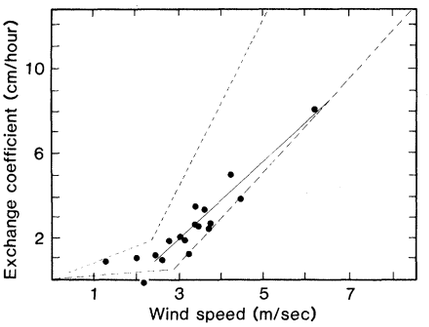

Fig. 1. Plot of the gas-exchange coefficients verses wind speed from Table 1 (closed circles). The solid line is a least-squares fit to our data above a wind speed of 2.4 m/sec. The short-dashed curve is from the wind tunnel experiment of Broecker *et al.* (*11*). The long-dashed curve is our estimate of the relation between K and U if the wind were steady (*14*).

Concentrations averaged over all samples for each sampling day (C_w) are listed in Table 1. Since the concentration in the water at equilibrium with atmospheric SF_6 is negligible ($<10^{-15}$ mol/liter compared with $C_w > 10^{-12}$ mol/liter), the gross gas-exchange coefficient ($\overline{K}$) for the whole period can be expressed as $\overline{K} = H\, d\ln C_w/dt$, where H is the mean lake depth. A plot of $\ln C_w$ versus time t from Table 1 yields a curve that is straight overall, with day-to-day fluctuations in slope that are well correlated with wind speed. A linear least-squares fit to the data gives $\overline{K}$ = 2.2 cm/hour, while the average wind speed for the period was 3.3 m/sec. Of course, one must exercise caution in using such long-term averages if the wind speed dependence is nonlinear (see below).

The changes in concentration from one sampling time to the next may be used to calculate average gas-exchange coefficients (K) for the intervening period. Values for K and average wind speeds (U) are listed in Table 1. We have adjusted the data to the initial water temperature of 10°C, assuming that K varies with $(D/\nu)^{0.5}$ (*8, 9*), where D is the diffusion coefficient of SF_6 in water estimated from the empirical equation of Hayduk and Laudie (*10*) and ν is the kinematic viscosity of water. The water temperature had decreased to 5°C by the end of the experiment, resulting in a maximum adjustment of about 20 percent.

The exchange coefficient is well correlated with wind speed above wind speeds of about 2.4 m/sec and appears to increase linearly up to 6.2 m/sec, our highest average wind (Fig. 1). We can say little about the exchange coefficient at wind speeds below 2.4 m/sec except that it is small and must increase much more slowly with wind speed than it does above 2.4 m/sec. A similar transition at around 2 m/sec has been observed in several wind tunnel experiments (*11, 12*)

Table 1. Data for the Rockland Lake gas-exchange experiment.

Date (1983)	Water temperature (°C)	Average SF_6 concentration (pmol/liter)	S.D.* (%)	Wind speed† (m/sec)	Gas-exchange coefficient‡ (cm/hour)
11/10	10.89	17.6	4.1		
11/13	9.06	11.1	2.2	4.43	3.84
11/14	8.54	9.96	2.9	3.79	2.46
11/16	8.37	9.11	2.7	3.23	1.20
11/17	8.20	8.37	2.0	3.76	2.58
11/19	7.58	6.51	1.9	3.35	3.48
11/21	8.50	5.51	2.1	3.02	2.1
11/23	9.10	5.06	2.3	2.42	1.14
11/27	7.90	3.52	2.6	3.36	2.58
11/30	7.32	2.84	4.3	3.15	1.86
12/1	6.90	2.55	3.7	3.59	3.24
12/2	6.63	2.47	2.6	2.60	0.96
12/3	6.24	2.33	3.1	2.77	1.85
12/5	5.80	1.94	2.2	3.46	2.55
12/6	5.72	1.95	2.2	2.17	−0.18
12/7	5.61	1.49	2.1	6.19	8.04
12/8	5.25	1.28	2.9	4.19	4.98
12/9	5.07	1.24	3.9	1.25	0.80
12/10	5.03	1.20	3.7	1.99	1.06

*Standard deviation of all the samples taken on that day. †Average wind speed (U) over the preceding time interval. ‡Calculated exchange coefficient (K) for the preceding time interval.

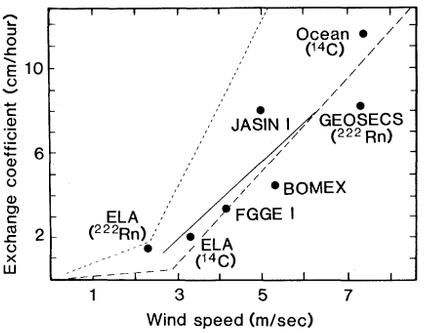

Fig. 2. Comparison with earlier field experiments. We have adjusted all exchange coefficients to compare with SF_6 at 10°C, assuming that K varies with $(D/\nu)^{0.5}$. The data for the Experimental Lakes Area in Canada (ELA) were obtained from evasion rate measurements of ^{222}Rn and ^{14}C (*16*), and the wind speeds are estimated from meteorological stations located in the area. The BOMEX (Barbados Oceanographic and Meteorological Experiment), JASIN (Joint Air-Sea Interaction Experiment) 1, and FGGE (First Global Atmospheric Research Program Global Experiment) 1 points are ocean-exchange coefficients obtained by the ^{222}Rn deficit method over a period of several weeks from ships located in the North Atlantic trade wind region (*17*), the North Atlantic west of Scotland (*18*), and the equatorial Atlantic (*18*), respectively. Also shown are the mean adjusted coefficients for the whole ocean inferred from ^{222}Rn [GEOSECS (Geochemical Ocean Section Study)] and ^{14}C measurements (*19*). We corrected the wind speeds for the ocean measurements taken at a height of 10 m to 1 m, assuming a logarithmic wind profile and a sea-surface drag coefficient of 1.5×10^{-3} (*20*). The curves from Fig. 1 are repeated for reference.

and has been associated with the onset of capillary waves (*11*). We speculate, however, that the transition may be related more directly to a jump in the level of turbulence beneath the waves.

Any nonlinearity in the dependence of K on U complicates interpretation of field experiments because of the variability of the wind (*13*). Since the wind for our averaging periods always varied over the upward break near 2.4 m/sec, values for K at a given average wind tend to be larger than if the wind had been steady. As a simple example, consider a wind histogram showing no wind half the time and a wind of 6 m/sec for the remainder of the time. Inspection of Fig. 1 should convince the reader that K would be larger than if the wind blew steadily at 3 m/sec, although the average wind, U, would be the same in both cases. We accounted for this effect, using the wind histograms provided by the anemometer to estimate the relation that would exist between K and U if the wind were steady (*14*). The lower dashed curve in Fig. 1 shows the result. Most of the data points lie above this curve as anticipated, and the curve shows the transition near 2.4 m/sec even more clearly.

Figure 1 also shows results from the wind-wave tunnel experiment of Broecker *et al.* (*11*). This experiment was chosen for comparison because the drag coefficient was similar to what one would expect on the lake for an anemometer height of 1 m. Two recent wind tunnel results (*12*) would lie roughly along the same line as that of Broecker *et al.* We see that the exchange coefficient increases much more strongly with wind speed in the wind tunnels than it does in the field. This difference may be due to the shorter and steeper waves at the very short fetch of the wind-wave tunnels compared with the field. Jahne *et al.* (*9*) showed that the exchange coefficient for different wind tunnels is better correlated with mean square wave slope than with wind stress. Whether this conjecture is correct or not, it is clearly impossible to extrapolate from wind-tunnel results to the field on the basis of the use of wind stress alone.

The results of several gas exchange measurements in natural systems are plotted in Fig. 2, along with the curves from Fig. 1. The measurements yield averages over several weeks or, in the case of ^{14}C measurements, several years, and are therefore subject to effects from the variance of the wind described above. Nevertheless, the field results are scattered about the trend we found in our lake experiment (indicated by the solid line in Fig. 2). This result is perhaps surprising in view of the much shorter fetch (≃500 m) on the lake than on the open ocean. It suggests that it is the smaller features of the wave field that are important in gas exchange.

We conclude that a quantitative relation between wind speed and gas-exchange coefficient, applicable to a wide range of natural systems, is finally beginning to emerge. Confidence in this relation will require additional experiments similar to the present one, in which measurements are made of the exchange coefficient over a range of wind speeds for individual natural systems (*15*).

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