Germany and Denmark although the zone of impact was about half that of the previous year. Samples from western Poland became available in 1987 and needles from 1985 showed even higher levels there (8-10 times the 'background') than elsewhere that year. By 1986, concentrations in nearly all regions were at the background level but samples from western Poland were still 6-8 times this level. These results are illustrated in a bar graph (Fig. 2).

We did not find the expected cumulative increased in tDDT residues in needle wax from 1986 to 1984. This could have been the result of photodegradation of the pesticide (to a substance other than DDE)[13,14] in the needle wax, to translocation into the interior of the needle or the rest of the tree[15], to re-volatilization, or to lack of sorption at times other than during needle growth. Degradation seems not to be indicated because the percentage of DDT was constant (mean 68%, r.s.d. 13%) throughout the study area and period and such a high DDT/DDE ratio is indicative of freshly applied DDT. Revolatilization of the study compounds is not indicated[16] either.

In the case of the PCP results, the Swedish samples were found to contain at least twice the levels found elsewhere in Europe. This observation includes a site in the far north of Sweden where we expected levels of pollution to be lower. This overall observation for PCP is surprising because the compound has been totally banned in Sweden since 1978 (partially since 1972) although it is still in use in much of the rest of Europe including Finland. Use in the latter country could potentially contribute to the Swedish burden but the prevailing winds do not favour this. As there are no apparent changes in concentration levels over the years, we conclude that the source is still present.

The PCBs are well known pollutants in the atmosphere and elsewhere and were found in all the samples at roughly the same concentration levels (mean 6.2 ng g^{-1}, r.s.d. 26%). There were no apparent geographic or temporal trends. The HCH isomers are also well-known ubiquitous atmospheric pollutants and, as in the case of PCBs, we observe no patterns in their needle-wax concentrations. Examination of the proportion of the γ-HCH isomer (the pesticide lindane) shows that it is present in larger amounts in the French samples (mean 62%, r.s.d. 14%, 11 points) during 1985 and 1986 than elsewhere (mean 29%, r.s.d. 11%, 34 points), indicating a near-by source. As observed with tDDT residues, the ratio becomes 'normal' with increased distance and time from the apparent source.

It seems that the pine needle can provide a suitable sampling matrix for evaluating atmospheric contaminants. This seems particularly true when determining regional exposures from a single-year class and may also have relevance for trend analysis between years. The widespread distribution of the pine suggests that it may provide trend data for much of the Northern Hemisphere. In Eurasia, *Pinus sylvestris* (Scots pine), is found in most areas north of the Mediterranean and south of the Arctic circle[17]. In North America, the Scots pine is an imported species but is sufficiently common that it may have utility there as an environmental biomonitor. The species *P. banksiana* (Jack pine) and *P. contorta* (Lodgepole pine), however, may be more useful for evaluating ambient conditions east and west of the Rocky Mountains, respectively. The long life of the pine, compared with other biomonitors, potentially permits sampling from the same individual over periods as long as one hundred years. □

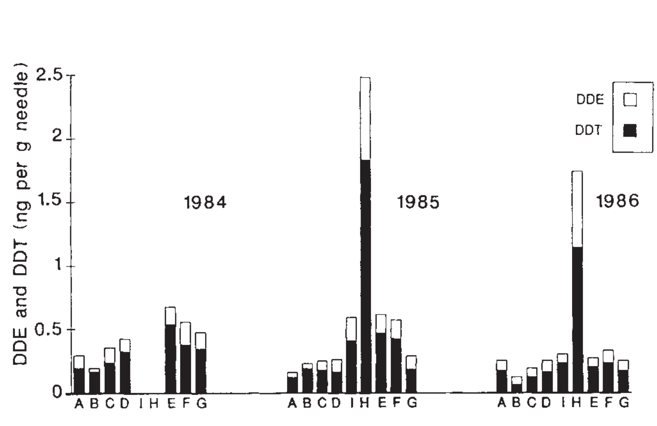

FIG. 2 Distribution of DDT and DDE in pine needles (fresh weight) (see Fig. 1 for area designations; samples were not available for areas H and I in 1984).

Received 3 April; accepted 7 August 1989.

1. Olsson, M. & Reutergardh, L. *Ambio* **15,** 103-109 (1986).
2. Academy of Agricultural Science, Institute for Plant Protection Research *1987/88 Plant Protection: List of Substances* (VEB Deutscher Landwirtschafts, Berlin, 1986).
3. Peakall, D. B. *Atmos. Envir.* **10,** 899-900 (1976).
4. Kerler, F. & Schonherr, J. *Archs envir. Contam. & Tox.* **17,** 1-6 (1988).
5. Lyman, W. J., Reehl, W. F. & Roseblatt, D. H. in *Handbook of Chemical Property Estimation Methods: Environmental Behaviour of Organic Compounds.* Ch. 1 (McGraw-Hill, New York, 1982).
6. Schuck, H. J. *Flora* **161,** 604-622 (1972).
7. Gaggi, C., Bacci, E., Calamari, D. & Fanelli, R. *Chemosphere* **14,** 1673-1686 (1985).
8. Thomas, W., Ruhling, A. & Simon, H. *Envir. Pollut.* A**36,** 295-310 (1984).
9. Jensen, S. *Nordisk Biocid-Information* **7,** pap. la (Nordforsk's Biocidsekretariat, Stockholm, 1966).
10. Hadley, N. F. *Biol. Rev.* **56,** 23-47 (1981).
11. Fries, G. F. *J. envir. Qual.* **11,** 14-20 (1982).
12. Schonherr, J. *Planta* **131,** 159-164 (1976).
13. Gothe, R. *et al. Tetrahedron Lett.* **49,** 4501-4504 (1976).
14. Moilanen, K. W., Crosby, D. G., Soderquist, C. J. & Wong, A. S. *Envir. Sci. Res.* **6,** 45-60 (1975).
15. Fuhremann, T. W. & Lichtenstein, E. P. *J. agric. Fd Chem.* **28,** 446-452 (1980).
16. Quistad, G. B. & Mean, J. J. *Residue Rev.* **85,** 173-197 (1983).
17. Hulten, E. & Fries, M. in *Atlas of North European Vascular Plants.* Vol. I, plate 80. (Koelz Scientific, Konigstein, 1986).

Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of regional climate change

Yehouda Enzel*, Daniel R. Cayan†, Roger Y. Anderson* & Stephen G. Wells*

* Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131, USA
† Climate Research Division, Scripps Institution of Oceanography A-024, University of California, San Diego, La Jolla, California 92903, USA

IT is commonly thought that the climate conditions that supported lakes over a period of years in the Mojave Desert in southern California, only existed before 8,000 yr BP and that the environment has been arid since[1,2]. Here we look at a drill core in the Silver Lake playa at the terminus of the Mojave River and find Holocene lake deposits which indicate that shallow lakes existed for at least a few decades. These deposits were radiocarbon dated at 3620±70 and 390±90 yr BP, corresponding to the early Neoglacial and the 'little ice age' respectively[3]. To identify the conditions necessary to produce these Holocene lake events we have examined the modern climate and hydrological patterns that produce ephemeral lakes in this usually arid watershed. Available data indicate that there is a link between anomalous winter atmospheric conditions over the North Pacific and Mojave River floods that produced ephemeral lakes in the Silver Lake playa and that the Mojave River filters out small to medium floods and allows only the extreme floods to reach the terminal playa and leave a record of the anomalous conditions. We suggest that the late Holocene lakes may have resulted from persistent similar atmospheric circulation patterns and winter floods.

The Silver Lake playa is the remnant of the late Pleistocene Lake Mojave[3-6] and the present terminal basin of the closed arid watershed of the Mojave River. At 9,500 km^2 (Fig. 1) this watershed is the largest hydrological system in the Mojave

Desert. Present climate within the Mojave River watershed varies spatially. Its headwaters at 1,200–2,700 m in the eastern slopes of the San Bernardino Mountains (Fig. 1), are characterized by Mediterranean semi-arid to humid conditions (mean annual precipitation 500–1,250 mm), with most of the precipitation occurring between November and March. Most of the Mojave River watershed and the terminal playa region where the lakes form is hyperarid, with <100 mm year^{-1} precipitation, summer temperature often >40 °C and consequently >2000 mm year^{-1} potential evaporation[7,8].

The Mojave River flow is a result of intensive winter storms at the high elevations of the San Bernardino Mountains[8,9]. Annual discharge records (Fig. 2)[10] along the Mojave River demonstrate that significant flow reaches the Afton gauging station only during those years with large discharge at The Forks in the Mojave River headwaters (Fig. 1). This is due to discharge loss to a shallow aquifer between Victorville and Afton. Hydrographs of the 1969 and 1978 winters events (Fig. 2) are characteristic of an extreme winter flood which, in turn, is related to the annual peak discharge (Y.E., Thesis in preparation). During such winter events lakes formed in Cronese Lake and the Silver Lake playas. It seems that only flood events with high peak discharge are able to exceed the loss by infiltration into the alluvial bed between Victorville and Afton (Figs 1, 2). This relation and the annual peak-discharge data[10] indicate that discharge losses along the Mojave River allow only the larger floods to reach Afton. During this century a peak discharge >300 m^3 s^{-1} at the Fork has been required for flows to reach Afton and ~500 m^3 s^{-1} to reach the Silver Lake playa (Fig. 1).

We suggest that similar filtering of smaller floods occurred in the past, at least in the late Holocene. The modern conditions suggest that increased frequency of flows exceeding this natural threshold are needed and may have led to a net accumulation of water in the playas during the late Holocene.

Since 1894, eight ephemeral lakes have been documented in the terminal basins of the Mojave River (Y.E., unpublished data). Each ephemeral lake is the result of heavy precipitation during a winter storm and flooding in the Mojave River headwaters. Rainfall in several of these storms exceeded the average monthly precipitation by two standard deviations[11]. Extreme rainfall intensity of over 25 mm h^{-1}, and as much as 250–400 mm day^{-1}, has been observed[12] in the Mojave River headwaters at elevations >1750 m. These high precipitation intensities were probably enhanced by the orographic effects of strong southerly to southwesterly winds forcing a moist Pacific air mass to cross the north-west to south-east oriented San Bernardino Mountains[13].

The eight lake stands that were produced from these storms occupied the normally dry playa for 2–18 months (Y.E., thesis in preparation). In some of these events antecedent conditions of soil moisture in the headwaters and a wet channel along the Mojave River may have played a role as relatively large floods in the headwaters predated some of the lake-building flood events[3].

To overcome the filtering mechanism of the river and to form a lake in its watershed requires a vigorous storm, unusual for southern California. We constructed the mean meteorological pattern associated with these storms and lakes. Composite monthly sea-level pressure (SLP) values (which we use because of their availability over a Northern Hemisphere grid since 1899[14]) and the SLP anomalies over the North Pacific and western North America were calculated for the months that included the eight cases of lake events (Fig. 3). The SLP values for each month in which a lake event occurred were subtracted from the long-term mean SLP (1947–1972)[15] of the specific month to determine the monthly SLP anomaly. Although the actual flooding occurred on specific days with more intense SLP features than the monthly mean, several of the flooding events were associated with a persistent succession of storms that conformed to a particular pattern. The monthly SLP patterns provide an overall indication of the large-scale pattern that produced the particular storm or storm sequence.

During months in which lakes formed, the sub-tropical high in the eastern North Pacific weakened, giving way to an anomalously low-pressure system along the west coast of the United States. The anomalous low represents an eastward shift of the central North Pacific winter low, with vigorous storms penetrating the west coast of the United States much further south than normal. These storms produced the heavy precipitation in the San Bernardino Mountains.

The composite SLP pattern (Fig. 3) shows a tendency for a 'split' Aleutian low with higher than normal SLP in the Aleutians and an anomalously low SLP over Kamchatka. The blocking high pressure in the eastern Aleutian region during this type of

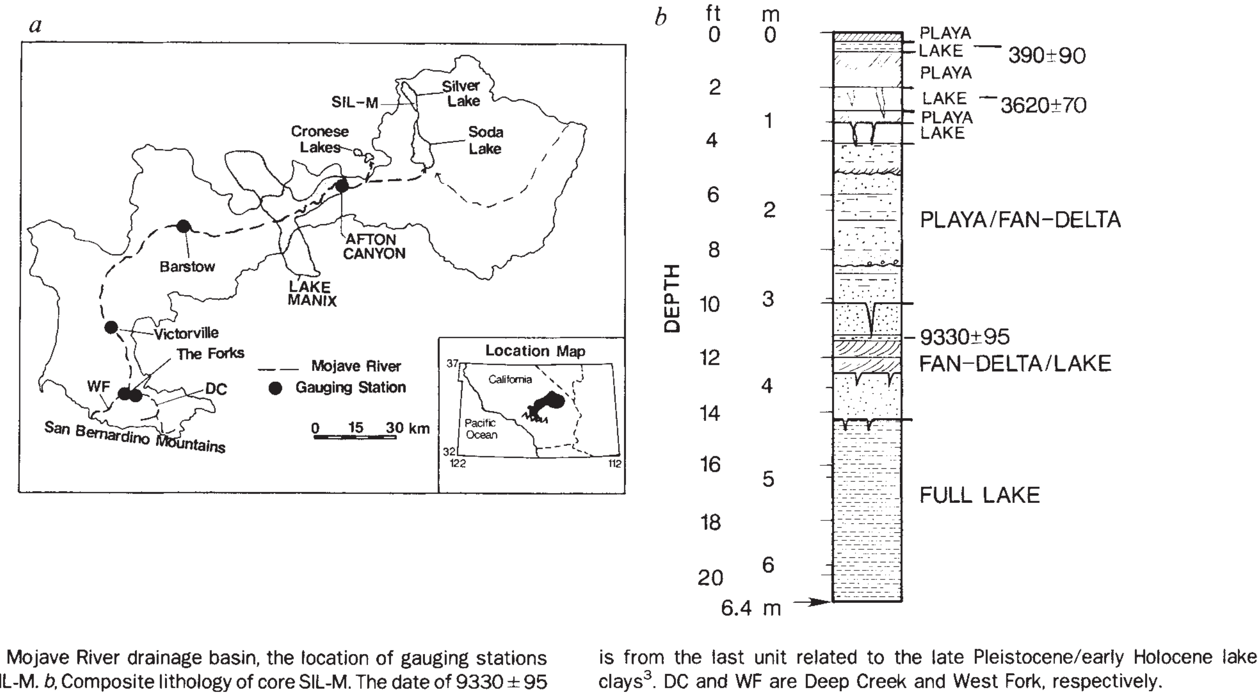

FIG. 1 *a*, The Mojave River drainage basin, the location of gauging stations and of core SIL-M. *b*, Composite lithology of core SIL-M. The date of 9330 ± 95 is from the last unit related to the late Pleistocene/early Holocene lake clays[3]. DC and WF are Deep Creek and West Fork, respectively.

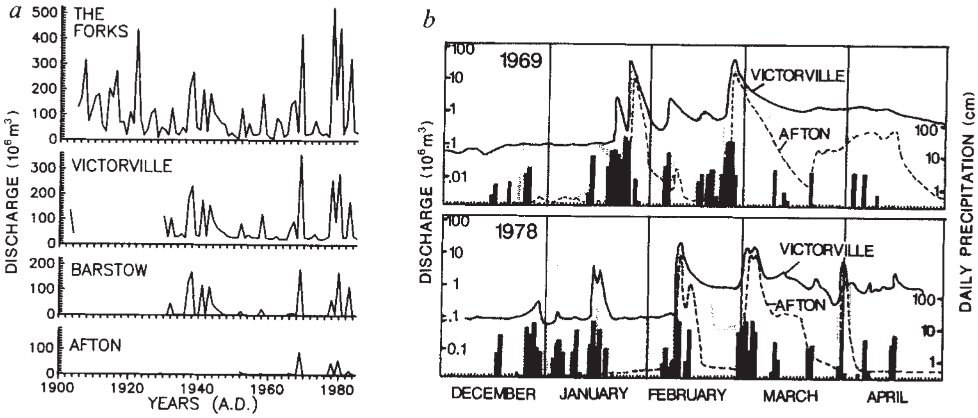

FIG. 2 *a*, Annual discharge in downstream direction (from top to bottom) for: 1) The Forks (1905–1985)—the combined discharge of Deep Creek and West Fork, which are the two tributaries that form the Mojave River, 2) Lower Narrows near Victorville (1903–1904 and 1929–1985), 3) Barstow (1930–1985), and 4) Afton (1930–1931 and 1952–1985). *b*, Average daily discharge (left-hand scale) during December–April 1968–1969 (upper) and 1977–1978 (lower) for Victorville (solid line) and Afton (dashed line) in response to precipitation (right-hand scale) in the San Bernardino Mountains (bars), modified from ref. 9. The shaded area shows where discharge loss occurs between Victorville and Afton. Logarithmic scales are used for both discharge and precipitation.

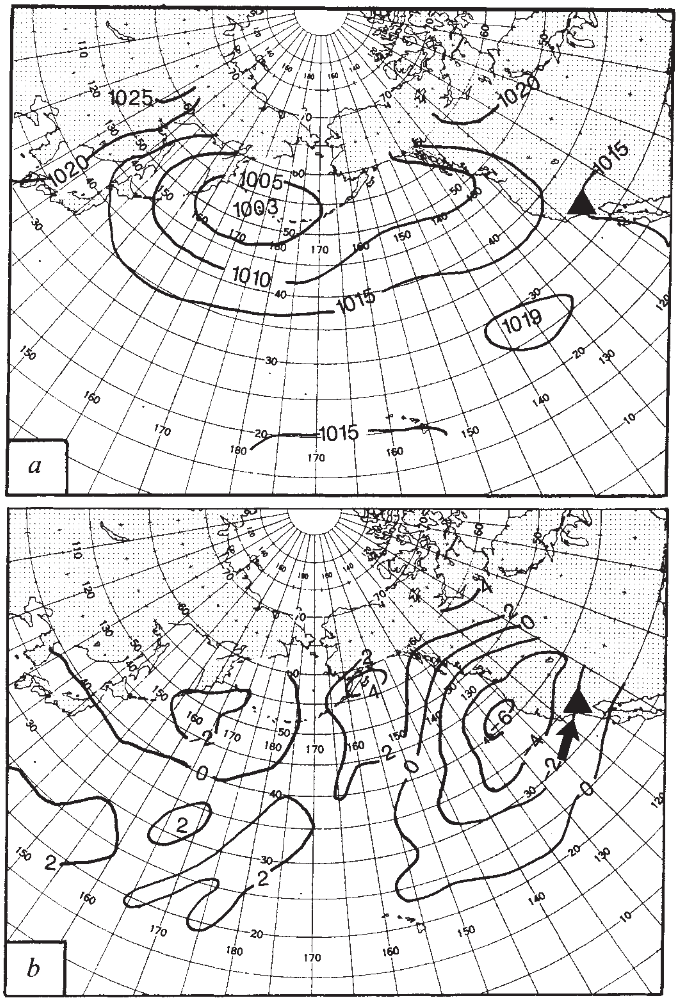

FIG. 3 *a*, Composite North Pacific sea-level pressure for the eight months with lake-building flood events. Triangle indicates location of the San Bernardino Mountains. *b*, Composite SLP anomaly for the same eight months. The arrow shows the anomalous component to the mean wind direction that results from the anomalous SLP. The enhanced southwesterly wind advects moist warm Pacific air over the San Bernardino Mountains and the negative pressure anomalies indicate the necessary vorticity for extreme precipitation events.

event is also borne out by inspection of daily maps. This synoptic pattern has been diagnosed as a potent flood-producing condition in California[13]. The Mojave River flood and lake events are symptoms of this pattern.

The strong negative anomaly of −6 mbar at 40° N, 130° W (Fig. 3) represents 1.5–3.0 standard deviations from the long-term monthly mean (depending on the specific winter month in which the flood occurred). Other studies of winter and monthly average precipitation and stream flow have shown this condition to favour heavy precipitation and stream flow in California[16–18].

Individual 500-mbar and 700-mbar height maps, satellite images, and previous studies[17,19] for the winter and the months of the floods in 1969, 1978, 1980 and 1983 floods, reveal two recurrent synoptic patterns. The most frequent pattern featured an unusually deep trough or cut-off low pressure offshore from California and a blocking high pressure in the Gulf of Alaska with a southerly displaced storm track entering California. In some of these cases, such as the 1969 storm[20], moisture and strong winds of these storms were assisted by the activity of the sub-tropical jet stream. A second pattern that emerged, was a sequence of storms embedded in strong southerly-displaced westerlies that spanned the entire eastern North Pacific. This pattern occurred during the 1980 and 1983 events.

There is evidence[21] that ocean surface boundary conditions may have played a role in the development of these storms. Highly persistent patterns of sea-surface-temperature (SST) anomalies were found in the North Pacific during the winters of 1969, 1978 and 1980, in which lakes were formed. Although probably not a necessary condition, such winter-SST-anomaly patterns may increase the frequency of extreme storm episodes.

Water-budget calculations suggest that an order of magnitude increase in the modern average annual discharge at Afton Canyon (from 9.4×10^6 m^3 to 90×10^6 m^3) is required to maintain a lake in the terminal playas. Water volumes similar to the latter discharge have been measured during the short-term extreme historical floods. Decreasing evaporation alone will not maintain a lake without the large runoff increase[3]. Because the extreme floods are relatively rare (recurrence intervals of 34 years in Afton), the modern average annual river discharge is not representative of the actual volumes that can reach the playas during the large floods. If the volumes of the modern extreme floods are used as the total annual input over a series of years in the lake's hydrological budget calculations, a lake can be established in Silver Lake[3]. An increase in the frequency of flood events with magnitudes similar to the modern largest floods would therefore result in a perennial lake in the Silver Lake playa. This may have caused the formation of the late Holocene lakes.

Analyses of tree-ring data from southern and central California[22,23] indicate that more-frequent wet conditions occurred in the late 1500s and early 1600s at the same time that the 'little ice age' lake was maintained in Silver Lake basin[23]. The high-frequency, high-magnitude annual precipitation and stream flows that have been inferred for that period in southern California[22,23], support our suggestion of increased frequency of the high-magnitude precipitation and runoff events during the 'little ice age' lake stand. As the lake-building storms of the past century were all vigorous eastern North Pacific cyclones that occurred during the winter, we postulate that similar North Pacific disturbances were more frequent during the late 1500s and early 1600s. Reconstructions of North Pacific SLP from tree-ring chronologies[24] showed that the early 1600s to have had a high frequency of the pattern of North Pacific SLPs similar to the SLP pattern of the wet lake-forming winter of 1978. LaMarche[25] suggested that persistent 'little ice age' and earlier climate anomalies can be explained by changes in the frequency of anomalous circulation types. One of these types was characterized by upper-level trough centred over the Pacific Coast of North America.

We suggest that extreme modern hydrological events in the Mojave River watershed serve as an indicator of particular atmospheric forcing patterns over the North Pacific and thus can be used as analogues for conditions during the Holocene when lakes formed in the watershed. An increased frequency of these extreme events can explain the observed lake deposits in the Silver Lake playa. □

Received 22 May; accepted 31 July 1989.

1. Smith, G. I. & Street-Perrott, F. A. in *The Late Pleistocene* (ed. Porter, S. C.) 190–212 (University of Minnesota Press, 1983).
2. Van Devender, T. R. *et al.* in *The Geology of North America* vol. K-3 (eds Ruddiman, W. F. & Wright, H. E.) 323–357 (Geological Society of America, Boulder, 1987).
3. Wells, S. G. *et al., Rep.* 249 (New Mexico Water Resources Research Institute, Las Cruces, 1989).
4. Thompson, G. D. Water Supply Paper 578 (United States Geological Survey, Washington, DC, 1929).
5. Ore, H. T. & Warren, C. N. *Geol. Soc. Am. Bull.* **82**, 2553–2562 (1971).
6. Wells, S. G. *et al. Quat. Res.* **27**, 130–146 (1987).
7. Blaney, F. H. *Am. geophys. Un. Trans.* **38**, 209–215 (1957).
8. Troxel, H. C. & Hofman, W. in *Geology of Southern California* (ed. Jahns, R. H.) Bull. 170 Ch. 5, 13–17 (California Division of Mines, San Francisco, 1954).
9. Buono, A. & Lang, D. J. *Open File Rep.* 80–207 (United States Geological Survey, Menlo Park, 1980).
10. United States Geological Survey, *WATSTORE Peak Flow Files* (United States Geological Survey, 1987).
11. Wells, S. G. *et al. Eos* **68**, 1270 (1987).
12. National Climatic Center, *Hourly Precipitation Data* vol. California (United States Department of Commerce, National Atmospheric and Oceanographic Administration, Asheville.
13. Weather Bureau, *Hydrometeorological Report* 37 (United States Department of Commerce, Weather Bureau, Washington, DC, 1962).
14. Trenberth, K. E. & Paolino, D. A. *Mon. Weath. Rev.* **108**, 855–872 (1980).
15. Namias, J. *CalCOFI Atlas* No. 22 (Scripps Institution of Oceanography, La Jolla, 1975).
16. Klein, W. H. & Bloom, H. J. *Mon. Weath. Rev.* **115**, 2118–2132 (1987).
17. Namias, J. *Proc. 5th Annual Clim. Diagnostics*, Workshop 35–50 (United States Department of Commerce, National Atmospheric and Oceanographic Administration, Asheville, 1980).
18. Cayan, R. D. & Peterson, D. H. in *Aspects of Climate Variability in the Pacific and Western Americas* (ed. Peterson, D. H.) (American Geophysical Union, in the press).
19. Wagner, J. A. *Mon. Weath. Rev.* **97**, 351–358 (1969).
20. Bonner, W. *et al. Rep.* E-3270(N) (Department of Meteorology, University of California, Los Angeles, 1971).
21. Namias, J. *et al., J. Clim.* **1**, 682–703 (1988).
22. Michaelsen, J. & Haston, L. Final Rep.—Water Resources Center Project W-707 (Department of Geography, University of California, Santa Barbara, 1988).
23. Schulman, E. *Bull.* (Laboratory of Tree-Ring Research, University of Arizona, Tucson, 1947).
24. Fritts, H. C., Lofgren, G. R. & Gordon, G. A. *Quat. Res.* **12**, 18–46 (1979).
25. LaMarche, V. C. *Science* **183**, 1043–1048 (1974).

ACKNOWLEDGEMENTS. We thank B. Allen, B. Brown, R. Balling, T. Bullard, B. Harrison and C. Yapp for insightful discussions and W. Wendland for a constructive review. We also thank Bruce Allen for help with the drilling. Funding was provided by a grant from New Mexico Water Resources Research Institute and the US Geological Survey to S.G.W. and R.Y.A. D.R.C. acknowledges funding from the US Geological Survey and University of California Water Resources Center.

Storm wave reactivation of a submarine landslide

D. B. Prior*, J. N. Suhayda†, N.-Z. Lu‡, B. D. Bornhold§, G. H. Keller‖, W. J. Wiseman*, L. D. Wright¶ & Z.-S. Yang‡

* Coastal Studies Institute and Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana 70803, USA
† Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana 70803, USA
‡ Ocean University of Qingdao, Qingdao, People's Republic of China
§ Geological Survey of Canada, Pacific Geoscience Centre, Sidney, British Columbia, Canada V8L 4B2
‖ Research Office, Oregon State University, Corvallis, Oregon 97330, USA
¶ Virginia Institute of Marine Science, Gloucester Point, Virginia 23062, USA

SUBMARINE landslides move large amounts of sediment and are often hazardous to offshore installations. Marine surveying techniques effectively define landslide locations and geometries (for example, refs 1–4) in various underwater geological settings, including deltas, fjords and earthquake-prone areas[1–5]. Movement rates and mechanics are generally inferred from indirect evidence, such as cable breaks and damage to sea-floor structures (for example, refs 6–8) but actual measurements of landslide behaviour are sparse. Using bottom-deployed pressure sensors, tiltmeters and accelerometers, we have collected data on sea-floor landslide reactivation involving sediment collapse and remoulding on the submarine slopes of the Huanghe delta, China. The sensors were emplaced into sea-floor clayey silts on 4 October 1987 and recovered on 16 October after the passage of three severe storms.

The Huanghe delta provides an ideal natural laboratory for the measurement of depositional and post-depositional deformations[3,9] of the sea floor. The delta has very high deposition rate[10] and the delta front is subjected to storm waves. Further, the shallow water facilitates the deployment of instruments.

Post-depositional slope failure creates collapse depressions and silt flows on the underwater Huanghe delta in water depths of 4–15 m and over gradients of 0.3–0.4° (Figs 2, 3). Roughly circular collapse depressions (0.5–1.0 m depth) occur mainly on

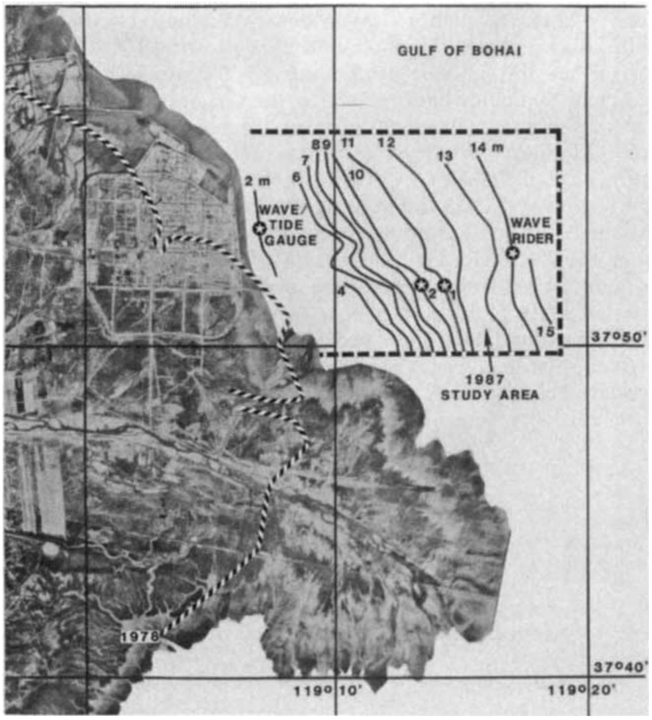

FIG. 1 Location of *in situ* measurement on the north-east flank of the Huanghe delta. Shoreline position is the 1987 position; former (1978) shoreline is outlined.