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Newsletter

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Sierra Nevada Runoff into San Francisco Bay — Why Has It Come Earlier Recently?

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By the time most of the Sierra Nevada snowpack has melted each summer, freshwater outflows from the Sacramento-San Joaquin Delta to San Francisco Bay are typically small, even after the wettest winters. These small delta outflows during the warm months (in comparison with the large flows of winter and spring) are overwhelmed by salty coastal waters, and the bay becomes more and more salty as summer progresses. Because longer low-flow seasons allow the bay to become saltier, timing of the Sierra Nevada snowmelt and runoff, which are the source of the delta flows, has a profound influence on the salinity of the bay and, thus, can affect its ecosystems (Peterson *et al* 1995).

Consequently, a recent tendency toward earlier snowmelt and runoff — described in this article — is a matter of concern. Is it a symptom of global warming? Is it a response to local or regional urban heat-island effects? Or is it just a normal part of the variability of California's hydrology? These possibilities raise concerns also about how much earlier the low-flow seasons in San Francisco Bay might begin in the future if the observed trends continue and how well the bay ecosystems will be able to cope with the flow-timing changes.

The "earlier runoff" trend was first noted by Maurice Roos, DWR, in 1987 (Roos 1987). Although it has much year-to-year variability, the runoff-timing trend can be detected by eye (Figure 1a) and is significantly different from random-chance occurrences according to a range of statistical tests (Dettinger and Cayan 1995). Since early in the century, the average April-June fraction of annual runoff has diminished from almost 50% to less than 40%. The trend toward smaller late-spring and early-summer fractions of each year's streamflow from the Sierra Nevada is shown in Figure 1a. This trend has been compensated for by a subtler set of opposite trends toward more winter and early-spring streamflow during the same period. The influence of these monthly trends on the overall timing of streamflow in the American River near Sacramento is shown in Figure 1b, in which the average recent flow regime is compared with the average flow regime from 30 years ago, when flows usually peaked almost a month later. Inspection of a large collection of streamflow records indicates that similar changes occurred throughout much of the western United States. A clue to their origin is that in the Sierra Nevada these changes are most accentuated in middle altitudes and are muted in streamflow records representing very high (more than 2,500 m) or very low (less than 1,000 m) altitudes.

The mechanism involved in these trends is mostly a hastening of the peak snowmelt period in recent decades in response to an observed trend toward warmer Januaries, Februaries, and Marches in the Sierra Nevada (Figure 2). Actually, this temperature influence is somewhat surprising, because historically the dominant control on seasonal runoff-timing fluctuations has been precipitation timing rather than temperature (Cayan *et al* 1993). Since the late 1940s, however, temperatures throughout the year in the Sierra Nevada have increased, with the January-March season experiencing the greatest warming, a total of about 2°F) in 50 years (Dettinger and Cayan 1995). During the same period, precipitation timing has shown little if any overall

CONTENTS

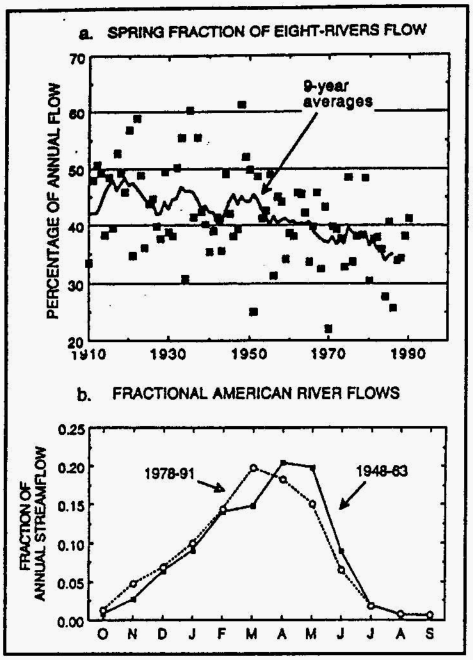

Figure 1
CHANGES IN RUNOFF TIMING
a. April-June Fractions of Annual Streamflow in Eight Major Rivers
b. Mean Monthly American River Flow Fractions

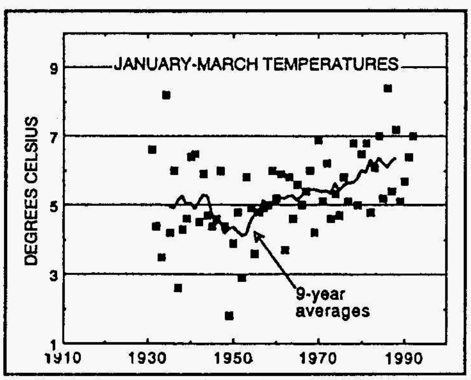

Figure 2
WINTER MEAN TEMPERATURE IN AN AVERAGE OF FOUR SIERRA NEVADA WEATHER STATIONS

trend. The runoff-timing response is most pronounced at middle altitudes because at these altitudes the snowpack and winter runoff are most sensitive to small changes in winter temperature. At low altitudes, temperature is less important because precipitation falls mostly as rain; at high altitudes, winter are so cold that fluctuations of a degree or two do not matter. About 67% of Sierra Nevada watersheds are in the sensitive middle-altitude range. Notably, the warming since the late 1940s has led to earlier snowmelt and runoff of winter and spring precipitation but no detectable change in the quantity of total runoff — in keeping with recent watershed-simulation studies by Dettinger and Jeton (1994).

To answer questions about the nature of these trends, we turned to broader-scale climate measures. Analysis of the historical fluctuations of winter-time atmospheric circulation over the North Pacific Ocean and western North America identifies broad, slow changes that have been the immediate causes of the warming and runoff-timing trends (Dettinger and Cayan 1995). The circulation changes are illustrated in Figure 3 in terms of a statistical measure of long-term changes in the atmospheric-pressure fields about one-third of the way up into the atmosphere — at 3 km above sea level. The Kendall's-tau statistic plotted in that figure is a measure of the correlation between time and the pressure series at each point on the map. These statistics range from +1 when applied to an uninterrupted rising trend, to 0 for a non-trending series, to -1 for steady negative trends. The long-term pressure changes found signify an increasing tendency for the winter wind pattern over the North Pacific and West Coast to bend away from the usual paths along latitude circles to something like the arrow in Figure 3. This wind pattern has brought air to California from farther south more often than usual in recent winters. The progression of the winter winds toward this configuration can be illustrated by a time series of "pattern correlations" between each winter's average wind pattern and the contours in Figure 3. (Like the Kendall's-tau statistic, these pattern correlations range from +1 when calculated for two maps that are the same at each point, to 0 for two maps that bear no overall resemblance to each other, to -1 for a map and its photographic negative.) This measure of the resemblance between winter circulation patterns and the contours of Figure 3 is shown in Figure 4, in which it is evident — amidst considerable year-to-year variability — that the resemblance has grown in recent decades. Thus, the change in circulation has unleashed a chain of

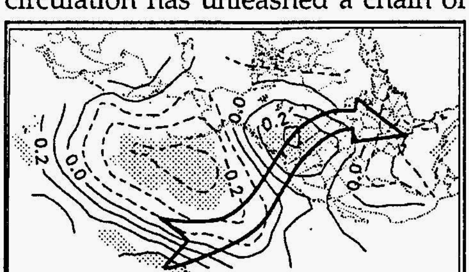

Figure 3
KENDALL'S-TAU TREND-TEST STATISTICS FOR JANUARY-MARCH 700-MBAR HEIGHT ANOMALIES, 1948-1992
Shaded where significantly trending and dashed where negative.

effects: a more southerly source for winter winds, leading to warmer winter temperatures in the Sierra Nevada, leading to earlier snowmelt and runoff, and contributing to early peaks of delta outflow to the bay (Peterson *et al* 1995).

A further aspect of these atmospheric-circulation changes concerns the persistence of weather patterns during the course of each winter and, thus, the predictability of winter weather. One measure of the month-to-month similarities between winter/spring climate patterns over the North Pacific Ocean is the season-average lagged-pattern correlations of sea-surface temperature, also shown in Figure 4. Lagged-pattern correlations are high (approaching +1) when the monthly average circulation patterns do not change much from month to month during a given season, and they are small when each month's pattern is different from the preceding month's pattern. The lagged-pattern correlations (plotted with open symbols and dashed curve in Figure 4) show year-to-year and decade-to-decade variations in the persistence of sea-surface temperatures of the North Pacific Ocean, variations which are closely related to the specific atmospheric-circulation patterns implied by Figure 3. As is clearly shown in Figure 4, month-to-month persistence of sea-surface temperature patterns has been increasing in recent decades and, even more dramatically, pattern persistence and similarity to the contours of Figure 3 go hand in hand on decadal scales (with an annual cross-correlation coefficient of +0.6). The most persistent sea-surface temperature patterns have been shown (by Dettinger *et al* 1994) to be most often

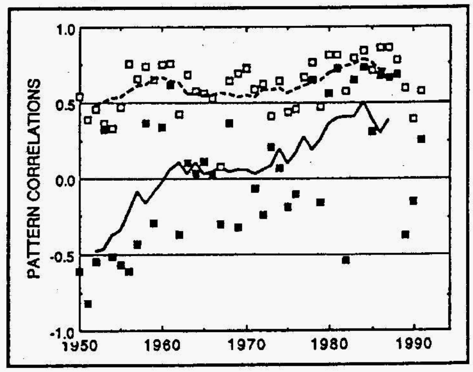

Figure 4
SPATIAL AND TEMPORAL CORRELATIONS AMONG ATMOSPHERIC AND SEA-SURFACE PATTERNS
Solid symbols and curve are correlations between contours of Figure 3 and winter mean 700-mbar anomalies. Open symbols and dashed curve show average January-May lag-one-month pattern correlations of North Pacific sea-surface temperatures.

associated with the pattern in Figure 3, which itself is the most persistent winter atmospheric-circulation pattern. Together these sea-surface and atmospheric-circulation patterns must mutually reinforce each other to sustain such persistent conditions with such regularity.

The recent trend toward more persistent ocean-air relationships and the frequent correspondence of persistence with the wind pattern of Figure 3 supports optimism that snowpack and runoff-timing prediction with several months lead time is possible. Knowledge early in the season that a winter's air-sea patterns are closely replicating the persistent patterns can suggest that circulations are most likely to persist in that mode, ultimately to fulfill the runoff-hastening potential that this atmospheric pattern holds for the Sierra Nevada. In contrast, recognition that circulation patterns are not in the persistent mode has been an indication historically that winter North Pacific climate will be highly variable and that runoff from the Sierra Nevada would be contingent on the particular (unpredictable) course of the winter to follow. This strategy was exploited in a preliminary prediction scheme for April snowpack water content in the Pacific Northwest — based on the January sea-surface temperature patterns associated with persistence — which captured 70% of the year-to-year snowpack variability between 1948 and 1987 (Dettinger *et al* 1994).

Thus, a major component of the atmospheric changes discussed here is a trend toward more frequent occurrence of the wind pattern of Figure 3. In effect, the pattern in Figure 3 has become more and more the normal weather pattern over the North Pacific and North America in recent decades. It probably is not coincidental that this pattern is associated with particularly persistent conditions in both the atmosphere and ocean. Reassuringly, further analyses (not shown here) of longer-term data series indicate that ocean-air patterns also lapsed into such persistent patterns during prior episodes in the 1920s and early 1960s. This suggests that these changes are probably part of the natural decadal variations of Pacific climatology on decadal time scales and need not be interpreted as part of some new phenomenon such as the greenhouse effect. If, however, they are part of some human-induced change in the global system, then the changes must be assuming the shapes of natural-looking mechanisms of climate variation.

The atmospheric changes discussed here are much slower than, and not directly associated with, year-to-year global fluctuations such as El Niño/Southern Oscillation (ENSO). ENSO fluctuations are usually considered to be rapid variations around some "normal" tropical state. In recent decades, however, there have been indications that the "normal" tropical state may be changing. Indeed, recently, 5 years of El Niño and near-El Niño conditions have been sustained without the usual interruptions by "anti"-El Niño conditions. This sustained El Niño/near-El Niño state has led some climatologists to suggest that near-El Niño conditions may have become the new normal tropical condition (Monastersky 1995). At least some of the long-term changes associated with this "tropical drift" actually began in the late 1940s — with the commencement of a gradual sustained warming of the western tropical Pacific. Perhaps not coincidentally, this also is when the North Pacific changes, the Sierra Nevada warming, and the runoff-timing changes began.

In summary, we find that the timing of delta outflows to the bay are linked through air temperatures over the western United States and in the Sierra Nevada to climatic fluctuations over the North Pacific and beyond. Since the late 1940s, these linkages have resulted in a statistically significant trend toward earlier annual Sierra Nevada snowmelt and delta outflow. Many other western streams show a similar trend. The trend seems to be associated with interdecadal variations of the North Pacific climate system and, possibly, with long-term changes in the tropical Pacific. As we come to understand them more, these distant linkages may form the basis for long-term Sierra-climate and delta-outflow predictions. At present, the recent trends seem to reflect natural variability of California's climate and, thus, are part of the natural variability of the San Francisco Bay ecosystem. If so, these long-term fluctuations would be part of the hydroclimatic range within which the bay ecosystems developed and, thus, probably are not threats to the viability of the ecosystems; they are extremes, however, that cannot be safely ignored in the evaluation of human influences on those ecosystems (such as the long-term decrease in spring delta outflows resulting from long-term increases in water exports).

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