

A LONG-TERM (~50-YR) HISTORICAL PERSPECTIVE ON FLOOD-GENERATING WINTER STORMS IN THE AMERICAN RIVER BASIN

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INTRODUCTION

Because of the broad range of altitudes spanned by its catchment, the American River is notable for its occasional, very large winter floods. These floods typically are spawned by warm and exceptionally wet storms that deposit heavy rain or wet snows on broad expanses of the river's watershed, generating rapid runoff and high streamflows. On flood and longer time scales, the American River is notable for the balancing act that characterizes its flows and floods. Overall, discharge of the American River derived in almost equal proportions from rainfall and snowmelt (Jeton et al., 1996), unlike the more snowfed rivers farther south in the range and the more rainfed rivers farther north. Because of the nearly equal contributions by rain and snow in the American River discharges, some storms bring substantial and immediate flood risks, whereas others are more inclined to build snowpacks with less attendant flood risk.

Historically, the flood-generating winter storms in the American River basin have gained much of their impact from their intense precipitation, their particular orographic distributions of precipitation, and (often) their warm temperatures. Intense and warm storms are frequently associated with so-called "pineapple express" circulations that bring exceptionally warm and moist air from the subtropics and tropics into the central Sierra Nevada. Given the greater flood-generating capacity of heavy rains (compared to heavy snowfall), the extent to which precipitation rates in a given storm are heaviest at highest altitudes, where most precipitation falls as snow, or at lower altitudes, where the changes of rainfall are greater, also plays a key role in flood generation in the basin. Therefore, the long-term histories of two particular types (aspects) of winter storms of the American River basin are analyzed here: (a) the storm-to-storm, and winter-to-winter, differences in orographic enhancement of precipitation at high versus low altitudes, and (b) the recurring pineapple-express storms. Both of these aspects will be placed in long-term historical and geographic contexts spanning the 52-yr period from 1948-1999.

DATA AND METHODS

For long-term historical analyses, winter storms can be characterized usefully by the daily large-scale patterns of water-vapor transport into the central California area. For this study, these patterns were computed from the NCAR/NCEP Reanalysis I fields (Kalnay et al., 1996, and updates thereto), in terms of daily, vertically integrated west-to-east and south-to-north vapor-transport rates on 2.5° x 2.5° global grids. Vertical integration of the Reanalysis wind, humidity, and geopotential height fields provided total daily rates of vapor transport between the surface and 300 mbar heights in the

atmosphere (about 7 km above sea level). Details of the procedure used to determine these transports are described by Dettinger et al. (2004).

The resulting daily chronology of vapor-transport patterns serves as a unified, objective summary of each day's pertinent atmospheric circulations, temperatures, tropical and extratropical moisture supplies, and wind fields, reduced to two numbers at each location: the west-to-east transport rate and the south-to-north transport rate. For example, Fig. 1 illustrates the resulting vector field of vapor transports for January 1, 1997, and allows comparison to a satellite image and weather map for the same day. Vapor convergences and divergences, and, particularly of interest here, the source regions and directions of approach of the storm circulations above the eastern Pacific and western North America can be inferred from these chronologies and searched/summarized to provide objective, long-term perspectives on flood-generating conditions in the basin.

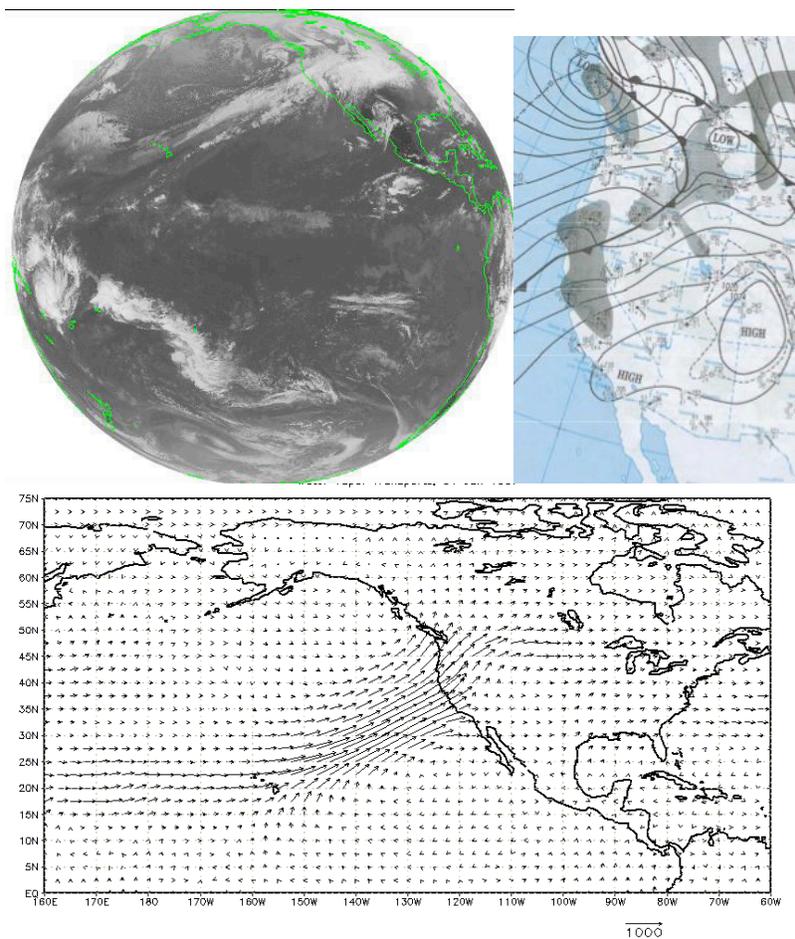


Fig. 1—Infrared weather-satellite imagery of the Pacific Ocean basin (GOES-West) from 1800 hours GMT on 1 January 1997 (top left) and corresponding daily weather map (top right) and vertically integrated water-vapor transport directions and relative rates (bottom); arrow at bottom indicates length of a 1000 kg/m/s transport.

Daily chronologies of these transports for the five decades prior to 2000 are used here to identify (a) storms that yield particularly large amounts of low-altitude (rainy) precipitation and (b) the notably warm and intense pineapple-express storms. Ratios of

averages of the precipitation at three low-altitude weather stations (Marysville, Sacramento, and Stockton) and at three middle-altitude stations (Bowman Lake, Central Sierra Snow Laboratory, and Yosemite Park Headquarters) provide a measure of daily and seasonal variations of orographic-precipitation enhancement over the central Sierra Nevada around the American River basin. Wintertime vapor transports were stratified according to whether each storm yielded high or low values of these orographic ratios (OR) to determine the optimal directions for high-altitude orographic precipitation enhancements in the basin. Winter to winter differences in storm OR values shed light on the relations between orographic precipitation and the tropical El Niño-Southern Oscillation (ENSO) climate regimes (Cayan and Webb, 1992). Lessons from this exercise then will be extended to the whole of California to show that flood generation in the American River basin may be particularly susceptible to orographically weak storms associated with El Niño winters, while basins farther to the south in the Sierra Nevada may be more susceptible to orographically weak storms during La Niña winters.

For this study, pineapple-express circulations were identified by tracing the sources and pathways of vapor arriving each day at the West Coast, seeking days when vapor at the West Coast is intensely and more-or-less directly derived from the subtropics and tropics near Hawaii (see Dettinger, 2004, for details). All such days were declared to have pineapple-express circulations, and the precipitation and temperature conditions in the central Sierra Nevada, associated with those days, were summarized to provide one version of the 50-yr history of pineapple-express episodes in the American River basin. Notably, the relatively coarse, $2.5^\circ \times 2.5^\circ$ resolution of the Reanalysis atmospheric fields precludes identification of many probable pineapple-express storms with vapor-transport pathways from the tropics that were too narrow or transitory to be well described in that dataset. Many pineapple-express storms are narrow and rapidly evolving (Ralph et al., 2004), so that the present chronology must be viewed as representing a subset of only the largest scale examples.

OROGRAPHIC-PRECIPIATION ENHANCEMENTS

The extent of orographic enhancement of precipitation rates varies from storm to storm, from season to season, and from basin to basin. On a daily scale, in the vicinity of the American River, orographic enhancements measured by OR range from less than one (low stations receiving more precipitation than high) to almost 30 (much more precipitation at higher altitudes), in winter storms from 1954-99 (Dettinger et al., 2004). The OR variations depend on circulation patterns and the vertical structures in the atmosphere during the storms (Browning et al., 1975; Neiman et al., 2002). The complete distribution of transport directions on days with particularly large OR values (days in the upper quartile of OR values from among 723 wet days studies) and particularly small values (lower quartile) are compared in Fig. 2a; the corresponding transport-direction distributions for days that were particularly wet, at both high and low altitudes, and for days that were drier at both are shown in Fig. 2b. Despite some overlap in the distributions, storms with high OR values have tended more often to involve transports (winds) from the west-southwest than have storms with low OR values. Large storms, on the other hand, have tended to be supplied by transports from the south-southwest (verifying the results of Pandey et al., 2000). This relatively subtle difference between

transport directions during large-OR storms and large-precipitation storms reflects the tendency for the southwesterly winds in the warm sectors of winter storms to bring the most precipitation overall, whereas the more westerly winds in cool sectors of storms enable stronger orographic enhancements (Dettinger et al., 2004). In no small part, the distinction is because the warm-sector winds bring warmer and moister air from the subtropics and tropics to the region—thus supplying copious precipitable water—whereas, in contrast, the westerly winds associated with large OR values are almost ideally oriented to approach and be uplifted by the west-southwest facing western face of the central Sierra Nevada.

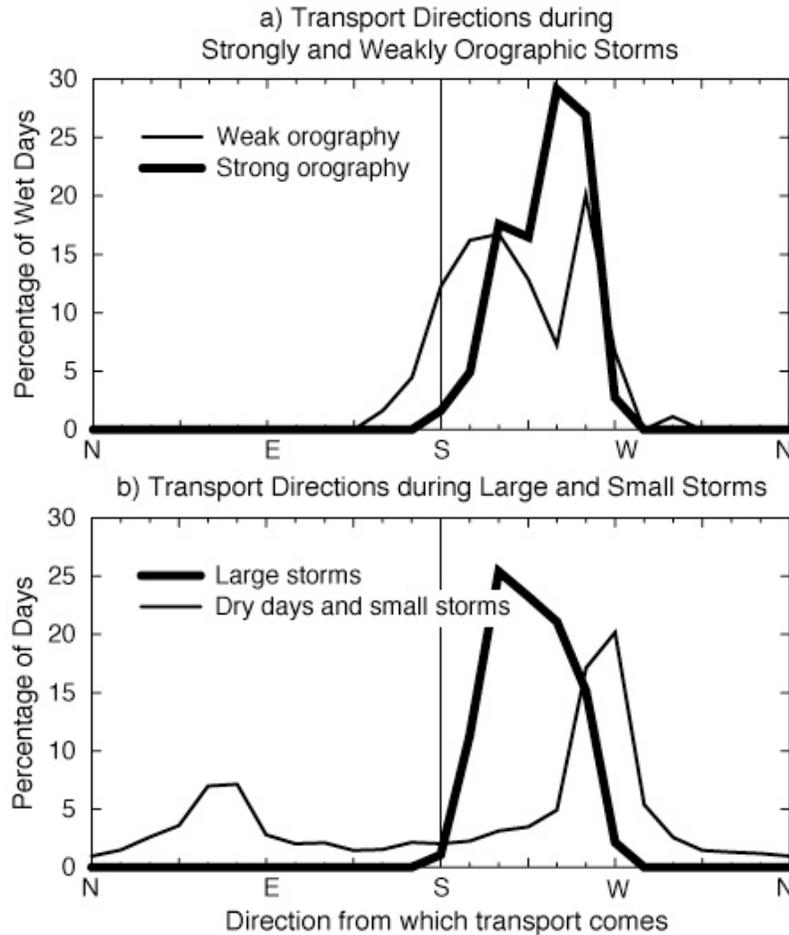


Fig. 2. Distributions of vertically integrated water-vapor transport directions associated with storms that are (a) weakly or strongly orographic, and (b) large or small storms and dry days.

Summed over whole seasons, storms in some winters yield more overall orographic enhancement than others. At the seasonal time scale, the time history of ratios of average precipitation at the three middle-altitude and three low-altitude weather stations along the central Sierra Nevada (listed earlier and described by Dettinger et al., 2004) have varied from slightly less than one to five, as shown in Fig. 3. The time series from the particular weather stations used in this study, averaged as in this study, do not

trend overall during the study period (although orographic ratios have trended in many pairs of high and low stations, as described and analyzed by Givati and Rosenfeld, 2004). The OR ratios do, however, vary considerably from year to year.

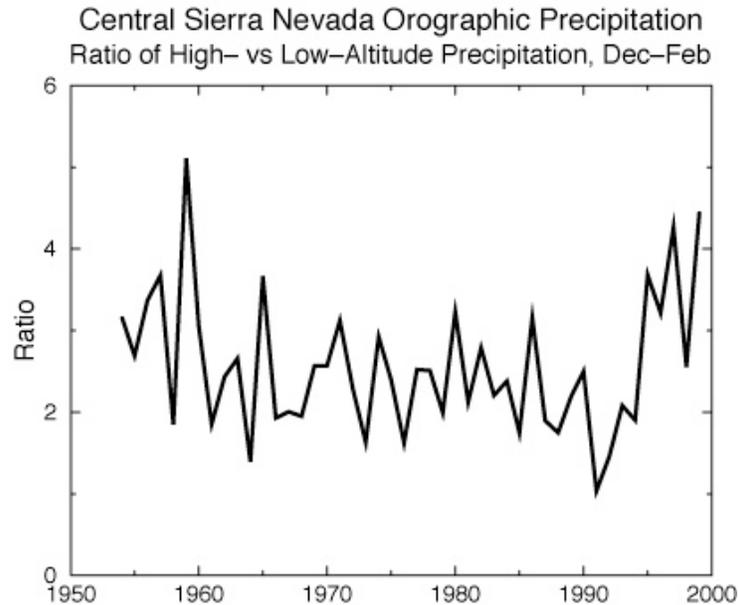


Fig. 3—Ratios of high- to low-altitude December-February precipitation totals, 1954-1999.

The winter-to-winter differences in OR values reflect differences in the mixes of storm types, differences that, in part, are modulated by winter-to-winter differences in ENSO conditions. The distributions of transport directions from all wet days in El Niño and La Niña winters are compared in Fig. 4a. Amidst even more overlap than in Fig. 2, vapor transport during storms in La Niña winters are shown to arrive more often from the west-southwest than during storms in El Niño winters (Fig. 4b). Thus, storms in La Niña winters are more often better suited to yield large OR values than are storms in El Niño winters. Conversely, transports during El Niño storms arrive, about half the time, from the south-southwest, a direction that is particularly well suited for supplying some of the largest precipitation totals. The long-term variations of the North Pacific climate under the irregular buffeting of year-to-year ENSO fluctuations, encapsulated in the Pacific Decadal Oscillation (Mantua et al., 1997), affects OR similarly, but much less reliably than does ENSO (as shown in Dettinger et al., 2004).

The influence that ENSO has on OR values in the American River basin comes, largely, from the coincidence of the preferred transport direction during La Niña storms and the steepest-ascent direction of the western slope of the Sierra Nevada in this area. When the winds and transports arrive from the direction most perpendicular to the range, the tendency for orographic uplift is largest, and this transport direction happens to be especially common during La Niña winters. Extending this consideration to the rest of California, Fig. 5 maps areas where the large-scale transport directions on wet days are most frequently perpendicular to local topography during El Niño winters, La Niña

winters, or neither. Notably the American River basin lies astride the broadest expanse of the western Sierra Nevada that is “properly” oriented to extract orographic precipitation during La Niña winters (grey areas in Fig. 5). Other areas that also may see large OR enhancements during La Niña winters appear in the northern Coastal Ranges. Enhancements of OR during El Niño winters are anticipated—from the relative orientations of transports and topography—in the southern Sierra Nevada around the Kern River drainage (where the Sierra Nevada high country falls off to the south and southwest), as well as in several of the smaller mountain ranges of south-central California (black areas in Fig. 5).

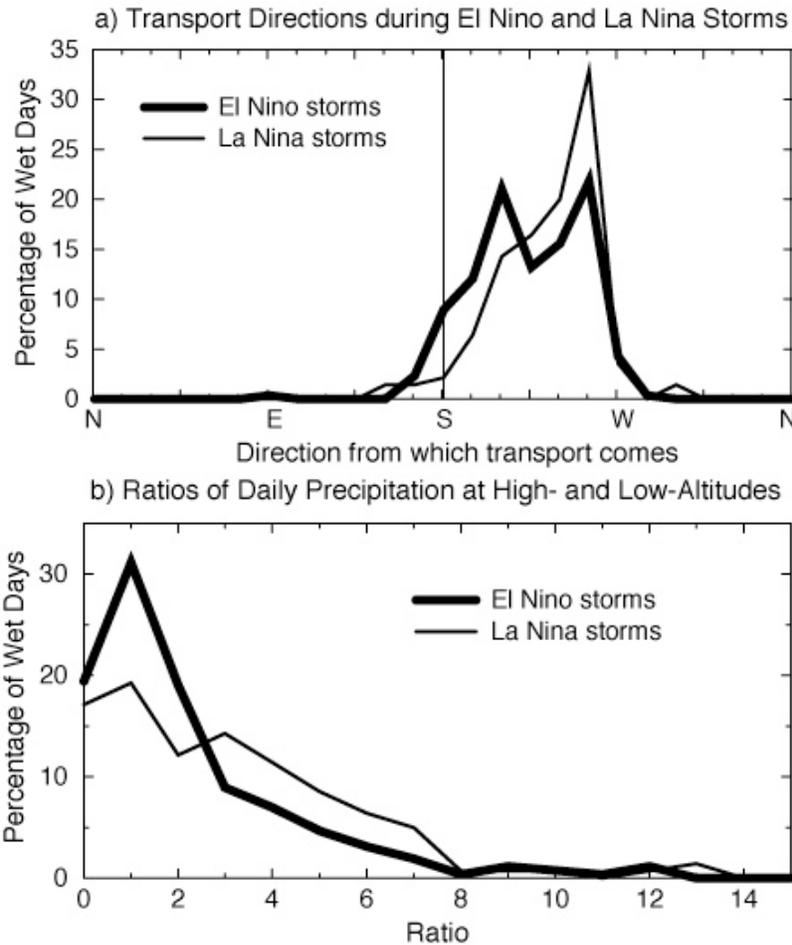


Fig. 4.—Distributions of (a) water-vapor transport directions and (b) orographic-precipitation ratios associated with storms during El Niño and La Niña winters, 1954-99.

Dettinger et al. (2004) manipulated precipitation inputs to detailed hydrologic models of the American and Merced Rivers, to show that lower seasonal OR values can yield larger floods and earlier overall runoff. When more precipitation falls at lower altitudes, more falls as rain and runs off quickly. When more precipitation falls at higher altitudes, more falls as snow and then runs off more gradually during the spring snowmelt season. The American River was especially responsive to these differences.

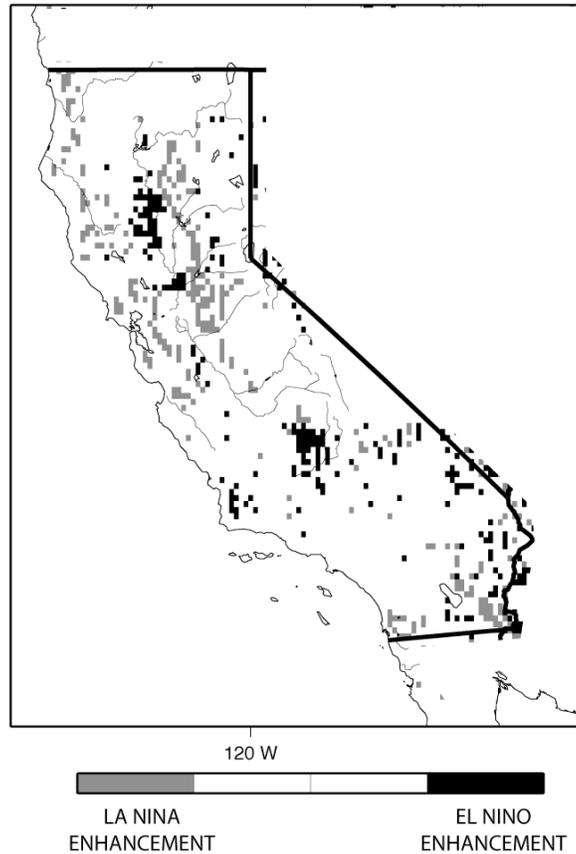


Fig. 5—Areas in California where the aspects of 10-km smoothed topography are better suited for orographic precipitation enhancement during wet days in El Niño winters (black), in La Niña winters (grey), or no preference (white), 1948-1999.

PINEAPPLE EXPRESS STORMS

A strong tendency for the largest (high- *and* low altitude) precipitation totals in the American River area to be associated with large-scale south-southwesterly transport directions was illustrated in Fig. 2b. Pineapple-express storms form a particularly challenging subset of the wettest storms. Pineapple-express storms are so called because they draw heat and vapor from the subtropics or tropics near Hawaii and route that heat and vapor directly into the West Coast. Three ways of visualizing one such storm, the notorious New Years 1997 storm, were shown in Fig. 1. In particular, the bottom panel of Fig. 1 shows the vertically integrated water-vapor transports on that day, illustrating—on the coarse Reanalysis grid—the strong transport of vapor from over Hawaii into the West Coast, crossing the coast near 40°N. By searching for days with transport patterns like this, with strong southwesterly vapor transports extending unbroken from the West Coast (anywhere between 32.5°N and 55°N) into the subtropics between 170°E and 120°W, a catalog of days with large-scale pineapple-express circulations was developed by Dettinger (2004, with details of the detection procedure presented therein).

The resulting catalog of 206 days with large-scale pineapple-express circulations is displayed in Fig. 6; the complete chronology appears as a table in Dettinger (2004). Although every day in the 1948-99 period was analyzed for the presence of a pineapple-express circulation pattern, all pineapple-express circulations occurred between October and April, with a strong seasonal maximum in Januaries and Februaries. Pineapple-express circulations are a form of the “atmospheric rivers” described by Ralph et al. (2004), which form in warm sectors of midlatitude cyclones along the warm side of cold fronts that drape far enough south to extract air from the subtropics and tropics. Thus, the nearer the storm centers are to the subtropics, the more readily they can tap into those regions (Dettinger, 2004). The seasonality of pineapple-express storms reflects the seasonality of the average latitudinal location of the jet stream and storm tracks over the North Pacific, which—on average--reach their southernmost locations, closest to the subtropics and tropics, during January and February.

Pineapple-express circulations—as identified by the method used here—cross the West Coast with almost equal frequency anywhere from 32°N to 55°N, with no specific latitudes preferred in any particular month. These circulations vigorously draw warm and moist air into the West Coast, and when temperature and precipitation fields associated, with the 100 most intense examples of these circulations are averaged, the patterns shown

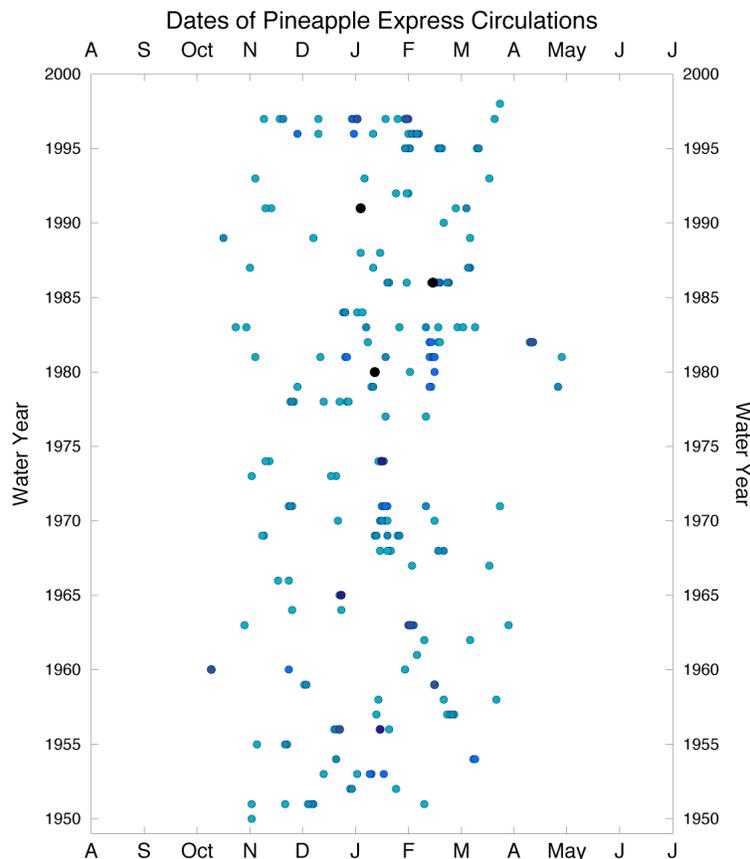


Fig. 6.—Historical occurrences of pineapple-express circulation patterns identified by the vapor-transport tracking approach described here and in Dettinger (2004); darker dots corresponds to increasing intensity of vapor transports.

in Fig. 7 are obtained. Not unexpectedly, a swath of unusually intense precipitation extends from northeast of Hawaii to the West Coast during the “average” intense pineapple-express storm. The average West Coast center of this anomalous precipitation is at about 45°N (on the California-Oregon border) but the American River basin is well within the reach of the intense pineapple-express precipitation (Fig. 7, bottom). Pineapple express storms bring anomalously warm conditions to most of the western conterminous states, with a maximum warming that—on average--crosses directly over the American River basin (Fig. 7, top). The relation of pineapple-express storms to cold and warm sectors of midlatitude storm systems is illustrated in Fig. 7 (top) by the strong temperature gradients (band of white) extending from Hawaii to Seattle and thence along the Canadian border, on average. This abrupt geographic transition from warm eastern anomalies to cold western anomalies in Fig. 7 (top) is the form that the average of the many cold fronts that power pineapple-express storms takes in the coarse Reanalysis fields.

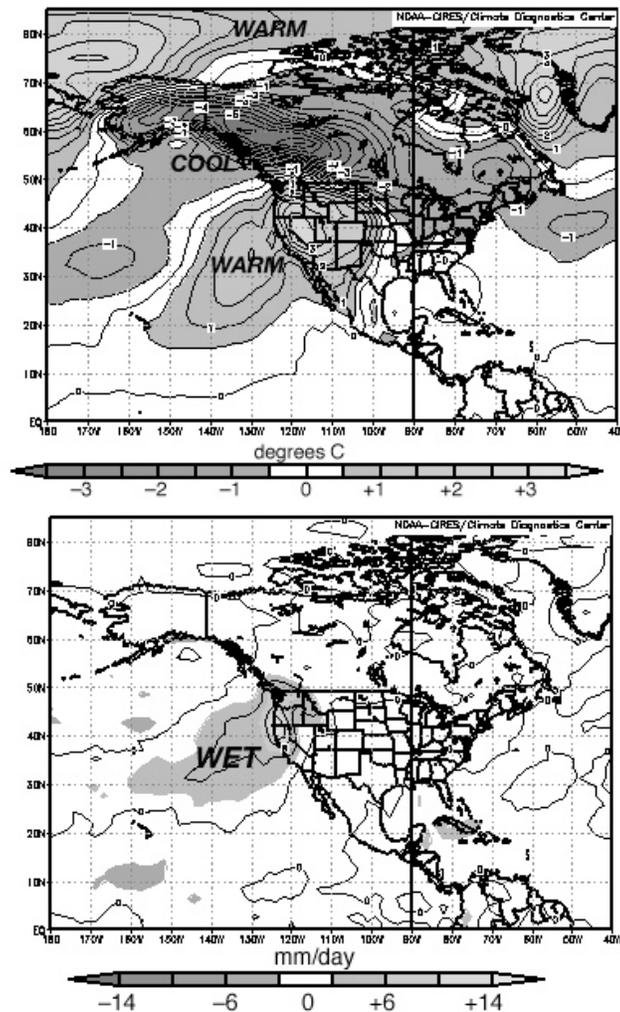


Fig. 7.—Average of deviations, on the 100 days with the most intense pineapple-express circulations, of surface-air temperatures (top) and precipitation rates (bottom) from long-term mea; graphics courtesy of the NOAA/Climate Diagnostics Center.

The number of pineapple-express circulations arriving varies considerably from year to year (Fig. 6). The annual numbers of episodes does not appear to have trended significantly in the past five decades, although the Reanalysis fields are less reliable (especially over the Pacific Ocean) prior to the satellite era, so that trend detection would be suspect in any event.

Year-to-year ENSO fluctuations have not had any large effects on the number (not shown) or overall intensity (Fig. 8a) of pineapple-express circulations. In particular, years with especially vigorous pineapple-express circulations (indicated by year labels in Fig. 8a) have occurred in all three ENSO statuses (El Niño, La Niña, and ENSO-neutral years). However, every El Niño winter in the 1948-99 period yielded some pineapple-express storms, whereas La Niña and ENSO-neutral winters occasionally have passed without any identified pineapple-express storms.

On longer multi-decadal time scales, winters with the most vigorous pineapple-express circulations have tended to occur during the El Niño-like positive phase of the PDO (Fig. 8b). During this phase of PDO, the Aleutian Low pressure system over the North Pacific is typically enhanced and storm tracks are more likely to be shifted southward, making it easier for cold fronts to draw heat and moisture northeastward from the subtropics and tropics. Taken together, the panels of Fig. 8 indicate that, historically, the most intense pineapple-express seasons (labeled dots) have tended to occur when PDO was positive and ENSO was near neutral. The winter of 2005 included some notable pineapple-express episodes, and generally may have been another example of this PDO-ENSO dependence: during the November 2004-February 2005 period, the average PDO value was slightly positive (+0.45) and, by the measure used in Fig. 8a, ENSO was only slightly into its El Niño phase (+0.52).

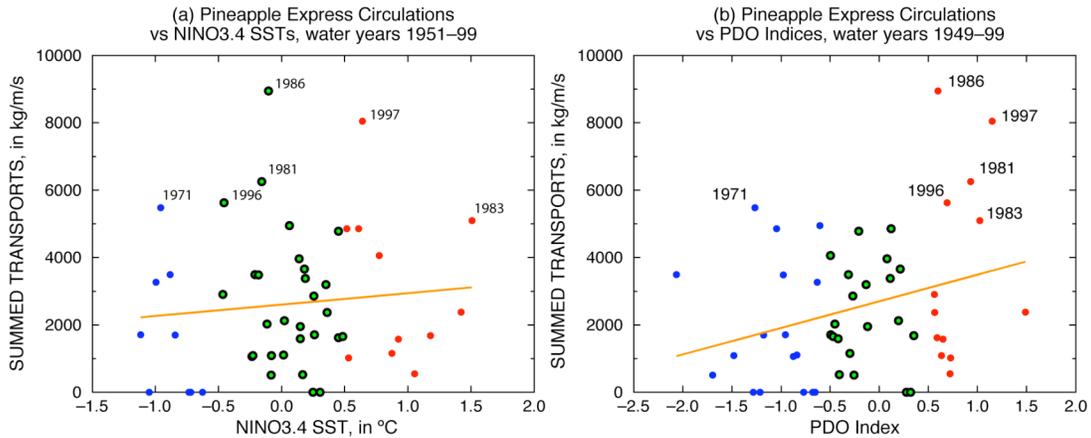


Fig. 8—Relations (a) between the NINO3.4 sea-surface temperature (SST) index of the El Niño-Southern Oscillation and the sum of daily water-vapor transports by pineapple-express circulations, and (b) between the Pacific Decadal Oscillation (PDO) index and the circulations. The rightmost third of the plots correspond to (a) El Niños and (b) El Niño-like PDO years; the leftmost thirds indicate (a) La Niñas and (b) La Niña-like PDO years; open circles are neutral years. Lines are regression fits.

SUMMARY

The long-term perspective taken here reveals that, historically, El Niño conditions have favored having more low-altitude precipitation (relative to the usual high-altitude orographic enhancement) that, falling most often as rain rather than snow, may tend to increase flood risks. Pineapple-express patterns and the flood risks that they entail, on the contrary, appear to have been favored by near-neutral (non-El Niño) tropical conditions during El Niño-rich decades (warm phases of the Pacific Decadal Oscillation).

Furthermore, this long-term perspective confirms our suspicion that the risks for flood generation in the American River basin are special in several ways. With its broad expanses of moderate-altitude terrain and its near equal mix of rainfed and snowmelt runoff, the basin is particularly sensitive to storm-by-storm variations in the amounts and distributions of rainfall. The orientation of the western slopes of the Sierra Nevada in the vicinity of the American River is particularly well suited to yield significant ENSO-modulated year-to-year increases in orographic precipitation enhancement during La Niña winters, rivaled in the Sierra Nevada only by the southern ramparts of the range where topography may favor El Niño orographic enhancements. Pineapple-express storms bring particularly warm and wet storms to the area and thus pose important flood risks. On long-term average, the American River has the dubious distinction of being situated beneath the margins of most intense precipitation associated with pineapple-express circulations and of being situated at the point in the Sierra Nevada and Cascades where pineapple-express circulations (on average) bring the warmest temperatures.

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