Supporting Information

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SI Text

Summer Fog Extremes. The summers of extreme fog anomalies are important for understanding the full scope of observed variability. It is also desirable to verify these anomalies with other independent data sources. This opportunity is available for the strongly coupled system of the United States (U.S.) Pacific coast, in which a variety of climate parameters tend to covary with one another.

Particular emphasis here, as in the main text, is placed on the summers of 1951 and 1997. Validation of conditions in 1951 is particularly important, because this is the first year of the northern California fog record and a notable outlier (Fig. 2*A*). This summer was not, however, the first year of cloud measurement at either northern California site nor in coastal California more generally. Less complete records are available at Monterey beginning in 1945 and at Arcata in 1950. Cloud height archives at other coastal California stations begin as early as 1943. It is therefore unlikely that the 1951 regional fog anomaly is an artifact of early measurement practices.

The summer of 1951 featured strongly similar fog frequency values at both northern California stations, as well as the highest recorded levels (62% at Arcata and 61% at Monterey) (Fig. 2*A*). The regional 1951 anomaly reached 3.0 standard deviations (σ) above the mean (Arcata: 2.5σ; Monterey: 3.2σ). The day-to-day agreement between the two stations (Fig. 2*B*) also supports the validity of both records and a common response to synoptic-scale weather and climate.

The peak fog summer of 1951 is also notable for the strongest northerly winds on the Oregon coast, the greatest inland-coast T_{MAX} contrast as represented by PC 3, and the strongest inversion conditions at Oakland, CA (Fig. S3). The 1951 anomaly in Oakland inversion strength, the variable most directly related to coastal fog, reached 2.9σ, comparable to the magnitude of the fog anomaly. This summer also experienced the second-lowest sea-surface temperature (SST) at the California–Oregon border, marginally surpassed by the summer of 1975. Corroborating evidence from several coastal indicators indicates that the summer of 1951 was unusual within the 1951–2008 climate record.

The summer of 1997 featured the lowest frequency of fog in the Arcata record (24%) and the third lowest at Monterey (30%). This summer also experienced the smallest T_{MAX} contrast within the past 58 years as captured by PC 3, as well as the highest coastal SST, and the weakest northerly winds at the California–Oregon border (Fig. 3*B* and Fig. S3). Inversion conditions at Oakland were the second weakest on record, after the summer of 1983. A variety of independent data sources therefore supports the existence of anomalous coastal conditions during the minimum fog summer of 1997.

Fog and Regional T_{MAX}. Principal components analysis was performed with the correlation matrix of 114 U.S. Historical Climatology Network Version 2 (USHCN v2) Pacific coast T_{MAX} records for June–September summers from 1901 to 2008. The western boundary of the spatial domain was defined by the U.S. Pacific coastline, and the eastern margin was delimited by the eastern boundary of California and by the 120°W longitude line in Oregon and Washington, which continues the California boundary northward. This area covers approximately the first 300 km of the U.S. Pacific coastal region. All stations within this area were used in the analysis.

T_{MAX} PC 1 (Fig. S4*A*, *D*, and *G*) captures 41% of total interannual variance and reflects coherent variations over nearly the entire region, with all stations but one sharing PC loadings of the same sign. Santa Cruz, CA is the sole exception, with a loading slightly below zero. The PC 1 time series is virtually identical to the unweighted mean of all 114 station records ($r > 0.99$). This T_{MAX} region mean series displays a positive trend (0.64 °C per century), in addition to a low-frequency component with a period of approximately 70–80 years. By comparison, coastal SST at 42° N, 124°W (California–Oregon border) shows a trend of 0.84 °C per century. T_{MAX} PC 2 (Fig. S4*B*, *E*, and *H*) explains 12% of variance and captures a north–south contrast. This pattern has relatively little influence in coastal northern California, which lies near the dipole pivot.

T_{MAX} PC 3 (Fig. S4*C*, *F*, and *I*) accounts for 10% of variance and primarily reflects a coast–interior contrast. The PC 3 time series displays strong correlations with northern California fog frequency ($r = 0.84$) and Oakland, CA inversion strength ($r = 0.80$) over the 1951–2008 period. This degree of correlation, in addition to the spatial pattern of the PC loadings, suggests that this mode is physically significant and reflective of the larger regional dynamics that contribute to fog presence and inversion conditions in coastal northern California. The pattern of recent (1951–2008) station T_{MAX} correlations with PC 3 (Fig. S4*C*) closely matches that obtained with the northern California fog frequency index (Fig. 4*B*). Over the longer 1901–2008 period, the zero line of PC 3 loadings occurs slightly inland of its recent location (Fig. S4*F*), particularly in Oregon and central California.

The regional PC 3 series is exemplified by the T_{MAX} difference between Ukiah, CA, located in the northern California Coast Range interior, and Berkeley, near San Francisco Bay (Fig. S5). These stations also display the strongest positive ($r = 0.53$) and negative ($r = -0.67$) fog correlations, respectively. The station T_{MAX} difference, on the basis of the end points of its linear least-squares fit, was ~50% greater in 1901 (9.6 °C) than in 2008 (6.3 °C). This change involves a positive T_{MAX} trend at Berkeley (2.2 °C per century) and a negative trend at Ukiah (−0.9 °C per century).

Most temperature stations within the Western U.S. Pacific region display positive T_{MAX} trends, consistent with positive loadings on the leading PC 1. As suggested by PC 3, positive trends are generally stronger at coastal sites than in the interior. The 31 coastal stations, identified by negative fog correlations, have a median T_{MAX} trend of 1.08 °C per century, whereas the remaining interior stations have a median trend of 0.52 °C per century. When the zones are defined by the signs of the PC 3 loadings, the coastal median trend (58 stations) is 1.25 °C per century, and the interior median trend is 0.09 °C per century.

Prior studies have attributed a lack of strong positive summer T_{MAX} trends in California's Central Valley to the effects of agricultural irrigation, through a reduction in sensible heating of the land surface (1–4). The involvement of both coastal and interior T_{MAX} anomalies with PC 3 on both interannual and longer time scales suggests, however, that some fraction of damped interior warming may be related to changes in larger-scale dynamics with influence on both areas. This interpretation is also supported by PC 3 loadings over the interior that encompass areas unaffected by intensive irrigation, including the Klamath Mountains and Sierra Nevada of California and the Great Basin of NE California and eastern Oregon. Likely, related mechanisms include reductions in regional subsidence and adiabatic warming, a weakened coastal temperature inversion, and greater upward and inland penetration of marine air masses.

1. Bonfils C, Lobell D (2007) Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proc Natl Acad Sci USA* 104(34):13582–13587.
2. Christy JR, Norris WB, Redmond K, Gallo KP (2006) Methodology and results of calculating central California surface temperature trends: Evidence of human-induced climate change? *J Climate* 19(4):548–563.
3. Kueppers LM, Snyder MA, Sloan LC (2007) Irrigation cooling effect: Regional climate forcing by land-use change. *Geophys Res Lett* 34(3):L09705.
4. Lobell DB, Bonfils C (2008) The effect of irrigation on regional temperatures: A spatial and temporal analysis of trends in California, 1934–2002. *J Climate* 21(10):2063–2071.

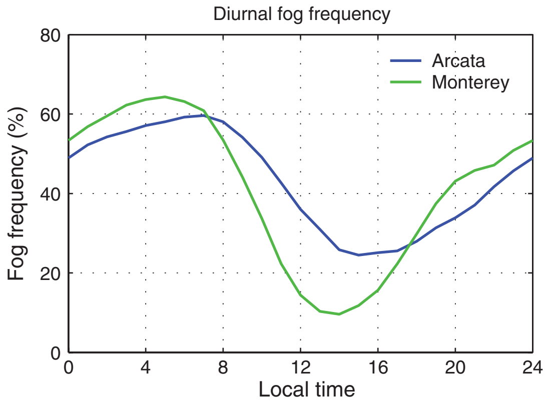

Fig. S1. Diurnal patterns of fog frequency. Mean summer fog frequency by hour at Arcata (*Blue*) and Monterey (*Green*).

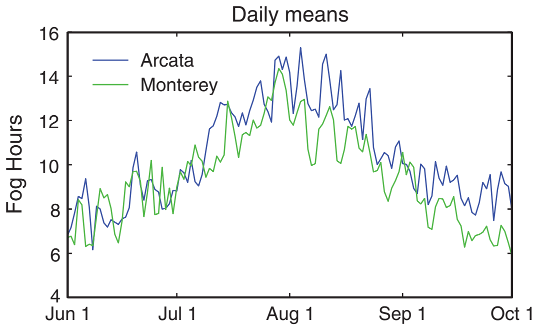

Fig. S2. Seasonal patterns of fog frequency. Hours of fog per day at Arcata (*Blue*) and Monterey (*Green*).

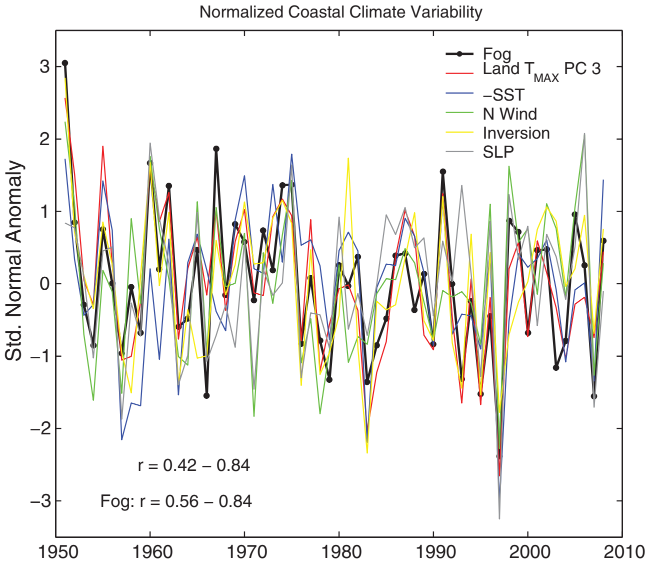

Fig. S3. Comparison of northern California fog frequency and related coastal climate variables. Plot includes: northern California fog; U.S. Pacific coast T_{MAX} PC 3; SST 42°N, 124°W (inverted); northerly wind 45°N, 125°W; Oakland, CA inversion strength; sea-level pressure 47.5°N, 132.5°N. All series normalized to zero mean and unit variance.

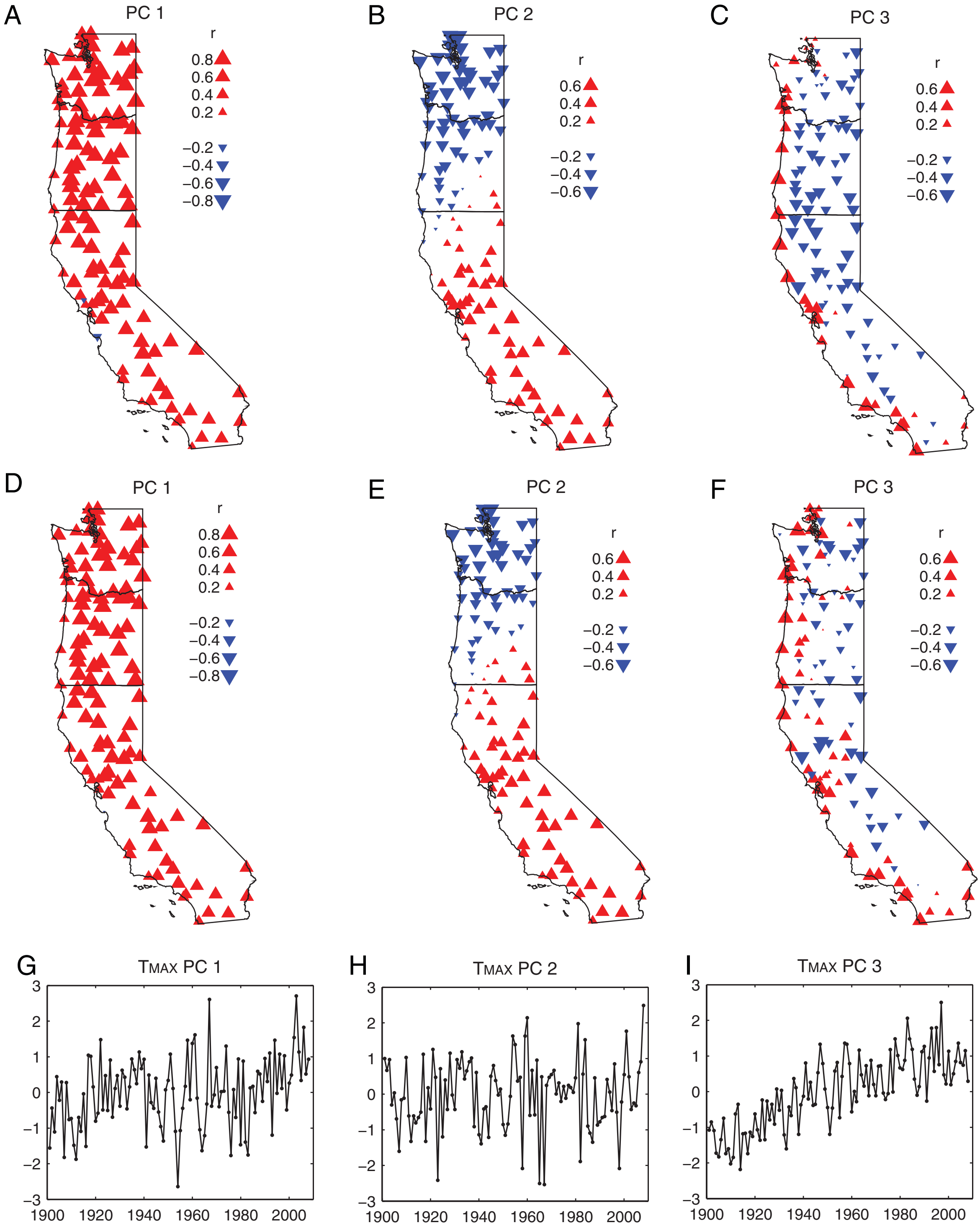

Fig. S4. T_{MAX} principal components. (*A–C*) Station correlations with each PC time series below (1951–2008). (*D–F*) Station PC correlations (1901–2008). (*G–I*) PC time expansion coefficients. PCs 1–3 account for 41%, 12%, and 10% of T_{MAX} variance, respectively. Each series normalized to zero mean and unit variance.

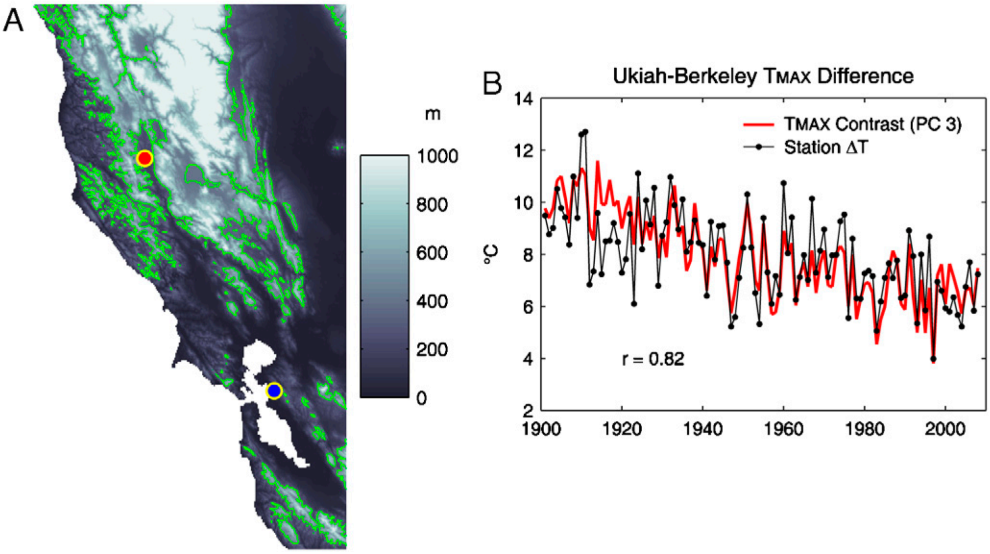

Fig. S5. Ukiah–Berkeley T_{MAX} difference. (*A*) Station locations and regional topography. *Blue*: Berkeley 37.87°N, 122.27°W, 91 m; *red*: Ukiah 39.15°N, 123.20° W, 193 m. Green lines trace the 400 m elevation contour. Ukiah, though situated below 400 m elevation, is sheltered from marine air by a ∼1000 m ridge to the W-NW, so that it behaves as an interior site, whereas Berkeley is directly exposed to marine air and fog. (*B*) Ukiah-minus-Berkeley T_{MAX} difference, compared to western U.S. T_{MAX} PC 3.

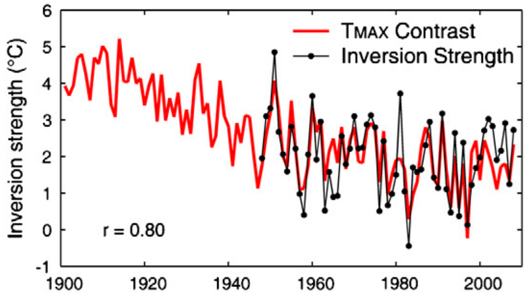

Fig. S6. Oakland, CA summer inversion strength. The black line reflects actual values (1948–2008), calculated as the mean temperature difference between atmospheric layers from 1000–2000 and 0–400 m elevation. The red line reflects U.S. Pacific coast T_{MAX} PC 3 (1901–2008), scaled as a univariate linear least-squares predictor of inversion strength.

Other Supporting Information Files

Dataset S1 (XLS)