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Interpretation of Recent Temperature Trends in California

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Regional-scale climate change and associated societal impacts result from large-scale (e.g. well-mixed greenhouse gases) and more local (e.g. land-use change) "forcing" (perturbing) agents. It is essential to understand these forcings and climate responses to them, in order to predict future climate and scoietal impacts. California is a fine example of the complex effects of multiple climate forcings. The State's natural climate is diverse, highly variable, and strongly influenced by ENSO. Humans are perturbing this complex system through urbanization, irrigation, and emission of multiple types of aerosols and greenhouse gases. Despite better-than-average observational coverage, we are only beginning to understand the manifestations of these forcings in California's temperature record.

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~~Recent congressional testimony (Christy 2006) cited disagreement between simulations of greenhouse warming and local temperature observations in California in concluding that "we are unable with any confidence to predict climate outcomes from policy options." Such statements should be regarded cautiously, however, since n~~ Neither the nature of climate trends in California, nor their causes, are well-understood. ~~Trends in other, less complex, regions may be easier to observe, interpret and predict. Also, future climate change may be easier to simulate than historical changes, since greenhouse-gas forcing will likely dominate other, more poorly-understood forcings~~. This article discusses recent temperature trends in California, the role of climate models in understanding these trends, and research needed to improve ability to predict regional climate change.

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How have temperatures changed in California during the last 50-100 years? Datasets analyzed by Bonfils *et al.* (2006a) show rapid increases in State-wide temperatures in late Winter and Spring, less rapid increases in Summer, and no clear trend in Fall. Warming
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has been more rapid at night than in daytime. Smaller-scale trends are less clear. Gridded data sets indicate that, in seasons when warming has occurred, it has affected nearly the entire State. Observed trends are generally consistent among different data sets. An exception is that of Christy *et al*. (2006) who analyzed station data in the Sierra Nevada mountains and nearby Central Valley. Unlike other investigators, they found no warming **(actually nighttime cooling)** (COMMENT: THIS SEEMS TO CONTRADICT A LATER ITEM – SEE BELOW) in the Sierra. This trend, however, is probably much more
uncertain than acknowledged by the investigators, since the removal of one of 137 data segments completely eliminates the apparent trend (Bonfils *et al.* 2006b).

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Warming measured by thermometer is consistent with findings from other types of temperature indicators. California river flows have shifted towards earlier in the year (Stewart *et al*., 2005), indicating earlier melting of snow, and a shift in precipitation from snow to rain. Snow water content has declined (Mote, 2004), and certain plant species are blooming earlier in Spring (Cayan *et al*., 2001). Loss of snow and altered river flows indicate warming specifically in the higher elevations, in contrast to the findings of Christy *et al*. (2006).

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What is causing these trends? Bonfils *et al*. (2006a) showed that rapid increases in observed daily average and daily minimum temperatures in California exceed those possible from natural internal climate variability alone, as estimated by global climate models. This means that some external factor(s), e.g. urbanization or greenhouse warming, must be acting to increase temperatures in California.

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Models are of limited help in identifying these factor(s), or in interpreting observed temperature trends in California. Global model simulations of the 20th century archived in
the IPCC database at LLNL do not in general reproduce observed temperature trends in California (Bonfils *et al*, 2006a). While all simulations show warming, none reproduce the observed seasonal or diurnal cycle of temperature increases. However, these simulations do not treat all relevant forcings: none includes effects of irrigation and few include other types of land-use changes (such as urbanization), most use simplified treatments of only
limited types of aerosols. (Agricultural aerosols, for example, are omitted.) Some
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regionally-varying forcings are not characterized well enough to allow them to be represented in climate models. The biggest problem, however, is probably the coarse spatial resolutions used in the IPCC simulations, which prevent simulation of the complex topography and ocean-land interactions in California. (For example, coarse resolution will reduce or eliminate any snow-albedo feedback, since snow amounts are much less than observed, and may be zero.) Also, coarse resolution
makes it difficult to represent regionally-varying forcings or responses to them.

Thus, even ignoring possible inherent inadequacies in how models represent relevant physical processes, it is hardly surprising that these simulations do not accurately reproduce observed temperature trends in California. Finer resolution global or limited domain models should be able to better represent regional climate forcings, processes, and responses; however most of the simulations that would be needed to interpret observed trends in California have not been performed. To guide interpretation of observed trends, simulations of individual forcings (as have been performed with the DOE/NCAR Parallel Climate Model
(PCM) (EXPLAIN ACRTONYM) global model), as well as simulations of multiple forcings in combination, are
needed.

Based on the apparent contrast between temperatures trends found in the Central Valley and the Sierra region ~~(discussed above)~~, Christy *et al.* (2006) ~~speculate~~ suggest that irrigation has been the dominant influence on California temperatures, causing **rapid (?) nighttime warming in affected localities (IS THIS CORRECT? SHOULD THIS BE COOLING? correct as stands)**. Observations and simulations both show that while irrigation can be locally important, its effects are very different from those proposed by Christy *et al.* Observational studies indicate that irrigation has had a large cooling effect on local summertime daytime temperatures in California (Bonfils *et al*. 2006c, Lobell and Bonfils, 2006); any effect on nighttime temperatures, however, is minimal, contrary to the ~~speculation~~ suggestion of Christy *et al*. (2006). Indeed, irrigation is used to influence the quality of wine-grapes (Aljibury *et al*., 1975) and avocados (Miller *et al.*, 1963) in California through a local cooling effect. Modeling studies (Kueppers *et al*, 2006; Lobell *et al*. 2006a,b) generally support the hypothesis that irrigation produces significant daytime cooling and little temperature effect at night. this ~~picture~~. The cooling effect of irrigation results from increased latent heat fluxes, which in turn reduce sensible heat. Lobell *et al.* (2006b) further show that irrigation can interact interestingly with greenhouse warming: by

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keeping surface soil wet, irrigation can shut off a positive feedback in which warming would otherwise reduce soil moisture and amplify warming.

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~~Interpretation of temperature trends in California is aided by consideration of trends in other, particularly surrounding, regions.~~ Temperature trends in California share some important characteristics with trends elsewhere, including most of the Western U.S. Cayan *et al*. (2001), for example, showed that springtime temperatures have increased in nearly all of Western North America since 1950. Similarly, trends in temperature indicators such as snow water content (Mote *et al*. 2005) and river flow timing (Stewart *et al*., 2005) are also coherent across much of the Western U.S. This supports the hypothesis (Dettinger and Cayan, 1995); Peterson *et a*l., 2000) that these trends result from large-scale (e.g. greenhouse-gas) rather than local (e.g. irrigation or urbanization) forcings. Bonfils et al. (2006a) attribute warming observed during January – March in the Western U.S. to a large change in atmospheric circulation in the Northern Pacific resulting from greenhouse-gas–induced warming.

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Within the State, regional scale forcings (land-use, aerosols) may be important. Irrigation has very strongly influenced local trends in daily maximum temperatures (T_{max}). While this effect likely contributes to the smaller state-wide T_{max} trend in Summer compared to Winter and Spring, the observation of a similar seasonal cycle of warming in other regions indicates that other mechanism(s) must also be important. Similarly, urbanization creates a significant local heat island (Ladochy *et al.*, 2007), and simulations (Bereket *et al*. 2005) indicate that this warmth can be advected at least short distances.

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Because of the complexity of regional climate processes, it is difficult to attribute observed trends to specific forcings without performing detailed model simulations;

qualitative arguments are likely to be misleading. As noted above, simulations of individual forcings, as well as of multiple forcings in combination, performed at fine spatial resolution, are needed. Ideally, ensembles of simulations with both individual and multiple models would be performed for each combination of forcings. This would allow characterization of climatic signatures of individual forcings, which could then be

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searched for in the observational record. Besides a major effort, this would require improved characterization of some relevant forcings, e.g. aerosols and urbanization.

What does this mean for future climate in California and elsewhere? The 21st century may well be less complex climatically than the 20th, in that greenhouse warming is likely to become dominant over at least most of the multiple climate influences that have recently been similar in magnitude. Stricter regulation of air quality is likely to reduce aerosol forcings; the extent of irrigation and the magnitude of evaporative losses are likely to decrease as development spreads and water becomes valuable. By contrast, however, the climatic signature of urbanization is likely to strengthen. These anticipated reductions in cooling-type forcings (aerosols and irrigation) combined with increases in warming-type forcings (greenhouse and urbanization) may lead to more rapid warming in California than is now expected. Nonetheless, we would gain confidence in climate projections if we could identify the signatures of individual forcings in the observational record, and show that models accurately represent those that will be important in the future. ~~Other regions that are less climatically diverse and have fewer important forcing agents than California may be easier to make projections for.~~ Nonetheless, the key to more confident projections of future climate is better understanding of recent observed trends.

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