California-2100:
Assessing Future Water Resources over California

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Abstract

This project implemented the initial phase of California-2100 (Cal21), which is aimed at making and evaluating high resolution estimates of climate change over California out to the year 2100. The initial WRC component of this project has been focused on evaluating how well regional climate models reproduce the variations of important components of the water budget for California, and estimating the effects of the increases over the past century in irrigation in California on regional climate, especially snow accumulation. The results show that global warming has a large effect on precipitation, snow water, surface temperature, low level winds and soil moisture They also show in summer that irrigation has a strong effect on the differences between recent and past conditions in maximum temperature, surface latent and sensible heat fluxes, surface moisture, and surface humidity.

Introduction: The Goals of Cal21

Climate change is expected to affect the frequency and magnitude of extreme weather events, due to higher temperatures, an intensified hydrological cycle or more vigorous atmospheric motions. California decision-makers in government, NGOs, industry, and the general public need detailed information on future California climates. Only with this information is it possible to quantify the risks brought about by a changing climate reflecting the continuous anthropogenic emission of greenhouse gases and other changes. Such quantifications are absolutely necessary to formulate and implement realistic adaptation and mitigation strategies.

Projections of California climate change exist but are deficient in terms of regional detail and in terms of the characterization of uncertainty associated with them. The assessment of potential impacts of climate change has, to date, generally relied on data from coarse resolution Atmospheric-Ocean General Circulation Models (AOGCMs), incapable of resolving spatial scales of less than ~300km. However, AOGCM information is insufficient in simulating the spatial structure of temperature and precipitation in areas of complex topography and land use distribution. The description of regional and local atmospheric circulations (e.g. narrow jet cores, mesoscale convective systems, sea-breeze type circulations) and the representation of processes at high frequency temporal scales (e.g. precipitation frequency and intensity distributions, surface wind variability) are likewise insufficient to provide useful information.

The urgent need for improved numerical models and scenarios becomes particularly apparent when considering extreme events. The importance of extreme events for our economy and environment has drastically been demonstrated during the last few years with a number of serious events affecting California, such as ENSO related flooding, extensive droughts, severe freezes, and acute air pollution events. It is anticipated that climate change will affect the frequency and magnitude of extreme events, as driven by an intensified hydrological cycle. A major limitation to such studies in the past has been the lack of appropriate computational resolution (which smears out the character of the events), the lack of long-term integrations (which drastically reduces the statistical significance), and the lack of co-ordination between different modeling groups (which led to unresolved differences between different studies).

Procedure

The utilized regional model is the widely used MM5 running at 30km grid spacing and having 45 levels. There are three primary experimental runs. The modern run (labeled 1996) has boundary conditions from the ERA-40 reanalysis (Uppala et al., 2005) for August 1 1995 through September 30, 1996. This time period was chosen to represent neutral El Niño conditions. The atmospheric carbon dioxide concentration is 365ppm (Watson et al., 2001). An important aspect of this run is that irrigation water is applied every tenth day, when the top soil layer temperature is above 12ºC. This threshold and the applied amount, which is equivalent to approximately one meter of water for an irrigation season, are chosen from a survey of typical irrigation times and amounts in California (California Department of Water Resources, 1986). Also, for the urban land use grids the soil moisture is fixed at a relatively low value of 0.05kg/kg to approximate the influence of extensive paving and the fast runoff of precipitation.

For the other two runs the irrigation rate is set to zero, and the default urban and agricultural land surface types are converted to shrub land. For the run labeled No_Irrig the boundary conditions and carbon dioxide concentration are the same as 1996. For the run labeled 1901 the carbon dioxide concentration is set to the approximate 1901 value of 310ppm, and the boundary conditions are constrained to represent the 1900-1901 time period. These boundary conditions are derived from the ERA-40 1995-96 values adjusted using the 1900-99 trends in the monthly means of the highly respected HadCM3 (Johns et al., 2003) global climate model, which is forced by known changes in greenhouse gas concentrations, volcanic aerosols and solar output. The HadCM3 trends are used each 6-hour period for temperature, humidity, winds and geopotential at all heights using formulae such as

$$T_{1901} = T_{1996} + Trend(t_{1901} - t_{1996}) \qquad \text{Eqn. 1}$$

In Eqn. 1 T_{1901} is the estimated 1901 temperature, T_{1996} is the ERA-40 6-hour temperature, *Trend* is the best fit slope at each grid and each calendar month of the corresponding HadCM3 monthly temperature changes between 1900 and 1999, and the t’s are the times in decimal months from January 1, 1900. Fig. 2 illustrates the trends in ground (sea) temperatures and 500hPa flow. It should be noted that the model is influenced only by the sea temperatures and the variables at the boundaries. The 1901 boundary conditions, derived in this way are largely free of the mean biases in atmospheric structure inherent in all ocean/atmosphere global climate models, and maintain the daily variability of the ERA-40 observations. The latter factor allows for the straightforward comparison of the 1996 and 1901 runs.

An ensemble of six runs is also created to allow the calculation of statistical confidence estimates. The ensemble is derived from control runs, for which the land use properties are those of 1996 with no irrigation. To create the ensemble the model is run using the control and two alternate rainfall parameterizations (Reisner et al., 1998) and the control and an alternate boundary layer scheme (Hong and Pan 1996). Plotted model differences are significant at the 95% significance level (Von Storch and Zwiers, 1999).

Results

As discussed for a very similar model run in Kueppers et al. (2006), the 1996 model results replicate quite well many aspects of the Climate Research Unit (CRU) 0.5ºx0.5º gridded observations, which are derived from surface station data (Mitchell and Jones, 2005). However, the model has slightly greater, and more variable, precipitation. The spatial patterns of the model and CRU winter and summer near surface temperature and specific humidity are very similar. However, the model has a cold bias of about -3ºC and also a dry bias of about 15% of the mean specific humidity. Preliminary investigations suggest that these biases are related to the fact that the model has persistent high thin cloud that reduces incoming solar radiation at the surface forcing an artificially low land skin temperature.

Fig. 3a shows the 1900-1999 linear trends in CRU winter precipitation. These trends may be compared to those for the 1900-1994 period in Karl et al. (1996), which largely indicate decreases over all of California and increases elsewhere. Such a comparison highlights the substantial uncertainties in the observational record of long term trends, which are related to the lack of observations in many regions, especially in the mountains and deserts and the fact that fewer stations are available in the earlier part of the century. No attempt has been made to establish the statistical significance of the CRU trends, but emphasis should be given to the broad regions of larger values. Fig. 3b shows that 1996 minus 1901 differences in model winter precipitation are negative nearly everywhere; comparable decreases in snow water also occur. Note that the decreased rainfall is consistent with the enhanced anticyclonic flow of the HadCM3 input (Fig. 2a). These results are in good agreement with the 1900-1994 trends, but disagree with pattern of the CRU trends (Fig. 3a) near the southern California coast.

Fig. 3c and d show the CRU trends and model differences in winter mean surface temperatures. There is fair agreement over most of the region except again in southern California. Fig. 3e and f show the results for the summer mean temperatures. Agreement is good over the length of the California Central Valley, but there is considerable disagreement elsewhere. Christy and his coworkers (2006) illustrate comparable changes for both winter and summer in their analysis of observed trends of minimum and maximum temperatures for a portion of the

California Central Valley. Mitchell and Jones (2005) indicate increases in annual mean surface temperatures throughout this region.

The discrepancies between different estimates of observed trends and model results make it difficult to reach definitive conclusions concerning the details of regional change changes in California in the past century. Although it appears that many of the changes are consistent with the large scale influences of global warming, some of the changes are probably also due to the regional affects of changes in land use. In order to better understand the possible interactions between the influences of global warming and regional land use changes in California, we further explore the factors that force differences between the 1996 and 1901 model runs.

Fig. 4a and b show the 1996 minus 1901 and No_Irrig minus 1901 summer T_{max} differences. The primary differences between the 1996 and No_Irrig runs are that the latter excludes the influence of irrigation. Clearly, irrigation has a substantial daytime cooling effect in the areas of the California Central Valley and the Imperial Valley. The 1996 minus 1901 result is in good agreement with the observational trends of Karl et al. (1996). Fig. 4c and d illustrate the primary reasons for the differences in T_{max} in the two model runs. Surface latent heat fluxes and soil moisture between the surface and 7cm are much larger in the regions of irrigation; no such changes are observed in the No_Irrig minus 1901 difference (not shown). Nearly equal magnitude decreases in surface sensible heat fluxes are also evident (not shown). These changes suggest that for 1996 during the day in summer much more surface solar heating is used to evaporate water than heat the ground and lower atmosphere than in the drier soil moisture conditions of the No_Irrig run. At night surface heat fluxes are small as are the differences in model nighttime minimum temperatures (not shown). These daytime results are comparable with a 15-day modeling study for the U.S. high plains (Adegoke et al., 2003). The modeled changes in T_{max} are also consistent with trends computed by (Kalnay and Cai, 2003) based on global reanalysis temperature estimates (Kalnay et al., 1996) for the whole United States. Differences in both temperatures and latent heat fluxes are small in winter, when irrigation is generally negligible.

Fig. 4e illustrates the 1996 minus 1901 differences in summer surface winds and percent change in snow water content. The substantial shifts in the winds suggest an enhanced broad cyclonic flow, which increases the dry continental flows into northern California and Nevada. This may partially explain the lower soil moistures in this region shown in Fig. 4d. The wind changes also indicate a stronger alongshore flow, which is consistent with enhanced coastal upwelling and a cooler near shore sea surface (Snyder et al., 2003) as seen in Fig. 2b. Analogous wind shifts are observed in the No_Irrig minus 1900 differences.

The substantial decreases in snow water content over northern California between the 1996 and 1901 runs are consistent with observational studies showing a decrease in spring snow cover (Dettinger and Cayan, 1995) and earlier snow melt river flows (Stewart and Cayan, 2005) over the past approximately 75 years. Continued decreases in snow cover are also predicted by a recent modeling study (Snyder and Sloan, 2005). Fig. 4f indicates another possible important consequence of anthropogenically-driven climate change. Daily mean 1996 surface specific humidity values are higher than the 1900 values by more than

20% over nearly the entire region, and substantially more near the areas of intensive irrigation. Away from the areas of irrigated agriculture this is in contrast to the decreases in soil moisture. Few significant changes are associated with the small number of urban grids (see Fig. 1).

There are a number of uncertainties associated with these results. Global and regional climate models are imperfect. Our experiments with different precipitation and boundary layer parameterizations show that our results are quite insensitive to the uncertainties in these important physical processes. In addition Kueppers et al. (2006) shows that many of these results are not at all sensitive to the particular choices of regional model or specific assumptions concerning irrigation.

Despite these uncertainties several important conclusions are possible. In winter global warming appears to have contributed to less precipitation and snow cover and slightly higher temperature over most of the study region. In summer global warming has led to slightly higher temperatures, which have been partially masked by the influence of increases in irrigation over much of California. As to the future, since the acreage of irrigated agriculture is unlikely to increase in the future (California Department of Water Resources, 1994), the cooling and moistening effects of irrigation will probably not offset a broader warming. Thus, nearly all of the region should anticipate warming temperature, less snow cover, drier soils, and perhaps less precipitation in the foreseeable future.

References

Adegoke, J.O., R. A. Pielke Sr., J. Eastman, R. Mahmood, and K.G. Hubbard (2003), Impact of irrigation on midsummer suface fluxes and temperatures under dry synoptic conditions: A regional atmospheric model study of the U.S. high plains. *Mon. Wea. Rev.* **131**, 556-564.

California Department of Water Resources (1986), *Crop Water Use in California*. Bulletin 133-4 (Cal. Dept. Water Res., Sacramento, CA, USA).

California Department of Water Resources (1994), *California Water Plan Update, Volume 1*. Bulletin 160-93 (Cal. Dept. Water Res., Sacramento, CA, USA).

Chen, F. and J. Dudhia (2001), Coupling an advanced land surface-hydrologymodel with the Penn State-NCAR MM5 modeling system. Part I: Modeling implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569-585.

Christy, J.R., W. B. Norris, K. Redmond, and K. P. Gallo (2005), Methodology and results of calculating central California surface temperature trends: Evidence of human-induced climate change. *J. Climate*, **19**, 548-564.

Dettinger, M. D. and D.R. Cayan (1995), Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California, *J. Climate* **8**, 606–623.

Dudhia J. (1993), A nonhydrostatic version of the Penn State NCAR mesoscale model - validation tests and simulation of an Atlantic cyclone and cold-front. *Mon. Wea. Rev.*, **121**, 1493-1513

Grell, G. A. (1993), Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon.Wea. Rev*., 121, 764-787.

Hong S.Y. and H.L. Pan (1996), Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast Model. *Mon. Wea. Rev.*, **124**, 2322-2339

Janjic, Z.I., (1994), The step-mountain Eta coordinate model—Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev*., **122**, 927–945.

Johns T.C. , et al. (2003), Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. *Cli. Dynam*. **20**, 583-612

Kalnay, E., and M. Cai (2003), Impact of urbanization and land-use change on climate. *Nature*, **423**, 528-531.

Kalnay, E., M. et al. (1996), The NMC/NCAR 40-Year Reanalysis Project". *Bull. Amer. Meteor. Soc*., **77**, 437-471.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle (1996), Indices of climate change for the United States. *Bull. Amer. Meteor. Soc*., **77**, 279-292

Kueppers, L.M., M.A. Snyder, L.C. Sloan, D. Cayan, J. Jin, H. Kanamaru, M. Kanamitsu, N.L. Miller, M. Tyree, H. Du, and B. C. Weare (2006), Regional climate effects of irrigation and urbanization in the western United States: A model intercomparison. California Energy Commission PIER Report CEC-500-2005-031D.

Mitchell T.D. and P.D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids *Int. J. Climatology* **25**, 693-712

Mlawer, E. J., S. J. Taubman, P. D. Brown, R. J. Iacono, and S. A. Clough (1997), Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res*., **102**, 16 663–16 682.

Reisner J., R.M. Rasmussen and R.T. Bruintjes (1998), Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Royal Meteorol. So*c. **124** , 1071-1107

Snyder, M.A., L.C. Sloan, N. S. Diffenbaugh, and J.L. Bell (2003), Future climate change and upwelling in the California Current. *Geophys. Res. Lett*., 30, 1823-1827.

Snyder, M.A. and L.C. Sloan (2005), Transient future climate over the western United States using a regional climate model. *Earth Interact*., 9, paper 11, 21pp.

Stewart I.T., D.R. Cayan, and M.D. Dettinger (2005), Changes toward earlier streamflow timing across western North America. *J. Climate*, **18**, 1136-1155.

Tao, W. K., J. Simpson, and M. McCumber (1989), An ice-water saturation adjustment. *Mon. Wea. Rev*., **117**, 231–235.

Uppala, S.M. et al. (2005), The ERA-40 re-analysis. *Quart. J. Royal Meteor. Soc*., 131, 2961-3012.

Von Storch, H., and F.W. Zwiers (1999), *Statistical Analysis in Climate Research*. Cambridge University Press, 484 pp.

Watson, R.T. and Core Writing Team (Ed.) (2001), *Climate Change 2001: Synthesis Report* , Cambridge University Press, 397pp.

Figures

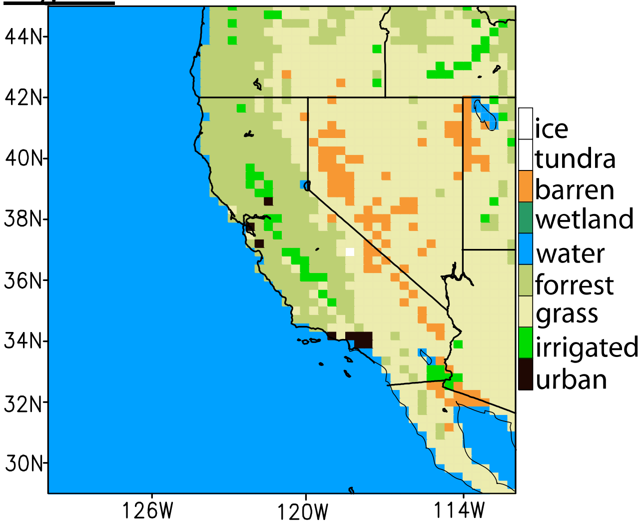

Fig. 1 Abbreviated land use types. The regions of irrigation and urbanization are denote by bright green and black, respectively.

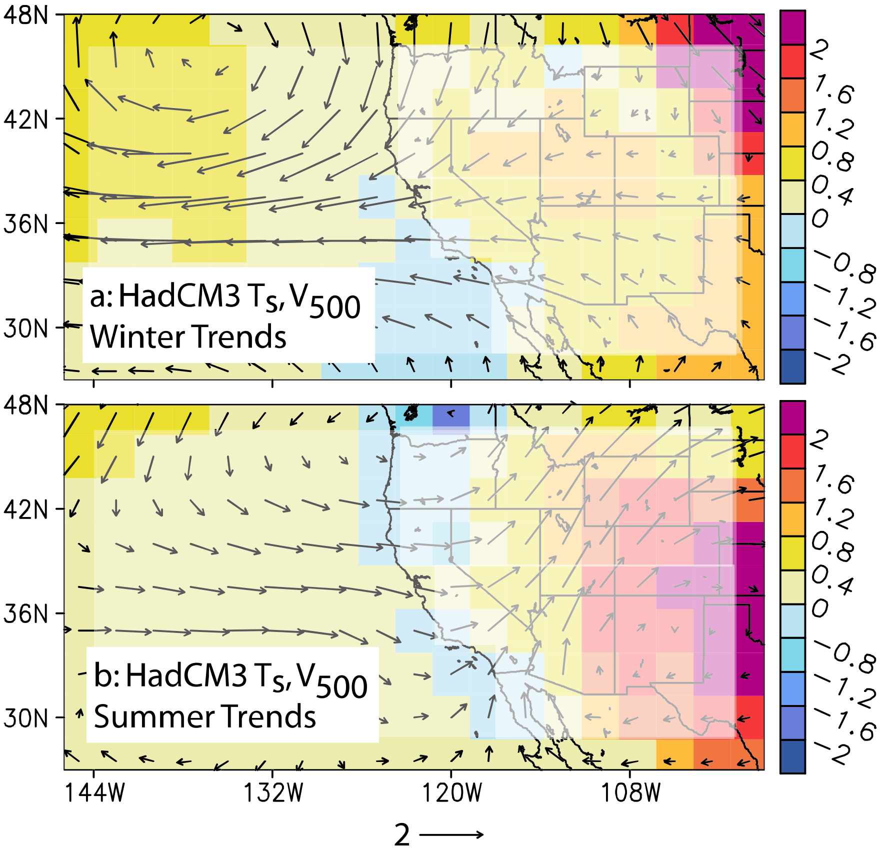

Fig. 2 1900-1999 trends in HadCM3 a)winter and b)summer ground (sea) temperature (C/century) and 500hPa winds (ms^{-1}/century). DRCM is driven only by variations in the sea temperature and variables on the boundaries; the maps illustrate the approximate full model domain.

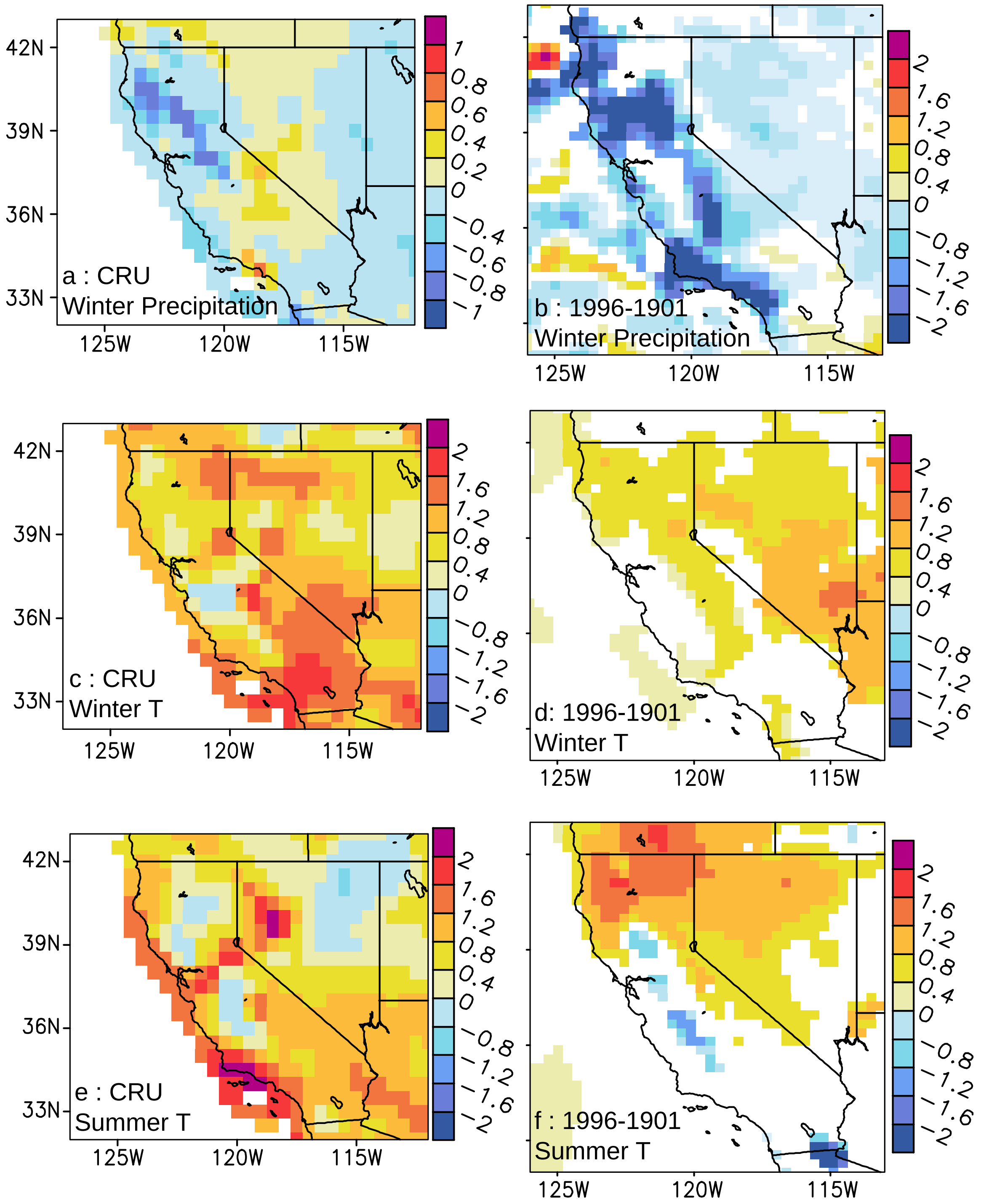

Fig. 3 a) CRU 1900-1999 winter mean precipitation trend (cm/century); b) 1996-1901 winter mean precipitation difference (cm); c) CRU 1900-1999 winter mean surface temperature trend (K/century); d) 1996-1901 winter mean surface temperature difference (K); e) CRU 1900-1999 summer mean surface temperature trend (K/century); f) 1996-1901 summer mean surface temperature difference (K). Only model differences which exceed the 95% confidence level are plotted.

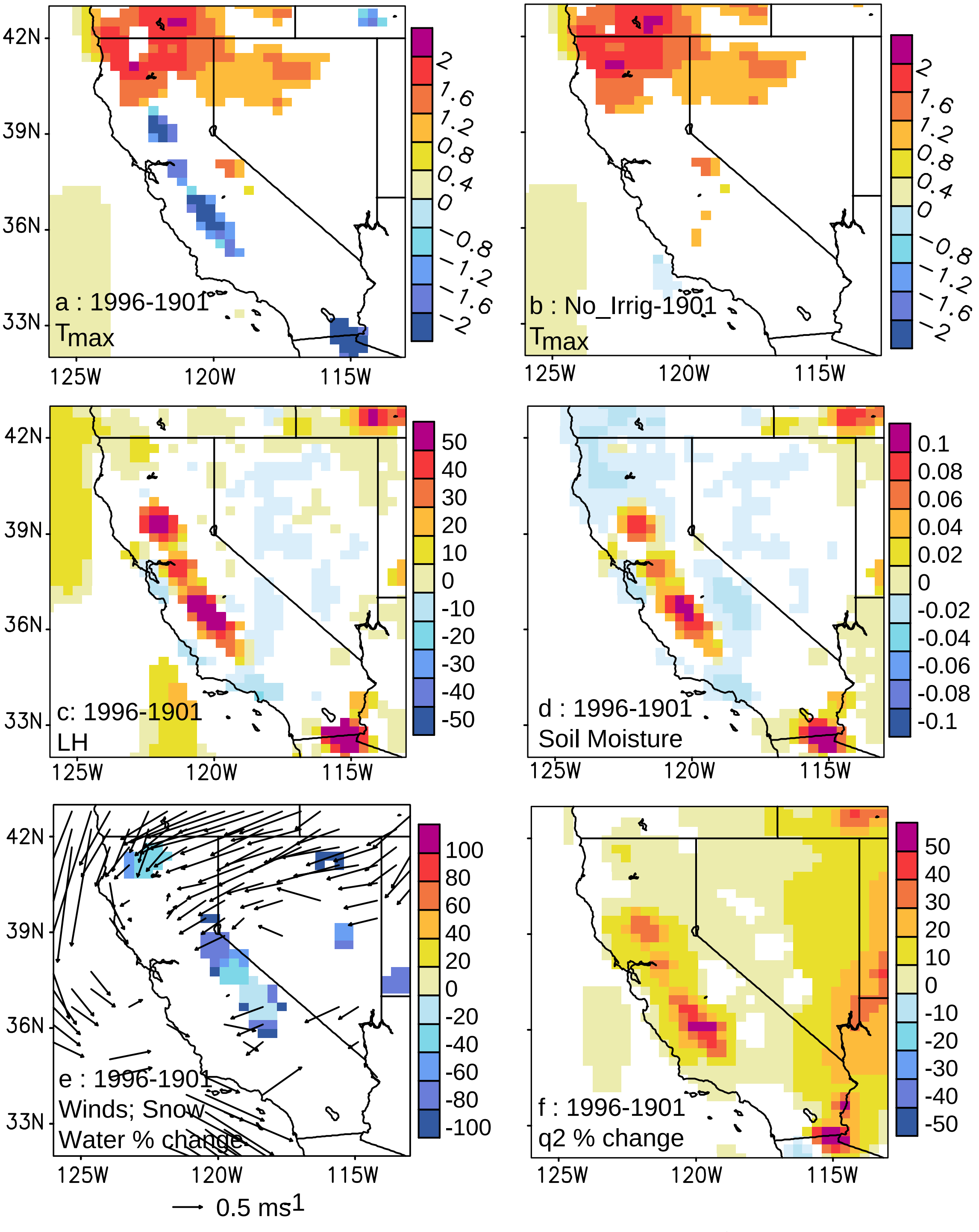

Fig. 4 Summer mean model results: a) 1996-1901 maximum surface temperature difference (K); b) No_Irrig -1901 maximum surface temperature difference (K); c) 1996-1901 latent heat flux difference (Wm^{-2}); d) 1996 - 1901 soil moisture difference (kg/kg); e) 1996-1901 near-surface wind (arrows) and percent snow equivalent water difference; f) 1996-1901 percent surface specific humidity (q_{2m}) difference. Only model differences which exceed the 95% confidence level are plotted.

Publications

None