JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
JUNE AMERICAN WATER RESOURCES ASSOCIATION 2005

GROUND WATER/SURFACE WATER RESPONSES TO GLOBAL CLIMATE SIMULATIONS, SANTA CLARA-CALLEGUAS BASIN, VENTURA, CALIFORNIA[1]

Randall T. Hanson and Michael D. Dettinger,[2]

ABSTRACT: Climate variations can play an important, if not always crucial, role in successful conjunctive management of ground water and surface water resources. This will require accurate accounting of the links between variations in climate, recharge, and withdrawal from the resource systems, accurate projection or predictions of the climate variations, and accurate simulation of the responses of the resource systems. To assess linkages and predictability of climate influences on conjunctive management, global climate model (GCM) simulated precipitation rates were used to estimate inflows and outflows from a regional ground water model (RGWM) of the coastal aquifers of the Santa Clara-Calleguas Basin at Ventura, California, for 1950 to 1993. Interannual to interdecadal time scales of the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) climate variations are imparted to simulated precipitation variations in the Southern California area and are realistically imparted to the simulated ground water level variations through the climate-driven recharge (and discharge) variations. For example, the simulated average ground water level response at a key observation well in the basin to ENSO variations of tropical Pacific sea surface temperatures is 1.2 m/°C, compared to 0.9 m/°C in observations. This close agreement shows that the GCM-RGWM combination can translate global scale climate variations into realistic local ground water responses. Probability distributions of simulated ground water level excursions above a local water level threshold for potential seawater intrusion compare well to the corresponding distributions from observations and historical RGWM simulations, demonstrating the combination's potential usefulness for water management and planning. Thus the GCM-RGWM combination could be used for planning purposes and – when the GCM forecast skills are adequate – for near term predictions.
(KEY TERMS: ground water hydrology; surface water hydrology; climate change; climate cycles; modeling; water management.)

Hanson, Randall T. and Michael D. Dettinger, 2005. Ground Water/Surface Water Responses to Global Climate Simulations, Santa Clara-Calleguas Basin, Ventura, California. Journal of the American Water Resources Association (JAWRA) 41(3):517-536.

INTRODUCTION

Climate variations have important roles to play in the successful management of many ground water resources (Alley, 2001). They drive significant variations of recharge, discharge, and withdrawal of the resources in concert with, and independently from, the climatic influences on surface water resources. Ground water hydrologists and water managers for too long have neglected these climate induced variations or have treated them as purely random. Too often they have neglected the variations in near-term policy and operational decision making on seasonal to interannual time scales and have ignored them in long-term policy and capital investment decisions on interdecadal time scales (Gleick and Adams, 2000). Thus, short-term and long-term perspectives are needed on the relation of climate variability as it relates to the use, development, and sustainability of ground water resources (Alley *et al.,* 1999).

Recent studies (Hanson *et al.,* 2002, 2004) have identified quasi-periodic variations in hydrologic time series that appear to reflect a wide range of quasi-periodic climatic forcings (Dettinger *et al.,* 1998). For example, observed ground water levels and streamflow rates in the Santa Clara-Calleguas Basin of coastal Southern California reflect climatic forcings on time scales that range from days to decades (Hanson and Dettinger, 1996; Hanson *et al.,* 2002). These quasi-periodic hydrologic variations represent teleconnections that appear to be driven by climatic forcings that are recurrent and persistent climatic patterns

[1]Paper No. 03162 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2005). **Discussions are open until December 1, 2005.**
[2]Respectively, Research Hydrologist, U.S. Geological Survey, Water Resources Division, California District, 5735 Kearny Villa Road, Suite O, San Diego, California 92123; and Research Hydrologist, Scripps Institution of Oceanography and U.S. Geological Survey, Climate Research Group, University of California, San Diego, California 92093 (E-Mail/Hanson: rthanson@usgs.gov).

over large parts of the Earth's surface. For example, in the coastal Southern California basins, the largest variations in ground water levels and streamflow appear to be related to the PDO (Latif and Barnett, 1994; Mantua *et al.,* 1997; Gershunov *et al.,* 1999; Chao *et al.,* 2000; Mantua and Steven, 2002) and to the ENSO (Diaz and Pulwarty, 1994; Jiang *et al.,* 1995; Kumar *et al.,* 2000; Dettinger *et al.,* 2001). These variations combined can have profound effects on hydrologic systems. This is due in part to the magnitude and phase relation of the interannual and interdecadal climatic forcings that, when combined, can cause average or extreme climatic forcings that may not be obvious from any single climatic component (e.g., Minobe, 1999). The time scales and amplitudes of the hydrologic responses to climate variations depend on the time scales and mechanisms of the climate forcings, on how closely the ground water and surface water systems are coupled to each other and to climate variations, and whether the overall hydrologic responses in a given setting depend more on slower aquifer responses or more rapid streamflow responses.

In some settings, especially where resources have been allocated to the brink of overdraft and where surface and ground water are tightly coupled, foreknowledge of likely climatic variations a season or more in advance (i.e., in the short term) may be a useful addition to ground water planning and management. Modern seasonal climate forecast systems are achieving levels of forecast skill that may be useful for ground water management, especially in regions where seasonal climate variations are significantly conditioned by interannual ocean/atmosphere processes such as ENSO (Gershunov *et al.,* 1999; Stern and Easterling, 1999; Koster *et al.,* 2000).

In this paper, the results from a GCM linked to an RGWM of the Santa Clara-Calleguas Basin (Figure 1) are presented. Ten-member ensembles of simulated atmospheric circulation and attendant conditions from 1950 to 1993 from the climate model have been used to explore the range of climatic response of the RGWM and to evaluate the potential predictability of ground water systems on seasonal time scales. Simulated ground water level and streamflow responses to the ensemble climate simulations were compared with the observed hydrologic variations during the same period and with hydrologic simulations driven by observed climate variations.

Climate Forecasts for Ground Water Models

Most models that simulate ground water and surface water flow at the regional scale of complete watersheds are developed to assess the impacts of ground water developments and operational aspects of various resource management schemes. For this reason, most of the models eventually are used to simulate projections of realistic future conditions. The challenge of forecasting combined ground water and surface water conditions is knowing the distribution of supply and demand beforehand. Future demand is based largely on anthropogenic effects and typically is uncertain. In turn, the future variations of supplies of ground water natural recharge and surface water infiltration are driven largely by variations in precipitation. Some variations of agricultural demands for irrigation water supplied from ground water also are based on these same climatic fluctuations of precipitation.

Statistical syntheses of these fluctuations are possible (Hanson and Dettinger, 1996; Hanson *et al.,* 2002), but an alternative is to use dynamic climate forecasts from global and regional climate models to provide the driving forces for forecasting the inflows to regional river and aquifer systems (Hanson and Dettinger, 1999). Global climate forecasts and simulations include seasonal to interdecadal climate variations of the sort that are present in hydrologic time series (Hanson and Dettinger, 1996; Hanson *et al.,* 2004) and thus can provide realistic climate series for assessing the outcomes of ground water management. On seasonal and slightly longer time scales, climate forecasts may even support forecasting with ground water flow models.

The simulated linkages presented here demonstrate potential mechanisms for water purveyors and resource managers to systematically assess the impact of human decision making on the sustainability of the water resources in light of climate forecasts. This has already been demonstrated by linking this RGWM to evaluate specific future management scenarios (Hanson and Dettinger, 1996; Hanson, 1998; Hanson *et al.,* 2002) and by linking the RGWM with simplified response rules through the use of optimization techniques (Reichard, 1995). Although the present focus is on making linkages between near term climate simulations and forecasts with RGWMs, these same linkages provide avenues for assessing impacts on ground water by global climate change (York *et al.,* 2002; Younger *et al.,* 2002; Yusoff *et al.,* 2002). The purpose of this study was to establish the linkage, to assess the transmission of climate variability between models, and to evaluate the feasibility of such GCM-RGWM linkages for seasonal to interannual forecasting of ground water/surface water systems.

This study addresses two basic questions about the linkage between GCMs and RGWMs. First, on what time scales and where within the ground water/surface water system can the GCM and RGWM

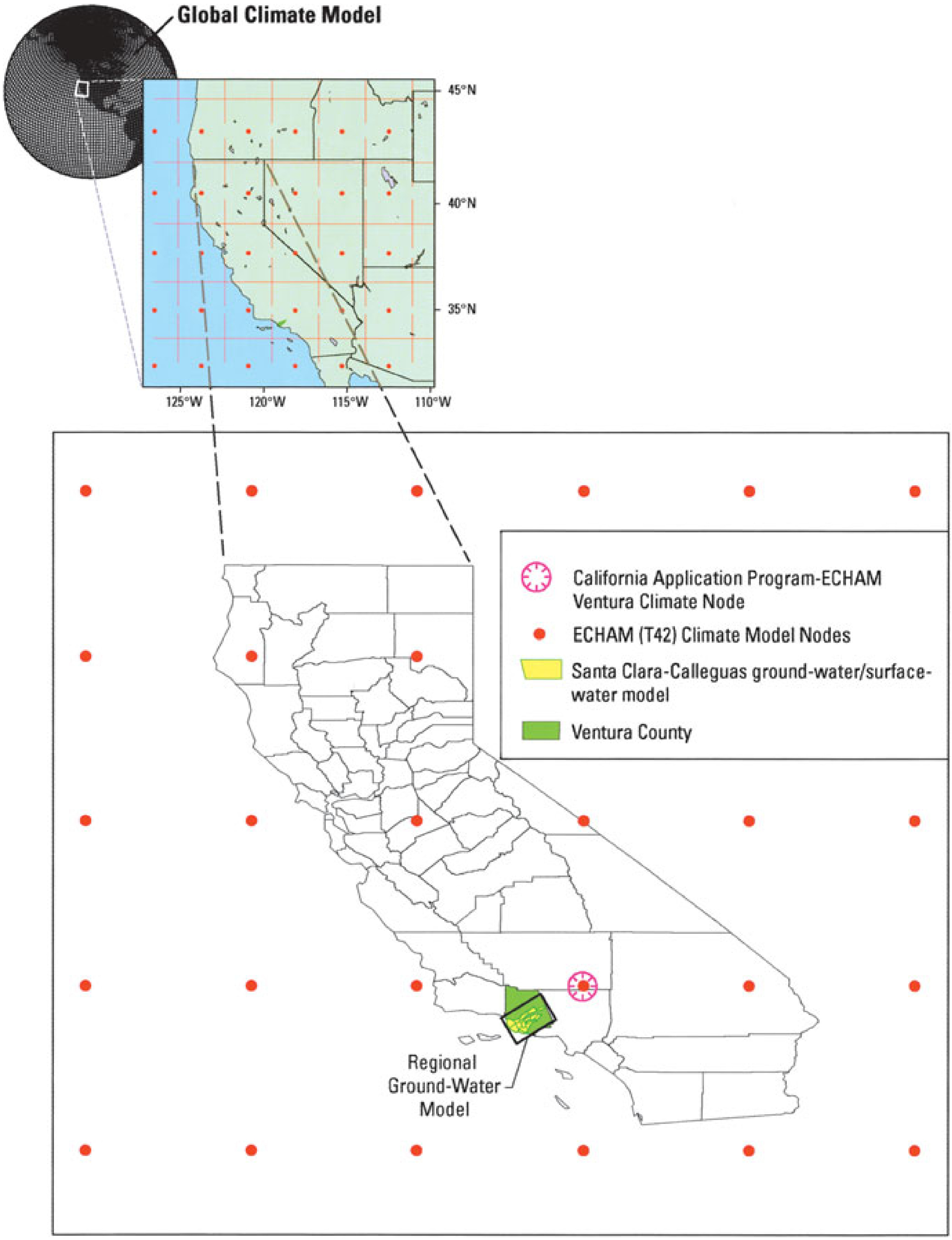

Figure 1. Map Showing the Relation of the Global Climate Model Grid to Southern California and to Santa Clara-Calleguas Basin, Ventura County, California.

combination transmit climatic variability (i.e., teleconnections)? And second, can the ground water responses on these time scales be forecast on seasonal or longer (i.e., interannual) time scales, given near-perfect sea surface temperatures (SST) projections?

Linking GCMs With Ground Water Flow Models

Because GCMs are coarsely gridded in comparison with RGWMs (Figure 1) and because they are less tightly constrained by imposed boundary conditions, several aspects of scaling and timing are problematic when linking the two kinds of models. GCMs simulate precipitation, temperatures, winds, insulation, and humidities that should be useful for estimating inflows and discharges from regional ground water and surface water flow systems. However, in many models – especially in many ground water models – such climatically based inflow and outflow estimation has not been undertaken in any reliable detail. Even if the appropriate linkages between climate and inflows-outflows were available, GCMs typically do not represent the spatial characteristics of climate or climatic variations in detail. Thus, orographic and coastal patterns that determine the distributions of inflows and outflows within most basin scale hydrologic models are not present at all in the GCM outputs, owing to the coarseness of the GCM grids (typically measured in degrees of latitude and longitude) in comparison with the RGWM grids (typically measured in hundreds of meters or kilometers). In contrast, the differences in temporal discretization are opposite: the GCM time steps usually range from minutes to hours, while RGWM time steps typically range from a month to years. Finally, GCMs are not calibrated to forecast or even simulate the climatic conditions well at every location, as they were designed and calibrated against more global scale considerations and observations. Thus, unlike RGWMs, which typically are calibrated specifically for the particular locale of interest, the performance of a GCM over any given basin needs to be affirmed rather than assumed.

Unlike an RGWM, a GCM represents a combination of the small part of the climatic variations that is driven by distant, specified SST boundary conditions with the large part of climate variation that is inherently chaotic and unpredictable in any precise temporal or spatial detail. Thus, even historical climate simulations are not expected to reproduce the precise sequence of climatic variations at any one location, unless the GCM is continually stopped, reinitialized with observations, and then restarted once to several times per day. This arduous process was not undertaken with the simulations here because it would not represent the realistic uncertainties associated with seasonal and longer forecasts. Rather, climates were simulated with five decades of observed global SST variations imposed in all cases, but with each simulation in the ensembles initiated only once from a different (global) initial condition of the atmosphere. However, projections of less than a few years would have closer proximity to initial conditions and may better predict short-term conditions. Because the climate system and GCM are chaotic systems, the different ensemble members rapidly diverge from each other. In principal, averaging the ensemble members can yield indications of the part of the climate variations that are associated with the boundary conditions that they share (Krishnamurti *et al.,* 2000; Richardson, 2001; Zhu *et al.,* 2002); that is, the inherent and least predictable variations of the chaotic climate system would be expected to average out in a sufficiently large ensemble. Looking beyond averages, however, the range of outcomes represented by the individual ensemble members (imprecisely) reflects prediction uncertainties associated with the sensitive dependence of the climate on uncertain initial conditions. Thus, the ensemble range gives a sense of how much uncertainty and unforced variability might be expected in the real climate system. Therefore, the ensemble of historical simulations used here may be viewed as an approximation of other climatic histories that could just as well have occurred as the actual historical climate.

In contrast, RGWMs generally are tightly constrained by specified boundary forcings and conditions that require a regional mass balance, and RGWMs are strongly damped, so that historical simulations by RGWMs generally are expected – and certainly are calibrated – to reproduce the historically observed fluctuations and magnitudes in ground water levels, streamflow, land subsidence, and related mass flow as closely as possible. The RGWM used here simulated 103 years of historical ground water-surface water interactions with a root-mean-square error at the end, in 1993, of 6.2 m for the entire model region and 3.3 m within the Oxnard Plain (Hanson *et al.,* 2002). The uncertainties in inflows and outflows related to historical calibrations range from 5 to 20 percent (Hanson *et al.,* 2002), which in turn can result in several meters of potential model error. When compounded with other local uncertainties driven by tidal fluctuations, the resulting errors even for calibrated models can easily exceed a meter. As with most RGWMs, the historically calibrated model adequately reproduces long-term historical changes in flows and in ground water levels on a regional scale but is also able to reproduce seasonal changes throughout most of the Oxnard Plain as demonstrated by depth-specific water level comparisons (Hanson *et al.,* 2002).

Thus the GCM-RGWM linkage demonstrated here requires merging an inherently chaotic, largely unpredictable climate model (and real world system) to a heavily damped and constrained ground water model. The spatial scales of the models are wildly disparate. The time scales of climate variability simulated by the GCM range from hours to decades, whereas the RGWMs have traditionally been used almost exclusively to simulate year-to-year or longer-term hydrologic responses to climatic and management driven fluctuations.

For all these reasons, coupling RGWMs and GCMs requires some artful experimental design and detailed spatial "downscaling" to transform simulated climate variations into appropriate inputs (mass inflow) for the calibrated RGWM. Initially, fairly simple connections are used to identify key GCM-RGWM linkages and to obtain a sense of RGWM predictability before attempting to resolve several outstanding difficulties. The goal is to determine what parts of GCM-based climate predictions would influence ground water projections in a coupled GCM-RGWM system and whether those projections would be better or worse than the climate predictions used to drive them.

SETTING

Ground water is the main source of water in the Santa Clara-Calleguas ground water basin, which covers about 803 km^2 in Ventura County, California (Figure 2). A steady increase in the demand for surface and ground water resources since the late 1800s has resulted in streamflow depletion and ground water overdraft. The sustainability of the water resources has been threatened by this steady increase in water use, which has caused adverse effects of

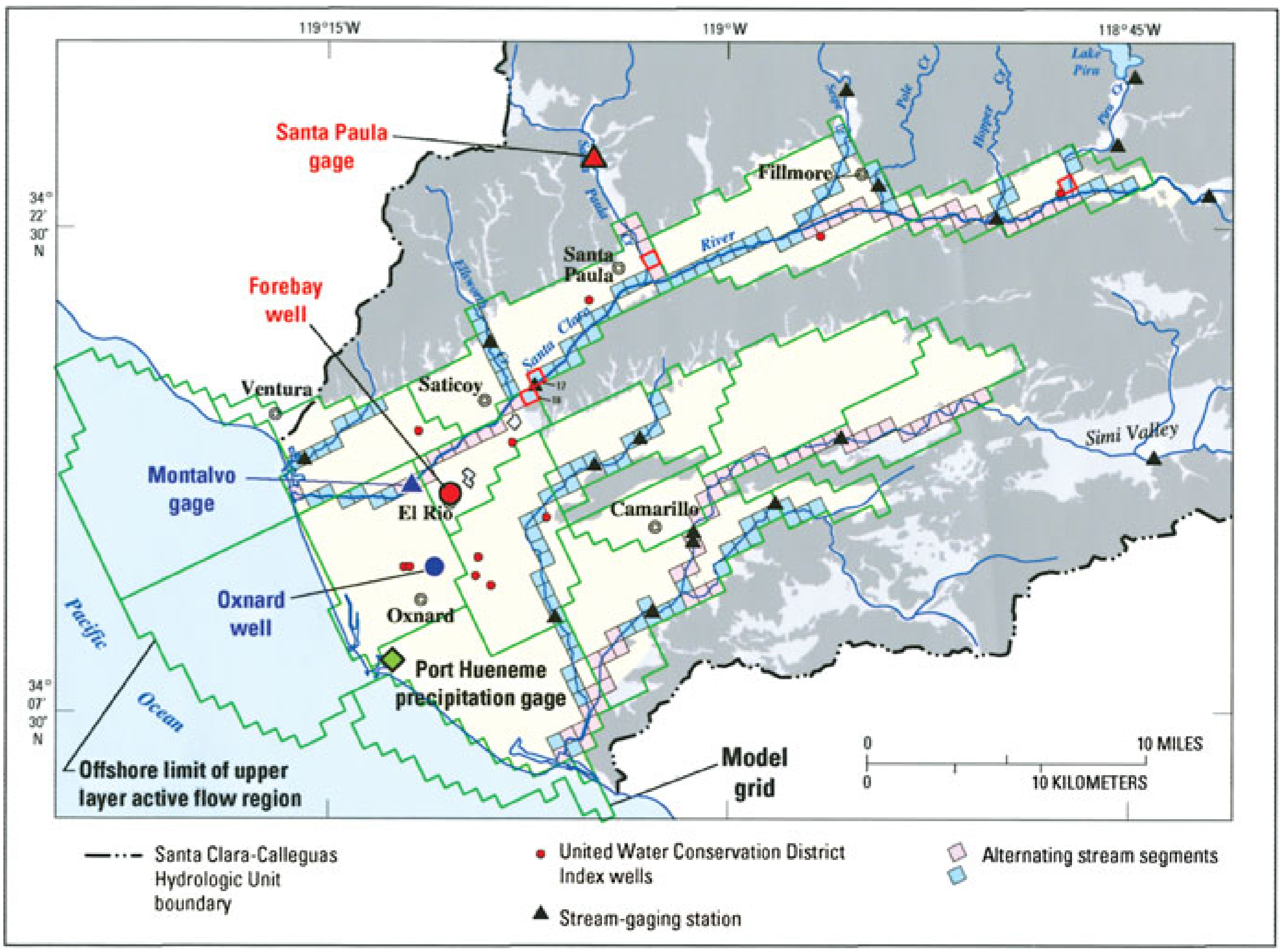

Figure 2. Map Showing Model Grid for the Regional Ground Water Flow Model of the Santa Clara-Calleguas Basin With Selected Precipitation and Streamflow Gaging Stations and Wells.

storage depletion, seawater intrusion, undesirable interaquifer flows, land subsidence, and ground water contamination (Hanson *et al.,* 2002).

The Santa Clara-Calleguas Basin lies in a coastal watershed in Southern California that contains several regional aquifers, which are grouped into upper and lower aquifer systems. The layered aquifer systems are bounded below by regional unconformities that are overlain by extensive basal coarse grained layers. These basal layers are the major pathways for lateral ground water flow, including the flows that support discharge from wells and allow seawater intrusion. The aquifer systems extend beneath the coastal ocean, where they crop out along the edge of the submarine shelf and within coastal submarine canyons. These submarine canyons have dissected the regional aquifer systems and provide direct connections between the ocean and aquifers. Coastal landward flow (seawater intrusion) occurs within each of the six major aquifers that compose the upper and lower aquifer systems (Hanson *et al.,* 2002).

Influxes of water to the regional ground water flow system are from natural and artificial recharge, the ocean, and storage in the coarse-grained beds and from compaction of fine-grained beds. Simulation of surface water and ground water inflows included streamflow routed through the two primary rivers and their tributaries; infiltration of mountain front runoff from ungaged drainage basins and bedrock outcrops; percolation of precipitation on the valley floors; and artificial recharge by diverted streamflow, irrigation return flow, and treated sewage effluent. All natural recharge and estimated pumpage used in the calibrated model were adjusted for wet and dry period seasonal variations of inflows and outflows (Hanson *et al.,* 2002).

Santa Clara-Calleguas Basin Water Resource Management

The water managers and purveyors in the Santa Clara-Calleguas (SCC) Basin face supply and demand issues that are linked to climate-driven variations of supply and demand, continued agricultural demand, and a growing demand on urban water supplies. The ground water resources in the SCC Basin are predominantly supplied by natural recharge supplemented by artificial recharge (Figure 3). Pumpage of water from the aquifers is partly supplemented by a system of streamflow diversions and pipelines that supply water for agriculture (Figure 3). For the period 1984 to 1993, outflow from the ground water system included about 304.6 cubic hectometers/year (247,000 acre-ft/yr) of ground water pumpage and an additional 76.5 cubic hectometers/year (62,000 acre-ft/yr) of imported water. During this same period inflow to the ground water included about 282.4 cubic hectometers/year (229,000 acre-ft/yr) of recharge, which is about 93 percent of the ground water pumpage (Hanson *et al.,* 2002). Most of the natural recharge occurs in the winter and spring, while artificial recharge and pumpage occurs throughout the year, with the heaviest pumpage occurring in the summer and fall. Therefore, supply and demand are seasonal, with most of the supply occurring prior to the period of greatest demand. Water purveyors such as United Water Conservation District need to make reservoir-management storage and release decisions at the headwaters reservoir Lake Piru to purchase and store water imported from Northern California for use and recharge and to manage diversions below the reservoir for direct delivery and artificial recharge (Figure 2). The lead times between these decisions and their implementation range from days to seasons into the future (Bachman and Detmer, 2001). In addition, water managers such as the Fox Canyon Groundwater Management Agency (FCGMA) must address ground water recharge and protection issues related to seawater intrusion and subsidence that impact the sustainability of the resources years to decades into the future (FCGMA, 1997). In addition, water purveyors and managers are involved in policy implementation or capital improvement projects that affect the continued development and sustainability of the resources years to decades into the future (e.g., Hanson *et al.,* 2002).

APPROACH

This study develops linkages between GCMs and the SCC RGWM and uses the combination of models to begin assessing predictability that may be potentially available in climate driven ground water flow conditions. The ensembles of climate simulations were forced by imposed historical variations of global sea-surface temperatures. They collectively simulate variations of precipitation in the Ventura County area that are associated with (and predicted from) global ocean SST patterns, such as ENSO variations in the tropical Pacific, the PDO, and other air/sea interactions. Because the GCM ensemble members were influenced by the sensitive dependence of climate models to initial condition differences, the historical sequence of weather episodes and even seasonal totals were not reproduced in the climate simulations. Instead the range of possible (simulated) responses of the regional climate to the specified SSTs was sampled by the ensemble (Kalnay *et al.,* 1996). Therefore, it is not appropriate to ask whether the ground

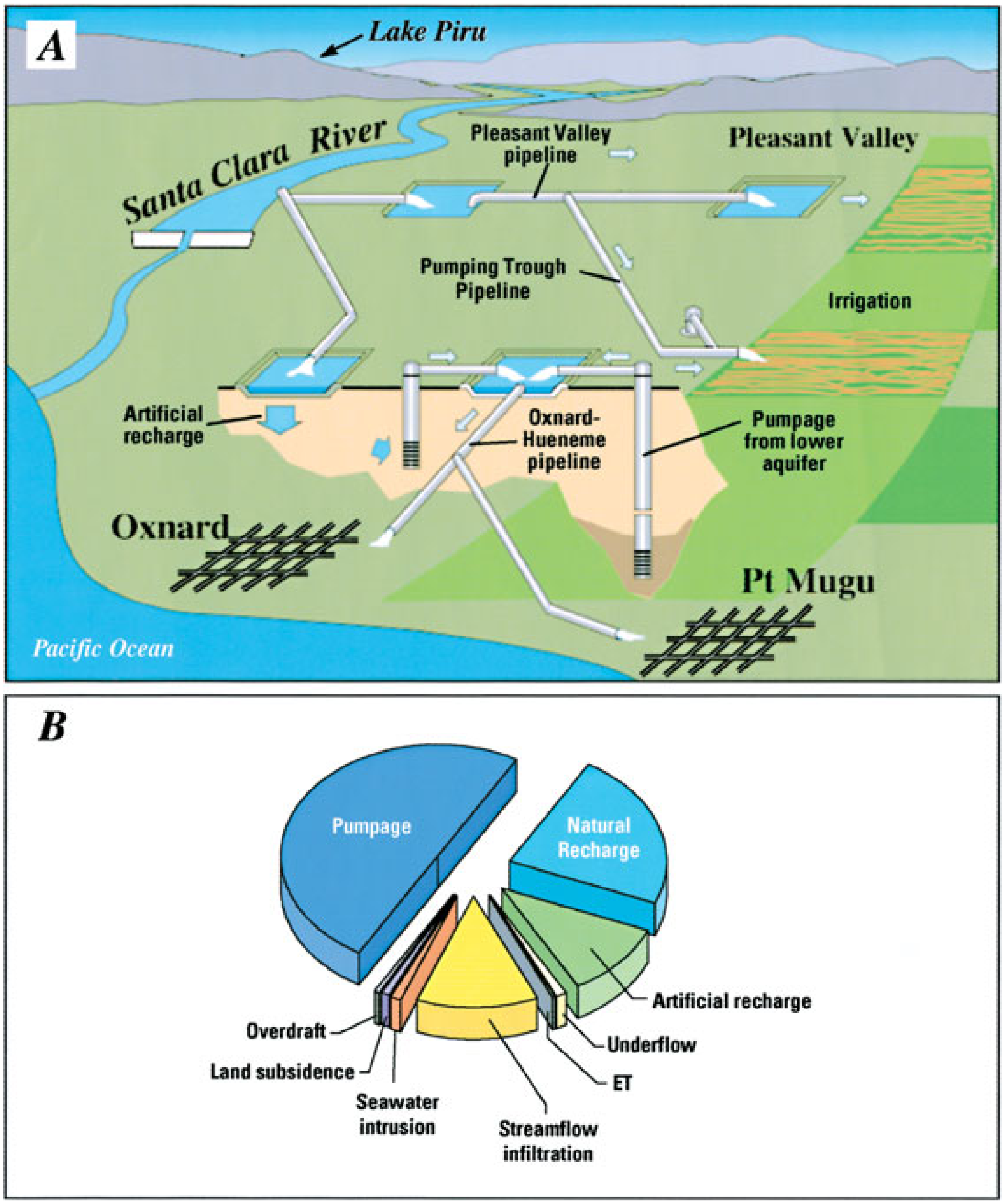

Figure 3. (A) Diagram Showing Components of Water Resource Extraction and Distribution System; and (B) Generalized Ground Water Budget for the Santa Clara-Calleguas Basin, Ventura County, California.

water/streamflow simulations reproduced particular events in the historical record; rather it is appropriate to question whether the distributions of events in the ensemble simulations reproduced those in the historical record and how often that distribution could have provided useful guidance for hydrologic forecasts.

The presence of interannual to interdecadal precipitation variations, largely attributable to PDO and ENSO processes, has been established for the Ventura area, with 60 percent of the variance in the precipitation and ground water levels captured by just a few time scales (Hanson and Dettinger, 1996; Hanson *et al.,* 2002). Linkages between streamflow in the coastal Santa Paula Creek (Figure 2) and Pacific SSTs are presented as correlations for periods of less than seven years (ENSO scales; Figure 4B) and for periods greater than seven years (PDO scales; Figure 4C). The pattern of correlations between streamflow in Santa Paula Creek and SSTs demonstrates a stronger and more southern negative correlation for ENSO time scales (Figure 4B) and a weaker and more northern negative correlation for PDO time scales that are

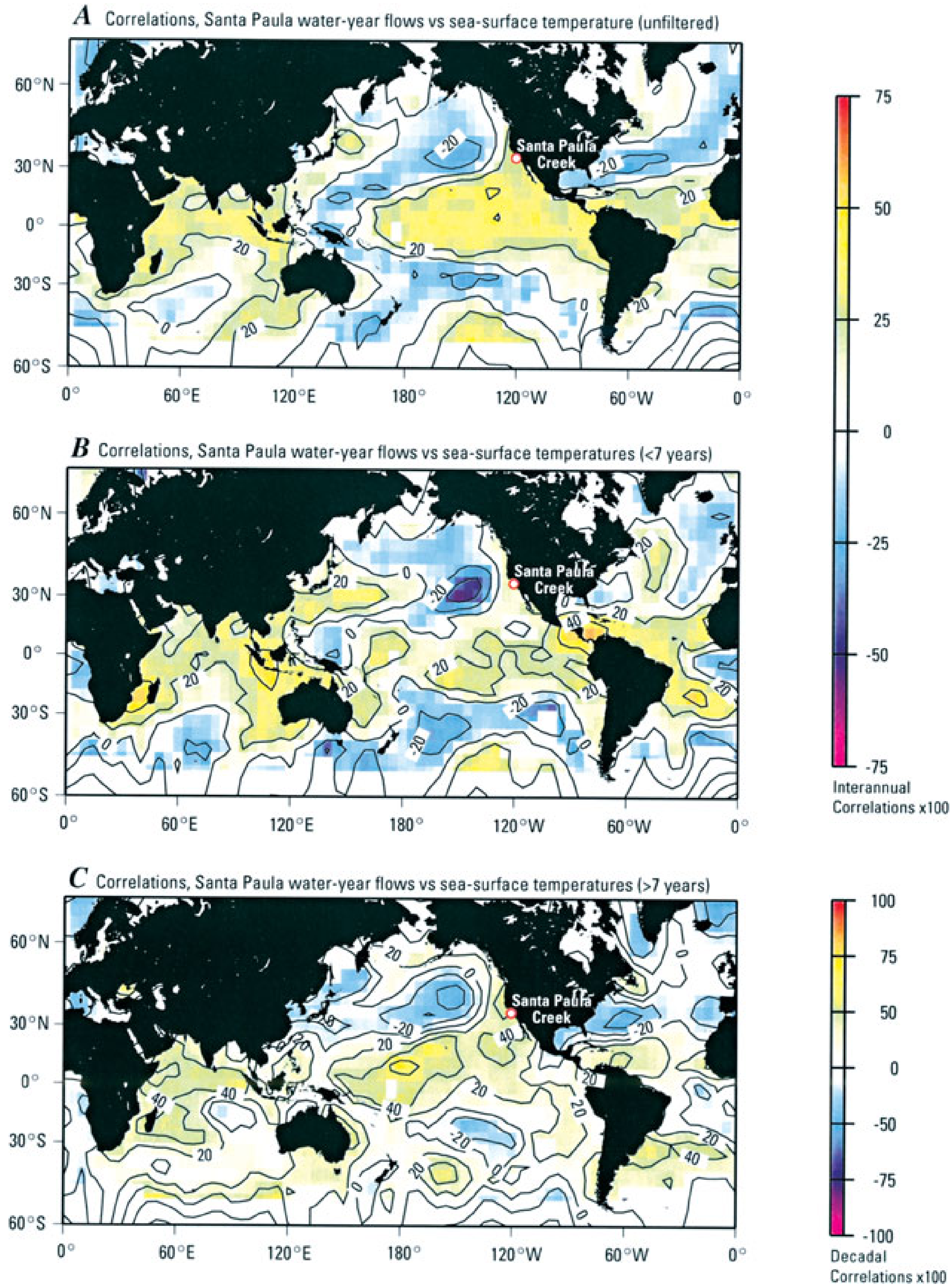

Figure 4. Maps Showing Correlations Between Streamflow in Santa Paula Creek and Sea Surface Temperatures.

not as apparent in the unfiltered correlations (Figure 4A).

Neither the value of the correlations with the SST for forecasting SCC hydrologic conditions nor the ability of a GCM-RGWM combination to capture the observed linkages has been demonstrated in past studies. The ultimate goal for such evaluations would be to develop seasonal to interannual forecasts of RGWM simulated ground water/surface water flow driven by GCM output to guide short-term operational decisions, short-term and long-term management policies, and long-term capital improvement projects. Such a model linkage may not provide an exact predictive tool of the future but would provide purveyors and managers with a systematic and quantitative assessment of the potential near term climate driven variations that they could use to rank the probability of changes in the state of the ground water and surface water flow within the context of uncertain future supply and demand conditions. Eventually, to use such forecasts with reasonable assurance, evaluations will be required to determine which GCMs would have performed best for particular climate variables and time scales of most importance for the ground water systems in question. This level of detail is beyond the scope of this paper because, at present, it must still be determined whether a typical GCM provides climate variations that matter in the RGWM and whether the RGWM responds realistically to simulated climate history. To determine these basics, the time scales of simulated climate and simulated ground water level variations (i.e., changes in ground water storage) are compared to those observed and the average simulated ground water level response to SST variations are compared to observed changes in ground water levels.

In this study, monthly precipitation from three existing GCMs is used to estimate recharge and streamflow inflows to an existing RGWM. The three GCMs used in this study were the ECHAM-3.6, NCEP, and CCM3 atmospheric general circulation models (Kumar *et al.,* 2000). Ten-member ensembles of simulated global climate from 1950 to 1994 at T42 resolution (2.8 by 2.8 degrees gridding with 19 levels) responding to specified observed monthly SSTs were simulated in the manner of the Atmospheric Model Intercomparison Project (Gates, 1992). Ensemble members differed only in the particular initial atmospheric conditions used to start each simulation.

The ECHAM-3.6 GCM is an atmospheric general circulation model developed by the German Climate Research Group that is formulated in spherical harmonics (DKRZ, 1993). This GCM uses vorticity, divergence, temperature, surface pressure, water vapor, and cloud water as prognostic variables within the T42-19 layer spatial discretization with the global surface estimated from mean terrain heights that were computed from high resolution digital elevation data. The boundary conditions include SSTs and sea ice imposed on numerical solutions with a temporal discretization of 2.4 minutes. The model also incorporates other surface boundary features such as terrain roughness, vegetation, and albedo. The model contains physical parameterization of radiation, clouds, convection, the planetary boundary layer, selected land-surface processes, horizontal diffusion, and gravity wave drag. The outputs from the model include surface precipitation, temperature, relative humidity, and wind speed and directions. The ECHAM-3 model was found to exhibit slightly more realistic responses to Pacific SSTs and to ENSO derived atmospheric anomalies than the NCEP and CCM3 GCMs (Peng *et al.,* 2000). For the purposes of demonstrating the linkage between a GCM and the RGWM, only results from the ECHAM model are presented in this paper.

A numerical model of the ground water/surface water system of the SCC Basin in Ventura County (Figure 1; Hanson *et al.,* 2002) was developed using MODFLOW (McDonald and Harbaugh, 1988) by the U.S. Geological Survey to better define the geohydrologic framework and assess the distribution of water resources of the regional ground water flow system and to help analyze the major problems affecting water-resources management of a typical coastal aquifer system. The model was calibrated to historical surface water and ground water flow for the period 1891 to 1993. Such a calibration was largely based upon matching simulated and measured hydrologic time series throughout the basin. Measured time series included streamflows at downstream gages on the Santa Clara River and Calleguas Creek, diversions of streamflow on Piru and Santa Paula Creeks and the Santa Clara River, selected benchmarks in the southern Oxnard Plain, and water levels from tens of wells throughout the basin. The water levels are generally taken from water supply wells that straddle multiple aquifers and represent various composite heads from these aquifers as well as varying degrees of recovery from short-term pumpage. Therefore, the reliability of these data varies from well to well and through time. In this study, the last 43 years of this calibrated simulation, 1950 to 1993, and observed conditions during that period are compared with the RGWM responses to simulated precipitations from each ECHAM ensemble member for the same historical period.

Simulated precipitations, along with resulting estimates of flow, were used as input to the RGWM as annual and seasonal totals to assess the value of seasonal climate forecasts in the SCC coastal watershed. In particular, the simulated precipitation from a specific GCM node just northeast of the SCC Basin

(Figure 1) was rescaled to match the observed long-term mean and variance of precipitation at a coastal precipitation gaging station, Port Hueneme (Figure 2). The annual precipitation was then distributed to seasonal fractions on the basis of the observed patterns of precipitation within the watershed during historical wet year and dry year periods. The precipitation rates were rescaled or downscaled to accommodate the mismatch of spatial discritization scales of the GCM and RGWM and to adjust for differences between the GCM climatology and observed averages over the basin. The particular rescaling was chosen to preserve the mass balance of the historical flow because the RGWM contains nonlinear boundary conditions that would be adversely affected by dissimilar mass flows through the ground water and surface water systems. Other processes, such as evapotranspiration, are set at the constant rates of the calibrated model that are dependent on the simulated water levels and are not directly dependent on GCM input.

The rescaled GCM precipitation (Figure 5A) was then used to estimate time varying streamflow and recharge as mountain front recharge and infiltration along valley floors by the same regression and rule-based methods used to estimate inflows for the calibrated flow model from historical precipitation observations (Hanson *et al.,* 2002). The inflows of simulated streamflow were estimated from precipitation segregated into wet year and dry year periods through seasonal semi-logarithmic regression equations between historical precipitation and streamflow for gaging stations on the major rivers and tributaries that flow through the watershed (Hanson *et al.,* 2002). The resulting streamflow inflow rates thus correspond to simulated precipitation in a realistic way (Figure 5B, 5C); infiltration of this streamflow input is estimated within the RGWM from calibrated streambed hydraulic properties and the simulated ground water levels beneath the channels when streamflow was estimated to be occurring. Similarly, ungaged runoff that supplies mountain front recharge and infiltration of excess precipitation through valley floors were estimated using a modified rational method for wet year and dry year periods (Hanson *et al.,* 2002). These recharge components were applied at constant rates for each season, and the annual rates were apportioned between seasons on the basis of the same fractional rates estimated from the measured historical precipitation in the original calibrated flow model.

The anthropogenic forcings on the ground water system include ground water pumpage, artificial recharge, recovery of artificial recharge, and infiltration of treated wastewater. Agricultural pumpage, recovery of artificial recharge, and artificial recharge during wet year and dry year periods in the GCM

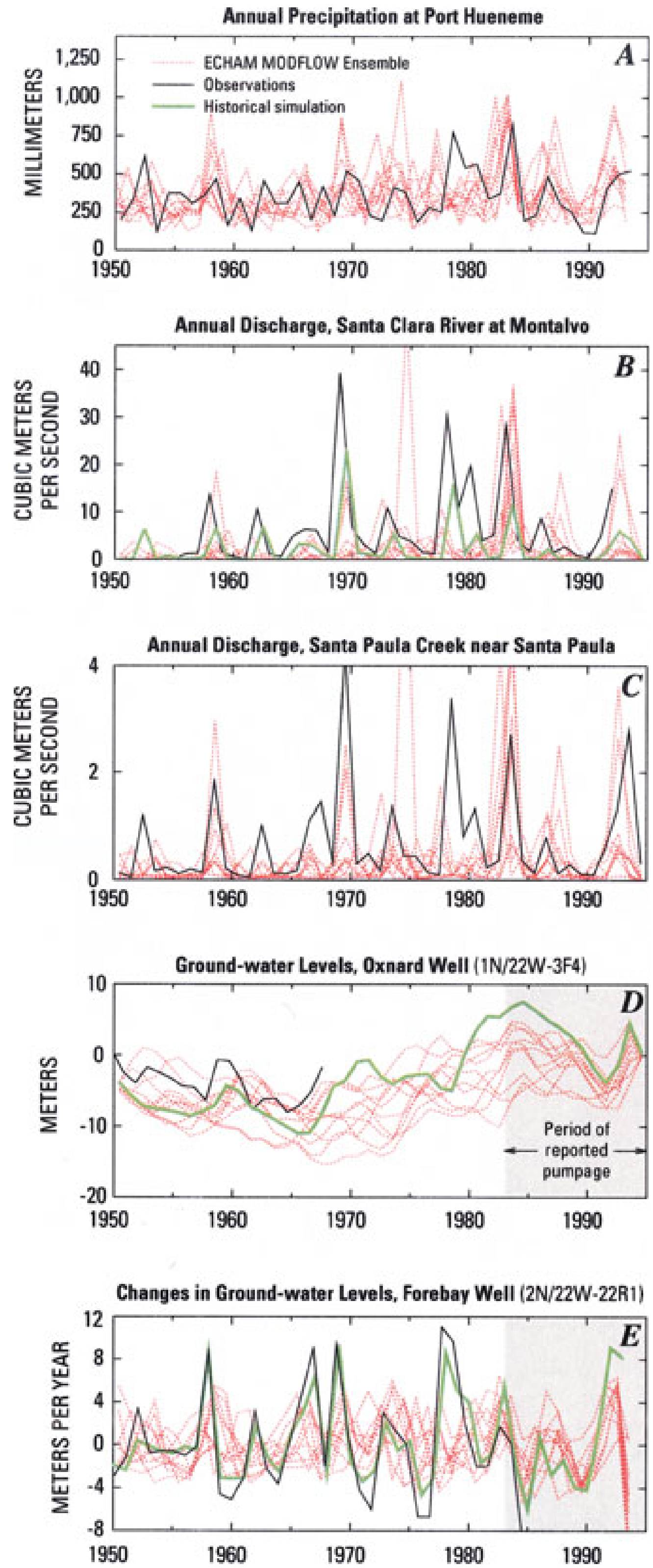

Figure 5. Graphs Showing Measured and Simulated Precipitation, Streamflow, and Ground Water Levels for the Santa Clara-Calleguas Basin, Ventura County, California.

simulations were increased or decreased according to rates developed for the observed wet year and dry year periods from 1950 to 1982 in the calibrated model. Infiltration of treated wastewater was kept the same as the original calibrated model simulation. In a manner similar to that of the original calibrated-model simulation, measured ground water pumpage was used for the last 10 years of the historical simulation, from 1984 through 1993 (Hanson *et al.*, 2002).

Power spectra (i.e., distributions of estimated frequencies) of the time series from the GCM-RGWM combination are compared with the spectra of precipitation at Port Hueneme (Figure 6A), streamflow on the Santa Clara River at Montalvo (Figure 6B) and Santa Paula Creek (Figure 6E), and ground water levels from wells in the Oxnard Plain and Forebay (Figure 2), both as historically measured and as simulated by the calibrated historical RGWM (Figure 6D, 6F). These comparisons allow us to determine which time scales of the climate variation are realistically represented in the GCM-RGWM combination and how deeply into the streamflow and ground water systems the various time scales penetrate. The spectral analyses were performed by the maximum entropy method, as implemented by Dettinger *et al.* (1995).

The potential predictability was further assessed by comparing (1) the response of GCM precipitation over Ventura to ENSO SSTs with the response of observed precipitation to SSTs (Figures 6A, 6B, and 7A); (2) simulated and observed precipitation-ground water level relations (Figure 7B); and (3) simulated and observed SST-ground water level relations (Figure 8). Together, these comparisons show that, given perfect foreknowledge of ENSO SSTs, the GCM- RGWM produces a reasonable simulation of the observed central tendencies of precipitation and ground water levels.

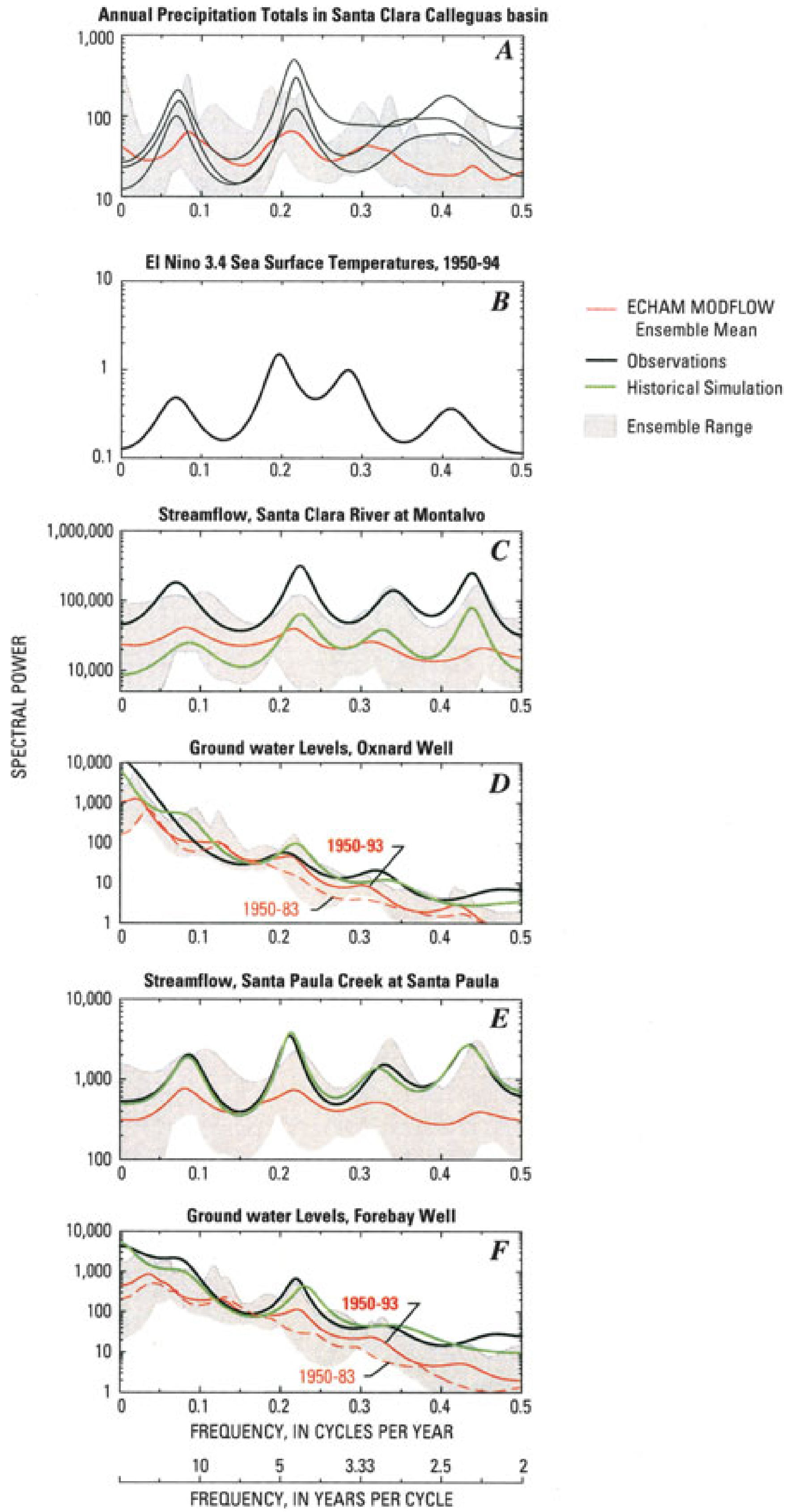

Figure 6. Graphs Showing the Power Spectra for Precipitation, Streamflow, and Ground Water Levels for the Santa Clara-Calleguas Basin (shaded zones indicate range of simulated results).

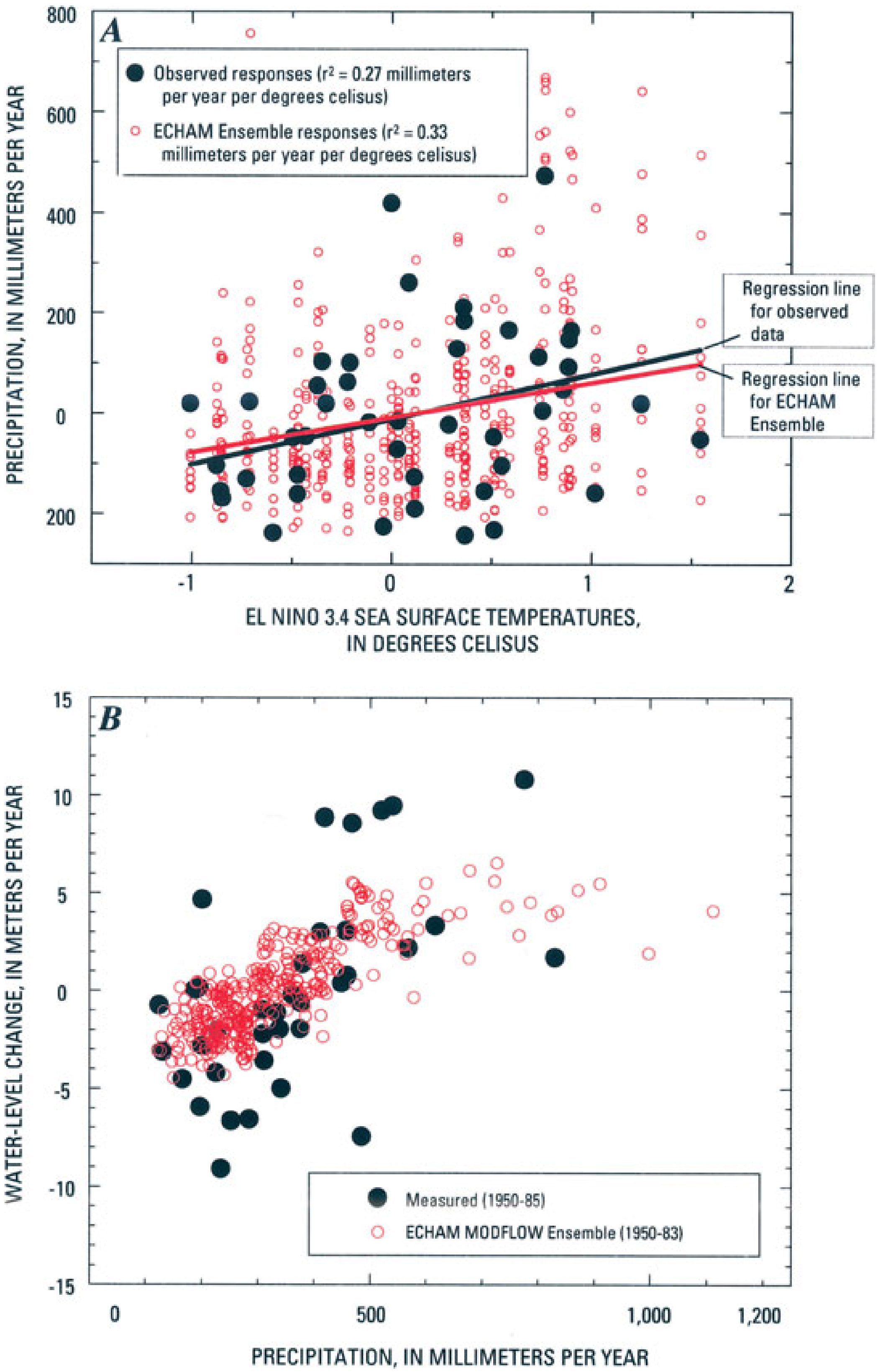

Figure 7. Graphs Showing the One-Year Lag Relation Between Precipitation and Ground Water Level Changes for the Santa Clara-Calleguas Basin, Ventura County, California.

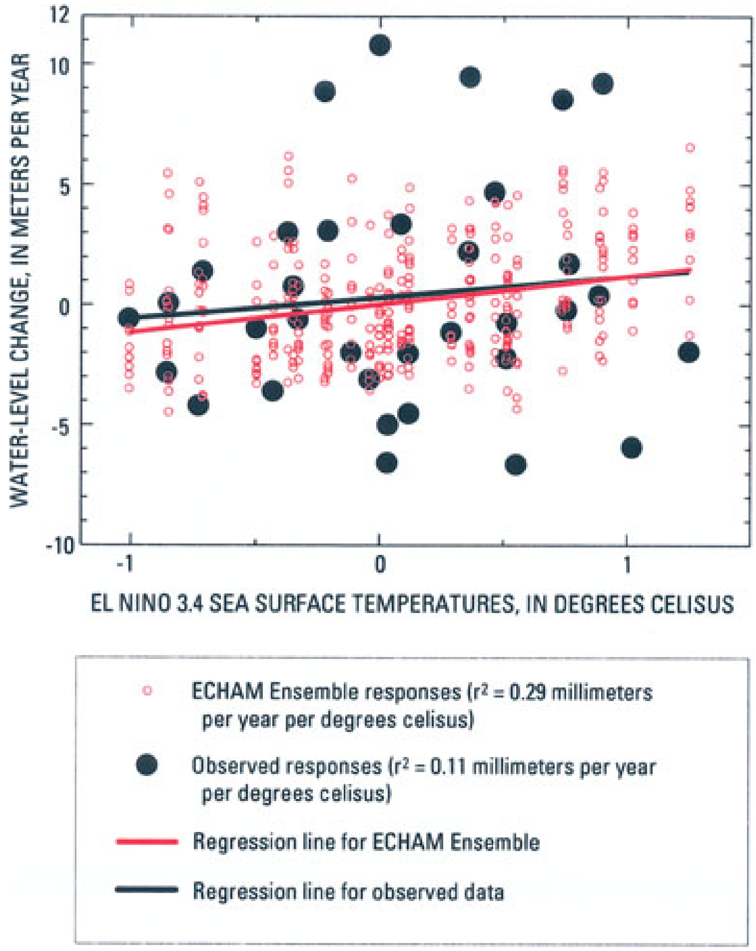

Figure 8. Graph Showing the Relation Between Measured and GCM Precipitation and One-Year Lagged Changes in Ground Water Levels for the Santa Clara-Calleguas Basin With Respect to El Niño 3.4 SSTs.

The probable long-term implications of the simulated ground water/surface water system with respect to potential seawater-intrusion management thresholds in the ground water/surface water systems also was addressed. These thresholds represent a lower limit on ground water levels below which management actions would be required to protect the aquifers from seawater intrusion (or land subsidence). This analysis presents cumulative probabilities to exemplify the potential application of forecast results for water resource management (Figure 9).

RESULTS

Specific precipitation events that are probably associated with strong ENSO events, such as those of 1969 and the early 1980s, are more successfully simulated and transmitted by the GCMs than dry year episodes such as the drought of 1976-1977 (Figure 5). Similarly, simulated streamflow and changes in ground water levels from the RGWM reflect these strong ENSO events that originate from the GCMs (Figure 6).

Comparisons of the power spectra of the ensemble driven ground water and streamflow simulations with historical variability in the basin indicate that the several important time scales of interannual SST variability are imparted to the simulated climatic and hydrologic variability in the ensembles, in the GCM-RGWM model, to the underlying ground water variations (Figures 6D, 6F). As shown for the ECHAM model, these time scales include spectral peaks at 2.5, 3.5, 5, and 15 years (Figures 6A through 6F). These time scales are essentially identical with the time scales that characterize the ENSO and PDO process during the time period of interest (Figures 6A through 6F). Notably, although the spectral distributions of ENSO, precipitation, and streamflow (Figures 6A. 6B, 6C, 6E) are made up of interannual spectral peaks resting on the fairly flat background that is characteristic of “white noise” (i.e., unstructured noise with no preferred frequencies), the ground water levels yield

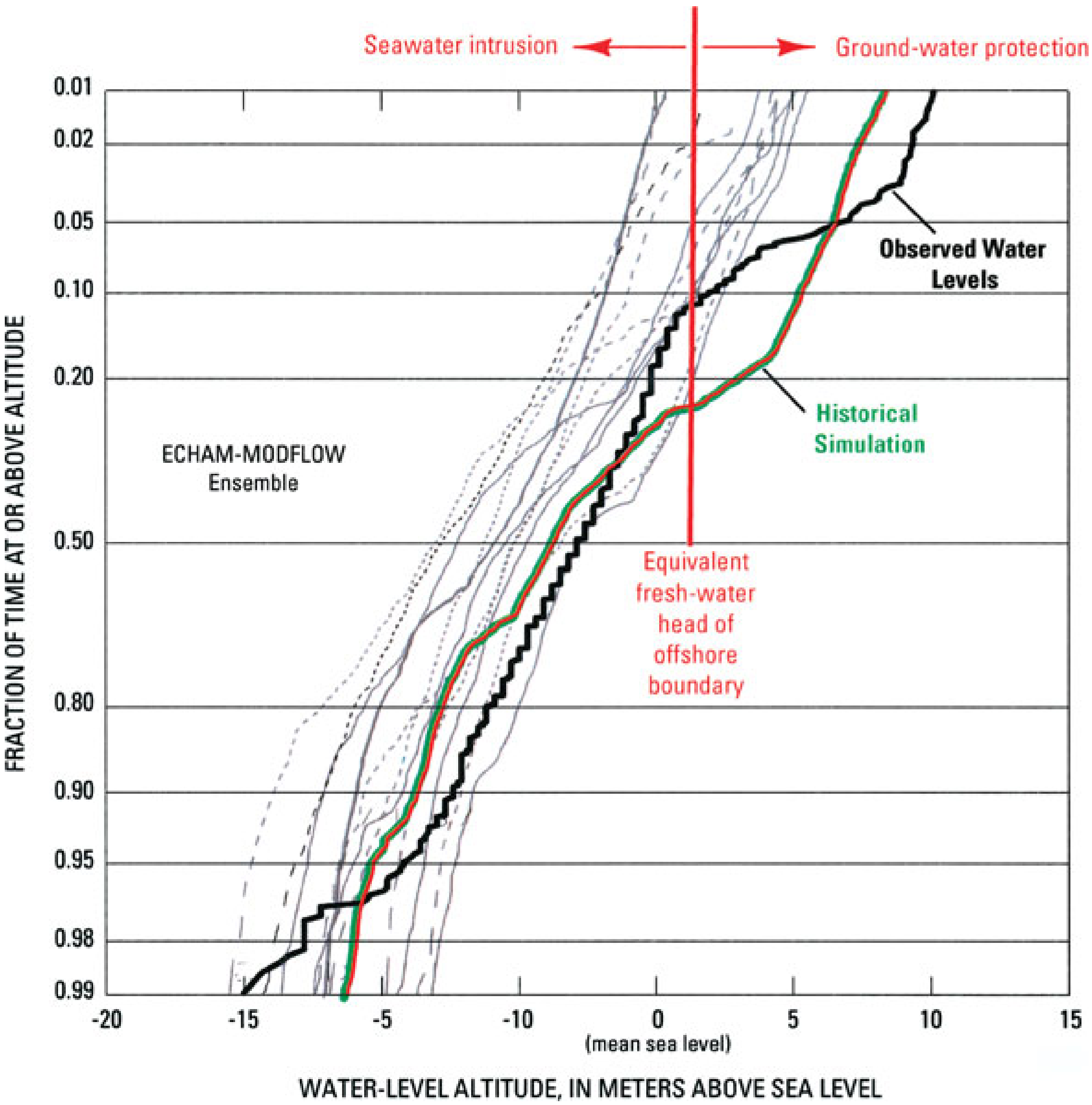

Figure 9. Graph Showing the Fraction of Time at or above Measured and Simulated Ground Water Levels for a Water Supply Well in the Santa Clara-Calleguas Basin, California.

spectra with similar peaks rising from the ramping background characteristic of "red noise" processes (i.e., structured noise that is progressively stronger at lower frequencies). Thus, the lowest frequency hydroclimatic variations (including noise) are preferentially expressed by the ground water system, and the higher frequency variations are selectively filtered from the observed and simulated ground water levels.

The expected tendency of these simulated hydroclimatic variations to differ from the precise sequence of observed hydroclimatic variations shows that the inherent variations of Southern California's climate will prevent the use of even perfect SST "forecasts" from yielding perfect (or even good) hydrologic forecasts on time scales of more than a season or two. However, the ranges of historical and simulated hydroclimatic variations (Figure 5) and the corresponding power spectra (Figure 6) are in good agreement, indicating that the GCM-RGWM combination, driven by historical or realistic SST variations, could be used to generate precipitation, streamflow, and ground water variations for analysis of ground water management scenarios.

The coupled GCM-RGWM model also simulates the average association of precipitation with tropical SSTs well (Figure 7A), despite large scatter associated with the inherent unpredictability of the extratropical climate (i.e., outside the tropical latitudes). The regression coefficient for Southern California precipitation simulated in the ECHAM GCM ensemble in response to El Niño 3.4 SSTs is 90 mm/ºC ($p < 0.01$) and is very similar to the corresponding regression coefficient for the measured precipitation rates (70 mm/ºC; $p = 0.04$); these two regression coefficients are not significantly different at 95 percent confidence level by a standard student t-test. The GCM precipitation responds realistically to historical SST variations both in central tendency, as expressed by these regressions, and in terms of the scatter around the regressions (Figure 7A). The scatters around the regression lines in Figure 7A are essentially the same, with standard deviations of both simulated and observed residuals equal to 157 mm/ºC. Those scatters reflect the observed chaotic unpredictability of the climate system and the realistic simulations of that inherent unpredictability, respectively.

The simulated changes in one-year lagged ground water levels in response to the precipitation variations, which in turn are simulated responses to tropical SSTs, are also quite realistic in their central tendencies (Figure 7B). The simulated scatter of ground water level responses to precipitation variations, however, is less than the scatter in observations, as will be discussed below.

Because of the realistic simulation of the central tendencies of ground water responses to precipitation (Figure 7B) together with the accurate average simulation of precipitation responses to tropical SSTs (Figure 7A), the coupled GCM-RGWM system accurately simulates the central tendencies of the relation between tropical SSTs and ground water levels (Figure 8), The regression coefficient between ground water level changes simulated by the GCM-RGWM model and El Niño 3.4 SSTs is 1.2 m/ºC ($p << 0.01$), and is very similar to the corresponding regression coefficient for the measured ground water level responses (0.88 m/ºC, $p = 0.38$). Thus the GCM-RGWM combination is able to translate the central tendency of the El Niño 3.4 SST-local precipitation relation into a realistic El Niño 3.4 SST ground water level response, in the mean.

Unlike the realistic simulation of precipitation scatter around the mean ENSO responses, however, simulated ground water levels scatter considerably less around the regression line in Figure 8 than do the observations. The scatter around the regression line for observations has a standard deviation of 4.6 m, while the scatter in simulations is only 2.2 m. This reduction in scatter of the "predicted" ground water levels occurs despite the close similarities in scatter between the simulated and observed precipitation responses to tropical SSTs (Figure 7A) and is rather clearly a function of the smaller than observed scatter of simulated ground water levels in response to precipitation rates shown in Figure 8. This suggests that the RGWM is damping the natural variability of precipitation, perhaps due to overly conservative linkages between the precipitation inputs and recharge and streamflow inputs to the hydrologic models. However, a similar comparison of the simulated and observed relations between El Niño 3.4 SSTs and streamflow at Santa Paula Creek (not shown) indicates that realistic levels of streamflow scatter are simulated in response to the precipitation inputs to the model; standard deviation of residuals from regression of observed streamflow values is 0.9 m and from simulated values is 0.7 m. Thus, much of the reduction in scatter in the simulated ground water levels compared to the observed levels is presumed to be due to nonclimatic influences that are not included in the present experiment. Nonclimatic influences presumably include economic, demographic, and technological shifts in demands on the SCC water resources. In addition, some of the dampening may result from using wet- and dry-year averaged pumpages prior to 1983 that do not adequately represent the full range of pumpage responses to precipitation.

The close match of the central tendencies suggests that ground water level responses to precipitation, and even tropical SSTs, are well simulated – on average – to the extent that precipitation can be correctly predicted. The dampening of scatter in the ground water simulations suggests that the ensemble scatter is an underestimate of the prediction uncertainties; an underestimate that can be attributed to nonclimatic influences.

The real limitation to predicting ground water level responses to tropical SST variations, therefore, is the limited extent to which the GCM simulations used here predict Southern California precipitation. The GCM simulations used were forced only by historical SSTs with no mid-simulation corrections to observed atmospheric conditions. A typical weather prediction, in contrast, would rely heavily on realistic (if uncertain) atmospheric initial conditions as well as observed SST conditions. Thus the present experiment does not fully capture even the mostly short-term predictive skill of current GCMs. However, the present experiment provides a sense of possible ground water predictability given more accurate precipitation predictions. The "potential predictability" (Koster *et al.,* 2000) of Southern California precipitation based on historical SSTs can be measured by determining how well the model can predict itself, under the influence of the SSTs in the presence of chaotic indeterminacies. The average correlation between the Southern California precipitation series from the ECHAM GCM ensemble is only 0.08 ($p = 0.07$). Thus the simulated precipitation series from the GCM ensemble used here mostly reflects the chaotic variations of extratropical climate and reflects nonchaotic precipitation responses to SSTs only slightly. The "actual predictability" of precipitation by this particular GCM ensemble is measured by the average correlation of the ensemble members with the observed precipitation history, which in this experiment (for Southern California) is 0.07 ($p = 0.33$). Neither of these correlations is significantly different from zero, and neither indicates much precipitation predictability in the SST-only GCM configuration used here.

Importantly, though, the potential predictability of the simulated ground water levels is substantially higher, with an average correlation among all the ensemble series of 0.33 ($p << 0.01$; Figure 7A). The actual predictability of the ground water levels is even higher, with an average correlation between observations and simulations of 0.37 ($p = 0.02$). Thus the ground water levels are actually more predictable than are the precipitation rates, probably as a result of the tendency of the ground water systems to respond more to low frequency climate variations that are somewhat better predicted by the GCM than are the higher frequency, more erratic precipitation variations and due to the nonclimatic influences that are shared by observations and all simulations. The GCM-RGWM combination is a more forgiving predictor than the GCM alone in this case.

When the comparison between historical calibrated and GCM simulations is restricted to selected index wells, the GCM outcome compares favorably with the calibrated model. For example, a difference of -0.31 m occurred in errors between the measured ground water levels minus the calibrated model water levels and measured water levels minus the average GCM model water levels at the Oxnard well for the entire 43-year historical period. This error is well within the band of higher frequency (daily to annual) variations of other background noise such as about 2 m of daily tidal fluctuations.

A key condition in management of the basin is the amount of time that ground water levels near the coast are low enough to threaten degradation of the aquifers by seawater intrusion (Bachman and Detmer, 2001). The measured and calibrated ground water levels from the water supply well in the Oxnard Plain (Figure 9) are closely aligned with a median ground water level of about 3 m below sea level and about 5 m below the threshold water level required to prevent coastal landward flow of ground water (i.e., seawater intrusion) from the submarine outcrops of the aquifers exposed to the ocean along the seafloor offshore from the ground water basin (Hanson *et al.,* 2002). Therefore, the ground water levels at this water supply well were generally below the required level of protection for 80 to 90 percent of the historical period, 1950 to 1993 (Figure 9). The GCM ensemble derived ground water levels show a similar distribution but indicate additional variation in the spread of cumulative probability curves. The median GCM-RGWM simulated water levels range from about 4 to 8 m below sea level, and the values are generally bounded by the measured and simulated curves. A bias in the coupled model is exhibited here with an underestimation of the GCM-RGWM median simulated water levels of about 2 meters below the median simulated water level from the calibrated model (Figure 9). The GCM-RGWM simulations yielded ground water levels that were below the threshold water level about 80 to 95 percent of the historical period. The differences and potential bias between calibrated-historical and ensemble climate simulations, in this regard, are probably a result of reduced variation in simulated mass flow owing to the reduced ground water variability discussed earlier. This ground water variance reduction may result in an overall reduction in the cumulative mass flow through the ground water/surface water system. The differences in mass flow might be less problematic for actual six-month to one-year forecasts that are shorter and always closer to observed initial conditions.

The close similarity between the historical, calibrated model and GCM-RGWM probability distributions of ground water levels indicates that the GCM-RGWM combination could be used to evaluate alternative management plans under the full ensemble range of ground water/surface water variations. This approach would yield more systematic and complete examination of the robustness of alternate management plans in comparison with the application of one "true" historical set of variations. In addition, this approach could be used with optimization modeling to define the probable feasible range of alternative management plans.

DISCUSSION

The linked GCM-RGWM simulations of climatically driven ground water responses in the SCC Basin demonstrate that such linkages can be made and that they are significant even in a thoroughly developed basin. The simulations show that, given perfect SST forecasts, the central tendencies of each year's precipitation, streamflow, and ground water level statistics can be captured by the linked models. Thus, expected values of ground water levels can be projected to the extent that the SSTs can be projected. The GCM ensembles yield realistic precipitation that has realistic variation around these expected values, which indicates that (1) the GCM can provide realistic scenarios for management decision making, and (2) the ensemble variability in the simulated precipitation is much larger than the projected changes in expected precipitation values that are used in the RGWM. Unless the precipitation forecast uncertainties imparted by this large ensemble variability can be reduced, the GCM "forecasts" can only be used to provide rather coarse probabilistic projections.

The GCM-RGWM simulated ground water levels captured the changes in central tendencies associated with the imposed SSTs, but they underestimated the scatter around those changes. The underestimation of scatter in projected ground water levels by the GCM-RGWM, together with its accurate representation of expected value responses, indicates that the present combination might be useful for forecasting "expected" changes in ground water levels but less so for scenario or probabilistic forecast development, unless the ensemble scatter were artificially augmented or better transmitted through the downscaling process.

The linkage of GCMs with regional ground water/surface water models demonstrated here offers opportunities for near-term forecasting and for long-term syntheses and projections of climatic influences on ground water/surface water management. Unlike previous statistically based methods of projecting future precipitation for ground water projections, this method is physically based. The correlation between predicted and actual ground water response will be dependent on the level of variation that is transferred from the GCM to the RGWM, as well as on the forecast skill of the climate models. Both can be improved. Notably, the skill may be improved by the inclusion of additional state variables, such as temperature, dewpoint, and wind data, as direct or indirect inputs to the RGWM. These additional parameters would additionally constrain the supply and demand components of the ground water system and related water use such as irrigation or public supply.

The GCM-RGWM simulations also demonstrate that certain cycles of climatic variation affect the ground water system more than others do. In particular, not unexpectedly, slow interannual to interdecadal variations are preferentially expressed in the ground water system. Climatic variations that persist most in a ground water system depend on the climatic and hydrologic setting of the point of observation. For example, water levels from a well in the floodplain may show stronger ENSO related fluctuations than do water levels in a well farther from the floodplain that are potentially dominated by PDO related fluctuations. The water levels from the well presented in this paper represent the climatic response in a confined aquifer system that is several kilometers from the floodplain where climate related variations are about 35 percent ENSO related and 25 percent PDO related (Hanson *et al.,* 2002). Thus, the ability to forecast ground water systems will depend on which climatic time scales dominate the responses and how well those particular processes can themselves be forecast.

In many ground water systems, anthropogenic actions also can have the most direct and significant impacts on the ground water system, and many of these effects are not related to climatic variations. However, some human influences are climatically conditioned. For example, dry year periods alone can increase agricultural pumpage by as much as 11 percent in the SCC Basin (Hanson *et al.,* 2002). In addition, degradation of the water resource owing to land subsidence and seawater intrusion occur because of increased pumpage from growth related long-term development and because of increased pumpage during seasonal and climatic periods. Because of the importance of human activities in developed ground water systems, improvements in the ability to predict human extractions and returns of water on the basis of climatic effects are urgently needed. In addition to the differences between ground water uses during wet and dry periods, other climatic influences need to be more fully explored. For example, water levels from wells in the agricultural sectors of the coastal SCC Basin also are affected by variations in pumpage for irrigation that depend not only on precipitation but also on other climatic factors such as temperature and the presence of fog. Such additional climatic influences may be derived from GCM forecasts. Similarly, importation of water from outside the watershed may require the incorporation of climatic factors from other geographic regions (e.g., Benson *et al.,* 2002).

To use linked GCMs and RGWMs for operational seasonal to interannual water resource management, near real time hydrologic data may need to be collected (e.g., Cunningham, 2001) to allow regular reinitialization of the RGWM each time a forecast is needed. Reinitializing the RGWM for forecasting cannot be accomplished without regular and systematic updates that keep the model current and available for predictive simulations with new GCM data. This will ultimately require self-updating models that are linked to local data networks. In addition to the physical requirements of maintaining the linkage for forecasting future hydrologic conditions, institutional policies and regulatory constraints need to be considered to explore possible alternatives to existing policies or projects. To facilitate and align the linkage with prevailing limits imposed by policy or physical capacity, the models also could be linked to optimization models (Reichard, 1995) that systematically determine the relation of potential outcomes with respect to a field of feasible outcomes that are contrained by physical, monetary, or political constraints.

Thus, the next steps in the development of a reliable linkage between GCMs and an RGWM such as the SCC ground water flow model include development of methods for capturing more of the variance in the inflows and related response in the ground water system. Monthly to seasonal temporal discretization of the linkage and the inclusion of more state variables in downscaling relations between GCM data and RGWM inflows could improve the skill of forecasts. And finally, operational forecasts will require a self-updating RGWM that can incorporate real time information to forecast future ground water conditions.

CONCLUSIONS

Climate variations can play an important, if not always crucial, role in successful conjunctive management of ground water and surface water resources, particularly if they can be projected realistically for long-term planning purposes or predicted accurately at seasonal and longer time scales for near-term management. This will require accurate accounting of the links between climate variations and the cycles of supply and demand that drive recharge and withdrawal of water resources. It also will require accurate projection or predictions of the climate variations and accurate simulation of the responses of the water resource systems.

To begin assessment of the linkages and predictability of climate influences on conjunctive ground water/surface water management, the RGWM for a heavily developed coastal aquifer system in Southern California has been linked to several GCMs. Global climate model simulated precipitation rates have been used to estimate natural recharge and surface water inflows, as well as ground water pumpage, surface water diversions, and artificial recharge, in a model of the coastal aquifers of the SCC Basin at Ventura, California. Simple statistical downscaling was applied to the GCM precipitation rates to correct for GCM biases associated with the coarse spatial resolution of the climate model relative to the basin itself, to preserve the water balance among the various RGWM inputs, and to preserve the correct spatial recharge and discharge patterns within the basin. Results from the combination of the GCM and RGWM are illustrated here using annual precipitation totals from a 10-member ensemble of climate simulations of the period from 1950 to 1993 by the ECHAM GCM with only the sea surface temperature boundary conditions specified to replicate the historical record in each case.

Simulations by this GCM-RGWM combination show that the primary interannual to interdecadal time scales of the ENSO climate variations of the tropical Pacific are imparted to simulated precipitation variations in the Southern California area and then are successfully imparted to the simulated ground water level variations through the climate-driven recharge (and discharge) variations. Furthermore, the GCM-RGWM combination yields the quantitatively correct long-term central tendency of the SST to precipitation and SST to ground water level relations (teleconnections); however, although the GCM ensembles produce realistic ranges of precipitation scatter around the SST to precipitation relation, the simulated scatter around the SST to ground water level relation is too small. This is due, in part, to simplified relations of precipitation to streamflow, other nonclimatically driven anthropogenic supply and demand variations, and reduced skill from annual discretization of the GCM precipitation to seasonal inflows. One-year lagged ground water levels and the corresponding seasonal precipitation variations in the ensemble climate compare well with those from the historical climate simulations for the period 1950 to 1993. Thus, if a GCM or other forecast method were able to provide good inter-seasonal or longer predictions of precipitation, the RGWM could “transform” them into fairly realistic projections of the corresponding changes in ground water levels.

In addition, an application of the ensemble of simulated ground water level responses to a management problem is illustrated by estimates of cumulative probability distributions of “historical” ground water levels. The simulated ensembles of ground water levels show similar distribution to the measured and calibrated RGWM water levels relative to a local water level threshold for potential seawater intrusion. The application of GCM-RGWM ensembles could be used to assess alternative management plans and their potential feasible range of application.

The further development of linkages between GCMs and RGWMs will require the inclusion of some additional physical and institutional components. Improving the combination model is likely to require improvements in the downscaling procedures relating GCM simulated climate variations to recharge and discharge variations imposed on the RGWM, including perhaps the use of GCM simulated temperature, relative humidity, and wind data. A more complete representation of institutional components would require a means to evaluate the probable future state of the ground water system subject to physical, monetary, or political constraints and provide water purveyors and water resource managers with a means to systematically evaluate these outcomes and use these probable changes in hydrologic conditions to guide decision making. Alternatively, the nonclimatic influences of institutions that are missing in the GCM-RGWM combination may need to be accommodated by reducing the time scales considered to time frames within which the institutional changes can be predicted externally. This could be done by representing their influences, such as pumpage or streamflow diversions, as stochastic disturbances (e.g., Reichard, 1995) or by otherwise recalling the range of scatter (error bars) associated with the projections and forecasts. The ability to capture more variance and possibly obtain greater precision in the potential forecasts through better down-scaling techniques is the focus of further research. To place such a combination model into practical application in the ground water system would eventually require a more complete data network that can be used to improve the parameterizations of the local inflows to the system and to allow regular updates of the ground water/surface water flow model and a self-updating model that can use these data to keep itself current and available for forecasting. However, even without these improvements, the present results indicate that a GCM-RGWM combination can be used for hydrologic and resource projections for planning purposes and – when the GCM forecast skills are adequate – for near-term predictions.

ACKNOWLEDGMENTS

The authors wish to acknowledge Dan Cayan and Bill Alley for their review comments. The information and research in this paper has been funded by the National Oceanic and Atmospheric Administration through the California Application Program at the Scripps Institution of Oceanography.

LITERATURE CITED

Alley, W.M., 2001. Ground Water and Climate. Ground Water (39)2:161.

Alley, W.M., T.E. Reilly, and O.L. Franke, 1999. Sustainability of Ground Water Resources. U.S. Geological Survey Circular 1186, Denver, Colorado, 79 pp.

Bachman S. and D. Detmer, 2001. Surface and Groundwater Conditions Report Water Year 2000 Supplement. United Water Conservation District, Groundwater Resources Department Report, September 2001, Santa Paula, California, 60 pp.

Benson, L., M. Kashgarian, R. Rye, S. Lund, F. Paillet, J. Smoot, C. Kester, S, Mensing, D. Meko, and S. Lindstrom, 2002. Holocene Multidecadal and Multicentennial Droughts Affecting Northern California and Nevada. Quaternary Science Reviews (21):659-682.

Chao, Y., M. Ghil, and M.C. McWilliams, 2000. Pacific Interdecadal Variability in This Century's Sea Surface Temperatures. Geophysics Research Letters (27):2261-2264.

Cunningham, W.C., 2001. Real-Time Ground Water Data for the Nation. U.S. Geological Survey Fact Sheet 090-01, 2 pp.

Dettinger, M.D., D.S. Battisti, R.D. Garreaud, G.J. McCabe, and C.M. Bitz, 2001. Interhemispheric Effects of Interannual and Decadal ENSO-Like Climate Variations on the Americas. *In:* Interhemispheric Climate Linkages, Vera Mark Graf (Editor). Academic Press, San Diego, California, Chapter 1, pp. 1-16.

Dettinger, M.D., D.R. Cayan, H.F. Diaz, and D. Meko, 1998. North-South Precipitation Patterns in Western North America on Interannual-to-Decadal Time Scales. Journal of Climate (11):3095-3111.

Dettinger, M.D., M. Ghil, C.M. Strong, W. Weibel, and P. Yiou, 1995. Software Expedites Singular-Spectrum Analysis of Noisy Time Series. EOS, Transactions of the American Geophysical Union (76), 2 pp.

DKRZ (Deutsches Klimarechenzentrum Modellbetreuungsgruppe), 1993. The ECHAM3 Atmospheric General Circulation Model. DKRZ-Model User Support Group Report No. 6, Revision 2, 184 pp., Hamburg, Germany.

Diaz, H.F. and R.S. Pulwarty, 1994. An Analysis of the Time Scales of Variability in Centuries-Long ENSO-Sensitive Records. Climatic Change (26):317-342.

FCGMA (Fox Canyon Groundwater Management Agency), 1997. Ordinance 5.5: An Ordinance to Reduce Groundwater Extractions. Board of Directors of the Fox Canyon Groundwater Management Agency, Ventura County Public Works Agency, Water Resources Division, Ventura, California, 13 pp.

Gates, W.L., 1992. AMIP – The Atmospheric Model Intercomparison Project. Bulletin, American Meteorological Society (73):1962-1970.

Gershunov, A., T.P. Barnett, and D.R. Cayan, 1999. North Pacific Interdecadal Oscillation Seen as Factor in ENSO-Related North American Climate Anomalies. EOS, Transactions, American Geophysical Union (80):3 pp.

Gleick, P.H. and D.B. Adams, 2000. Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. The report of the Water Sector Team of the National Assessment of the Potential Consequences of Climate Variability and Change for the U.S. Global Research Program, Pacific Institute for studies in Development, Environment, and Security, 151 pp. Washington D.C.

Hanson, R.T., 1998. Paleoclimatic Analyses for Historical and Future Simulations of Ground Water/Surface Water Flow in the Santa Clara-Calleguas Basin, Ventura County, California. *In:* Proc. 15th Annual Pacific Climate (PACLIM) Workshop, Technical Report 64 of the Interagency Ecological Program for the Sacramento-San Joaquin Estuary. 15th Annual PACLIM Conference, American Geophysical Union, p. 133.

Hanson, R.T. and M.D. Dettinger, 1996. Combining Future Ground Water and Climate Scenarios as a Management Tool for the Santa Clara-Calleguas Basin, Southern California. Transactions, American Geophysical Union 77(46):F55.

Hanson, R.T. and M.D. Dettinger, 1999. Simulations of Ground Water/Surface Water Responses to Ensembles of Global Climate Model Hindcasts, Santa Clara-Calleguas Basin, Ventura County, California, 1950-1993. Transactions, American Geophysical Union 80(46):F215.

Hanson, R.T., P. Martin, and K.M. Koczot, 2002. Simulation of Ground Water/Surface Water Flow in the Santa Clara-Calleguas Basin, Ventura County, California. U.S. Geological Survey Water-Resources Investigation WRIR 02-4136, 214 pp. Sacramento, California.

Hanson, R.T., M.W. Newhouse, and M.D. Dettinger, 2004. A Methodology to Assess Relations Between Climate Variability and Variations in Hydrologic Time Series in the Southwestern United States. Journal of Hydrology 287(1-4):253-270.

Jiang, N., D. Neelin, and M. Ghil, 1995. Quasi-Quadrennial and Quasi-Biennial Variability in the Equatorial Pacific. Climate Dynamics (12):101-112.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, Roy Jenne, and

Dennis Joseph, 1996. The NCEP/NCAR Reanalysis Project. Bulletin of the American Meteorological Society (77) 3:437-471.

Koster, R.D., M.J. Suarez, and M Heiser, 2000. Variance and Predictability of Precipitation at Seasonal-to-Interannual Timescales. J. Hydrometeorology (4):408-423.

Krishnamurti, T.N., C.M. Kishtawal, T. LaRow, D. Bachiochi, Z. Zhang, C.E. Williford, S. Gadgil, and S. Surendran, 2000. Multimodel Superensemble Forecasts in Weather and Seasonal Climate. J. Climate (13):4196-4216.

Kumar, A., A.B. Barnston, P. Peng, M.P. Holderling, and L. Goddard, 2000. Changes in the Spread of the Variability of the Seasonal Mean Atmospheric States Associated With ENSO. Journal of Climate (13)17:3139-3151.

Latif, M. and T.P. Barnett, 1994. Causes of Decadal Climatic Variability Over North Pacific and North America. Science (266):634-637.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. A Pacific Interdecadal Climate Oscillation With Impacts on Salmon Production. Bulletin of the American Meteorological Society (78):1069-1079.

Mantua, N. and Steven, H., 2002. The Pacific Decadal Oscillation. Journal of Oceanography (58)1:35-44.

McDonald, M.G. and A.W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground Water Flow Model. Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 6, Chapter A1, 586 pp., Washington, D.C.

Minobe, S., 1999. Resonance in Bidecadal and Pentadecadal Climate Oscillations Over the North Pacific: Role in Climate Shifts. Geophys. Res. Lett. (26):855-858.

Peng, P., A. Kumar, A.G. Barnston, and L. Goddard, 2000. Simulation Skills of the SST-Forced Global Climate Variability of the NCEP-MRF9 and the Scripps-MPI ECHAM3 Models. Journal of Climate (13)20:3657-3679.

Reichard, E.G., 1995. Ground Water/Surface Water Management With Stochastic Surface Water Supplies: A Simulation-Optimization Approach. Water Resources Research (31)11:2845-2865.

Richardson, D.S., 2001. Measures of Skill and Value of Ensemble Prediction Systems, Their Interrelationship and Effect of Ensemble Size. Q.J.R. Meteorological Soc. (127):2473-2489.

Stern, P.C. and W.E. Easterling (Editors), 1999. Making Climatic Forecasts Matter. National Academy Press, Washington, D.C., 192 pp.

York, J.P., M. Person, W.J. Gutowski, and T.C. Winter, 2002. Putting Aquifers Into Atmospheric Simulation Models: An Example From Mill Creek Watershed, Northeastern Kansas. Advances in Water Resources (25):221-238.

Younger, P.L., G. Teutsch, E. Custodio, T. Elliot, M. Manzano, and M. Sauter, 2002. Assessments of the Sensitivity to Climate Change of Flow and Natural Water Quality in Four Major Carbonate Aquifers of Europe. *In:* Sustainable Groundwater Development, K.M. Hiscock, M.O. Rivett, and R.M. Davison (Editors). Geological Society, London, Special Publications (193):303-323.

Yusoff, I., K.M. Hiscock, and D. Conway, 2002. Simulation of the Impacts of Climate Change on Groundwater Resources in Eastern England. *In:* Sustainable Groundwater Development, K.M. Hiscock, M.O. Rivett, and R.M. Davison (Editors). Geological Society, London, Special Publications (193):325-344.

Zhu, Y., Z. Toth, R. Wobus, D. Richardson, and K. Mylne, 2002. The Economic Value of Ensemble Based Weather Forecasts. Bull. Amer. Meteorological Society (83):73-83.