A single, preferably continuous, drill core through the approximately 2-kilometer-thick Messinian evaporite sequence in the Levantine Basin would allow the evolution of a salt giant to be unraveled, and this would shed important new light on fundamental aspects of the Earth system. Such a drill program would greatly advance our understanding of the Mediterranean salt giant, and also of geologically much older counterparts elsewhere.

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Author Information

Christian Hübscher, Institut für Geophysik, Universität Hamburg, Germany; E-mail: christian.huebscher@zmaw.de; Joe Cartwright, School of Earth, Ocean and Planetary Sciences, Cardiff University, U.K.; Heribert Cypionka, Institut für Chemie und Biologie des Meeres, Oldenburg, Germany; Gert J. De Lange, Department of Earth Sciences: Geochemistry, Utrecht University, Netherlands; Alastair Robertson, School of Geosciences, University of Edinburgh, U.K.; Jean-Pierre Suc, Laboratoire Paléo Environnements et PaléobioSphère, Université C. Bernard, Lyon, France; Janos L. Urai, Geologie-Endogene Dynamik, Aachen, Germany.

Future Climate of the North Pacific Ocean

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Major changes in species distribution and abundance in North Pacific marine ecosystems are often correlated with climatic shifts in the twentieth century. Species affected in the past include halibut in the Gulf of Alaska, sardine near Japan, and various species along the Oregon/California coast [*Chen and Hare*, 2006; *Zhang et al.*, 2004; *Peterson and Schwing*, 2003]. Because these changes can affect the fishing industry, we have investigated possible future climate patterns in the North Pacific based on the evaluation of 22 coupled atmosphere-ocean general circulation models (GCMs). These GCMs were made available to the science community for independent evaluation in preparation for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC).

This analysis of a reduced set of 10 models, which simulate the variability of twentieth-century North Pacific sea surface temperatures (SST) reasonably well, finds that anthropogenic impacts on future North Pacific climate will be as large as those of natural climate variability in 30–50 years under a midrange greenhouse gas emissions scenario. The spatial pattern of the future warming trend will be more uniform than the main pattern of climate variability from the twentieth century, suggesting that existing climate-ecosystem-fisheries relationships might not be robust long into the 21st century. According to the models, the North Pacific climate system will likely enter into an unprecedented state with regard to near-surface ocean temperatures sometime during the first half of the 21st century.

In comparison with the IPCC Third Assessment Report, both the spatial resolution and physics of GCMs in AR4 have improved. For example, there is less or no reliance on prescribed ocean conditions, mobile sea ice, and improved parameterizations of clouds/radiation and land/atmosphere fluxes (www-pcmdi.llnl.gov/ipcc/info_for_analysts.php). We consider a middle-range IPCC greenhouse gas emissions scenario, A1B, and note that there are small differences between scenarios for the first half of the 21st century.

North Pacific Temperature and Climate Patterns

One tenet of global change has been that the impact from anthropogenic forcing in northern latitudes might manifest as a shift in the frequency distribution of the major existing patterns of atmospheric circulation variability such as the North Atlantic Oscillation or Pacific North American pattern [*Palmer*, 1999]. However, a recent study [*Van Ulden and van Oldenborgh*, 2005] shows that part of the projected temperature change in Europe may not be directly related to changes in major atmospheric circulation

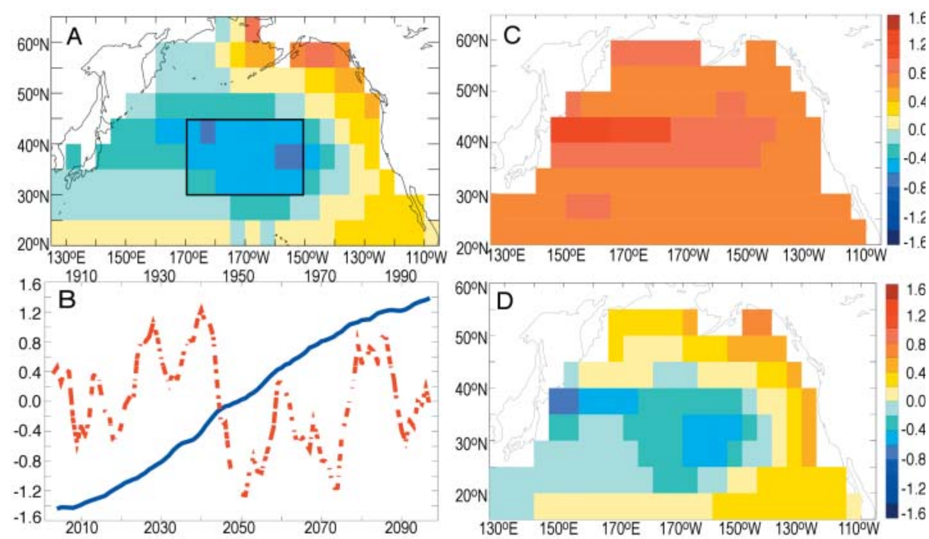

Fig. 1. (a) The first leading empirical orthogonal function (EOF) pattern of the North Pacific winter (November–March) sea surface temperature (SST) anomalies for 1901–1999 based on Hadley Centre SST analysis (i.e., the Pacific Decadal Oscillation (PDO)). (b) Principal component (PC) time series corresponding with the pattern in Figure 1a for the twentieth century (dashed curve, time axis on top). The solid line is the PC series for the 21st-century mean model projections (time axis on bottom). (c) The first leading EOF pattern of winter SST for the period of 2001–2099 based on the ensemble mean of 10 models: CGCM3.1(T47), CGCM3.1(T63), CCSM3, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2(hires), MIROC3.2(medres), MRI-CGCM2.3.2, and UKMO-HadCM3. The corresponding model mean PC series is shown by the solid curve in Figure 1b (time axis on bottom). (d) The mean of the second leading EOFs for the 21st-century model projections. The PDO structure in Figure 1a is clearly present in this pattern, and it has spatial correlation with the twentieth-century observed PDO at 0.82. The box in Figure 1a outlines the region of SST projections shown in Figure 3.

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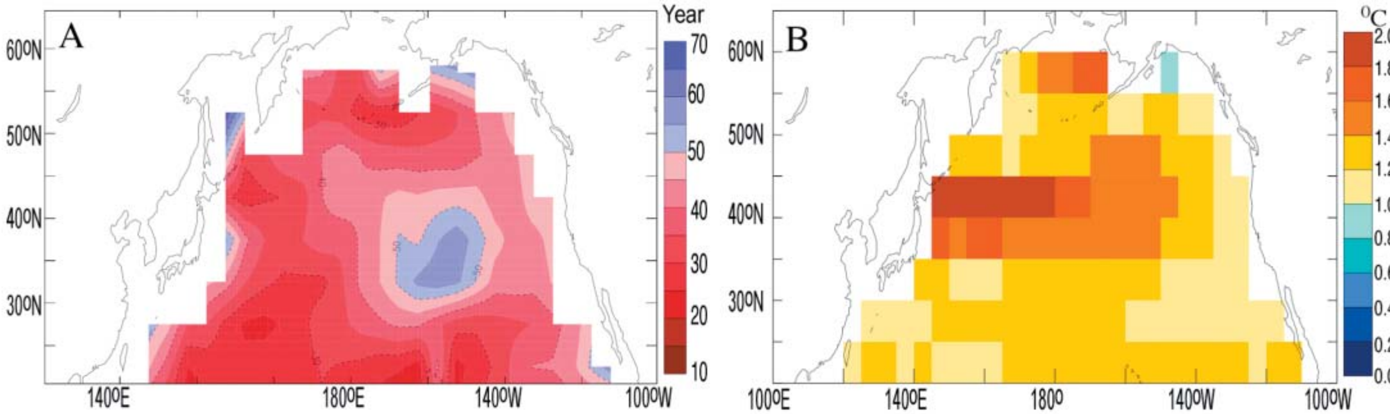

Fig. 2. (a) An estimate of the year when the induced temperature anomalies forced by anthropogenic emissions of greenhouse gases would equal the magnitude of natural variability, calculated as two standard deviations of the observed winter SST divided by the 10 model mean trend at each latitude/longitude grid cell. (b) Model-averaged projected future decadal winter mean (2040–2049) SST anomaly relative to 1980–1999 under the A1B emissions scenario.

patterns. We find a similar result for the North Pacific, described below.

Past studies indicate that one method to increase confidence in possible future climate predictions is to constrain the number of models by validating their simulations against observations [*Knutti et al.*, 2006]. Here we require that model simulations at least capture much of the natural variability on decadal and longer timescales when compared with the observed SST climatology of twentieth century. Among 22 available models, 18 have archived SST fields for their control runs (no external forcing), twentieth-century simulations, and 21st-century projections under the A1B scenario.

One indicator of decadal variability in the North Pacific is the first empirical orthogonal function (EOF) of observed winter SST (November–March) for the twentieth century, which is termed the Pacific Decadal Oscillation (PDO) [*Mantua and Hare*, 2002]. The PDO has a general east-west dipole spatial structure (Figure 1a) and decadal variability (dashed curve in Figure 1b). EOFs are an efficient way to display the relative importance of covariances in spatial fields, although they are a statistical pattern and not based directly on dynamics.

We retain 12 of the 18 models that have a spatial correlation of 0.7 or greater between observed and model-simulated PDO spatial patterns in their twentieth-century and control run simulations, and have decadal variability in their respective principal component (PC) time series power spectra. An additional two models were excluded because their simulated SST variance is less than the observed SST variance everywhere in the region for the twentieth century. Projections of 21st-century climate are based on the remaining 10 models, as listed in Figure 1.

When an EOF analysis is conducted for the 21st-century model projections, the first EOF of SST variability for all 10 models is a new, rather uniform, single-signed loading pattern (Figure 1c) with a corresponding PC time series with an upward trend (solid curve, Figure 1b). The second leading pattern of the 21st-century EOF analyses (Figure 1d) shows the spatial variability of the PDO dipole pattern, similar to the twentieth-century observed field (Figure 1a). For the second EOF, the corresponding PC time series have magnitudes and the random phasing of decadal variability similar to the model simulations of the PDO for the twentieth century. These model results suggest that the twentieth-century pattern of decadal variability will continue nearly the same into the 21st century, but there will be an additional upward trend field of SST. In the future, both decadal variability and the long-term trend will be evident in the North Pacific.

The influence from the anthropogenic forced trend in the SST will be as large as the natural variability in North Pacific SST by 2030–2050, measured relative to the spatial pattern of winter SST standard deviation for 1950–1999. Figure 2a shows the estimated year when the two influences are equal. The years are calculated by dividing twice the observed twentieth-century SST standard deviation by the mean future trend from the 10 models at each latitude/longitude grid box. The earliest trends are in regions of low standard deviation, mostly around the periphery of the central North Pacific basin. Figure 2b shows the change of the model mean SST in 2040–2049 relative to 1980–1999; the range is generally small across the North Pacific, from 1.2° to 1.8°C.

The collection of different IPCC model results and the different individual runs of each model (called ensemble members) provide an indication of both the most probable future climate trend and the range of possible trajectories for future climate. For further analysis, we selected a region at the southern pole of the PDO (Figure 1a, 30°–45°N, 170°E to 150°W). Figure 3 shows the mean SST trend averaged over all the 10 models (bold blue curve) and the individual projec-

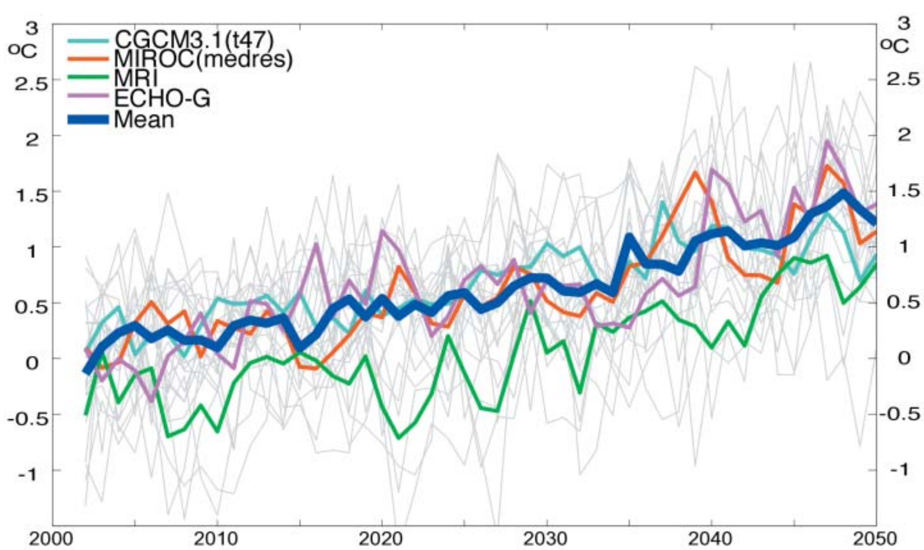

Fig. 3. Projected winter SST anomalies (°C) relative to a 1980–1999 base period for central North Pacific as shown in Figure 1a. The thin gray curves indicate the range of individual ensemble member projections from the 10 models under the A1B scenario, while the colored curves are the ensemble means from four of the models. The bold blue curve indicates trend of the all-model mean.

tions from each ensemble member (thin grey curves), which represent a range of potential trajectories that the future North Pacific climate could follow. As with the PDO in the twentieth century, the timing of future SST maxima and minima are not predictable because of the differences between the possible trajectories due to intrinsic climate variability. The envelope of individual ensemble member projections in Figure 3 does provide a range of future North Pacific SST variations, suggesting warmer maximum and minimum temperatures.

An estimate of future uncertainty in the trend, based on model to model differences in physical parameterization and other factors, can be seen from the means over the ensemble members for individual models (thin colored curves). Thus to characterize the future climate state, it is important to consider more than one model to sample parameterization uncertainties and more than one run for each model to sample the range of natural variability.

Future Climate Effects on North Pacific Ecosystems

The response of marine ecosystems to climate variability is an active area of fisheries oceanographic research. More than 100 papers published since 1999 discuss the PDO and its relation to biological systems. Of particular note were the widespread changes in population dominance due to ocean processes associated with the strengthening of the Aleutian low-pressure system and positive phase of the PDO after 1976. One can assume that populations have adapted to this primarily east-west contrast in North Pacific climate through the PDO over centuries, if not much longer.

What will happen with a more geographically uniform increase in temperature? At present there are few quantitative estimates. The result from one model study is a change in the seasonal cycle of phytoplankton and herbivore concentrations, moving from a regime characterized by strong variability with low wintertime values and a spring bloom, to more constant yearly values [*Pierce*, 2004]. A reduction of yearly averaged primary productivity accompanies this shift. Corals and monk seals at the northwestern end of the Hawaiian Archipelago appear to be near their thermal limit. Further increases in SST may increase the number and severity of coral bleaching events and contribute to declines in monk seal pup survival (J. Polovina, personal communication, 2006). On the west coast of the United States and Canada, northward shifts of fish populations due to replacement of productive subpolar waters with less productive warmer waters can be expected.

The availability of IPCC climate model results from multiple institutions, coupled with steps to constrain the number of projections by validating the model simulations against observations, has contributed to increased credibility in the IPCC AR4 process.

Given the present and anticipated anthropogenic loadings over the next few decades and the improvement in radiative parameterizations in present generation GCMs, confidence in these projections may in part be based on simple processes, such as a greenhouse blanket over most of the oceans. This is not to say that localized climate responses due to more complicated physics related to teleconnection, equatorial, moisture, salinity, runoff, and feedback processes will not also play a role in climate change over this century. The IPCC AR4 models do not necessarily handle these processes well.

Our concern is that the combined influence from modest projected trends in SST and a continued large range in decadal natural variability will initiate ecological consequences over wide regions of the North Pacific before 2040. Even if the real world turns out to be much more complicated than is portrayed in the IPCC AR4 GCMs, much of the basic radiation physics for large-scale temperature change in these models should be valid for the first half of the 21st century.

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Author Information

James E. Overland, NOAA Pacific Marine Environmental Laboratory, Seattle, Wash.; E-mail: james.e.overland@noaa.gov; and Muyin Wang, JISAO, University of Washington, Seattle.