The Role of Direct Observation in Predicting Climatic Change

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Introduction

The National Oceanic and Atmospheric Administration Center for Ocean Analysis and Prediction (COAP) in Monterey, California, has assembled information to suggest how NOAA's facilities for observing the ocean and atmosphere might be applied to studies of paleoclimate. This effort resulted, indirectly, in several projects that combine direct observations of the ocean/atmosphere system with studies of past climate of the Pacific region. This article considers concepts that link the two kinds of investigations. It defines the thesis that direct observation of systems that generate paleoclimatic information is the nexus upon which understanding of climatic variability begins and upon which prediction of climate and global change depends.

A "predictive understanding" of climate change and its effects is the primary goal of climate and global change programs (CES 1989). However, both instrumental and proxy climate records reveal such a complex pattern of climatic variability that predictions, in the usual sense of predicting climatic events, would appear to be ruled out, at least within a time frame relevant to the human enterprise. Predictions in the context of global change are to be made by physical models that estimate the effect on regional climates of changes in the ocean-atmosphere system resulting from anthropogenic forcing (*e.g.*, CO_2, ozone, *etc.*). Regional climatic variability, in this same context, is important mainly for estimating the confidence level of a model prediction for a given region (CES 1989).

A climate prediction at an estimated level of confidence, however, is not a simple concept. It is widely recognized, for example, that the brief period (about 100 years) of instrumental observation is not sufficient for estimating confidence levels for the next 100 years, or even for the next few decades.

Pisias' (1978) proxy record for sea-surface temperature from the Santa Barbara basin, derived from changes in distribution of planktonic radiolarians (Figure 1), reveals three strong millennial cycles in ocean temperature over the past 6000 years. A model prediction with a confidence level based only on the previous century, made from most points in the time series, would be overtaken within a few decades by natural variability related to the strong millennial cycle. Figure 1 and the strength of the millennial cycle illustrated imply that confidence levels must be based on much longer records of variability.

This example also suggests another principle to be considered before predictions based on physical models can be applied in a practical sense. Predicting climatic change is not the goal, *per se*. Rather, it is the effect a predicted change will have on other systems that motivates efforts to predict climatic change (CES, 1989).

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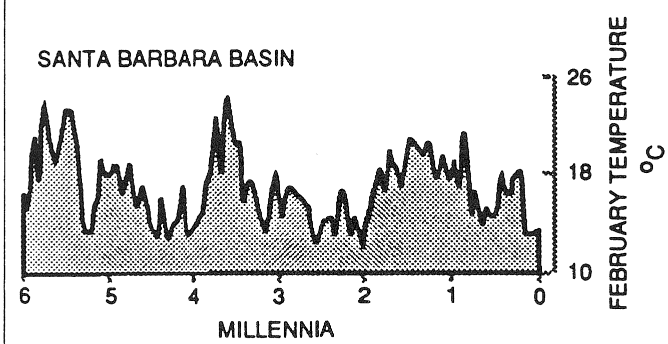
Figure 1
TEMPERATURE OF SURFACE WATERS IN SANTA BARBARA BASIN DURING THE LAST 6 MILLENNIA

The time series is part of an 8000-year proxy record of ocean water temperature derived from transfer functions based on studies of radiolarians in the Santa Barbara basin. Notice that pronounced cycles in water temperature are spaced about 2000 years apart. (From Pisias 1978)



In this regard, climatic proxies such as a tree-ring growth layers or radiolarian abundance are, in themselves, a means for estimating effects of climatic change on the environment. For example, radiolarians in the Santa Barbara basin are, in addition to recording climatic variability, a means for estimating effects of human-induced climate change on the marine system. If changes in the winter sea surface temperature in the Santa Barbara basin can be predicted by means of a coupled ocean/atmosphere model, it follows that changes in marine plankton and effects on fisheries, *etc.*, might be predicted also.

Climate proxies have a dual function. They provide a vital record of climatic variability, and they measure the response of environmentally important systems to climatic forcing. If climate predictions are to be applied, studies of environmental response systems by means of climatic proxies are as vital to the goal prediction as are efforts toward climate modeling. Most importantly, the response systems must be calibrated quantitatively against the climatic variables (*e.g.*, temperature, precipitation, winds) that are used for output of climate models, because a response prediction for a given region without such a linkage would be largely subjective and would have limited application.

Linkage: The Key to Climate Prediction

Climatic proxies do not measure climatic variables such as temperature, precipitation, and winds directly; they must be calibrated against other observations. Three methods are generally used to convert proxies to climatic indices or variables:

- Physical/Chemical Associations. This method measures a physical/chemical property that is related to a climatic parameter (*e.g.*, temperature). This method is mainly applied to isotopic analyses of geologic (biologic) materials.

- Climate-Gradient Associations. This method is based on distribution and abundance of biologic species in a modern climatic gradient. Species abundance is measured at different localities, then compared with climatic parameters (*e.g.*, temperature) from nearby sites. Statistical procedures are used to develop response functions that express species abundance as temperature, precipitation, *etc.*

- Time-Series Associations. This method directly and concurrently observes changes in climate-related proxies (*e.g.*, species abundance) and in climate parameters (*e.g.*, temperature) at the same site. Measurements are made at regular intervals over an extended period. A statistical association between a climate parameter and a proxy can be expressed as a climatic variable.

The second method, calibration of proxies by means of a climate gradient, has had the widest application and is most applicable to time-slice investigations and model-testing. This procedure uses instrumental climatic data along with regional surveys of biologic species abundance to statistically estimate response functions. Biologic data are compared with instrumental climatic data; therefore, the method does not depend on future observations.

The third method employs direct observation and comparison of time series of both climatic proxies and climatic variables over an extended period. This method has had limited application, and the few studies done have generally used climatic records that happened to be available from nearby instrumental recording stations.

The climate-gradient method and the time-series methods both rely on completeness and continuity of recent climatic data. Each has advantages and disadvantages. For example, the climate-gradient approach is not strongly site-dependent and assumes that the regional climatic gradient has a stronger influence on distribution of organisms than does the local environment. The climate-gradient method has been used successfully to calibrate shifting patterns of vegetation following the last glacial maximum. This application, however, lacks the temporal resolution to characterize decadal to centennial variability.

Unlike the regional climate-gradient method, the time-series or direct observation method takes advantage of differences among sites and employs a wide range of potential climatic proxies in addition to organisms, including sediment composition, texture, geochemistry, *etc.* Because the method is site-specific and site-dependent, regional climatic gradients are not a factor, and measured parameters must be calibrated against coincident changes in climatic variables over some unspecified interval.

Length of the Observation Period

An apparent disadvantage of the time-series method is the potentially long interval that may be needed to characterize the relationship between proxies and climatic variables. Few calibration studies of this type have been done. However, these examples illustrate the method and provide a rough estimate of the interval of observation that may be needed for calibration.

A Small Lake in the Mojave Desert

Lake sediments deposited 400 years ago, during the "Little Ice Age", recently were found in a dry playa in the Mojave Desert, one of the most arid regions of the world (Enzel *et al.*

1989). The U.S. Geological Survey and the State of California have monitored hydrology of the Mojave drainage basin and have maintained records of river discharge and playa flooding since about 1900. Analysis of these records showed that river discharge from exceptionally large storms was capable of creating a temporary lake in the playa and that such storms occurred only during a particular pattern of circulation (atmospheric pressure) in the North Pacific. Enzel *et al.* (1989) were able to link synoptic climatic data from the North Pacific with the record of river discharge and floods in the Mojave drainage and identify the pattern of atmospheric pressure over the Pacific most likely to have produced a lake in the terminal playa during the Little Ice Age (Figure 2).

This illustrates how geologic and stratigraphic information, if accompanied by climatic and streamflow data, can be used to interpret and calibrate effects of climatic change. A reconstruction was possible because a hydrologic monitoring program had been maintained for the Mojave drainage. In this case, about 90 years of observation established the pattern of discharge and lake flooding and provided the linkage to changes in Pacific climate.

Ice Cores and Corals

Calibration by means of time-series observations is also illustrated by studies of ice cores in South America. A comparison, over the last 400 years, between time-series for oxygen isotope ratios in the Quelccaya ice core in South America and northern hemisphere temperature reveals a long-term association (Figure 3). The isotopic ratios in the ice core are a reasonable facsimile of temperature changes in the northern hemisphere, and the association appears to be partly resolved in decadal variability. In the ice-core example, for sites that are widely separated geographically, more than a hundred years of observation appear to be needed to quantify associations for interdecadal variability.

Another example shows an association between strong westerly wind anomalies that signal the onset of El Niño and Mn/Ca ratios in annually banded corals in the equatorial Pacific (Figure 4). The trace-metal ratio reproduces, only approximately, the nearby zonal wind

Figure 2
ATMOSPHERIC PRESSURE AT SEA SURFACE FOR STORMS THAT PRODUCED FLOODS IN MOJAVE RIVER PLAYAS

Arrow shows the path of large, flood-producing storms south of a low-pressure anomaly and the suspected path of frequent storms during the Little Ice Age. (From Enzel et al. 1989)

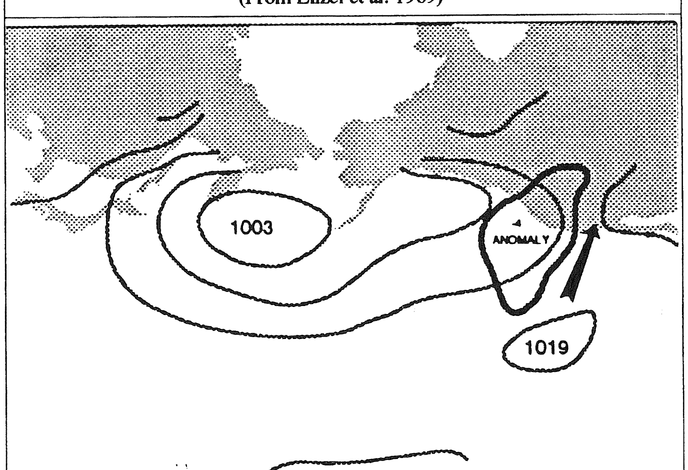


Figure 3
RELATIONSHIP BETWEEN ISOTOPE RATIO IN QUELCCAYA ICECORE AND NORTHERN HEMISPHERE TEMPERATURE

From Thompson et al. 1986

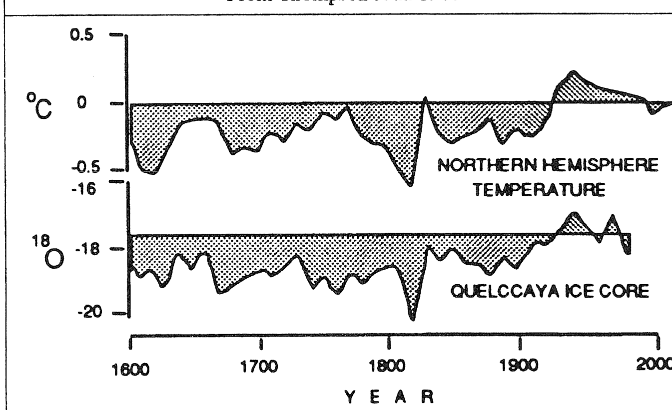
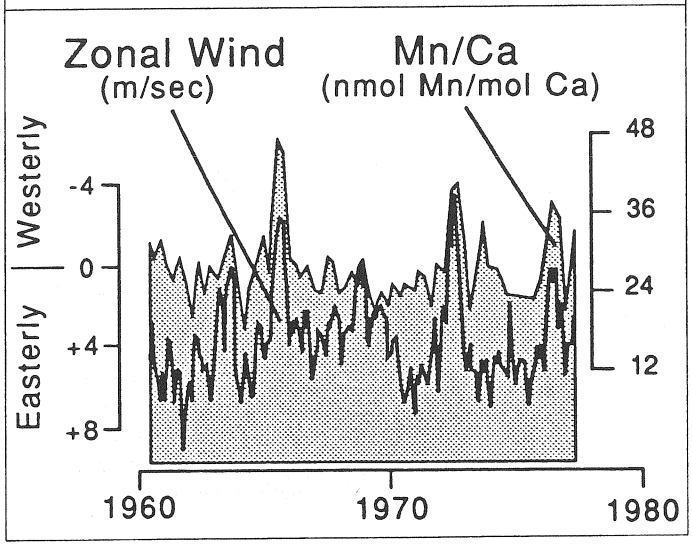


Figure 4
CHANGES IN Mn/Ca RATIO IN
BANDED CORALS AT TARAWA
COMPARED TO ZONAL WINDS AT TARAWA
From Shen 1990

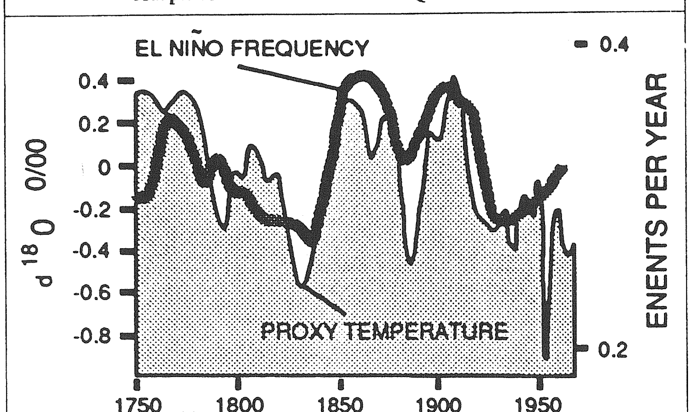


record at the island of Tarawa but exceptionally strong wind events are reflected in the Mn/Ca ratio (Shen, 1990). This example, and other parameters measured quarterly in corals suggests that the time-interval for calibrating interannual climatic variability using corals is at least several decades.

Evaluating and Extending Observations

Many decades seem to be needed to calibrate climatic proxies by the method of direct observation. However, it may be possible to reduce the period of observation through careful and comprehensive studies of the response of proxies during the annual climatic cycle. Seasonal forcing during the annual cycle is responsible for the life strategies, changes in sediment flux, and biogeochemical responses that generate climatic proxies. Responses during the annual cycle seem at least partly responsible for recording the longer and stronger cycles preserved in the sediment and stratigraphic record (Anderson 1986, Anderson *et al.* 1990). Because of the dominance of the annual cycle in processes that produce climatic proxies, it may be possible to calibrate a response to seasonal forcing and long-term changes in climate by observing relatively few annual cycles.

Figure 5
OXYGEN ISOTOPE CHANGES
(PROXY TEMPERATURE) IN *G. BULLOIDES* FROM
SANTA BARBARA BASIN AND
FREQUENCY OF EL NIÑO EVENTS SINCE 1750
Adapted from Dunbar 1983 and Quinn et al. 1987



The Santa Barbara basin is a favorable setting for a pilot study to determine the feasibility of calibrating a wide range of potentially important climatic proxies in the marine environment. This is illustrated by the oxygen isotope record in *G. bulloides* from the Santa Barbara basin since 1750, as reconstructed by Dunbar (1983). The reconstruction (Figure 5) defines 4-5 prominent cycles in isotopic ratio believed to be associated with sea surface temperature. Superimposed on these ~50-year cycles is a plot showing changes in the frequency of El Niño events for the same interval.

Notice that changes in isotopic ratio appear to correlate with changes in the number of El Niño events and that these changes occur in cycles of about 50 years and 100 years (Enfield 1989, Quinn *et al.* 1987). The wide range of potential proxies preserved in underlying varved sediments in the Santa Barbara basin (see inset below) offers an opportunity to observe changes during the annual cycle and to identify and calibrate those proxies with the greatest potential for a clear response to seasonal forcing during the annual cycle. Developments in marine technology and experiments with instrumented moorings suggest how such a calibration can be accomplished.

POTENTIAL CLIMATIC PROXIES IN THE SANTA BARBARA BASIN

Sedimentary	Geochemical	Biologic
Grain size distributions	Organic carbon flux	Centric diatoms, >24 species
Pollen grain distributions	Biogenic silica flux	Pennate diatoms, >10 species
Bioturbation effects	Carbonate flux	Diatom spores, >6 species
Mass flux; Terrigenous flux	Nutrient flux; P, N	Silicoflagellates, >6 species
	Trace-metal flux	Dinoflagellates, >6 species
	Isotopic ratios; $^{13/12}C$, $^{18/16}O$	Radiolarians, >17 species
	Organic composition	Planktonic forams, >7 species
		Benthonic forams, >6 species
		Planktonic gastropods, >3 species
		Nektonic organisms, >6 species

Compiled by A Soutar

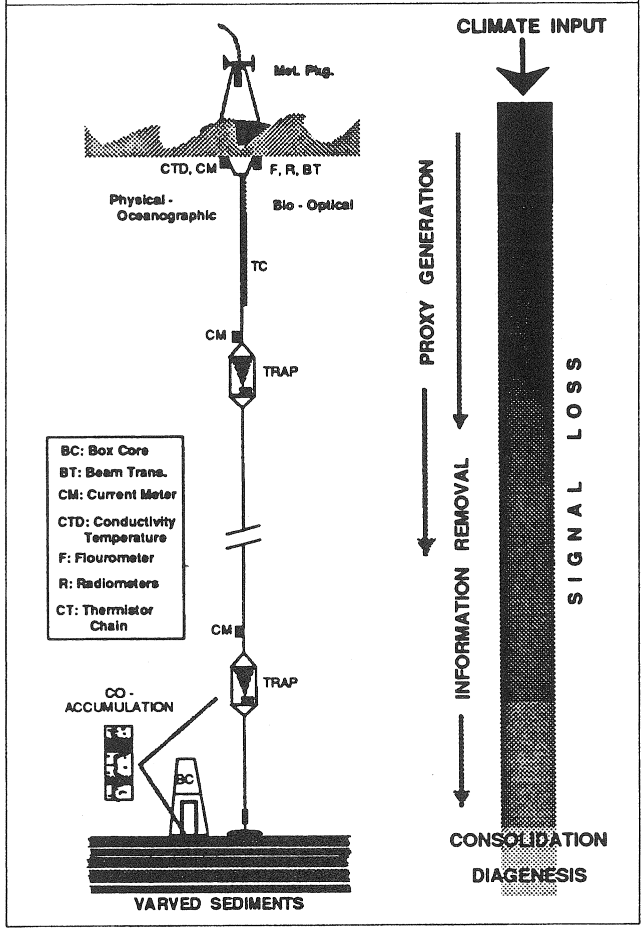
Observational Methods and Procedures

In the 1970s and 1980s, sediment traps were commonly deployed in lakes and oceans to examine relationships between climate variables and particle flux to the underlying sediment. The pathways for transferring climatic information to underlying sediments are many and complex, and trapping of particles alone does not complete the chain of observation needed to calibrate climatic records.

The first link in the chain for a marine setting such as the Santa Barbara basin is to collect atmospheric and oceanographic data (Figure 6). In a second step, the flux of sediment is measured and sampled concurrently with atmospheric and oceanographic measurements, generally by using several time-series sediment traps deployed at different depths in the water column. A third step collects sediments, by means of box cores, that have accumulated on the bottom during the period of observation. A fourth step collects cores and subsamples the underlying sediment. Finally, the physical, geochemical, and biologic properties are determined for all trap, bottom, and sub-bottom materials and compared with instrumental data, then potential climatic proxies are identified and transformed to response functions.

Although the calibration procedure is complex and has many steps in marine and lacustrine systems, similar linkage studies and procedures have been employed for years to transform tree-ring width data to climatic variables. Experience with tree-rings illustrates the utility and practicality of the approach. Calibration studies also have been employed in Antarctica and Greenland for connecting snowfall accumulations to meteorologic data.

Figure 6
MOORING AND INSTRUMENT ARRAY
TO BE USED FOR CALIBRATING
CLIMATIC PROXIES IN MARINE SEDIMENTS



Relationship to Pacific Climate Studies

The Pacific region, including adjacent parts of continents, is especially favorable for obtaining past records of climatic variability and for calibrating climatic proxies. These records include ice cores, tree rings, widely distributed corals, and marine and lacustrine varved and laminated sediments. Many marine sites have high accumulation rates, and some are in settings that have a tendency toward anoxia that limits bioturbation and favors preservation of original structures and temporal relationships. Even if varved sediments are not preserved, such sediments may have a temporal resolution in the range of decades to centuries. Some partly ventilated basins with accumulation rates of about 10 cm/1000 years, as the Sulu Sea, have preserved millennial scale variability (Linsley 1989).

In addition to having records of long-term climatic variability, Pacific sites lie climatically upstream to important agricultural and populated regions. The effects of ENSO phenomena reach far beyond the tropical Pacific, and ENSO contributes to the patterns of interannual to millennial climatic variability that will be important in predicting the effects of regional climatic change within the human time frame.

Several paleoclimatic studies that will employ instrumental devices to observe and calibrate formation of climatic proxies have recently been initiated in the Pacific region with the aid of NOAA and other funding. For example, investigations of coral heads in the Galapagos and in the Gulf of California by R.B. Dunbar and G.M. Wellington, Rice University, will be supplemented by instrumental studies of physical oceanographic and meteorologic conditions coincident with coral growth. Elsewhere, L. Thompson, Byrd Polar Research Center, will install a meteorological and snow-monitoring system in the Cordillera Blanca, Peru, to link observations of air masses and snow accumulation to the climate record preserved in ice cores.

Comprehensive observations of the generation of marine climate proxies remain to be implemented. However, preliminary experiments using instrumented and fixed moorings similar to the mooring employed by Dickey (1988) in the Sargasso Sea and to the mooring illustrated in Figure 6 are being carried out in Monterey Bay by C. Pilskaln and others at the Monterey Bay Aquarium Research Institute (MBARI). In addition, three moorings that collect sediment in time-series traps and also measure physical oceanographic properties have been deployed off the Oregon coast by Pisias and other investigators at Oregon State College of Oceanography. Isolated sediment traps without other instruments are deployed in Santa Barbara basin, Guaymas basin, and Saanich Inlet.

Many lakes lie climatically downstream from the Pacific basin and are potentially favorable sites for calibrating climatic proxies found in lacustrine environments (Anderson *et al.* 1985). Methods of direct observation of the marine environment also are applicable to lacustrine systems. Although little progress toward calibrating lacustrine climatic proxies can be reported, the U.S. Geological Survey is contemplating related research in lakes in Minnesota and in Washington State.

Summary: Prospects for Observational Studies and Climate Prediction

Predicting global climate change and its regional effects is a specific objective. Given this definitive mission, the kinds of paleoclimatic records needed and the paleoclimatic research that needs to be done are also bounded and specific. Do the needed records exist? If so, will the necessary research be initiated to determine if these records can enable predictions to be obtained from climate models? One can assume future research will be focused on materials with annual to near-annual resolution, including tree rings, ice cores, corals, and laminated lacustrine and marine sediments. The regional distribution of tree-ring records, ice cores, and corals is reasonably well known; paleoclimatic investigations using these materials are underway; and climatic calibration studies for ice cores and corals are just now beginning. Comprehensive investigations of laminated marine and lacustrine sediments, on the other hand, are still in an early stage of development.

When physical climate models are developed to a stage where they are accurate on a regional scale, predictions of regional effects will require confidence estimates based on long records of regional climatic variability. Tree rings, corals, and ice cores, by themselves, will not provide records that are long enough or that have a regional distribution adequate for estimating regional variability and its effects. The long paleoclimatic records that are needed will have to come from lacustrine and marine sediments with annual to near-annual stratigraphic resolution. It is not yet known if such records are of sufficient quality or if their numbers are sufficient regionally to provide a basis for predicting effects of regional climatic change. In any case, a major effort to investigate recent marine and lacustrine sediments, sustained at a high priority for many decades and focused on the generation of climatic proxies, is indicated if the goal is to obtain a predictive understanding of global change.

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