DATA ASSIMILATION AND PREDICTABILITY STUDIES FOR THE COUPLED OCEAN-ATMOSPHERE SYSTEM

By Michael Ghil and Carlos R. Mechoso

AS OCEANIC DATA SETS increase dramatically in quality and quantity in the near future, and both oceanic and atmospheric models improve apace, the predictability of the coupled ocean-atmosphere system will become more important on the theoretical level and more critical on the practical level. Predictability of the atmosphere with prescribed sea-surface temperatures (SST) has been evaluated; numerous studies indicate that two initially very similar atmospheric states will lead to time evolutions that on the average diverge and become uncorrelated over an interval on the order of 2 weeks. There is also a growing literature on the predictability of the upper ocean with prescribed atmospheric wind stress and heat fluxes. But the variability, and hence predictability, of the coupled system is quite different from the sum, product, or any other simple function of its parts (Ghil *et al.*, 1991a).

The long-term goal of our work at UCLA is to provide a description, understanding, and prediction of the coupled ocean-atmosphere system as complete and reliable as that which now exists for the atmosphere alone. Our approach is to develop methods for data assimilation from sequential estimation and control theory and for predictability studies from dynamical systems and statistical turbulence theory; these methods are then tested on a variety of models, ranging from simple models amenable to analytical treatment to coupled ocean-atmosphere general circulation models (GCMs).

Data Assimilation For The Coupled Ocean-Atmosphere System

The ambitious and elusive goal of data assimilation is to provide a dynamically consistent "motion picture" of the atmosphere and oceans in three space dimensions with known error bars. The ingredients for generating this four-dimensional space-time movie are a large number of observations with different spatiotemporal distributions and error characteristics, on the one hand, and an imperfect knowledge of and ability to solve the equations of fluid motion, on the other.

The purposes of generating such a movie can differ: in numerical weather prediction and in the emerging discipline of ocean forecasting, the main emphasis is on short "loops" between successive initial states for subsequent prediction, separated by 1 day (in the atmosphere) or 1 week to 1 month (in the oceans). In climate-related problems, whether atmospheric or oceanic, the emphasis is on full-length "feature movies," based on all the information available for long-time intervals, e.g., for the entire duration of a field experiment or of even longer historic data records.

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In meteorology, data assimilation is a well-established subfield described in books such as Bengtsson *et al.* (1981) and Daley (1991). In oceanography, the increase in data sets as well as the improvement in models are working a true revolution in the need for and interest in data-assimilation methods. The general problem of data assimilation for the atmosphere and oceans is discussed by Ghil (1989, 1990) and by Ghil and Malanotte-Rizzoli (1991).

A considerable number of methods with increasing degrees of sophistication have been developed for and applied to the assimilation of atmospheric and oceanic data. The key difficulty resides in ascertaining the relative confidence one has in, and therefore the relative weights one should assign to, various observations and various model predictions. In direct insertion, local observations are given complete credence and are used to simply replace model predictions at the time of observation. In variational methods with strong constraints, the model is considered perfect and observations are only allowed to help pick the succession of model predictions that are closest

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to the observations. Other methods try to use different theoretical ideas and computational resources, the common purpose being to assign relative weights to model values and observed values in inverse proportion to their estimated square errors; these methods include successive corrections, nudging, so-called optimal interpolation (OI) and variational methods with weak constraints (Daley, 1991; Ghil and Malanotte-Rizzoli, 1991).

The simplest way to test the performance of a data-assimilation method . . . is to run a so-called identical-twin experiment.

The best estimate of the current state of a geophysical flow field, based on past and current observations, is provided in the case of linear flow equations by the Kalman (1960) filter. The filter makes optimal use of information about the observational errors and the model errors to calculate the above-mentioned relative weights in computing the current flow-field estimate. It can be generalized to the more realistic nonlinear equations used nowadays in dynamic meteorology and physical oceanography via the so-called extended Kalman filter (EKF: Ghil *et al.,* 1981; Miller and Ghil, 1990). At UCLA, we have applied a full suite of the data-assimilation methods sketched above to models of varying complexity and with varying resolutions of the mid-latitude and tropical ocean.

Todling and Ghil (1991) investigated the ability of a data-assimilation system based on the Kalman filter to track rapidly developing barotropic and baroclinic instabilities in the atmosphere and oceans. The simplest way to test the performance of a data-assimilation method, used in conjunction with a given model and a given set of observations, is to run a so-called identical-twin experiment. First, a control integration is carried out with a given initial state; this integration is considered to provide the correct succession of states of the flow fields and therefore is also often named "the nature run." Next, random perturbations are added to the initial state (to reflect our lack of complete and accurate knowledge thereof) and to the model equations; this run is considered to represent the succession of states that we would obtain in the absence of any observations. Finally, an assimilation run is made with the same initial state as in the second, perturbed run, but using observations extracted from the control run at selected locations (according to an existing or planned observing pattern) and is blended with the model-predicted values while applying the weights provided by the assimilation method under study. The difference between the model state at any given time in the assimilation run and that in the control run is referred to as model anomaly and is measured typically by the corresponding root-mean-square (RMS) error; the performance of the data-assimilation method is reflected by the reduction of this error over time with respect to its initial value, or with respect to another appropriate comparison value (e.g., that in the second run, without observations).

For the barotropic case, Todling and Ghil (1991) produced an identical-twin simulation by adding random perturbations to the results of a run performed using a shallow-water model, initialized with an unstable velocity profile (Fig. 1). In the assimilation runs, the observations were assimilated using the Kalman filter method. In this way, Todling and Ghil (1991) showed that the Kalman filter results in a substantial reduction of the initial error, even for a limited number of observations (Fig. 2). Furthermore, they showed that observations made within the region of most unstable flow are more effective for the assimilation. This work is being extended to the baroclinic case; preliminary results for this case were reported by Todling and Ghil (1990).

An important problem for ocean prediction is the compensation of errors in atmospheric wind-stress data by the use of ocean data. This problem was explored by Hao (1991), using a linear, reduced-gravity model of a tropical ocean basin and an assimilation method based on OI. Hao forced the model with biased wind stresses and compared the effect of assimilating (at selected locations) either the height of the free surface (as would be the case if altimeter data were used) or the zonal velocity (as would be the case if current-meter data were used). Hao found that error reduction due to assimilation varies between the western, central, and eastern parts of the basin, and between the height and velocity field (Fig. 3). The dependence

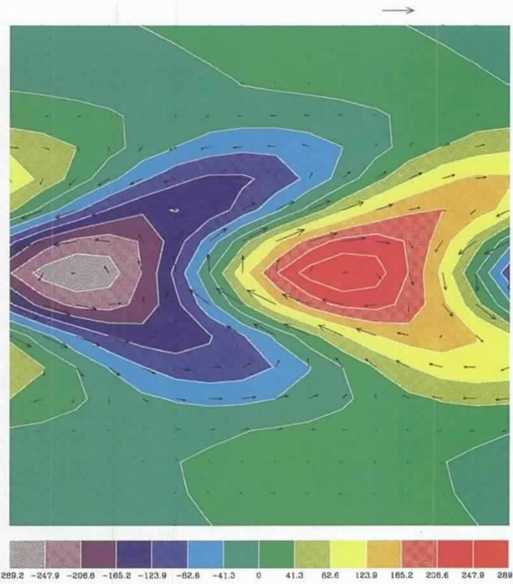


Fig. 1: The one-layer version of the shallow-water model exhibits strong barotropic instability for a basic meridional velocity profile of cosine-square shape (Kuo, 1973). Fields are shown after 10 days of model evolution. Units are m for heights; reference arrow (at top): 54 ms^{-1} for winds. (After Todling and Ghil, 1991.)

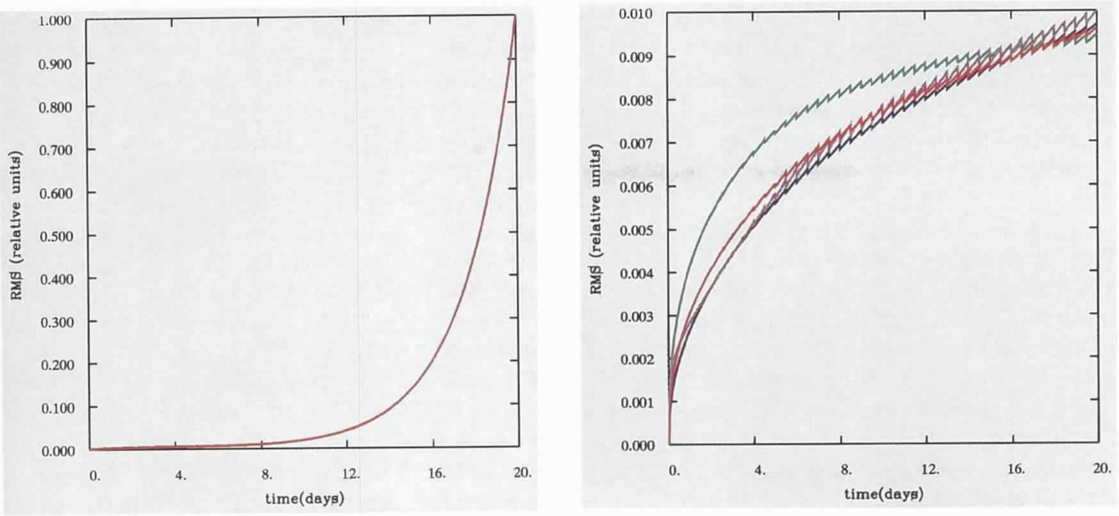
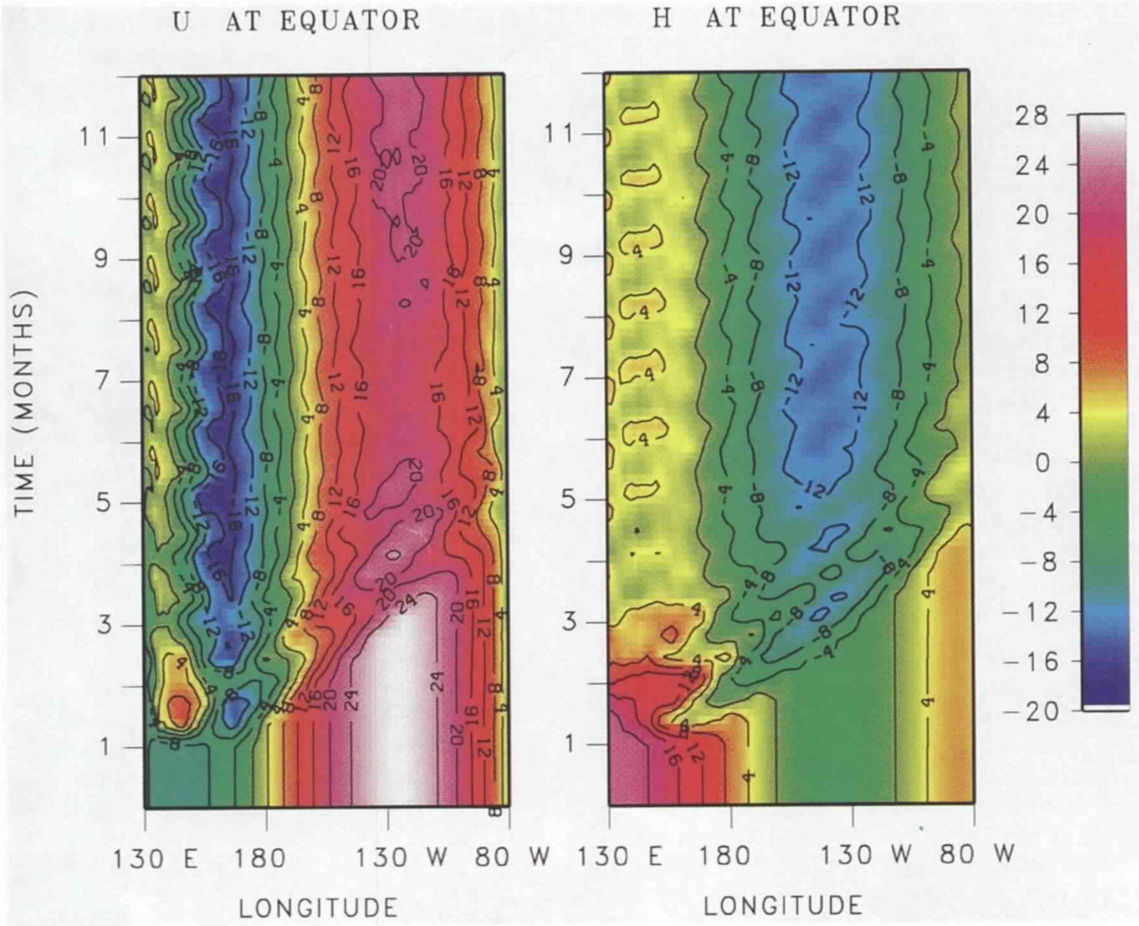


Fig. 2: Expected root-mean-square (RMS) deviation for zonal velocity (blue), meridional velocity (green), heights (purple), and total energy (red) from a Kalman filter applied to an unstable shallow-water model. The panel on the left shows the case without update by observations; curves are normalized by their maximum values and coincide due to the common growth rate of the unstable mode. Panel on the right shows curves for the case with update by observations every 12 hours; curves are normalized by corresponding values in the left panel.



. . . the Kalman filter results in a substantial reduction of the initial error, even for a limited number of observations . . .

Fig. 3: Data assimilation with an optimal interpolation (OI) scheme in the tropical Pacific. Model anomalies are shown when observations of height and zonal velocity are made only along a meridional line in the western part of the basin, at 140°E. Zonal-velocity anomaly (left), and thermocline-depth anomaly (right). Values are in nondimensional units, with a contour interval of four units. (After Hao, 1991.)

of error reduction on location and on the oceanographic field that is being updated arises from the special properties of equatorial waves, which propagate information from data-sparse to data-rich regions of the ocean and transfer information from one field variable (height or velocity) to another.

What can be expected from a data-assimilation method in the presence of strong nonlinearities? Miller and Ghil (1990) address this issue by applying three versions of the extended Kalman filter and several variational methods to a number of geophysical models of increasing complexity. Their provisional answer is that the most advanced assimilation methods are expected to capture transitions between different flow regimes and to provide reliable error estimates in cases of chaotic behavior.

Predictability Studies For The Ocean And Atmosphere

Our predictability studies have focused on two complementary aspects of the problem: instabilities in the open ocean and coastal regions, which limit predictability; and the stability of localized coherent vortex structures, which enhance predictability. We have found shortwave instabilities with rapid growth rates in both a coupled density front with zero potential vorticity (Paldor and Ghil, 1990) and a two-layer coastal front with the interface emerging at some distance from the coast (Paldor and Ghil, 1991). We are proceeding to the nonlinear, viscous treatment of the isolated front, which corresponds to the oceanographically most interesting case of the Gulf Stream north wall.

The coupled GCM [General Circulation Model] produces a realistic simulation of the seasonal cycle . . . , without any flux correction.

Concerning the stability of coherent vortices, we have demonstrated that, in agreement with field observations and numerical experiments, stationary (Sakuma and Ghil, 1990) as well as eastward- and westward-traveling (Sakuma and Ghil, 1991) vortex pairs are linearly stable. Our results provide a stronger criterion for the stability of such pairs than was previously available. The physical basis of these results can be explained by the stabilizing effect of rotation on geophysical flows in Sakuma and Ghil (1992).

Modeling Of The Coupled System

The oceanic global circulation model (OGCM) of the Geophysical Fluid Dynamics Laboratory at Princeton University and the atmospheric global circulation model (AGCM) of UCLA are the components of our coupled GCM. The AGCM provides the wind stress, heat and freshwater fluxes to the OGCM, and the OGCM returns sea-surface temperature (SST) to the AGCM (Mechoso *et al.*, 1991a). The OGCM has a Global version (Bryan and Cox, 1967; Cox and Bryan, 1984) and a Tropical Pacific version with enhanced resolution in the equatorial region (Philander and Pacanowski, 1980). They cover the ocean in the latitude belts from 60°S to 60°N and from 28°S to 50°N, respectively. The northernmost and southernmost parts of the domains are relaxed towards the observed climatology in both salinity and temperature fields. Incorporation of a sea-ice module is under way.

The AGCM has been developed under the direction of A. Arakawa, with the participation of his colleagues and students (Arakawa and Lamb, 1977). This effort has influenced similar developments around the world during the last 30 years. In the middle 1970s, a version of the model was implemented at the US Naval Environmental Prediction Research Facility and the Fleet Numerical Weather Center, both in Monterey, California. This version evolved into the operational NOGAPS (Navy Operational Global Atmospheric Prediction System) forecasting system (Rosmond 1981). The same version is extensively used for forecasting and climate studies at the Meteorological Research Institute in Tsukuba, Japan (Tokioka *et al.*, 1984).

The current version of the model has been used since the early 1980s at UCLA and Colorado State University (Randall *et al.*, 1985). The distinctive feature of this latter version is the treatment of the planetary boundary layer (PBL), which is considered well-mixed and is represented by the model's bottom layer, whose variable depth is predicted (Suarez *et al.*, 1983). The PBL parameterization is crucial for modeling heat and momentum fluxes at the ocean-atmosphere interface. Constant effort is dedicated to improvement of the finite-difference schemes and parameterizations of physical processes included in the model and to optimization of its computer code.

The coupled GCM produces a realistic simulation of the seasonal cycle (Mechoso *et al.*, 1991a), without any flux correction. Figures 4 and 5 show the simulated SST field for July, and the time series of simulated SST at the equator, respectively. Figure 4 depicts realistic configurations for the warm pool in the western Pacific and the cold tongue in the eastern Pacific. Figure 5 shows that the east-west temperature gradient is maintained throughout the year by the coupled system, with the extent of cold water largest in July. There is no evidence of significant climate drift, which is a major concern in modeling of the coupled system (Neelin *et al.*, 1992). The successful simulation of the seasonal cycle is a prerequisite for using the coupled GCM in support of our planned data assimilation and predictability studies. We plan to implement, for the OGCM, a four-dimensional data assimilation scheme based on OI and successive corrections.

The computer code of the coupled GCM is being restructured as part of our participation in the Corporation for National Research Initiatives (CNRI) Gigabit Testbed Initiative. In the final stages of this task, computations will be distributed among several supercomputers connected by a

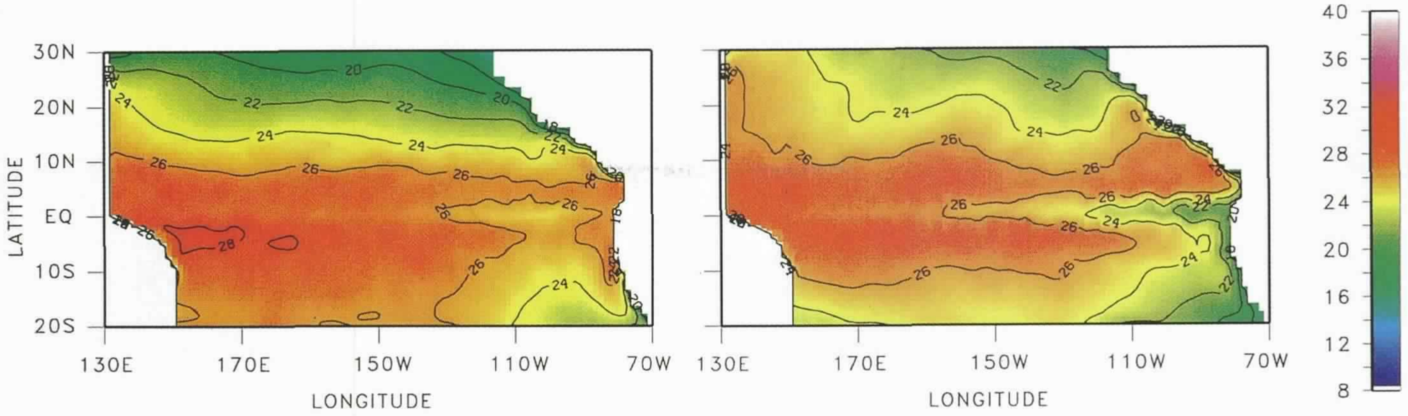


Fig. 4: Sea-surface temperature for January (left) and July (right) corresponding to year 7 in a simulation with the coupled ocean-atmosphere GCM. Units are °C. (After Mechoso et al., 1991a.)

wide-area high-speed (gigabit per second) network (Mechoso *et al.,* 1991b). Other avenues of parallelization for SIMD (single-instruction/multiple data) and MIMD (multiple-instruction/multiple data) architectures are being tentatively explored on simplified GCMs by Ghil *et al.* (1991b).

Concluding Remarks

Methodology for data assimilation and predictability studies on various time scales has been developed and tested on simple models and is ready to be implemented for the UCLA coupled atmosphere-ocean GCM. At the same time, simulations of the seasonal cycle and interannual variability with the coupled GCM are being evaluated. A number of interesting results on data assimilation and predictability for the ocean have been obtained in the process.

In the area of data assimilation, we have evaluated the relative merits of various assimilation methods for the atmosphere and oceans. We have shown the ability of the Kalman filter to track vigorous barotropic and baroclinic instabilities and of the extended Kalman filter to track regime changes in chaotic and stochastically perturbed flows. In the area of predictability, our results include the impact of physical parameterizations (such as that for radiative effects in the AGCM and vertical mixing in the OGCM) on the performance of the coupled system; the existence of shortwave instabilities in frontal structures, both near coasts and in the open ocean; and a theoretical justification of the stability of localized coherent vortex structures in the ocean.

As part of the technological basis for implementing advanced assimilation methods and performing extensive predictability studies on coupled GCMs, we also are exploring modern computer architectures and networks. We expect the coming decade to be one of great excitement for the description, understanding, and prediction of the coupled ocean-atmosphere system.

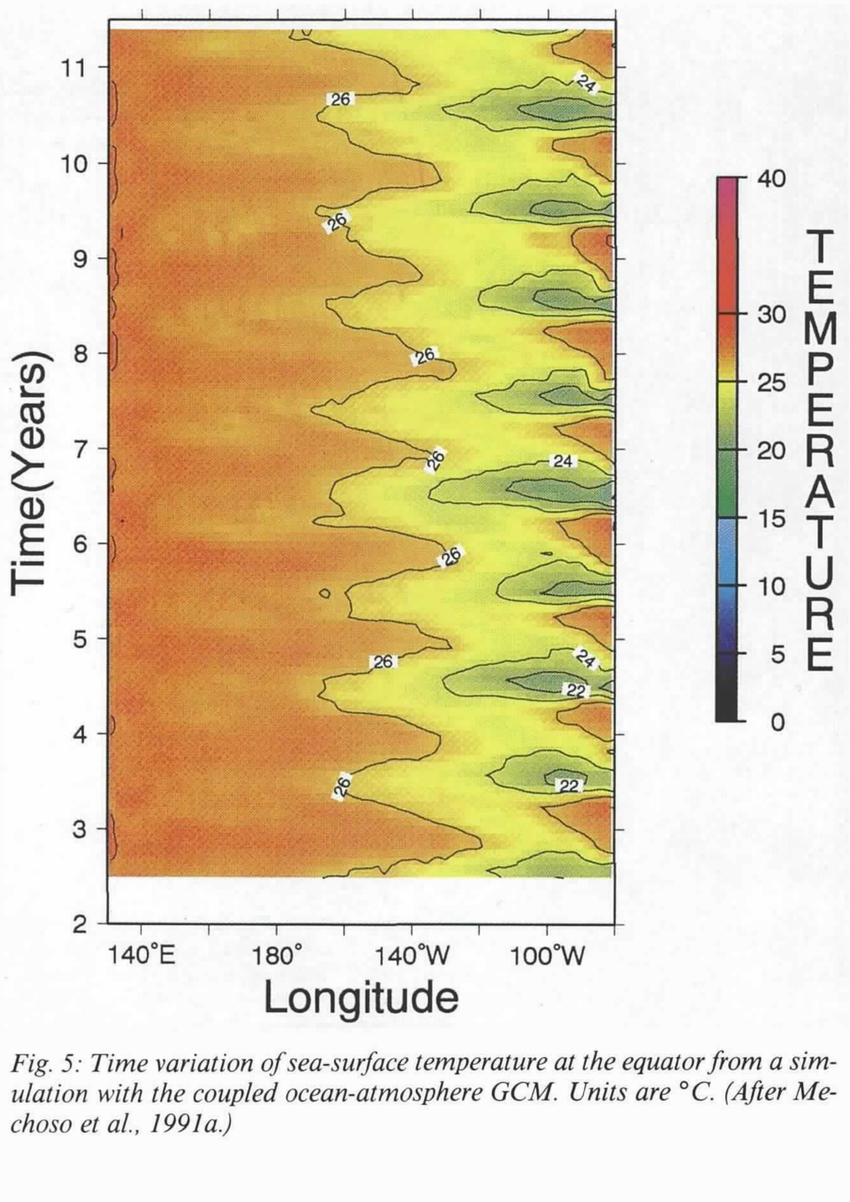


Fig. 5: Time variation of sea-surface temperature at the equator from a simulation with the coupled ocean-atmosphere GCM. Units are °C. (After Mechoso et al., 1991a.)

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