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Coupled general circulation modeling of the tropical Pacific

Pascale Delecluse,[1] Michael K. Davey,[2] Yoshiteru Kitamura,[3] S. G. H. Philander,[4]
Max Suarez,[5] and Lennart Bengtsson[6]

Abstract. During the Tropical Ocean-Global Atmosphere (TOGA) program substantial progress was made in the development of coupled general circulation models with regard to representation of the tropical mean state and climate variability. This paper provides a review of the main developments, focusing on the tropical Pacific region. Early coupled general circulation models were relatively crude; with coarse resolution and limited physical parameterizations and poor surface fluxes, the model drift from the observed mean state was often substantial, and their use for investigating climate variability such as El Niño-Southern Oscillation (ENSO) was limited. Improvements in resolution and parameterizations led to rapid progress. Through the TOGA program it has been possible to assess coupled model mean states and variability against high-quality observations, particularly for the tropical Pacific. Both components of the coupled system (ocean and atmosphere) have benefited from an improved understanding of the physics. Coupled experiments have revealed deficiencies in each model component that were concealed in separate forced runs. Several general systematic errors have yet to be eliminated, especially in the east Pacific. The variety of behavior obtained with coupled models provides evidence that more than one mechanism is active in the generation and evolution of ENSO events. There are also indications that interannual variability is linked to the mean structure of the equatorial Pacific.

1. Introduction

The international program Tropical Ocean-Global Atmosphere (TOGA) started in 1985, with progress toward understanding and predicting Pacific El Niño-Southern Oscillation (ENSO) events as major objectives. Planning for the program was already in progress in 1982 at the time when the 1982-1983 El Niño caught everyone by surprise. That event spurred numerous studies of ocean-atmosphere interactions, including the development of a spectrum of coupled models ranging from simple ones with reduced physics to coupled general circulation models (CGCMs) consisting of atmospheric GCMs (AGCMs) linked to oceanic GCMs (OGCMs). Ten years later, substantial skill in ENSO predictability at lead times of several months has been established using both coupled dynamical models and statistical methods [see *Latif et al.*, this issue]. However, TOGA ended in 1994 during a prolonged ENSO, whose longevity everyone failed to anticipate. That failure is a clear indication that much remains to be done, and the further development of CGCMs remains a high priority.

In 1984 the TOGA scientific plan [*Scientific Plan for the TOGA program*, 1985, p. 71] envisaged that "it is likely that the real test of predictability will be based on the use of coupled atmosphere-ocean dynamical models." However, "only a small number of institutions will have the resources to run coupled models based on the best available AGCM/OGCM combinations," and "it is expected that errors will arise more from errors in the forcing field and errors in the model physics than from errors which will build up naturally due to instabilities." [*Scientific Plan for the TOGA program*, 1985, p. 72] Through rapid advances in computer technology, computationally expensive CGCMs are nowadays available to and used by many research groups. These comprehensive models are yet the most versatile tool available to simulate climate and its variability. Their complexity means that behavior is often difficult to anticipate, and the interaction of many variables means that causes of errors are hard to diagnose. CGCM cost also severely limits scope for experimenting with parameters. Nevertheless, rapid and dramatic development over the last 10 years has considerably reduced the errors in the behavior of such models.

The exploration of the model behavior was facilitated by international collaborations; the TOGA Numerical Experimentation Group (NEG) was set up to help model development. Several meetings were held, at which state-of-the-art methods simulating interannual variability were presented [see *TOGA Numerical Experimentation Group*, 1987, 1988, 1989, 1990, 1991; *Stockdale et al.*, 1993]. TOGA NEG organized an intercomparison of tropical OGCMs on simulation of the mean seasonal cycle and a comparison of skill in the prediction of ENSO.

Some historical background to the development of CGCMs is given in section 2. In section 3 the major climate drift difficulty encountered by coupled systems is discussed. Different sources of errors can contribute to this problem, as illustrated by some examples. An important source of errors in early models was the very low spatial resolution used in each component; in section 4 the relevant scales in the ocean and in the atmosphere are described, and some examples illustrate how the choice of resolution can affect the behavior of the coupled system. Section 4 includes a discussion of resolution with regard to ocean-atmosphere coupling techniques. Some of the physical aspects of current ocean and atmosphere models

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[1] Laboratoire d'Océanographie Dynamique et de Cimatologie, Unité Mixte de Recherche CNRS/ORSTOM/UPMC, Paris, France.

[2] Hadley Centre, U.K. Meteorological Office, Bracknell, England, United Kingdom.

[3] Meteorological Research Institute, Tsukuba, Japan.

[4] Princeton University, Princeton, New Jersey.

[5] NASA Goddard Space Flight Center, Greenbelt, Maryland.

[6] Max Planck Institut for Meteorology, Hamburg, Germany.

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are described in section 5, with examples of how the choice of some physical parameters can modify the structure of the circulation in each component and in the coupled system. Correct simulation of the seasonal cycle is an important aspect of CGCM development, not least because the interannual variability seems closely related to the seasonal cycle. When long integrations are made with a CGCM, an important task is to evaluate the simulated mean seasonal cycle. Complex coupled feedbacks are involved in determining the asymmetrical structure of the tropical Pacific, and good simulation with a CGCM is difficult, as described in section 6. The interannual variability produced by CGCMs is discussed in section 7, with emphasis on the need for a conceptual framework to interpret their complex behavior. The conclusions review some critical issues raised during the TOGA program.

2. Historical Overview

Stimulated by weather prediction applications, AGCMs were first developed in the 1950s, with many subsequent improvements and additions to the atmospheric processes represented. Pioneering work at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton led to the first OGCMs in the 1960s [*Bryan and Cox*, 1967] and, subsequently, to CGCMs in the late 1960s; *Manabe and Bryan* [1969] used a very simple sector configuration to simulate air-sea coupling with a CGCM. CGCMs with more realistic geometry were developed in the 1970s [*Manabe et al.*, 1975; *Bryan et al.*, 1975]. Initial applications were to the mean climate and then to large scale changes such as might be induced by doubled CO^2.

Coupled climate study was extended to the ocean first by adding a swamp condition at the bottom of an AGCM [*Manabe et al.*, 1975]; next, a nondynamic slab oceanic mixed-layer, able to buffer air-sea net heat budget and allow inclusion of a seasonal cycle, was considered. When such experiments first took into account the oceanic circulation by coupling the AGCM to an OGCM, computer limitations (in both memory and speed) required the use of coarse resolution, with the ocean grid being comparable to the atmospheric grid and few vertical levels [*Manabe and Stouffer*, 1988; *Washington and Meehl*, 1989]. The mean climate state was distinctly different from the observed state. In a typical case, errors in the tropical Pacific were attributed to the oceanic resolution [*Meehl*, 1989]. Nevertheless, some of those models produced some interannual variability that resembled some aspects of the Southern Oscillation [*Sperber et al.*, 1987; *Meehl*, 1990b].

During the 1980s the application of coupled models to ENSO greatly increased. In 1984, at the first Liège meeting on coupled ocean-atmosphere models [*Nihoul*, 1985], several coarse-resolution CGCMs were presented, but ENSO behavior was analyzed with respect to the separate atmospheric and oceanic components. ENSO-like interannual oscillation in coarse CGCMs was reported at a meeting in London [*Charnock and Philander*, 1989], at the second Liège meeting [*Nihoul and Jamart*, 1990], and in a review by *Meehl* [1990a]. *McCreary and Anderson* [1991] provided a review of ENSO models, from a conceptual theoretical approach through CGCMs, which made evident the complex and sensitive nature of CGCMs.

Neelin et al. [1992] made the first comparison of tropical Pacific behavior of CGCMs (including several high- and low-resolution CGCMs), with the aim of identifying common behavior within some definite parameter range. Defining a taxonomy of model variability proved to be an impossible task, given the wide range of simulated mean states and variability covered by the different CGCMs. Many of these CGCMs had major errors in the mean temperature of the equatorial Pacific and its mean zonal gradient. Interannual variability ranged from very weak to moderate. In a more recent CGCM intercomparison, *Mechoso et al.* [1995] concentrated the analysis on the mean state in the equatorial Pacific and the mean seasonal cycle. The results show that large improvements have been made; most of the ocean models had the necessary resolution in latitude to resolve the equatorial upwelling, and most atmospheric models had improved physical processes (e.g., cloud and radiative scheme). All models considered were able to simulate the mean temperature within 2° or 3°C of the observed value and its mean gradient at least in the central equatorial Pacific. Nevertheless, the CGCMs still had substantial biases from the observed state, and it was difficult to relate the interannual variability to the seasonal cycle representation. Notably, poor seasonal behavior did not preclude reasonable interannual behavior and vice versa.

The development of CGCMs is an activity that depends on a measurement program, and on insights gained from theoretical studies. TOGA was successful in developing a monitoring program and stimulating theoretical and modeling developments side by side. CGCMs produce oscillations similar to but also different from the observed Southern Oscillation. As long series of observations emerge, different patterns and interpretations of ENSO appear; CGCMs are getting closer to observations, and their differences create an ensemble useful to cover the spectrum of the natural variability.

3. Drift Problem

CGCM behavior is much better than 10 years ago, largely because of a strong reduction in climate drift. This section will explore the main reasons for climate drift in CGCMs.

3.1. General Description of the Problem

Most atmospheric GCMs involved in ENSO experiments have been tested in numerous case studies with observed sea surface temperature (SST), and tuned to the point that their behavior is considered reasonable. The same is true for most ocean models, which compare reasonably well with (albeit limited) ocean observations when forced with prescribed atmospheric conditions. The problem when coupling ocean and atmosphere models is that an apparently insignificant error in one of the system components can be amplified by positive feedback and in due course strongly affect the behavior of the system. The reverse is also true; the coupling may generate negative feedbacks that help to maintain correct structures. For example, when a fixed net heat flux from a climatology is applied to an ocean model, a positive error in that heat flux can warm the ocean to a unacceptable level; on the contrary, when the turbulent fluxes are computed with evolving SST, a negative feedback (e.g., with increased latent heat flux) prevents SST from rising to the same extent.

The early comparison of CGCMs by *Neelin et al.* [1992] showed a huge variety of patterns. Many of the coupled models had a climate drift, which could occur either as a slow drift away from climatology on quite long timescales or as a rapid adjustment, leading to a state significantly different from observed climatology. The aim of the comparison was to provide a rough classification of an ensemble of models on the basis of their interannual variability. Two main classes of such variability were found in the coupled systems: zonally propagating SST modes or standing SST oscillations associated with subsurface wave dynamics. The comparison highlighted the large sensitivity of CGCMs; more than one mechanism appeared to produce interannual variability, and coupled feedbacks modified the mean state of the models. Though there was no clear relation between drift and the ability of a model to generate oscillatory behavior, the comparison suggested that an accurate simulation of Pacific climatology was important as a guide to the selection of the best parameters for the models.

The origin of the model drift can be difficult to determine. Part of the drift can be anticipated from the flux imbalance between both model components in separate forced simulations, but the air-sea feedbacks are highly nonlinear, and the coupled system might develop unexpected behavior. The drift of a coupled system can have numerous causes of varying severity. It may come from an imbalance of initial conditions, from internal parameterizations in one of the components, or from the coupling itself.

One source of drift is initial imbalance. One way to initialize a coupled system is as follows. The ocean model is driven toward equilibrium under prescribed atmospheric forcing, extracted from an atmospheric analysis or from the atmospheric model to which it will be coupled. (Note that the ocean has a lot of inertia and a heat capacity many times larger than that of the atmosphere. To respect this thermostat property, forced ocean models specify some feedback in the heat flux formulation in order to reduce the drift away from observed SST during spin-up.) In turn, the atmospheric model is driven by prescribed SST, then both models are coupled together and run forward. Typically, the system rapidly (within weeks) surges to a warm phase or a cold ENSO phase, triggered, for example, by an initial imbalance between the equatorial winds and the ocean equatorial pressure gradient. This form of rapid drift creates difficulties when using CGCMs to make climate predictions. It can be reduced by, for example, spinning up the coupled system with relaxation to prescribed SST.

At longer timescales, climate drift in coupled models becomes less dependent on the initial conditions and, as shown by *Moore and Gordon* [1994], inconsistencies in the air-sea interface fluxes arise from systematic errors inherent to each component. The atmospheric boundary layer and the oceanic mixed layer can reach a new equilibrium within a few months. (This is the typical timescale to balance the coupled system within the tropics. The full equilibrium of the global system takes much longer because it involves the global thermohaline circulation.)

3.2. Illustration of Drift

A few examples will illustrate the origin of the drift in some coupled experiments. When the origin of the drift has been clearly identified, it is possible to fix it and thus improve the results substantially. *Gordon* [1989] described a CGCM run at the U. K. Meteorological Office (UKMO) which quickly drifted to a very warm state in a 2.5-year run. A first problem arose because cooling by latent heat flux in convective regions was too low; this was due to very light model winds in those regions. Gordon used the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) data to relate convection to wind variability unresolved by the model and added a "gustiness" parameterization that effectively boosted fluxes in convective regions. The effectiveness of this formulation led atmospheric modelers to make adjustments to their flux parameterizations, and gustiness has now been replaced by better wind speed dependence of latent heat flux coefficients [*Beljaars*, 1995]. A second problem in the UKMO run was that shallow hot surface layers developed in the ocean. This effect was traced back to the vertical mixing; only mixing with coefficients related to the Richardson number [*Pacanowski and Philander*, 1981] were used with no explicit wind dependence. *Ineson and Gordon* [1989] added a bulk mixing model [*Kraus and Turner*, 1967] to their OGCM, and the wind mixing part of that scheme helped remove the shallow hot layers. This effect is discussed in some detail in the *McCreary and Anderson* [1991] review paper. The revised CGCM from UKMO had reasonable climatology with a slow cool drift in a 13-year run but no ENSO-like interannual variability (see the *Neelin et al.* [1992] review).

When essentially the same ocean was coupled to an improved AGCM, very little long term drift and good interannual behavior were obtained [*Ineson and Davey*, 1997]. A strong warm bias in east Pacific SST remained, however. This is another common error in CGCMs, and it is partly related to the general difficulty of maintaining marine stratus over eastern tropical oceans (see section 6).

A cool equatorial bias has often been observed in global coupled models [*Manabe et al.*, 1979; *Washington et al.*, 1980; *Gent and Tribbia*, 1993; *Moore and Gordon*, 1994; etc.]. It can occur because of insufficient incoming solar flux at the air-sea boundary, cloud cover can be too dense, or turbulent surface fluxes (latent and sensible) or oceanic upwelling can be too high, in connection with a strong surface stress. A cold surge was frequently observed in early coupled models associated with excessive oceanic equatorial upwelling (as identified by *Meehl* [1989] in his model where a 450-m-thick second layer was brought to the surface). Cold water rises to the ocean surface due to trade-wind-induced Ekman divergence, which competes with vertical diffusion within the ocean mixed layer. Too strong a divergent circulation was diagnosed by *Philander and Pacanowski* [1986] in an early GFDL model and noted recently in many Pacific models in the comparison with drifter data from the Surface Velocity Program (SVP) during the joint TOGA NEG-SVP meeting: vertical diffusion was not deep enough to compensate the divergence.

Even in the recent comparison reported by *Mechoso et al.* [1995] where oceanic components were high-resolution OGCMs, most models had a substantial annual mean cold bias in the equatorial Pacific [see *Mechoso et al.*, 1995, Figure 1]. Often, cold equatorial temperature is also associated with westward displacement of the main zonal gradient. Figure 1 illustrates the state of the art for equatorial Pacific SST (averaged between 2°N and 2°S) for April and October for nine CGCMs which are currently used to study ENSO. Each of the models shown is too cold in the central and west Pacific in April and October, and most have a substantial warm bias in the far eastern Pacific. The location of the cold tongue minimum in October (observed near 100°W) is displaced westward in most of the models.

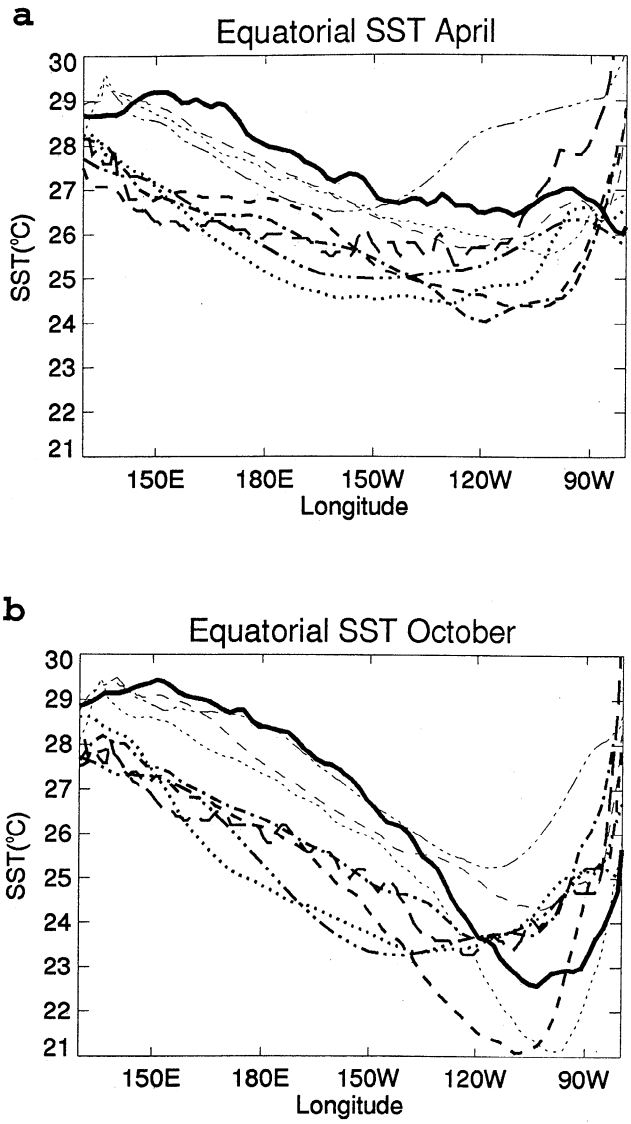

Figure 1. Equatorial section of temperature in April and in October between 2°N and 2°S for nine different coupled general circulation models (CGCMs); the solid line corresponds to observations

3.3. Flux Correction

In order to maintain CGCM climatology close to that observed, despite serious drift effects, the "flux correction" (or "flux adjustment") method [*Sausen et al.*, 1988] has been used in various forms by some modeling groups to take into account the imbalance of fluxes between ocean and atmosphere. The flux correction for heat can be estimated as follows.

1. A first estimation of net air-sea heat flux is made with the uncoupled AGCM run with prescribed SST.
2. The OGCM is driven by climatological forcing with a Newtonian term in the heat flux to keep SST close to observed climatology. Thus the net heat flux needed by the OGCM is determined.

The difference between these two net heat fluxes is considered as an imbalance between both models under climatological forcing and is applied in the CGCM as a constant (in time) correction which is independent of the state of the coupled model. Variants of this technique have been used by a number of coupled models to prevent substantial drift.

While flux correction is quite successful in reducing the drift, *Neelin and Dijkstra* [1995] have shown that it adds a spurious feedback mechanism that changes the dynamical system; the nature of ENSO variability in a coupled system may be quite different with and without flux correction. The difficulty of eradicating the drift from coupled models has driven the development of predictive CGCMs that use some kind of anomaly coupling [see *Latif et al.*, this issue].

With continued improvements to the OGCM and AGCM components, some current global CGCMs have been successfully run for several decades with no flux adjustment. Note that in limited region models, such as those with tropical Pacific OGCMs, the use of SST climatology outside the active ocean domain, plus prescribed ocean climatology at open boundaries, effectively provides a weak drift limitation mechanism.

4. Resolution Issue

Research with atmospheric models of varying resolution have shown that the main circulation features can be reasonably reproduced with a spectral model with a triangular truncation at 42 wave-numbers (T42) (equivalent to about 3° resolution in a gridpoint model) and with good representation of physical processes. T42 is sufficient to resolve the main baroclinic dynamical processes that are important in the maintenance of the mean circulation; even T30 may be adequate with careful tuning (for instance, *Boer et al.* [1991]). Of course, many physical processes happen at a smaller scale than the T42 grid. Recent analyses [*Williamson et al.*, 1995] have shown that while many statistics of the atmospheric circulation converge at increased resolution, processes that maintain the climate do not, especially on a regional basis.

The situation is different in the ocean. The typical oceanic baroclinic (Rossby radius) scale is 2 orders of magnitude smaller than in the atmosphere, being about 1° near the equator and smaller at higher latitudes. Fortunately for ENSO studies, it is not essential to resolve the baroclinic eddy scale globally. However, observations reveal strong baroclinic-scale features along the equator, such as the Equatorial Undercurrent, which are important for climate. Theoretical studies have shown the importance of the baroclinic wave guide properties within the equatorial ocean [e.g., *Moore and Philander*, 1977; *Cane and Sarachik*, 1979]. The equatorial Kelvin and Rossby waves travel relatively rapidly and propagate information efficiently along the equator. They exert a substantial influence on thermocline depth and hence on SST, remotely from sources of atmospheric forcing. Thus the baroclinic ocean scale should be resolved near the equator to represent equatorial currents, upwelling, and equatorially trapped Rossby and Kelvin waves properly.

Ng and Hsieh [1994] have analyzed the effects of resolution (and associated diffusivity constraints) on equatorial waves. To represent equatorial processes well, a numerical ocean model should have meridional grid spacing smaller than about 0.5°. Vertical grid resolution should also be high in the upper ocean (less than about 20-m spacing) to help represent vertical mixing and to resolve a strong thermocline that varies substantially with depth.

Coarse-resolution CGCMs have been shown to be capable of simulating first-order aspects of variability on a variety of timescales [*Stouffer et al.*, 1994; *Meehl et al.*, 1994; *Tett*, 1995; *Manabe and Stouffer*, 1996; *Tett et al.*, 1997b]. Analysis of interannual variability in low-resolution coupled models has been performed by *Gates et al.* [1985], *Sperber et al.* [1987], *Meehl* [1990b], *Lau et al.* [1992], *Moore* [1995], *Tett* [1995], and *Miller and Jiang* [1996] among others. Although they can generate low-frequency variability, the mechanisms involved are often different from those operating in high-resolution models. Nevertheless, it is useful to investigate low-resolution coupled GCMs from an ENSO perspective because they have global coverage and often run for several model decades and thus provide information on the relations between ENSO and wider space and timescales. They also help to highlight fundamental processes involved in the anomaly cycle.

To illustrate the role of oceanic resolution, it is useful to refer to the comparison by *Philander et al.* [1989] with the same atmospheric model coupled to a global coarse-resolution (4.5° spacing in latitude and 3.8° in longitude, with 12 vertical levels) ocean model, and to a high-resolution tropical Pacific ocean model (grid spacing 1/3° between 10°N and 10°S and increasing poleward, 1° in longitude and 27 vertical levels). The coefficient of horizontal dissipation was 2.5 x 10^5 m^2/s for the coarse model and 2 x 10^3 m^2/s for the other. Both models produced interannual variability in the tropical Pacific. The occurrence of interannual variations was more regular in the coarse-resolution model in which the events slowly migrated westward across the Pacific Ocean. By contrast, there was no definite pattern for events in the high-resolution model; they could develop as stationary patterns or move eastward. *Philander et al.* [1989] argued that the difference in the behavior of these CGCMs can be understood by the way the anomalous patterns of SST propagated. In the coarse model, SST was mainly evolving via horizontal advection; the deep well-developed South Equatorial Current (SEC) advected SST patterns westward. In the high-resolution model the SEC was weak, and the SST patterns were much more sensitive to vertical advection controlled by the eastward propagating Kelvin waves. These waves were rapidly dissipated in the coarse model by the necessary large damping. The contrast between the low- and high-resolution CGCMs was analyzed further by *Lau et al.* [1992] and *Philander et al.* [1992]. Note, though, that in this comparison the AGCM was that described by *Lau* [1985], with a rhomboidal truncation at 15 wavenumbers (R15). This low-resolution atmospheric model had limitations of its own, and the overall ability of the coupled model could not be judged in terms of one of its components alone.

Some biases can lead to compensation between different mechanisms. For instance, coarse-resolution AGCMs tend to develop trade winds which are too low at the equator. These low wind stresses reduce surface currents in the ocean and thus diminish advection. One defect (e.g., enhanced role of horizontal advection compared to wave dynamics) may compensate another (e.g., weak advection due to weak winds).

In some cases the same oceanic model has been coupled to different resolution AGCMs. Figure 2 shows a 10-year average of SST from the global OGCM OPA from the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC) [*Madec and Imbard*, 1996] coupled to T21 and T42 versions of the ARPEGE climate AGCM from the Centre National de Recherche Météorologique (CNRM) [*Déqué et al.*, 1994] (the experiment is described by *Guilyardi et al.* [1995]). The OGCM has equatorial resolution of 0.5° near the equator, which resolves the main equatorial waves. Both coupled experiments have similar biases in their mean structures; the tropical SST is too warm, and the gradients are weak; the cold tongue is thin and located in the eastern Pacific; and warm waters extend too far east, south of the equator. However the biases are less pronounced in the high-resolution model, and coastal eastern equatorial regions move from cold to warm SST. Biases also have a large effect on the surface salinity, which partly reflects the distribution of precipitation. In the coarse-resolution model it is not possible to distinguish northern and southern convergence zones: a single convergence area covers almost the whole central west Pacific. These modified mean states interact with the interannual variability, which is very irregular and weak in the high-resolution model and more regular and with a strong amplitude in the coarse-resolution model (more than 4°C).

Resolution also has coupling implications. The atmosphere is coupled to the ocean via the SST field. If the coupling is done with spatial interpolation of SST to a coarser AGCM grid, then detailed information about the SST is lost. Likewise, information that the ocean requires is degraded if calculated on the AGCM grid and simply interpolated to the ocean grid. In particular, wind stress curl can be underestimated through this effect. This coupling effect has been investigated by E. Schneider (private communication, 1996) who described model equatorial SST as computed on the ocean grid and as used by the atmospheric model via a coupling interface. He found that the narrow equatorial upwelling region is strongly damped by the coupling, and there is a strong reduction of the trades as a result of damping introduced by the coupling.

One way to overcome this problem, proposed by *Vintzileos and Sadourny* [1997], is to calculate fluxes at each oceanic model grid point using detailed atmospheric physics (clouds, convection, boundary layer dynamics, etc.). The information is then passed to the atmospheric model, with interpolation to the atmospheric grid for the dynamical calculation. Thus the interpolation is done within the atmospheric model itself, between the grid where the high-resolution physics is solved and the coarse dynamical grid. Such a technique allows conservative exchanges of heat, fresh water, and momentum fluxes between the ocean and atmosphere; it could easily be extended for land coverage and sea ice. This method represents a new approach to the climate problem, whereby there is strong emphasis on the air-sea interface rather than on separate components. However, it requires the computation of the physical processes of the AGCM at each ocean model point; as this is the most expensive part of the AGCM, the cost of computation is considerably increased.

5. Physical Issues

5.1. Ocean

In section 3 we emphasized the importance of reducing the errors in each component of the coupled system. A more complete review on the development of oceanic modeling of ENSO is presented by *Stockdale et al.* [this issue]. In tropical ocean models with resolution high enough to represent the main features of equatorial dynamics, a major source of uncertainty comes from the parameterization of mixing. Some examples will illustrate how the parameterization chosen for mixing processes can affect the oceanic state.

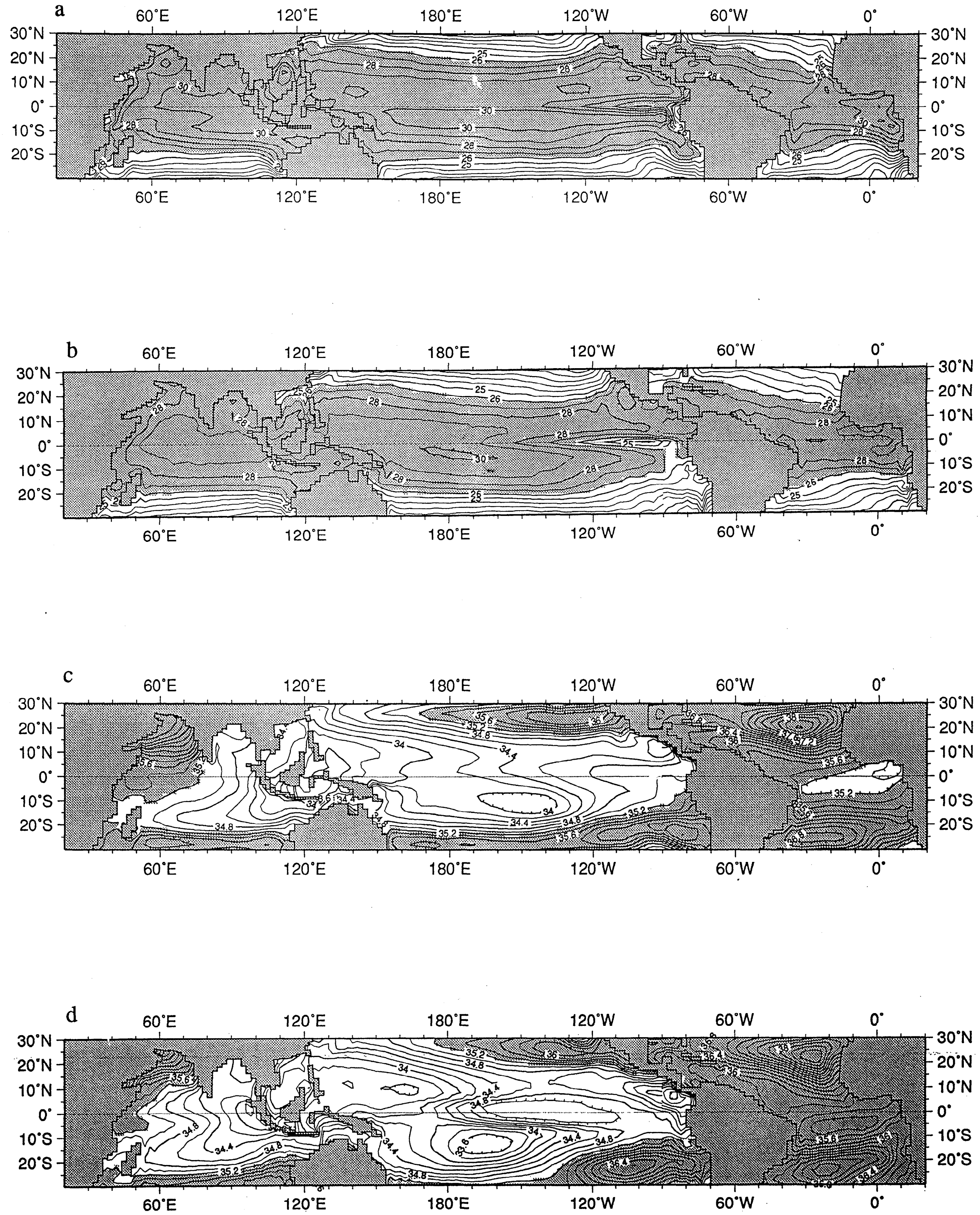

Figure 2. Ten-year-average (a,b) temperature and (c, d) salinity in tropical regions for the global ocean model coupled with the T21 atmospheric GCM (Figure 2a and 2c) and the T42 atmospheric GCM (Figure 2b and 2d). Contour interval is 1°C for Figure 2a and 2b; 0.2 psu for Figure 2c and 2d.

5.1.1. Horizontal dissipation and diffusion. The value of the coefficient of horizontal momentum dissipation is directly linked to the horizontal grid spacing; it is mostly chosen for numerical stability reasons. It is much larger than the molecular viscosity within the ocean and is supposed to simulate the large eddy activity which is not explicitly solved. A Laplacian (or bi-Laplacian) operator is often chosen for reasons of simplicity (on the basis of an analogy with the viscous tensor), but it is a poor choice to translate the turbulent activity as the source of mixing in the ocean. This is certainly an area where major efforts are needed to develop parameterizations more adapted to the proper description of mixing properties. For the coefficient of horizontal diffusion for tracers, its order of magnitude is chosen in accordance with in situ large-scale observations. For equatorial regions, there are very few studies on how these choices can influence the behavior of the ocean models.

Stockdale et al. [1993] analyzed several different OGCMs and suggested that the effect of reducing horizontal dissipation is to shift the SST cooling toward the east and that a low value of dissipation is needed to get realistic features. However, the OGCMs involved in the comparison had many other differences (in resolution, numerical scheme, boundary conditions, etc.), so the conclusions were tentative. In a more recent study, *Maes et al.* [1997] analyzed tropical simulations made with the same OGCM but three different orders of magnitude of horizontal dissipation. They concluded that the 10^3 m^2/s value proposed by *Stockdale et al.* [1993] is the order of magnitude which gives the most reasonable equatorial structures. When the coefficient is multiplied by 10, horizontal dissipation suppresses nonlinear physics along the equator and the viscously dominated system tends to generate erroneous recirculation in the meridional plane. The dynamics of the Equatorial Undercurrent is strongly affected by increased dissipation. By contrast, the use of a very small dissipation coefficient (10^2 m^2/s) tends to boost vertical diffusion. Maes et al. had a variable vertical diffusion coefficient, and their study also demonstrated strong interplay between the horizontal and vertical diffusion coefficients.

The use of a strictly horizontal diffusion operator creates problems by exaggerating diffusion across isopycnals, particularly where isopycnal slopes are relatively large. This difficulty can be overcome to some extent by rotating the stress tensor to make the diffusion follow the isopycnal shape rather than remain strictly horizontal [*Redi*, 1982]. More recently, *Gent and McWilliams* [1990] proposed a scheme to represent isopycnal diffusion induced by the loss of potential energy through baroclinic instabilities (see also the review by *McWilliams* [1996]). Their scheme computes an advective correction term that tends to diffuse isopycnal sharp structure. It has a large impact in coarse-resolution models where mixing through mesoscale activity is not resolved at all. For high-resolution tropical OGCMs, however, the advantage of these alternative schemes is not clear.

5.1.2. Vertical dissipation and diffusion. Vertical diffusion is very important in ocean models because it controls the transfer of information from the atmosphere-ocean interface to deeper levels. In equatorial regions the observed thermocline is sharp, and there is a well-mixed surface layer all year. This vertical structure should be represented in models to trap energy in the upper ocean. The vertical shear of currents is strong in the surface layers, and the impact of the wind stress forcing in the ocean is concentrated in a very thin Ekman layer where divergence is strong (see the analysis for the Atlantic Ocean presented by *Reverdin et al.* [1991]). The mechanism which maintains the equatorial cold tongue is very sensitive to the formulation of vertical mixing.

The coefficients for vertical diffusion and dissipation are several orders of magnitude smaller than the horizontal ones, corresponding to the much smaller vertical scales. If mixing is simply represented by a constant coefficient, there is a tendency to spread the thermocline toward a linear profile from top to bottom [*Philander and Pacanowski*, 1980]. Using a smaller value in the upper ocean inhibits the spreading of the thermocline but leads to a very thin surface layer isolated from the deep ocean.

For tropical oceans, *Pacanowski and Philander* [1981] introduced an empirical parameterization based on the local Richardson number to relate vertical mixing to vertical shear and stratification. It corresponds to a simple diagnostic approach to estimate the local value of the turbulent kinetic energy (TKE). Their simple formulation (widely adopted and often referred to as K theory mixing or the P-P scheme) is designed to produce relatively large values of vertical mixing in surface layers where stratification is weak and/or vertical shear of currents is large, with weak values in the thermocline region and below. This scheme is well suited for the generation of mixing due to the vertical shear of zonal currents present in the equatorial regions.

The standard P-P scheme is not able to generate strong enough mixing in surface layers and the simulated mixed layer is often too shallow. A turbulent source provided by the surface forcing is missing in the P-P formulation; one solution is to add an embedded wind mixed layer (on the basis of, for instance, a *Kraus and Turner* [1967] energy balance scheme) to increase turbulence due to wind stirring in surface levels. Such a scheme was introduced in the UKMO model by *Ineson and Gordon* [1989] and a similar hybrid scheme method using *Kraus and Turner* [1967] and *Price et al.* [1986] schemes has been implemented in a tropical Pacific OGCM by *Chen et al.* [1994].

More sophisticated (and correspondingly computationally demanding) formulations have been introduced in numerical models to compute vertical diffusion as a function of TKE and a mixing length [*Mellor and Yamada*, 1982]. *Smith and Hess* [1993] and *Halpern et al.* [1995] have compared tropical Pacific OGCM simulations using the P-P and *Mellor and Yamada* (M-Y) schemes: M-Y offers some advantages, but the much simpler P-P scheme performs quite well. *Ma et al.* [1994] found that the M-Y formulation gives a much better defined thermocline in the eastern Pacific.

A parameterization based on a 1.5-level turbulent closure (prognostic equation for TKE and diagnostic calculation for mixing length) has been tested for the equatorial ocean by *Blanke and Delecluse* [1993], and the results in the equatorial Pacific are presented by *Stockdale et al.* [1993]. Their analysis showed the effectiveness of the turbulent formulation in deepening the impact of the surface fluxes. *Yu and Schopf* (1997) has compared several mixing parameterizations in a quasi-isopycnal ocean model of the tropical Pacific. Their results confirm the need to get high surface mixing in the upper ocean layer, controlled by current shear and wind stress, and much lower mixing under the mixed layer.

Another alternative has recently been proposed by *Large et al.* [1994]. On the basis of atmospheric boundary layer "'large-eddy" mixing models, diffusivity and viscosity coefficients have vertical profiles that are zero at the surface, increase to a large maximum within the well-mixed layer, then decrease to low values at thermocline levels and below. One effect of this choice is that model Ekman layers are less surface concentrated.

The choice of a mixing scheme is an intrinsic part of an OGCM and must be carefully tuned for each model. The tuning is difficult because the best observed field (SST) is not a particularly good variable for evaluating parameter choices; SST is too sensitive to the specification of heat fluxes, and different internal oceanic structures can generate nearly identical surface fields via different mechanisms. Other oceanic observations such as currents and subsurface thermal structure are needed for validation, and the in situ observational programs of TOGA (e.g.; SVP drifters, Tropical Atmosphere-Ocean (TAO) moorings) are very valuable for this purpose.

5.1.3. Limited area models. Many ocean models are limited to the equatorial Pacific (30°S to 30°N or 50°S to 50°N). The limited ocean model can be run economically at much higher resolution than a global domain of comparable resolution. Observed temperature and salinity climatology can be imposed in diffusive boundary layers along the northern and southern limits of the domain. The atmospheric component of a corresponding CGCM has SST climatology imposed outside the ocean domain. For ENSO studies this strategy has an underlying assumption that ENSO can be treated independently of ocean-atmosphere interaction and thermohaline variations outside the tropical Pacific. This strategy may have important limitations. It has been recently proposed that the interannual variability in the equatorial Pacific can be modulated by decadal changes in the mean equatorial state that are associated with extratropical features [*Philander et al.*, 1996] via oceanic subduction at midlatitudes [*McCreary and Lu*, 1994; *Liu et al.*, 1994]. Subsurface anomalies, perhaps induced by ENSO itself, can be advected to the equatorial region and influence ENSO activity. A CGCM with an ocean component limited to the tropical Pacific will lack this process.

Another potential source of error could come from the effect of a limited domain on the location of convective areas (over land and over the Indian-Pacific region), which could be an important element for tropical variability. In particular, if the Indian Ocean is fixed at climatology and does not respond to events in the Pacific, then convection may move too readily to the central Pacific in response to Pacific warming.

A solid western boundary in a Pacific-only OGCM prevents communication with the Indian Ocean via the multiple paths that allow the Indonesian throughflow. The warm and fresh Pacific-to-Indian throughflow has a mass transport estimated in a range from 0 to 20 Sv, strongly variable in time. (See the May 15, 1996 special issue of the *Journal of Geophysical Research (Oceans)* on Pacific low-latitude western boundary currents and the Indonesian throughflow.) Its variability during the ENSO has been noted on expendable bathythermograph (XBT) data [*Meyers et al.*, 1995]. With solid western boundaries, Pacific-only OGCMs possibly overemphasize the role of boundary reflection in ENSO, but there is no convincing evidence that this is the case. Reflection of long equatorial waves at the western boundary is a fundamental ingredient of "delayed oscillator" theories for ENSO [*McCreary*, 1983; *Schopf and Suarez*, 1988; *Battisti*, 1988; *Battisti and Hirst*, 1989]. From observations, it is very difficult to prove the efficiency of this process. Recent data from TOPEX/POSEIDON analyzed by *Boulanger and Fu* [1996] clearly show the reflection at the eastern boundary, but the western reflection is more ambiguous.

A comparison has be done by *Nagai et al.* [1995] with an AGCM coupled to a Pacific-only OGCM and to an Indian-Pacific OGCM. Both coupled models exhibit very similar mean states and the interannual variability in the Pacific Ocean seems to follow identical mechanisms. The anomalous pattern of SST is stationary, and its cycle is sustained by a subsurface heat content anomaly propagating eastward. The open or closed boundary with the Indian Ocean does not seem to alter processes on the Pacific side. The atmospheric variability on the Indian Ocean is affected and shows much larger variability when the Indian Ocean is introduced in the coupling. However, the relationship between the ENSO variability and the Indian Ocean variability is not well established in this experiment.

5.2. Atmosphere

The representation of atmospheric physical processes in AGCMs varies widely; the response of AGCMs to a specified SST pattern can differ substantially from one model to another, as evidenced in results from the Atmospheric Model Intercomparison Project (AMIP). Surface fluxes present particular difficulties, as they are the product of several processes, and observations are subject to large uncertainties. There are many studies on the sensitivity of the atmosphere to different parameters, but there are only a few in a CGCM configuration because the experiments are computationally very expensive. When an AGCM is coupled to an ocean model, seemingly unimportant errors can be magnified by the coupling. The development of CGCMs has thus revealed some deficiencies in atmospheric physical parameterizations that need to be analyzed and corrected to improve the representation of the atmosphere.

Cloud sensitivity is very large and presents many different aspects. Some parameters affect the global coverage of clouds because they modify the whole radiative budget. Large changes in SST are expected as there is a global adjustment to the greenhouse effect. On the other hand, when a parameter affects clouds locally, the change of temperature can be compensated by other regions, and the global effect is reduced. However, the validation of tuning cannot be done with the sparse surface observations. Radiative fluxes from models need to be validated at the top of the atmosphere with satellite observations (from Nimbus 7 or the Earth Radiation Budget Experiment (ERBE), e.g., *Harrisson et al.*, [1990]).

Stockdale et al. [1994] have described coupled experiments with versions of the European Centre for Medium-Range Weather Forecasts (ECMWF) AGCM and the Hamburg Ocean Model in Primitive Equations (HOPE), in which the system rapidly drifted to a cold state. To reduce this drift, they performed sensitivity experiments involving the model clouds. One simple modification was to change the fractional cloud coverage within a grid box, which affects both the short wave and the long wave budgets. A reduction of cloud coverage from 32 to 16 % in the CGCM was sufficient to reduce the heat flux by 20 W/m^2 and to alleviate the drift considerably.

The fractional cloud coverage was also found to be a very sensitive parameter in the experiments performed by *Vintzileos* [1996] with the Laboratoire de Météorologie Dynamique (LMD) AGCM coupled to OPA OGCM. First experiments with this CGCM produced very little seasonal cycle and a reduced western Pacific warm pool [see *Mechoso et al.*, 1995]. Figure 3 shows SST in the CGCM after

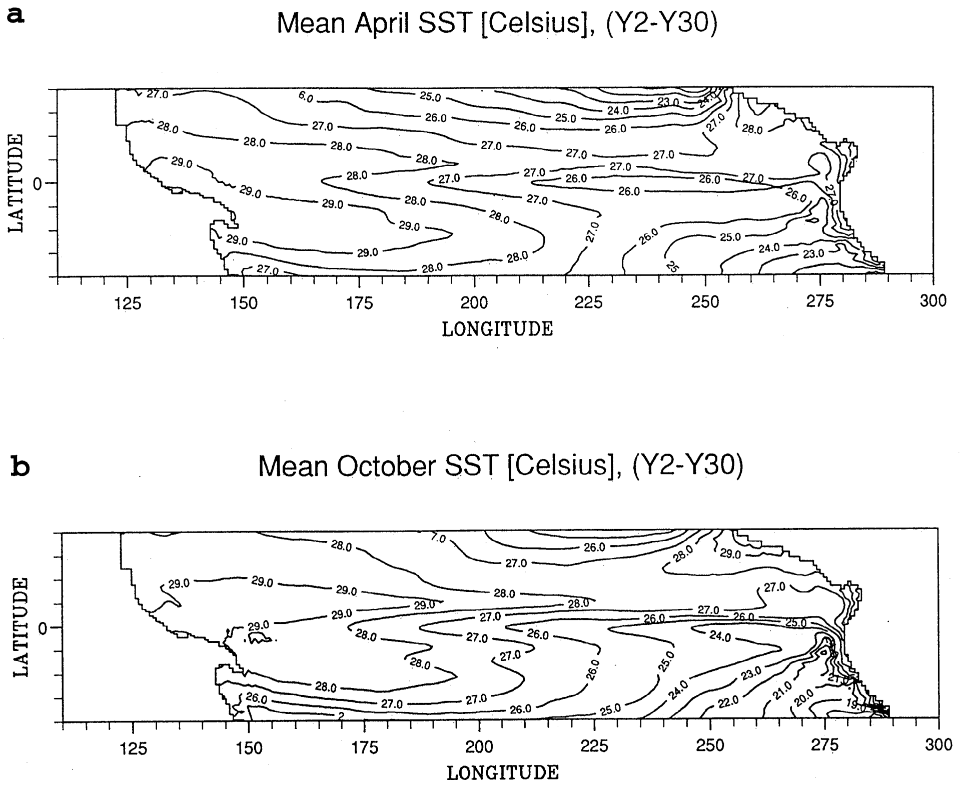

Figure 3. Thirty-year-average temperature in the tropical Pacific for (a) April and (b) October for a CGCM where fractional cloud cover has been modified. Contour interval is 1°C.

modification of this parameter to produce warming of the tropical system and a more marked seasonal cycle.

Sensitivity experiments to a change in cloud albedo feedback were also performed by *Meehl and Washington* [1995]. Results showed global scale changes with ENSO-like patterns, thus emphasizing the high coupled climate sensitivity to cloud feedback.

Many CGCMs have a tendency to generate water that is too warm to the south of the equator in the central and eastern Pacific [see *Mechoso et al.*, 1995]. The origin of this bias is not clear. A potential source for this problem lies in the excess of solar heating received in the subtropics. Several sensitivity studies have tried to identify the sensitivity of the coupled climate to the radiative forcing of the atmospheric model. *Ma et al.* [1994] showed that the distribution of SST is very sensitive to the radiative scheme used in the atmosphere. However it is quite difficult to interpret the results of the coupled system relative to an uncoupled one because of coupled feedbacks. For instance, an excess in radiative forcing could be compensated by increased evaporative cooling leading to colder rather than warmer SST. In order to reduce excessive solar heating in the subtropics in the eastern Pacific several groups have tried to augment the stratus clouds by physical or empirical parameterizations. *Ma et al.* [1996] tested the impact of a prescribed stratus cover in the eastern Pacific with a CGCM. The first effect is a reduction of SST beneath the prescribed cloud deck, because of a decreased solar radiation reaching the surface. Indirect effects involve the increase of the Hadley-Walker circulation and an extension of SST reduction due to enhanced evaporation and oceanic advection. Some improvement can be obtained, but the problem is still evident. The effect of extra clouds may lead to more or less radiative heat flux due to the competing effect of less incoming solar radiation and more long wave trapping.

Overwarm SST in the east Pacific may also be linked to the erroneous development of excessive convergence, particularly strong in April, south of the equator. A mean "double Intertropical Convergence Zona (ITCZ)" structure is common in CGCMs, corresponding to a quasi-permanent double ITCZ or to the convergence zone moving back and forth across the equator seasonally [*Mechoso et al.*, 1995]. The observed east Pacific ITCZ remains north of the equator year round, with only occasional split-ITCZ episodes. This ITCZ asymmetry is closely associated with oceanic asymmetry, with warmest water north of the equatorial cold tongue. On the basis of observations, *Mitchell and Wallace* [1992] discussed this meridional asymmetry and proposed that the development of the equatorial cold tongue was partly due to the onset of the northward winds during the northern summer monsoon and that positive feedbacks involving both the meridional and the zonal components of the wind contributed to the remarkable asymmetry of the eastern Pacific. This asymmetry has also been the subject of several recent studies [e.g., *Xie and Philander*, 1994; *Xie*, 1994; *Giese and Carton*, 1994; *Philander et al.*, 1996; *Li and Philander*, 1996] using both simplified and CGCM models. Several factors are important, such as land-ocean geometry, stratus clouds, and the shallowness of the mixed layer that makes SST very sensitive to surface heat and momentum fluxes. For example, relatively warm anomalies north of the equator will cause meridional wind stress anomalies, which enhance nearby evaporative cooling and help to maintain the north-south SST gradient. This picture is rapidly complicated by other considerations; the wind stress also drives ocean surface currents, generates upwelling and downwelling, and contributes to the determination of the vertical mixing scale. In the atmosphere the response depends on the atmospheric boundary layer structure and cloud physics. Several sensitive feedbacks are involved, and proper simulation of this region (and corresponding Indian and Atlantic regions) is a severe test for any CGCM.

The relation between SST and deep convection is another important AGCM issue. High SST is a necessary condition for active deep convection [*Gadgil et al.*, 1984; *Graham and Barnett*, 1987], the intensity of which increases with SST in the range from 26° to 30°C [*Zhang*, 1993]. However, convection can have a large spatial variability (high SST is not a sufficient condition) and its occurrence is intermittent, indicating that factors other than SST itself control it. CGCMs are very sensitive to the parameterization of convection. In convective regions, physical properties of clouds (temperature and humidity) are mixed with the surrounding air by detrainment. Convective entrainment is important in determining the vertical profile of temperature and humidity in clouds. If this term is too weak, convective cloud height is underestimated. By increasing convective entrainment in the low levels of an AGCM, less humidity is exported upward. This parameter has been tested in a CGCM by *Terray* [1998]; the resulting impact on SST is illustrated in Figure 4, which shows a reduction in SST over a wide area of the equatorial Pacific. Low-level humidity is increased, and the Hadley circulation is able to carry more humidity into convergence zones; the intensity of convection and the Walker circulation are also increased. The SST is cooled not only because the heat flux is reduced in the convective area but also because the large-scale structure of the Hadley-Walker cell is modified and the more vigorous atmospheric circulation contributes to cool the ocean.

Most of the above sources of errors were looking at different aspects of the heat budget. It is important to remember how oceanographers tend to regard the presence of cold water in the eastern Pacific. Colder oceanic water along eastern boundaries results from dynamical forcing by equatorward alongshore winds, which generate offshore Ekman transport and coastal upwelling. Strong upwelling driven by local wind is observed all along the South American coast. Strong southerly winds along the coast are necessary, but good simulation of these is difficult in climate resolution AGCMs, with the vicinity of the high Andes causing particular problems of representation.

6. Time and Space Structure of the Seasonal Cycle

The main features in the tropical Pacific are the west Pacific warm water pool, the east central equatorial cold tongue, the easterly trade winds, and the thermocline sloping from deep west to shallow east. These features depend on dynamic air-sea interaction and feedbacks and are closely related [see, e.g., *Philander,* 1990; *Gill*, 1982]. Their balance is modified seasonally by the annual solar cycle; the equatorial cold tongue is well developed in September-October, and much warmer in March-April. This oceanic response is linked to the southeast trade winds. Along the equator both the warm phase (in spring) and cold phase (in fall) of the SST seasonal cycle propagate west from the east to the central Pacific. In the western Pacific, there is little seasonal cycle on the equator; it is apparent on a much broader scale, with the movement of the Pacific warm pool from its position north of the equator in boreal summer to its southern position in winter following the Sun. In the east Pacific the seasonal cycle is characterized by a strong asymmetrical annual cycle structure, where warm waters north of the equator move seasonally with the ITCZ (closest to the equator in March-April and moving poleward until October).

The equatorial zonal asymmetry associated with the tilt of the thermocline and the equatorial upwelling were related to the zonal component of the trades in a forced oceanic context [see *Moore and Philander*, 1977; *Cane and Sarachik*, 1979; *Philander and Pacanowski*, 1980]. *Dijkstra and Neelin* [1995] have recently used a simplified coupled model to show how the mean structure of the equatorial Pacific system depends on the dynamical feedbacks between the ocean and the atmosphere. Their results highlight the sensitivity of the spatial pattern and intensity of the SST to the strength of the air-sea coupling, the strength of the coupling between SST and ocean dynamics, and the configuration of the uncoupled atmospheric response. They emphasized the similarity of the dynamical feedbacks for the mean balance to those involved in the ENSO cycle, relating back to the *Bjerknes* [1969] hypothesis. *Chang* [1996] has discussed the seasonal cycle using a simple coupled model to distinguish between coupled dynamical effects and the influence of the solar heating cycle.

The simplified coupled models demonstrate that accurate representation of several oceanic and atmospheric processes is required for CGCMs to simulate the seasonal cycle well. Although early TOGA-related CGCM experiments focused mainly on the ENSO cycle, there has since been an increase in attention on seasonal aspects of CGCM performance. *Giese and Carton* [1994] obtained a realistic annual cycle in a CGCM and carried out several experiments to study the effect of varying some solar forcing features. A good description of a CGCM seasonal cycle was obtained by *Robertson et al.* [1995a], who found a strong and realistic amplitude of the seasonal cycle despite an underestimated wind stress variability. *Terray et al.* [1995] also obtained a very good seasonal cycle for the equatorial temperature despite the development of a southern convergence zone in April and a very weak interannual variability.

Mechoso et al. [1995] described the mean seasonal cycle from 11 different CGCMs on the basis of multiyear experiments without flux correction. Although the oceanic component of most of the CGCMs was restricted to the Pacific Ocean, the CGCMs were developed independently and differed substantially in detail. Each CGCM was able to simulate the basic zonal asymmetry of the Pacific Ocean, with warm water in the west and a cold tongue in the east, and this is a clear progress from the earlier comparison presented by *Neelin et al.* [1992]. Beyond this basic feature a large variety of behavior was found. The exact morphology of the cold tongue and warm pool and its seasonal variability was difficult to capture; most CGCMs tend to develop a cold tongue too far to the west and too narrow around the equator. Warm water was correctly located north of the equator but often appeared south of the equator in April, a fact which is rarely observed. Most simulations had variability more symmetrical about the equator than observed; some generate a semiannual component along the equator, and some develop a convergence zone over the southeastern Pacific in March-April.

The relation of seasonal biases to interannual variability is not clear. The generation of interannual variability in models

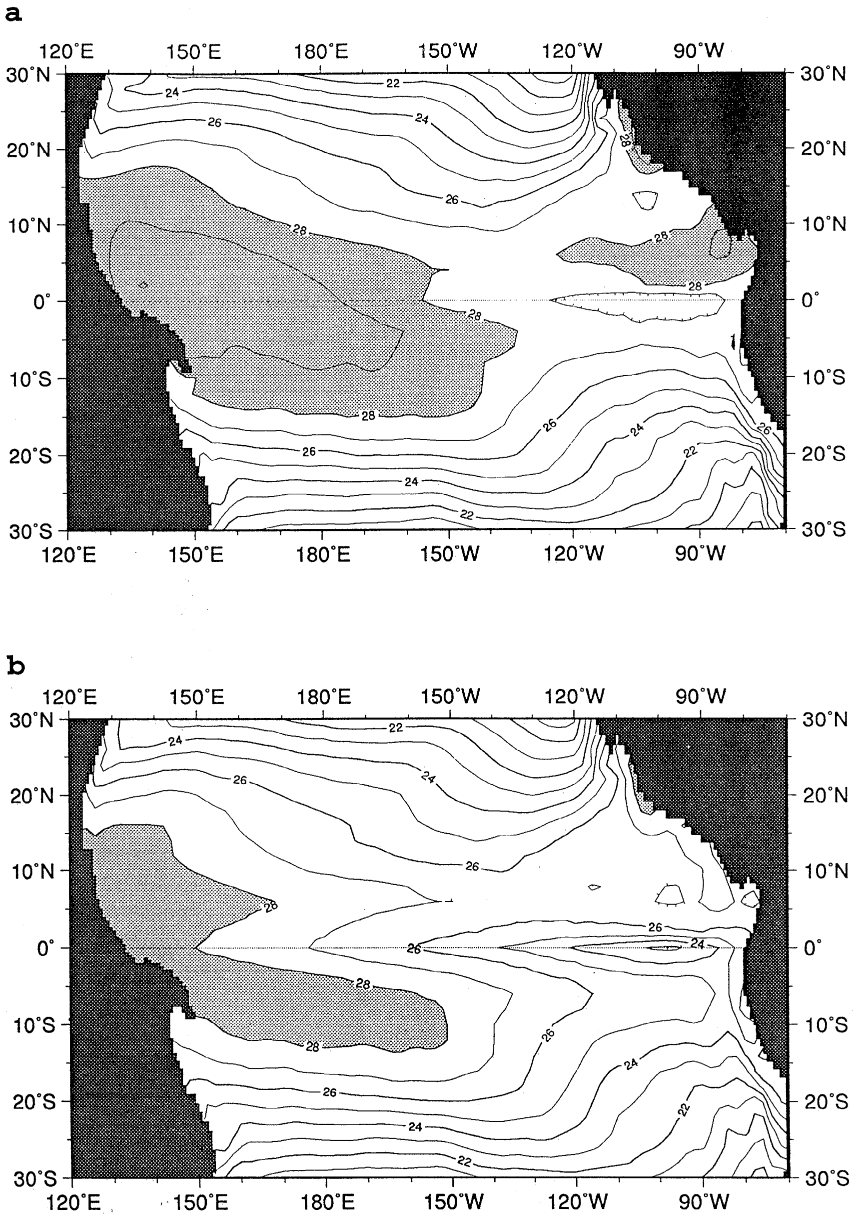

Figure 4. Three-year-average sea surface temperature in a CGCM in (a) the control case and (b) for increased convective entrainment. Contour interval is 1°C.

does not depend on good seasonal behavior, but given the similarities between seasonal and interannual dynamics, improvement of seasonal behavior should lead to interannual variability that is physically more realistic. Further, as ENSO seems to develop in a preferred season, one expects some interaction with the seasonal cycle. Indeed, such an interaction has already been reported by *Meehl* [1990b]; a coarse grid coupled model developed ENSO-like features locked to the seasonal cycle, but when the seasonal cycle was turned off, ENSO-like features continued to form but with a more irregular period.

Interannual behavior is also sensitive to the mean state. Some sensitivity studies by *Zebiak and Cane* [1987] with their simplified model have shown that the amplitude and period of ENSO-like anomalies were affected by modifications of the equivalent depth (which depends on the mean thermocline depth and the stratification); when the equivalent depth is reduced, the oscillations are stronger and develop at shorter periods. The sensitivity to the mean state of the system has been recognized in numerous studies [*Schopf and Suarez*, 1988; *Battisti and Hirst*, 1989; *Neelin*, 1991]. These results also suggest that improvement of the basic state of CGCMs is important with regard to ENSO simulation. Further, some studies [*Latif et al.*, 1994] have shown a relation between the seasonal cycle and prediction. The coupled feedbacks associated with the seasonal cycle offer a very difficult challenge to CGCMs.

7. Interannual Variability

A principal objective of TOGA CGCMs has been the simulation of interannual variability in the tropical Pacific region, particularly ENSO events. To validate CGCM behavior a comprehensive picture of the ocean-atmosphere evolution is necessary, and this information is an important output from the TOGA program [see *Wallace et al.*, this issue]. The best observed field is SST, so analyses of interannual CGCM behavior have tended to concentrate on SST anomalies. The enhancement of the observational network through TOGA has led to improvements in upper ocean data in particular, so the ability of models to reproduce the coordinated changes in winds, SST, and thermocline movement that characterize ENSO events can also be tested.

When the TOGA program started, the computational expense of running a CGCM for interannual timescales was prohibitive, but rapid increases in computer power soon made the application of such models to ENSO feasible. The problems of climate drift described above meant that the first such CGCMs had limited interannual success. At the time of the review by *McCreary and Anderson* [1991], very few papers on CGCMs with significant interannual variability had been published. *Sperber et al.* [1987] were the first to note ENSO-like behavior in a global coarse grid CGCM. *Philander et al.* [1989] compared different configurations of GFDL CGCMs. In one configuration (widely used thereafter) a high-resolution tropical Pacific OGCM was coupled to a low-resolution (R15) atmosphere: the seasonal cycle was omitted to concentrate on interannual variability in isolation. Despite significant drift, several warm and cold ENSO-like events of differing character occurred irregularly in a 28-year run. With the same AGCM coupled to a coarser OGCM with global domain, regular westward propagating interannual SST variability was found (see also section 4).

Detailed analysis of a global coarse CGCM was published by *Meehl* [1990 b]. *Lau et al.* [1992] provided a detailed analysis of the GFDL coarse CGCM, and *Philander et al.* [1992] analyzed the high-resolution version. Features noted in the high-resolution model were eastward (westward) propagation of interannual heat content anomalies along the equator (off the equator) and largely standing modes for SST and wind anomalies. By contrast, the interannual variability in the low-resolution version was dominated by westward propagating coupled interannual modes. Such behavior has been typical of many of the CGCMs that followed these early versions.

By the time of the *Neelin et al.* [1992] CGCM review, results from several CGCMs with high- and low-resolution ocean components and different formulations were available. The various models were analyzed in terms of their equatorial time-longitude SST behavior. The interannual behavior ranged from realistic to very low SST variability, with both propagating and standing modes occurring. The results provided evidence for different oscillation mechanisms and for the strong sensitivity of coupled models to apparently small model changes. One possible reason for the lack of variability in some models was that ocean-atmosphere coupling was too weak; this could in turn be due to a cold ocean bias, weak atmospheric response to SST anomalies, or the inclusion of damping to climatology. Perhaps more surprisingly, this review revealed that "climate drift appears not to be the major determining factor in the nature of the coupled variability found in these coupled models" [*Neelin et al.*, 1992, p. 100] and "a good simulation of the seasonal cycle does not guarantee that interannual oscillations will occur" [*Neelin et al.*, 1992, p. 100].

This wide variety of behavior was discussed further by *Neelin et al.* [1994], together with that of a series of much simpler coupled models. *Neelin et al.* [1994] also summarized theoretical developments that have benefited the interpretation of ENSO-like signals in CGCMs, on the basis of the analysis of simpler models that are reduced to physical processes thought to be fundamental to ENSO. In a series of papers, *Neelin and Jin* [1993] and *Jin and Neelin* [1993a, b] have provided a common framework to describe and connect differing mechanisms such as delayed oscillator modes [*Schopf and Suarez*, 1988; *Battisti and Hirst*, 1989], "slow SST modes" [*Neelin*, 1991], and propagating ocean modes [*Hirst*, 1986, 1988].

There have been several more detailed analyses of the interannual behavior of individual CGCMs, which give some insight into the coupled modes responsible for oscillatory behavior. For example, following several changes to an earlier CGCM version (including the removal of flux correction), Latif et al. [1993a, b] obtained realistic interannual variability in their CGCM with a high-resolution tropical OGCM. Through a principal oscillation pattern (POP) analysis of the surface wind, sea level, and SST fields, they were able to find a dominant interannual mode that resembled the main observed interannual POP mode, featuring slow eastward propagation of sea level (heat content) anomalies along the equator. *Latif et al.* [1993a] found aspects of both delayed oscillator and slow SST modes, suggesting that the modes may coexist or occur individually in the same model. In a CGCM with a Pacific OGCM component with 1° meridional resolution, *Nagai et al.* [1992] found weak interannual variability with delayed oscillator characteristics. *Moore* [1995] describes a slow SST mode in a coarse-resolution CGCM. He further found that by altering the mean climate of the CGCM the nature of the interannual variability could change qualitatively. POP analysis is one of several techniques that have been employed to extract a dominant signal from the irregular interannual variability that is typical of ENSO. For example, *Robertson et al.* [1995b] have used singular spectral analysis (M-SSA), a form of extended empirical orthogonal function (EOF) analysis, to analyze CGCM behavior and find quasi-biennial (QB) and quasi-quadrennial (QQ) modes. This method, first applied to climate problems by *Vautard and Ghil* [1989], is very useful for extracting the leading coupled signals.

Tett et al. [1997a] used lag correlations between analyzed [*Ji et al.*, 1995] upper ocean vertically averaged temperature (VAT) anomalies along the equator and observed SST anomalies in the east Pacific to diagnose the tendency for VAT in the west Pacific to lead east Pacific SST by several months and to propagate eastward (Figure 5). Well-behaved CGCMs should be able to reproduce such features. *Tett et al.* [1997a] similarly analyzed CGCMs with essentially the same AGCM component; the CGCM with a high-resolution Pacific OGCM reproduced this lag correlation better than the CGCM with a low-resolution OGCM.

Some CGCMs have prominent QB behavior, either in association with longer periods [*Latif et al.*, 1993a] or separately [e.g., *Robertson et al.*, 1995b]. This may occur because the model ENSO oscillates too fast [e.g., that of *Ineson and Davey*, 1997]; this may occur as part of a period-doubling cascade to longer timescales [*Münnich et al.*, 1991], or through some physical mechanism separate from (though related to) ENSO. There is observational evidence for QB behavior in the Indian-Pacific region, which may be related variously to ENSO and the monsoon cycle [*Meehl*, 1989, 1994; *Rasmusson et al.*, 1990; *Ropelewski et al.*, 1992].

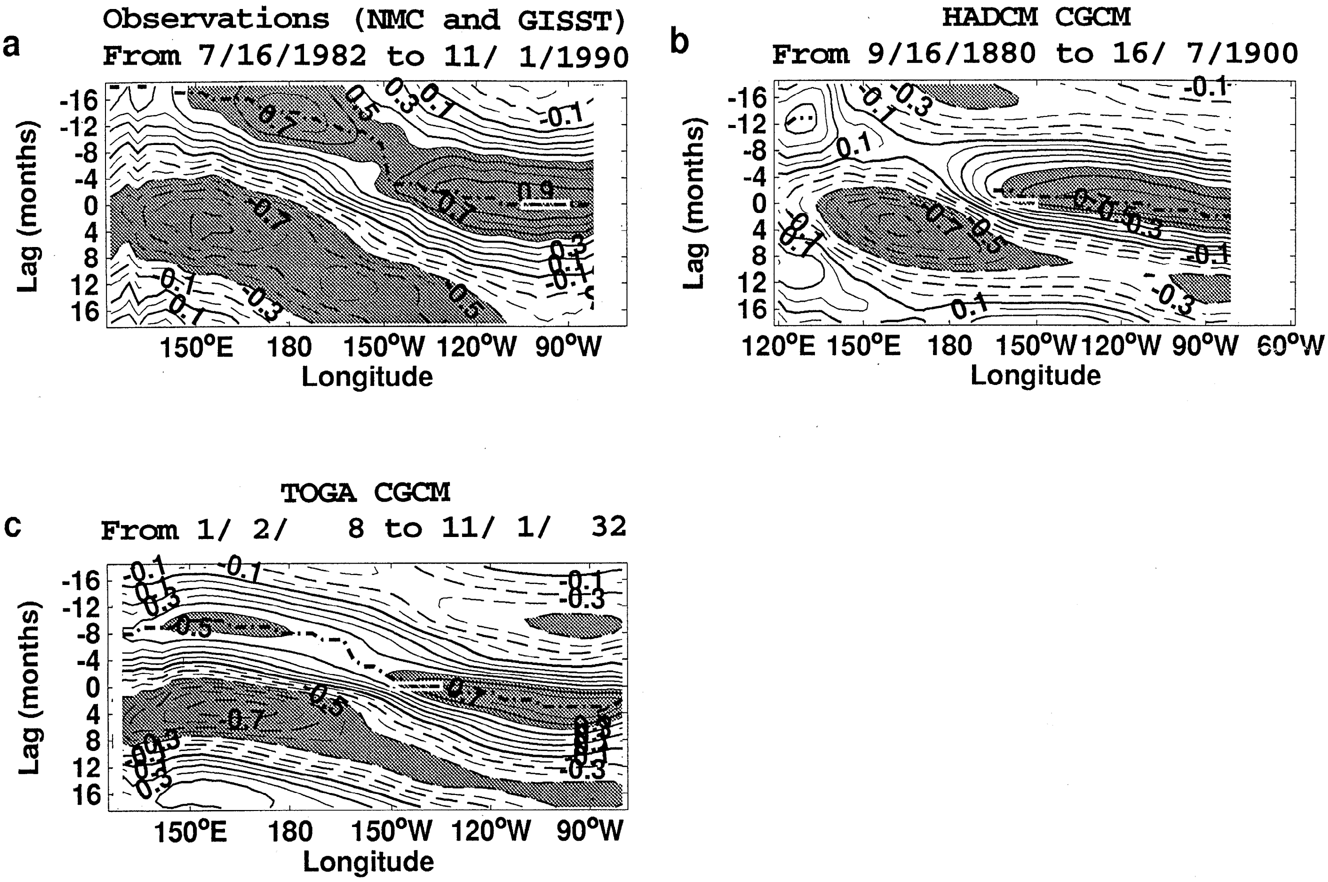

Figure 5. Pacific equatorial (5°N to 5°S) lag correlations. Vertically averaged temperature (VAT) over top 360 m at each grid point is correlated with sea surface temperature (SST) at the point where SST has most interannual variance. (a) Observed, (b) CGCM with AGCM (2.5° x 3.75°) and global OGCM (2.5° x 3.75°), (c) CGCM with AGCM (2.5° x 3.75°) and Pacific OGCM (1.5° x 0.33°)

Meehl [1994] has proposed a physical interpretation linking the ENSO timescales which characterizes the variability in the tropical Indian-Pacific oceans with the biennial variability of the Asian and Australian monsoons. There are likely to be complex interactions between seasonal, QB, and ENSO signals.

Through the period of the TOGA program, CGCMs have evolved and improved to the point that they are being used to predict interannual variability. *Latif et al.* [1993b] were the first to demonstrate skillful CGCM hindcasts of recent ENSO events at lead times of up to a year, and several different CGCMs are now being used to predict Pacific SST variations both experimentally and operationally. A more complete development on this point can be found in work by *Latif et al.* [this issue].

8. Conclusion

Nature provides only a limited number of anomalous situations to observe on the interannual timescale, and observational resources are limited. Numerical modeling, including comprehensive CGCMs, is an effective complementary means of advancing our knowledge on the ocean-atmosphere coupled system, with the added goal of making predictions about the evolution of that system.

Despite all the difficulties associated with the ocean and atmosphere components and their coupling, progress with CGCMs has been substantial in the course of the TOGA program, and that progress is continuing. With increased model resolution (particularly in the ocean) and improved physical parameterizations (particularly for the atmosphere), CGCM development has reached the point where a reasonable gross tropical mean state and substantial tropical variability are often obtained, and CGCMs are being used to make credible forecasts on the seasonal timescale. The use of coupled models has now been adopted by many research institutions which have the resources to run comprehensive CGCMs. Future work will concentrate on reducing remaining systematic errors (e.g., in the seasonal cycle and the east Pacific) and improving interannual characteristics such as the ENSO timescale and the spatial distribution of variance.

Measurements are necessary to evaluate model results and to improve physical understanding and process parameterization in the atmosphere and ocean. A comprehensive analysis of the time behavior of both fluids is needed to improve our knowledge of the system itself and our attempts to simulate it. An important legacy of TOGA is an observational database that can be used to obtain detailed descriptions of the evolution of the coupled tropical Pacific system.

During TOGA the observed interannual variability differed in character for different warm and cold phases. The diversity of CGCM behavior provides further evidence that the system is much more sensitive than first expected, and some critical issues have been raised, including the followings.

1. CGCMs are expected to oscillate realistically about a correct mean seasonal cycle. Further improvements are needed to get a reasonable seasonal cycle. The large systematic errors in the eastern equatorial Pacific need to be reduced. For an oceanic point of view the aim is to get a right balance between SST, zonal wind stress, and depth of the thermocline; for an atmospheric point of view the convergence zones should be right. One has also to find out whether a poor eastern Pacific climatology does really matter for interannual variability.
2. It is not clear that interannual variability could develop independently from intraseasonal scales (like the westerly wind bursts and the Madden-Julian Oscillations). Are these shorter scales needed for good interannual variability? Do they energize the low-frequency variability? Do they add noise to the prediction or are they essential to prediction? The scale interactions remain a very open question.
3. On longer timescales the link between ENSO and decadal variability needs to be clarified. Do decadal processes interact with the ENSO cycle? Are they part of it? What mechanisms sustain the source of variability?
4. Can ENSO be studied in the context of the equatorial Pacific alone? Connections to other tropical systems and to higher latitudes may be important, so a narrow equatorial Pacific view of ENSO may be misleading. The ENSO teleconnections need to be evaluated and improved.
5. Better estimates of the surface fluxes (wind stress and heat and freshwater fluxes) are needed for validation and improvements of CGCM simulations.
6. Can we estimate the coupling efficiency between ocean and atmosphere? Is mechanical coupling sufficient to explain the occurrence of interannual variability? How do the timescales and space scales of the ocean mixed layer relate to coupling efficiency?

Progress has been made during TOGA through an interplay between observations, simple models, theory, and GCMs. A hierarchy of approaches is necessary to gain a complete understanding of the system. After careful tuning, intermediate models have been very successful in exploring both ENSO mechanisms and predictability. The larger range of processes in CGCMs allows a wide variety of behavior involving complex balances of positive and negative feedbacks, which challenges our ability to understand it. (There is usually something to be gained from trying to explain even the more extreme and unrealistic excursions that the models can produce.) There is a need to synthesize the range of behavior explored by CGCMs and to identify, if possible, the main physical processes relevant to interannual variability. Part of this work is in progress with the development of projects like El Niño Simulation Intercomparison Project (ENSIP) organized by the Numerical Experimentation Group 1 from the Climate Variability and Predictibility Program (CLIVAR).

Seasonal prediction also poses a major challenge for CGCMs. The first weeks after coupling in a CGCM experiment is the period most sensitive to flux imbalances in the initial state when the model can drift away from its desired course. The initial state can be improved by progress with each component and by the use of data assimilation. One difficulty is that an initial state that is constrained close to the observations may not be well balanced for a prediction integration. The assimilation procedure for CGCMs prediction may require substantial development and also the maintenance of high-quality four-dimensional observations in atmosphere and ocean. A related problem is that of obtaining a suitable spread of initial conditions to explore probable future states efficiently. Although prediction with CGCMs is at an early stage, the hope is that the ability of CGCMs to represent (and forecast) many variables and processes will lead to predictive skills that justify their relative expense. Such development will build on the CGCM foundation laid during the TOGA program.

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L. Bengtsson, Max-Planck-Institute for Meteorology, Bundesstrasse 55, D-20146 Hamburg, Germany.

M. K. Davey, Hadley Centre, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SY, United Kingdom.

P. Delecluse, LODYC, Université Pierre et Marie Curie, Case 100, 4 place Jussieu, 75005 Paris, France. (delecluse@lodyc.jussieu.fr)

Y. Kitamura, Meteorological Research Institute, 1-1 Nagamine Tsukuba, Ibaraki 305, Japan.

S. G. H. Philander, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ 08544-0710,.

M. Suarez, NASA Goddard Space Flight Center, Greenbelt MD 20771.

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