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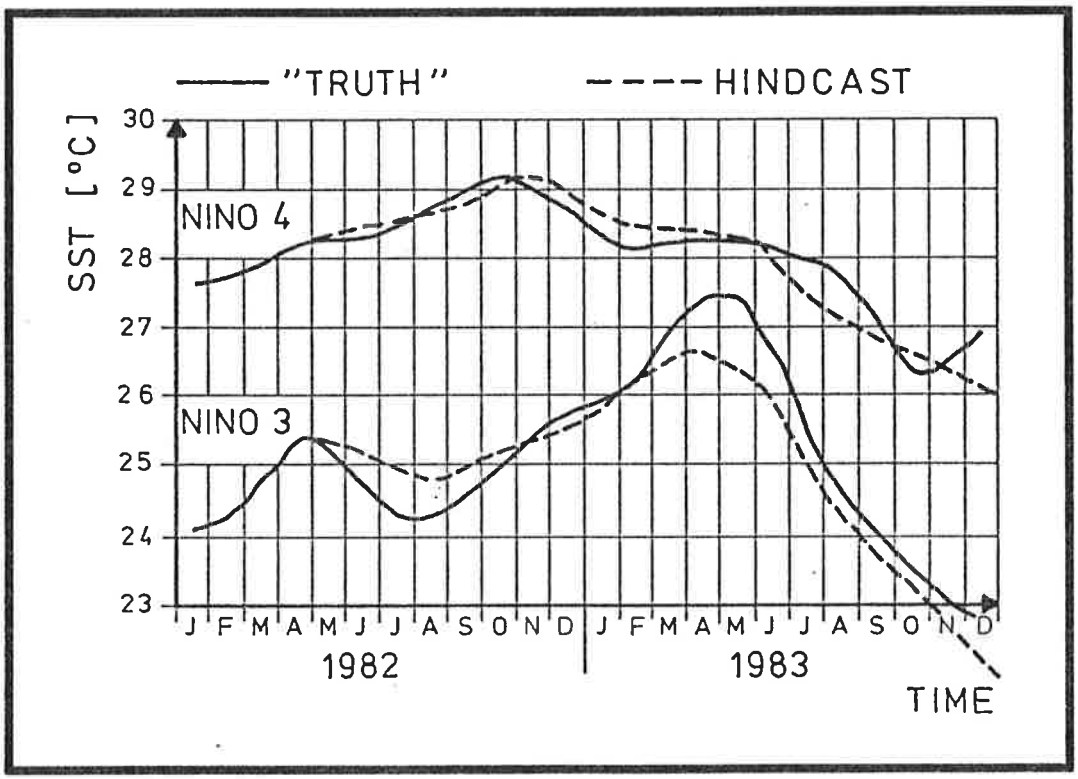

ENSO MODELLING AT MPI

by

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ABSTRACT

In this contribution the modelling activities of the climate research group at the Max-Planck-Institut fuer Meteorologie (MPI) concerning the El Niño/Southern Oscillation (ENSO) phenomenon are briefly reviewed. The studies described encompass the investigation of the atmospheric response to observed sea surface temperature (SST) distributions, the oceanic response to observed wind stress and studies with a coupled ocean-atmosphere model investigating large scale air-sea interactions in the tropics.

It is shown that the atmosphere model simulates realistically the Southern Oscillation during an extended range integration using near global SSTs for the period 1970 - 1985. In particular, low frequency changes of sea level pressure (SLP) as expressed by the Southern Oscillation Index (SOI) show a good correspondence with the observed changes. Furthermore, the spatial patterns of surface wind stress anomalies are simulated correctly, while the variance is somewhat underestimated by the atmosphere model.

The equatorial oceanic general circulation model captures basic aspects of observed SST variability in the Equatorial Pacific, when forced with observed wind stress patterns. Associated sea level and current changes are consistent with the available measurements.

In the next step the two models have been coupled together. Results are shown from three different experiments. In the first experiment the response of the coupled model to a westerly wind burst over the Western Pacific was investigated. It will be shown that the coupling of ocean and atmosphere is the most important factor for the persistence of SST anomalies in the Equatorial Pacific. The second experiment is an extended range integration with the coupled model over ten years. Low frequency variability is significantly underestimated in this run. The coupled model shows a climate drift consisting of a gradual cooling of the upper equatorial ocean. The coupled model was then used to study the possible role of anomalous snow cover over Eurasia for the initiation of ENSO events. By doubling the snow fall rate within the atmosphere model a weak El Niño event was induced in the Tropical Pacific Ocean.

Finally a simplified coupled ocean-atmosphere model was used for ENSO hindcast experiments. It will be shown that such a coupled system is quite successful in predicting the onset and the evolution of the 1982/1983 ENSO event.

1. INTRODUCTON

Low frequency variability of the climate system in the tropics is dominated by the El Niño/Southern Oscillation (ENSO) phenomenon (Rasmusson and Carpenter, 1982, Cane, 1986) during which anomalous warm surface waters appear for several months over the entire Tropical Pacific Ocean. ENSO events are accompanied by several oceanic and atmospheric circulation anomalies, such as sea level, surface and subsurface current anomalies, as well as rainfall and surface pressure anomalies. Furthermore, there is considerable evidence that ENSO influences the atmospheric Northern hemisphere winter circulation in total (Shukla and Wallace, 1983).

Although the ENSO mechanism is not yet fully understood, it is widely accepted that large scale air-sea interactions play an important role in the development of anomalous conditions during ENSO events. Bjerknes (1969) described these air-sea interactions in his pioneering work and established the concept of the "Walker Circulation". According to this concept, the ocean and atmosphere in the tropics are strongly coupled by the so- called "Walker Circulation", a thermally direct atmospheric circulation cell parallel to the equator. The Walker Circulation is driven by the east-west contrast of sea surface temperature (SST) at the equator. Air descends over the relatively cold Eastern Pacific and flows westward thereby being heated and supplied with moisture. Over the warm Western Pacific the air ascends and flows eastward in the upper troposphere. Any change in the strength of the Walker Circulation can lead to a change in the east-west contrast of SST, since the thermal structure of the upper equatorial ocean is determined by the low level wind field. A weaker than normal Walker Circulation, for instance, results in reduced equatorial upwelling and less advection of cold water, which decreases the SST gradient and further weakens the strength of the Walker Circulation. At least in this respect, ocean and atmosphere behave like a positive feedback system. The existence of these unstable air-sea interactions have been shown theoretically later by many authors (e. g. Philander et al., 1984).

ENSO modelling started with simple models using idealized forcing fields. Ocean models consisted of wave models, which revealed the importance of equatorial waves in the adjustment of the upper ocean (e. g. Mc Creary, 1976, Cane, 1979). Since equatorial waves are extremely fast (the phase speed of the first baroclinic mode is about 3 m/s) climate variations on relatively short time scales are possible near the equator. Later, simple models were successfully used to simulate observed sea level variations, driving the models with observed wind stress distributions (e. g. Busalacchi and O'Brien,

1981).

General Circulation Models (GCMs) of the oceans have been run during the last few years to simulate SST changes in the Tropical Pacific (Philander and Seigel, 1985, Latif, 1987). Although these models used rather crude estimates of surface heat flux they were remarkably successful, indicating that the equatorial SST field is largly determined by ocean dynamics.

Rowntree (1972) performed the first GCM experiment to investigate the influence of tropical SST anomalies on the atmospheric circulation. Subsequently, approximately ten GCMs of different groups have been run with a SST anomaly similar to the one observed during 1982/1983 (see Nihoul, 1985). The results demonstrate that the tropical response can be simulated realistically in all models; i. e., there is an eastward shift of the Walker Circulation associated with westerly surface wind and large positive rain anomalies over the Central Equatorial Pacific.

In more recent experiments GCMs were driven with time dependent SST fields taken from observations (Lau, 1985, Chervin, 1986, Biercamp et al., 1988). In all of these studies, the models successfully reproduced the time evolution of the Southern Oscillation.

Since ocean and atmosphere models gave satisfactory results when forced with observed boundary values ENSO was studied during the last few years also with coupled ocean-atmosphere models. As in the case of the uncoupled models, a hierarchy of coupled models exists ranging from simple models to sophisticated coupled GCMs. A very successful simple coupled model is the one described by Zebiak and Cane (1987) and Cane and Zebiak (1987). This model shows a quite realistic evolution of SST anomalies and other key ENSO variables during a 90-year integration. When used in hindcast experiments the model was remarkably successful in predicting the onset and evolution of ENSO events. Another simple model was developed by Schopf and Suarez (1988). In this model interannual variability was also simulated realistically and was attributed to the so-called "delayed negative feedback" mechanism, according to which the propagation of equatorial waves in the ocean is responsible for the phase reversals between ENSO (warm) and anti-ENSO (cold) events (Graham and White, 1988).

At present, coupled ocean-atmosphere GCMs are being developed in different institutions (e. g. Philander, pers. comm., Gordon, pers. comm., Latif et al., 1988). In this paper the various stages involved in the development of coupled ocean-atmosphere models at the Max-Planck-Institut fuer Meteorologie are reviewed. Section 2 describes the performance of an atmospheric GCM in simulating the Southern Oscillation. In section 3 the ability of an oceanic

GCM to simulate SST changes is discussed. Section 4 provides an overview of experiments performed with a coupled ocean-atmosphere GCM, while section 5 presents results from ENSO hincast experiments with a simplified ocean-atmosphere model. Summary and Conclusions close this paper.

2. ATMOSPHERIC MODELLING

The atmosphere model used at MPI is the "T 21"-version of the operational forecasting model of the European Centre for Medium Range Forecasts (ECMWF). The model described in detail by Fischer (1987) is a low resolution spectral GCM, which explicitly resolves waves up to total wavenumber n=21. There are 16 levels in the vertical. The model includes standard physics, a complete hydrological cycle and interactive clouds.

To test the model's performance in simulating the Southern Oscillation the "T 21" GCM was integrated for the period 1970 to 1985 using observed near global monthly mean SSTs. A detailed analysis of this run is given in Biercamp et al. (1988). The atmosphere model performed reasonably well in simulating low frequency changes in the tropical atmospheric circulation. This can be inferred from Figure 1, which shows the observed and simulated time series of the Southern Oscillation Index (SOI) Darwin minus Tahiti (Fig. 1a) as well as a cross spectral analysis of the two time series. At high frequencies both time series are not highly correlated, which was expected because of the limited predictability of the atmosphere. At lower frequencies the boundary forcing from the ocean becomes more and more important, and the model successfully reproduces the extremes of the Southern Oscillation, which results in high coherence for periods of 2 years and longer (Fig. 1c). The amplitudes, however, are clearly underestimated (Fig. 1b), as is most obvious for the two cold events of 1973 and 1975.

The most important forcing function for equatorial oceans is the zonal wind stress component. It is therefore of special interest how the atmosphere model simulates this quantity. Results from an EOF analysis of low pass filtered zonal wind stress anomalies are shown in Figure 2. The first eigenmode is clearly associated with the ENSO phenomenon, which can be inferred from the EOF time series (Fig. 2c). The atmosphere model simulates the spatial pattern of zonal wind stress variability with reasonable fidelity (Figs. 2a,2b). Both the observations and the simulation shows an anomaly pattern which exhibits a

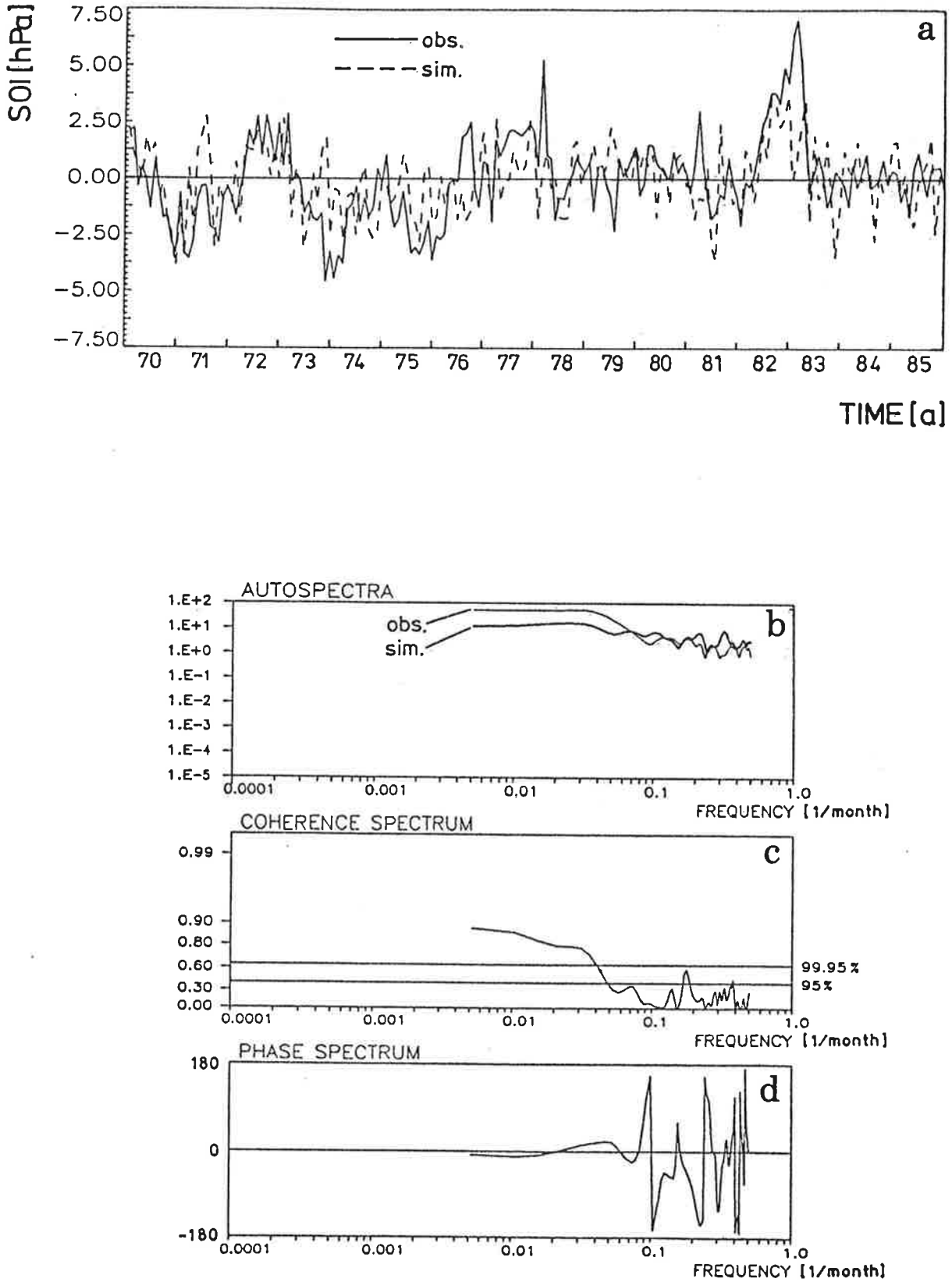

FIGURE 1: a) Evolution of the Southern Oscillation Index (SOI) Darwin minus Tahiti for the period 1970 to 1985. Dashed line: Observed SOI, solid line: Simulated by the atmosphere model; b) Autospectra of the two time series; c) Coherence squared spectrum of the two time series; d) Phase spectrum of the two time series.

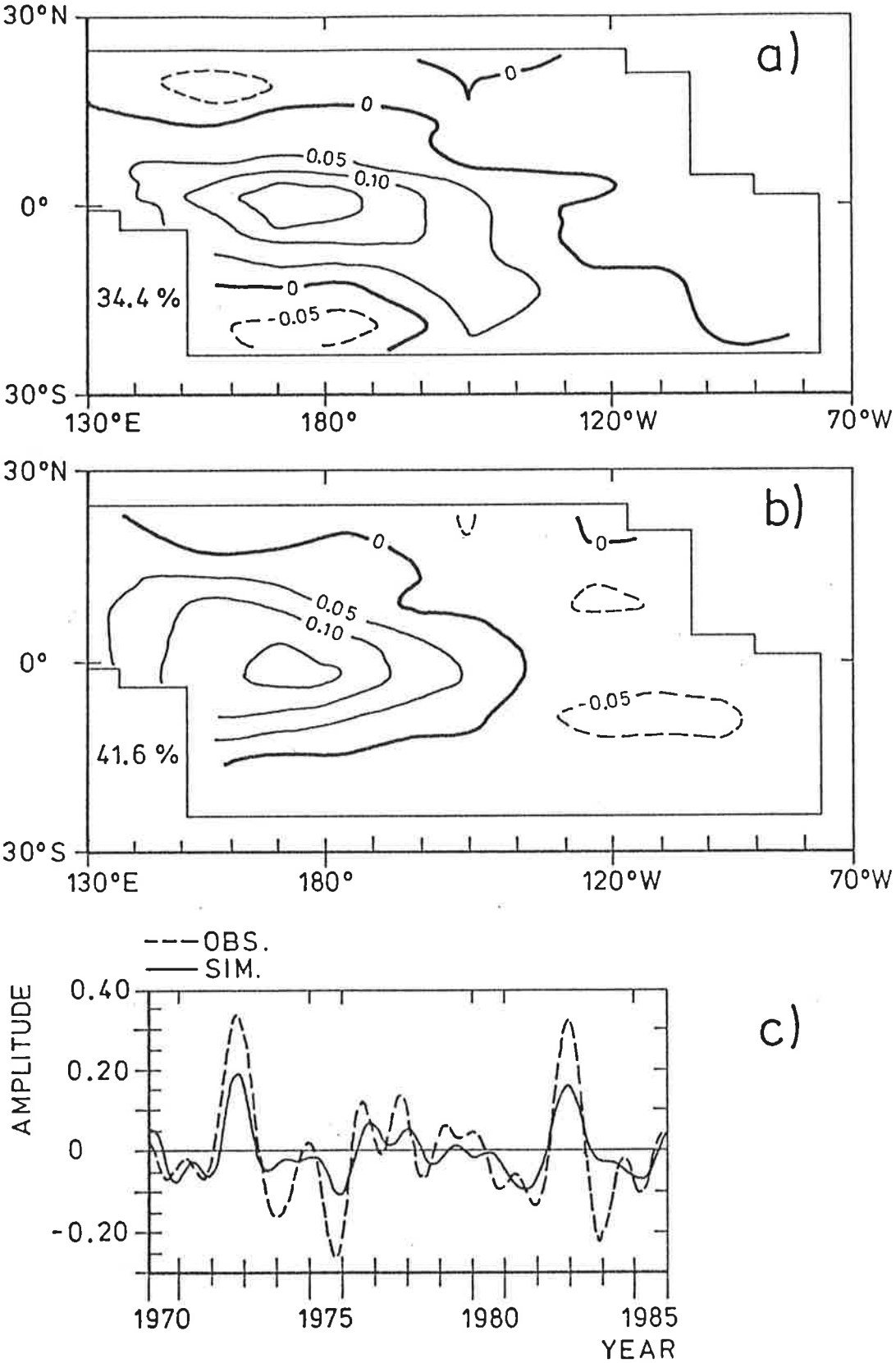

FIGURE 2: First EOF of low pass filtered zonal wind stress anomalies (filtering retains periods between 16 and 96 months). a) Spatial pattern derived from observations; b) Spatial pattern derived from the model simulation; c) EOF-time series, dashed line: observed, solid line: simulated.

region of strong positive values in the Western and Central Pacific. The two corresponding EOF time series (Fig. 2c) are highly coherent, but as for the SOI Index (Fig. 1) the variance is clearly underestimated in the model simulation. As will be discussed later, this model error may significantly influence the dynamics of a coupled system which uses the "T 21" model as atmospheric component.

3. OCEANIC MODELLING

The ocean model described by Latif (1987) is a primitive equation model which resolves the Tropical Pacific Ocean from 30°N to 30°S. It includes real coastlines but no bottom topography, so that the ocean floor is at a constant depth of 4000 m. The longitudinal resolution is constant with 670 km. In the meridional direction the resolution is variable, increasing from 50 km around the equator to about 400 km at the boundaries. Vertically, there are 13 levels, ten of them being placed within the upper 300 m.

Vertical mixing coefficients were assumed to be constant in earlier studies and are Richardson number dependent (Pacanowski and Philander, 1982) in more recent studies. The horizontal eddy viscosity is constant with a value of 10^8 cm^2/s, while explicit horizontal heat diffusion is not included.

The ocean model was driven with different observed wind stress fields for the time period 1947 to 1985. A comparison of simulated and observed SST anomalies is given in Figure 3 in terms of the leading EOFs, which account for approximately 60 % of the total variance. Both patterns show large scale behaviour with strongest anomalies at the equator. The anomaly pattern of simulated SSTs, however, is much more equatorially trapped than the observed pattern and the model simulates maximum anomalies in the Central Pacific rather than in the Eastern Pacific. The two EOF time series (Fig. 3c) are highly correlated, so that a close correspondence might be expected between simulated and observed SST anomalies within a few degrees of latitude of the equator. This can be inferred from Figure 4 which shows the time evolution of SST anomalies near the dateline at the equator, as observed and as simulated by the ocean model. The ocean model realistically simulates SST anomalies in this region, as is shown in the coherence and phase spectrum of the two time series (Figs. 4c, 4d). Figure 4 demonstrates that equatorial SST anomalies are

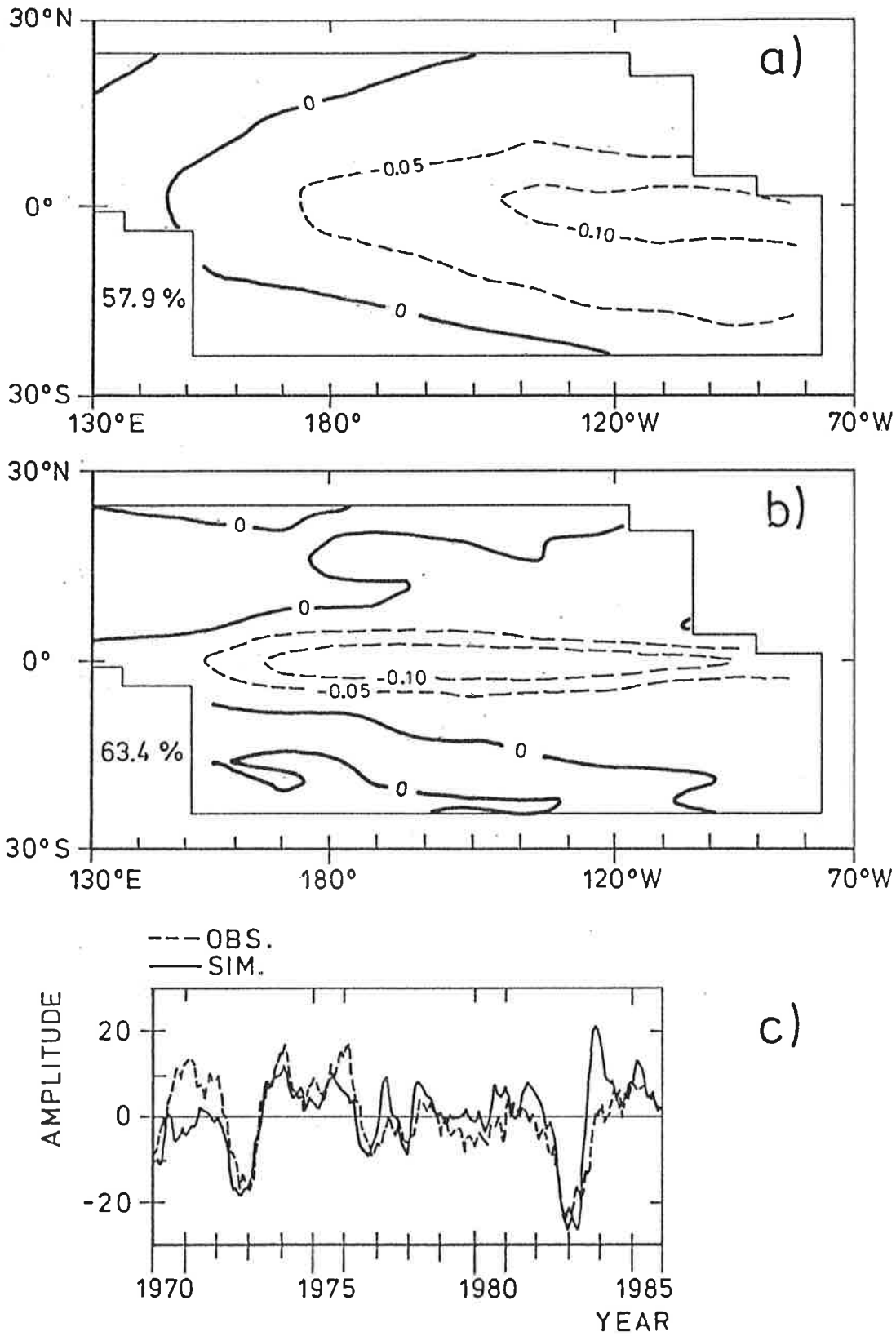

FIGURE 3: As Figure 2, but for SST anomalies. Filtering was not applied.

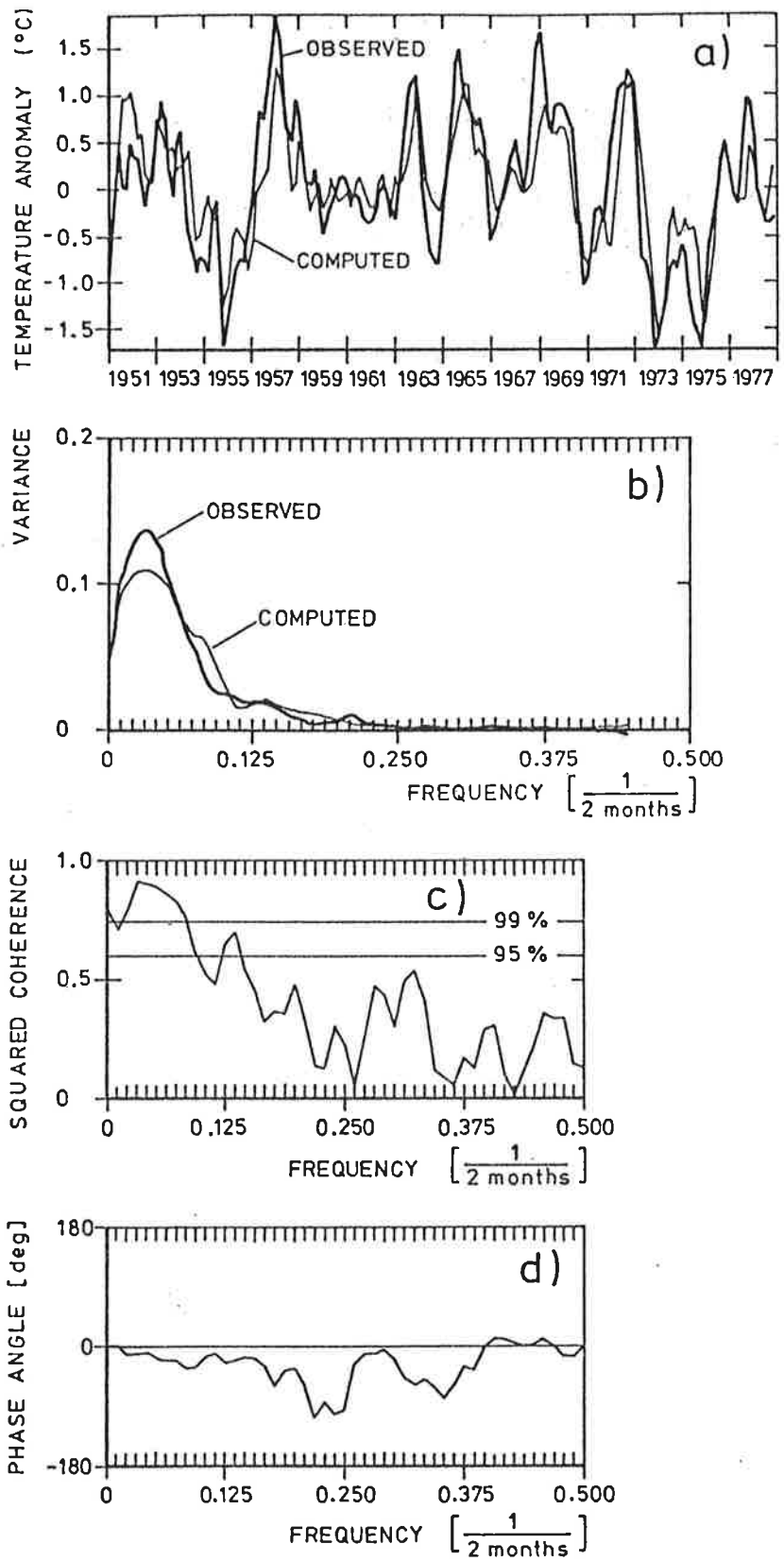

FIGURE 4: Evolution of SST anomalies at the dateline on the equator. a) Time series of observed (thick line) and simulated (thin line) SST anomalies; b) Autospectra of the two time series; c) Coherence squared spectrum of the two time series; d) Phase spectrum of the two time series.

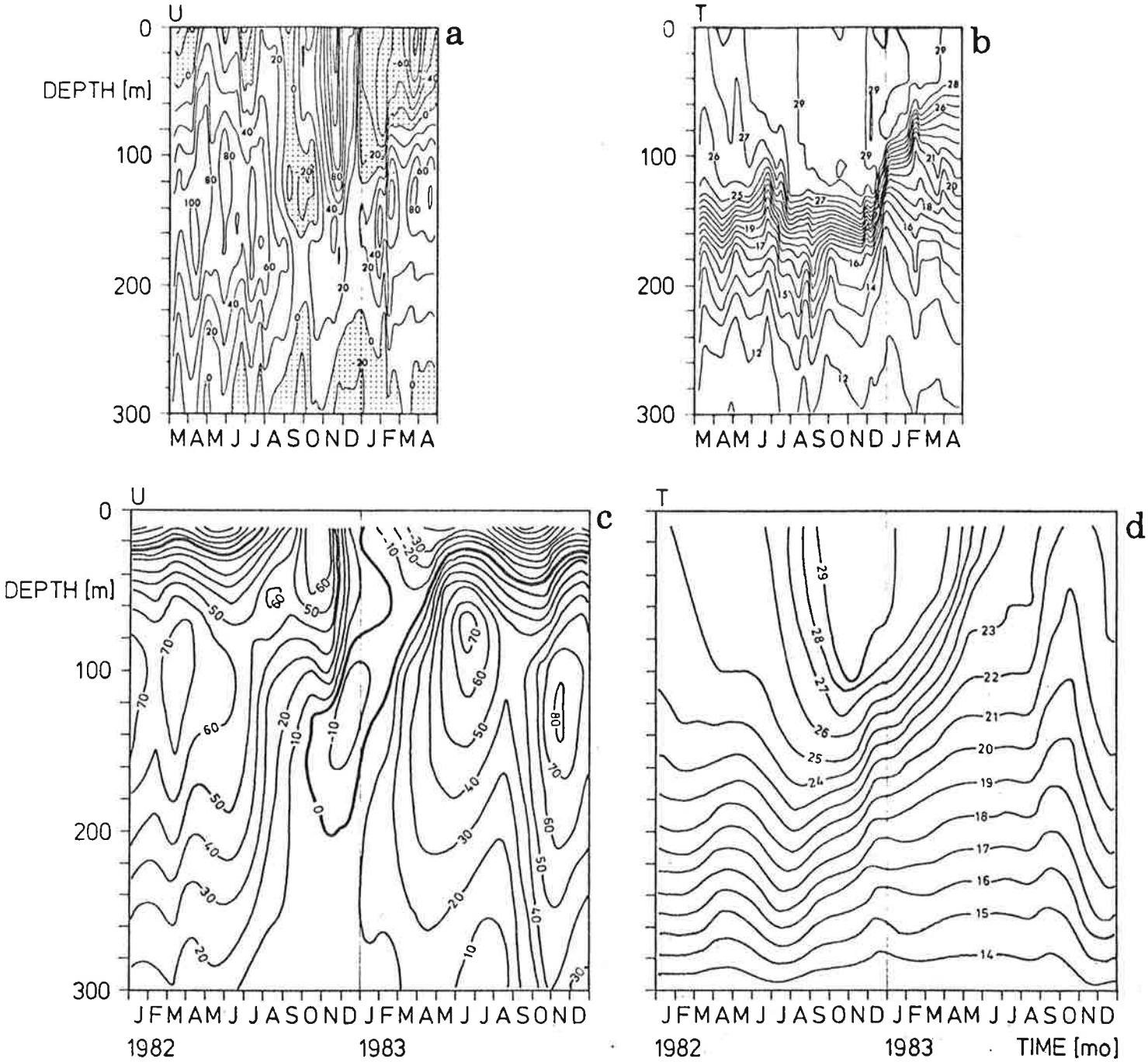

FIGURE 5: Time-depth sections of zonal currents and temperature on the equator at 159° W for the 1982/1983 ENSO event.a) Observed evolution of zonal currents (CI = 20 cm/s); b) Observed evolution of temperature (CI = 1° C); c) Simulated evolution of zonal currents (CI = 10 cm/s); d) Simulated evolution of temperature (CI = 1° C);

primarily caused by changes in surface wind stress, since all calculations were performed with rather crude estimates of surface heat flux.

The vertical structure of changes in the upper ocean during the 1982/1983 ENSO event is shown in Figure 5. Observations indicate the evolution of an eastward surface jet at the equator at the end of 1982 (Fig. 5a) with speeds of more than 100 cm/s. At subsurface levels there was a complete breakdown of the Equatorial Undercurrent, which is consistent with a strongly reduced zonal pressure force within the thermocline. This pressure force is maintained under normal conditions by the Trade Wind Field, which has a strong easterly component at the equator. As reported by many authors (e. g. Gill and Rasmusson, 1983) the Trade Wind Field collapsed entirely during the 1982/1983 ENSO event resulting in a diminished pressure force within the upper ocean and a subsequent deceleration of the Equatorial Undercurrent. The ocean model simulates both the evolution of the eastward surface jet and the breakdown of the Equatorial Undercurrent (Fig. 5c).

Significant changes in the upper ocean heat content during the 1982/1983 ENSO event are obvious in Figure 5b, which shows observed temperature as function of depth and time. A pronounced warming of several months duration is found up to a depth of about 100 m. The ocean model simulates basic aspects of this warming (Fig. 5d). One major deficiency of the model simulation is that the thermocline is too diffusive, which is clearly seen in Figure 5d.

4. COUPLED GCM

The equatorial ocean model and the "T 21" atmosphere model have been coupled together. Outside the domain of the ocean model SST is prescribed from climatology. At land points surface temperature is determined by the full heat budget, prescribing moisture content and temperature of the lowest soil layer.

The coupling is in both directions: the atmosphere model is driven by the SST calculated by the ocean model, while the ocean model is driven by the surface wind stress and surface heat flux generated by the atmosphere model. According to the flux correction technique proposed by Sausen et al. (1988), all interactive quantities (SST, surface wind stress, surface heat flux) are corrected by constant offset values previously calculated from uncoupled control runs.

4.1 BURST EXPERIMENT

In this particular experiment the surface heat flux is not fully interactive: although the atmosphere model computes its heat flux from the SST of the ocean model, this heat flux does not feed back onto the ocean. Instead, the oceanic heat flux is determined with a Newtonian Cooling flux parameterization using climatological air temperature and a relaxation time of about 30 days for the upper layer thickness of 10 m.

The experimental setup is as follows: during the first month of the coupled integration a westerly wind burst was introduced over the Western Pacific (details can be found in Latif et al., 1988). Thereafter, this initial disturbance was turned off, and the response of the coupled model to the wind burst was investigated. A similar experiment was performed with the uncoupled ocean model, and the results of the two experiments have been compared.

The most important result of this study is that the high persistence of SST anomalies observed during ENSO events is only found in the coupled case. While SST anomalies persist for a few months only in the uncoupled run (Fig. 6a) they have a much longer lifetime in the coupled integration (Fig. 6b). The response of the coupled system can be summarized as follows: the initial wind disturbance excites an equatorial Kelvin wave. In the wake of the eastward propagating Kelvin wave a SST anomaly develops as a result of anomalous zonal and vertical advection of heat. As soon as the atmosphere is allowed to interact fully with the ocean, the feedback of the atmosphere maintains anomalous conditions. In response to the eastward shift of the warmest water (Fig. 6b), the ascending branch of the Walker Circulation moves eastward, which can be inferred from the temporal evolution of rainfall along the equator (Fig. 7a). The eastward movement of the Walker Circulation is associated with low level westerly wind anomalies to the west of the heating region (Fig. 7b) driving intense eastward surface currents (Fig. 7c), which maintain the SST anomaly field in the ocean.

Although, the coupled simulation also shows some unrealistic aspects which are not observed during ENSO events, the long lifetime of equatorial SST anomalies is simulated correctly. This result demonstrates the importance of including coupled feedbacks within the tropical ocean-atmosphere system, and the requirement for coupled ocean-atmosphere models in order to investigate interannual variability in low latitudes.

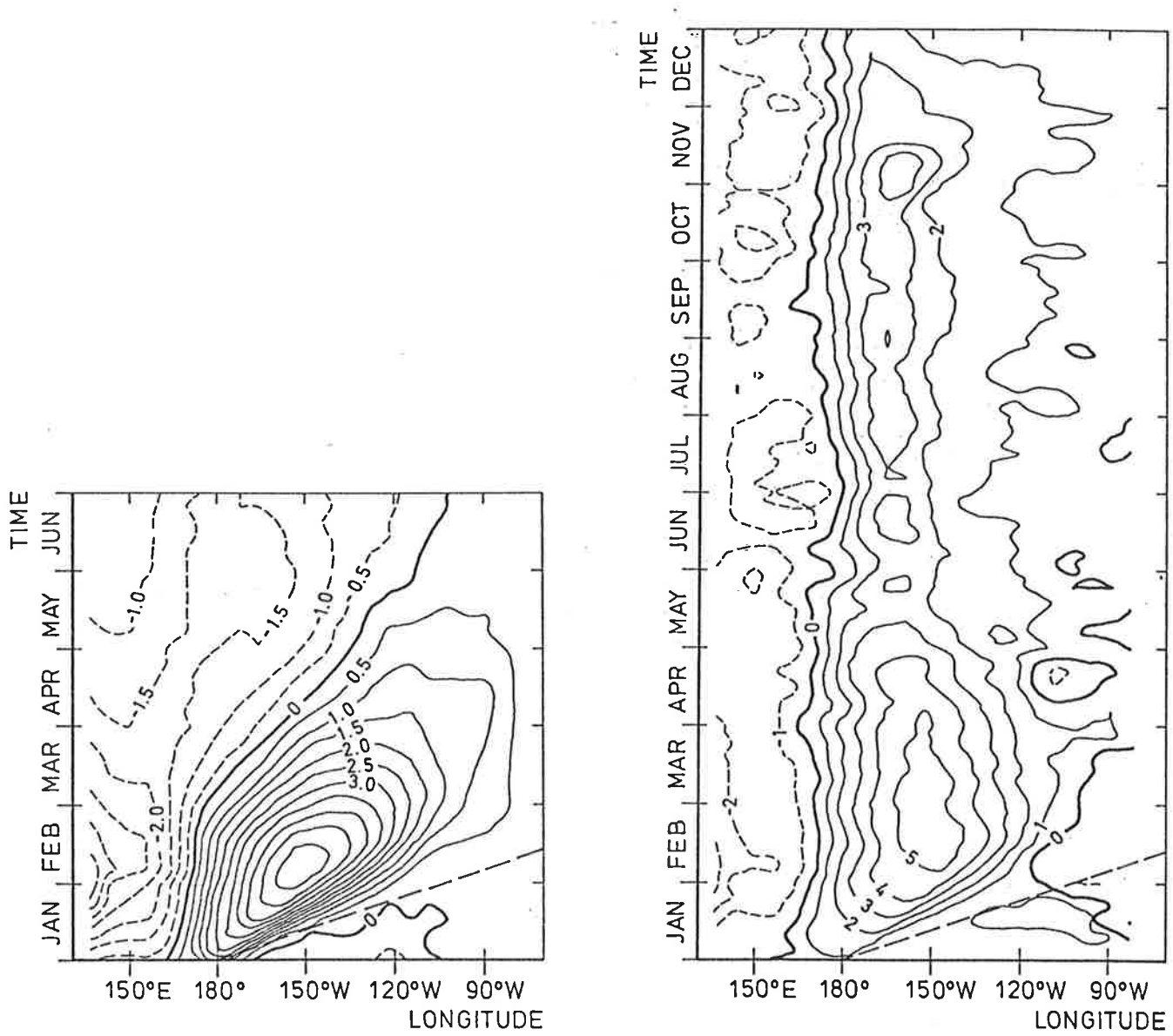

FIGURE 6: Evolution of SST anomalies along the equator in the a) uncoupled burst experiment (CI = 0.5° C), and b) coupled burst experiment (CI = 1° C).

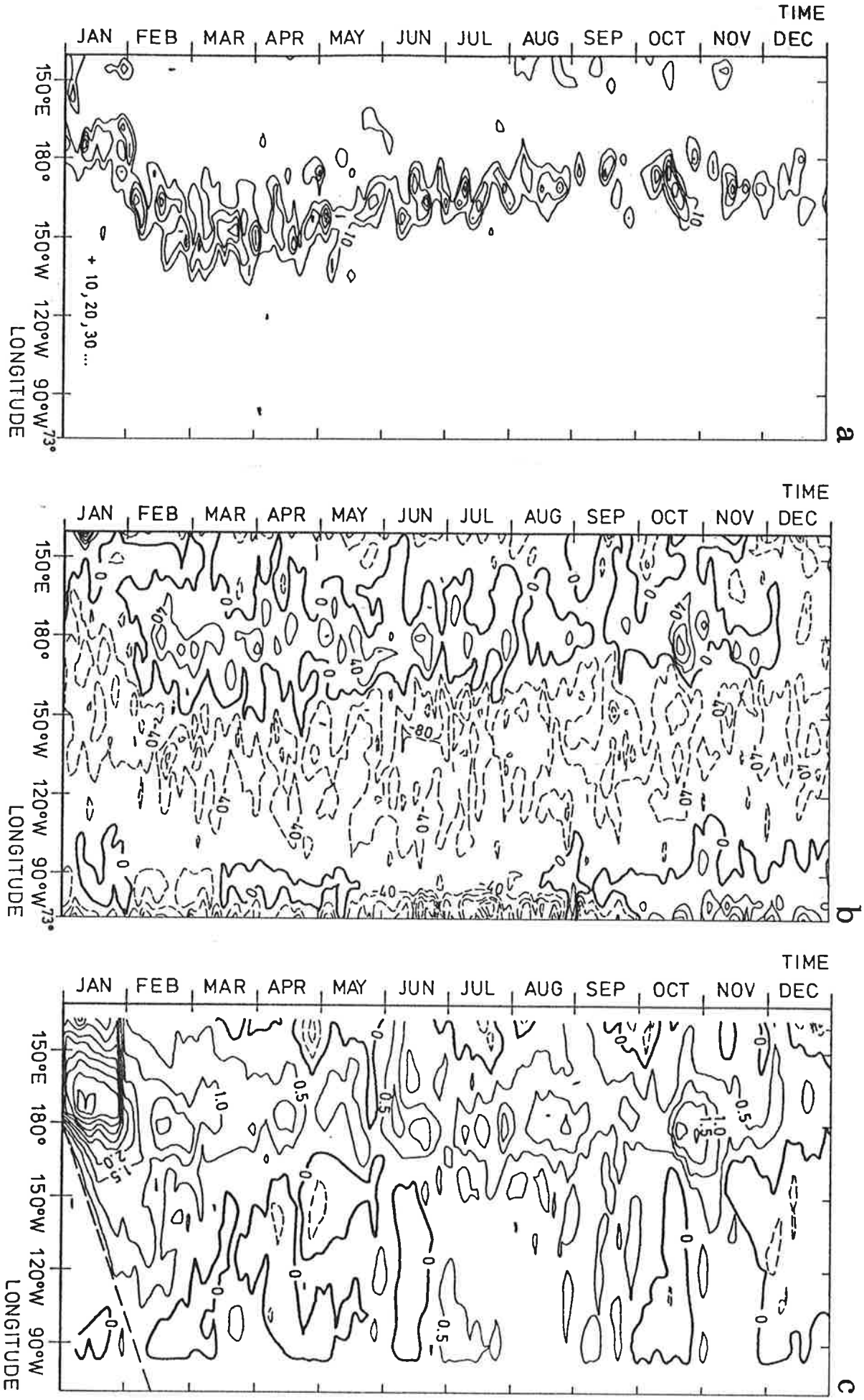

FIGURE 7: Evolution of different quantities along the equator in the coupled burst experiment; a) Convective rain fall (CI = 10 mm/d); b) Zonal suface wind stress component (CI = 40 mPa); c) Zonal surface current anomalies (CI = 0.5 m/s).

4.2 TEN YEAR RUN

In the next experiment the coupled GCM was integrated for ten years to determine its full variability spectrum (see Latif et al., 1989 for this study). The main results of this study are the occurrence of a climate trend during the integration and the reduction of interannual variability in the Equatorial Pacific. The evolution of SST along the equator (Fig. 8a) is dominated by an almost spatially uniform cooling, which is strongest during the initial phase of the ten year run. A preliminary analysis of the results shows that the cooling may be attributed to the closed geometry of the ocean model, which does not contain the processes maintaining the thermocline. Explicit and numerical diffusion lead therefore to a slow destruction of the model thermocline with cooling of the upper ocean and warming of deeper ocean layers. The cooling of the upper ocean affects the atmospheric circulation on a broad range of time scales. Mean seasonal atmospheric conditions, for example, show significant deviations when compared with mean seasonal fields derived from an uncoupled control integration (Fig. 9). The cooling of the upper ocean layers is clearly reflected in the entire atmospheric column above the Equatorial Pacific. As an example the 850 hPa temperature field is shown in Figure 9a. The anomalous cooling of the atmosphere leads to anomalous upper level convergence (Fig. 9b) and reduced rainfall over the Equatorial Pacific (Fig. 9c). These anomalies are consistent with a reduced strength of the Hadley Circulation in the coupled simulation. Significant extratropical anomalies are also found, as can be seen in the sea level pressure anomaly field (Fig. 9d).

High frequency variability within the atmosphere is also affected by the climate trend. In particular, the variability on time scales of a few weeks associated with the "30-60 day" oscillation is significantly reduced over the Western Equatorial Pacific (not shown). As pointed out by many authors (e. g. Wyrtki, 1985), ENSO events may be initiated by high frequency atmospheric disturbances such as the "30-60 day" waves.

The reduction of low frequency variability at the equator (see Fig. 8) may therefore be at least partly attributable to the reduction of high frequency atmospheric variability. Another possible reason for the reduction of interannual variability within the coupled run may be the weak variability of the atmosphere model in general (Figs. 1 and 2). Even if forced with a perfect ocean (observed SSTs) the atmosphere model generates surface stress anomalies

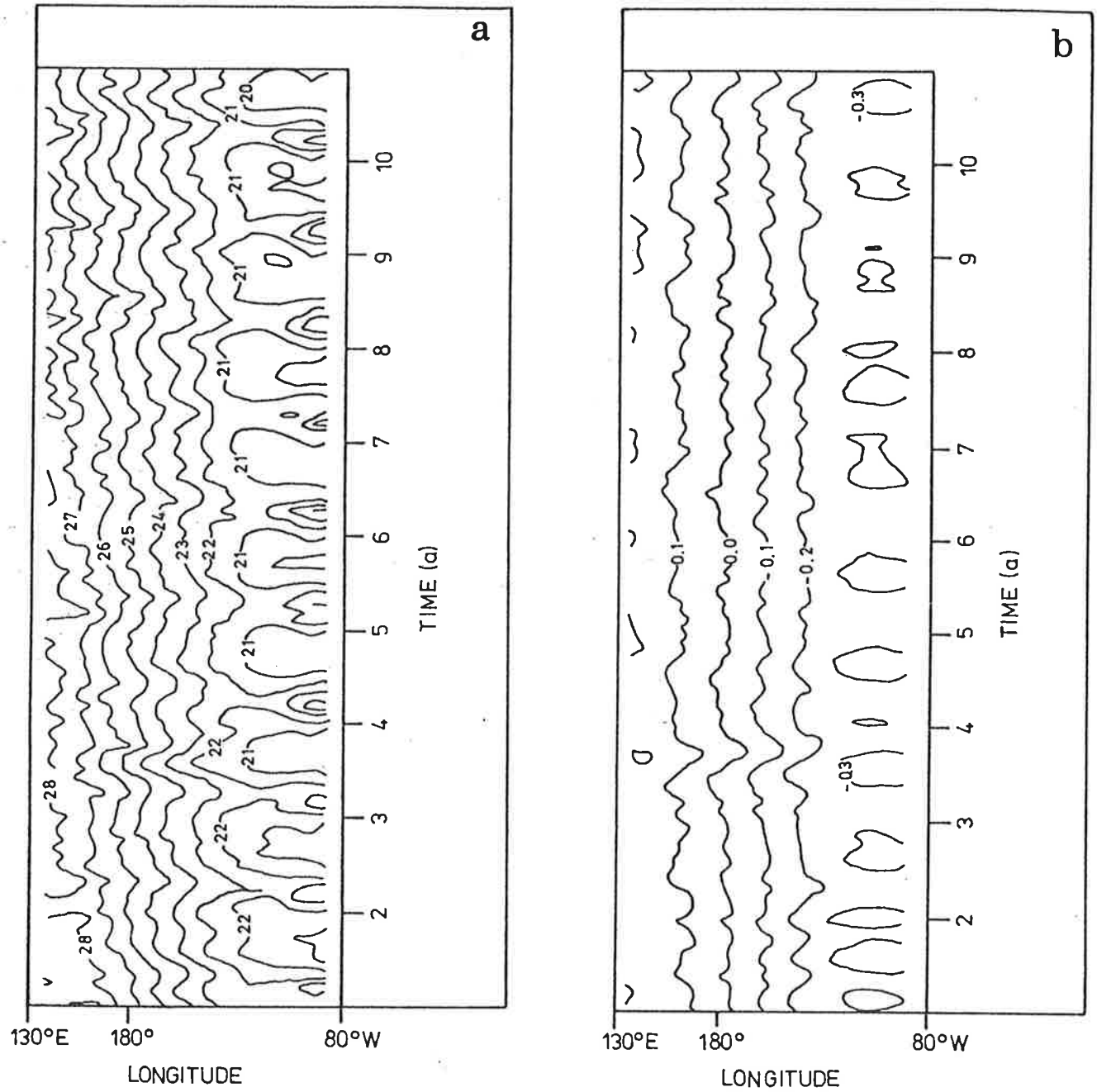

FIGURE 8: Evolution of oceanic conditions in the ten year run; a) SST (CI = 1° C) b) Sea level (CI = 0.1 m).

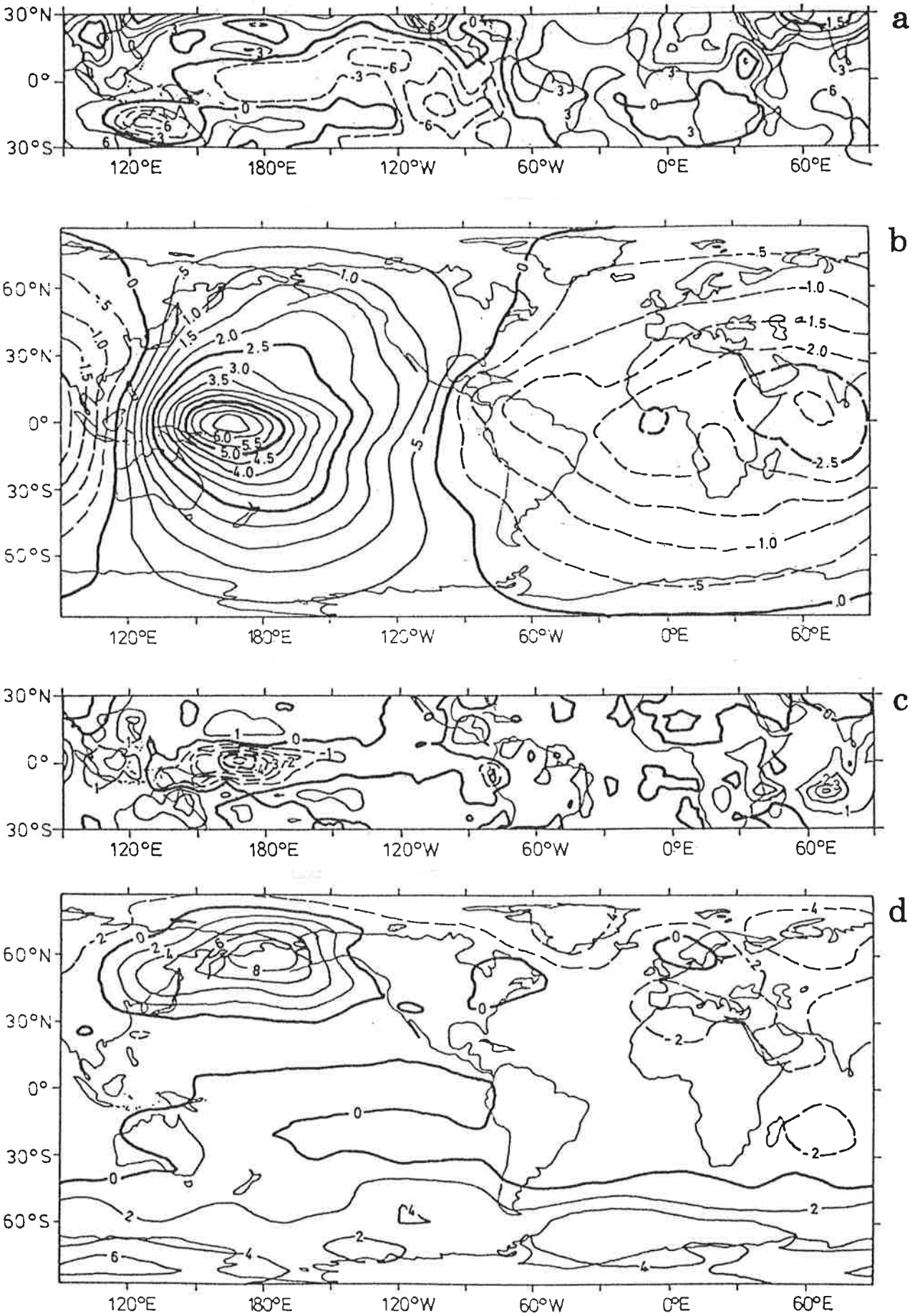

FIGURE 9: 10 year mean DJF (December, January, February) differences between some atmospheric quantities simulated with the coupled and with the uncoupled atmospheric model; a) 850 hPa temperature (CI = 0.3° C); b) 300 hPa velocity potential (CI = 10^6 m^2/s); c) Convective precipitation (CI = 1 mm/d);d) Sea level pressure (CI = 2 hPa).

that are much too weak (Fig. 2), so that the degree of air-sea interactions may be unrealistically low in the coupled system. The coupling strength is further reduced by the presence of the above desribed climate trend. A cooler ocean leads to less energetic air-sea interactions due to the nonlinearity of the Clapeyron Equation. In further experiments it is therefore necessary to control the climate trend during the coupled integration and to enhance the variability within the atmosphere model.

4.3 SNOW EXPERIMENT

The role of Tibetian snow cover in regional and global climate has been investigated by Barnett et al. (1988). As part of this study the coupled model in its fully interactive version (including interactive surface heat flux) was used to test the hypothesis that heavier than normal snow cover leads to a "poor" Monsoon and may trigger ENSO events. For this purpose the snow fall rate over Asia was doubled and the response of the coupled model to this perturbation was investigated.

As in a similar uncoupled experiment with the atmosphere model there develop westerly surface wind anomalies over the Equatorial Pacific, which force positive SST anomalies in this region (Fig. 10b). These SST anomalies are amplified by the feedback of the atmosphere model. This can be inferred from Figure 10a, which shows the response of the uncoupled ocean model driven by surface wind stress anomalies derived from the uncoupled "snow run" with the atmosphere model. During summer SST anomalies exceed $1^{o}C$ (Fig. 10b) and anomalous conditions are very similar to those prevailing during the onset of ENSO events. Thereafter, however, the event terminates rapidly, probably because of the climate trend, which tend to decouple the atmosphere model from the ocean model. Nevertheless, these results support the idea that anomalous snow cover over Asia can trigger ENSO events.

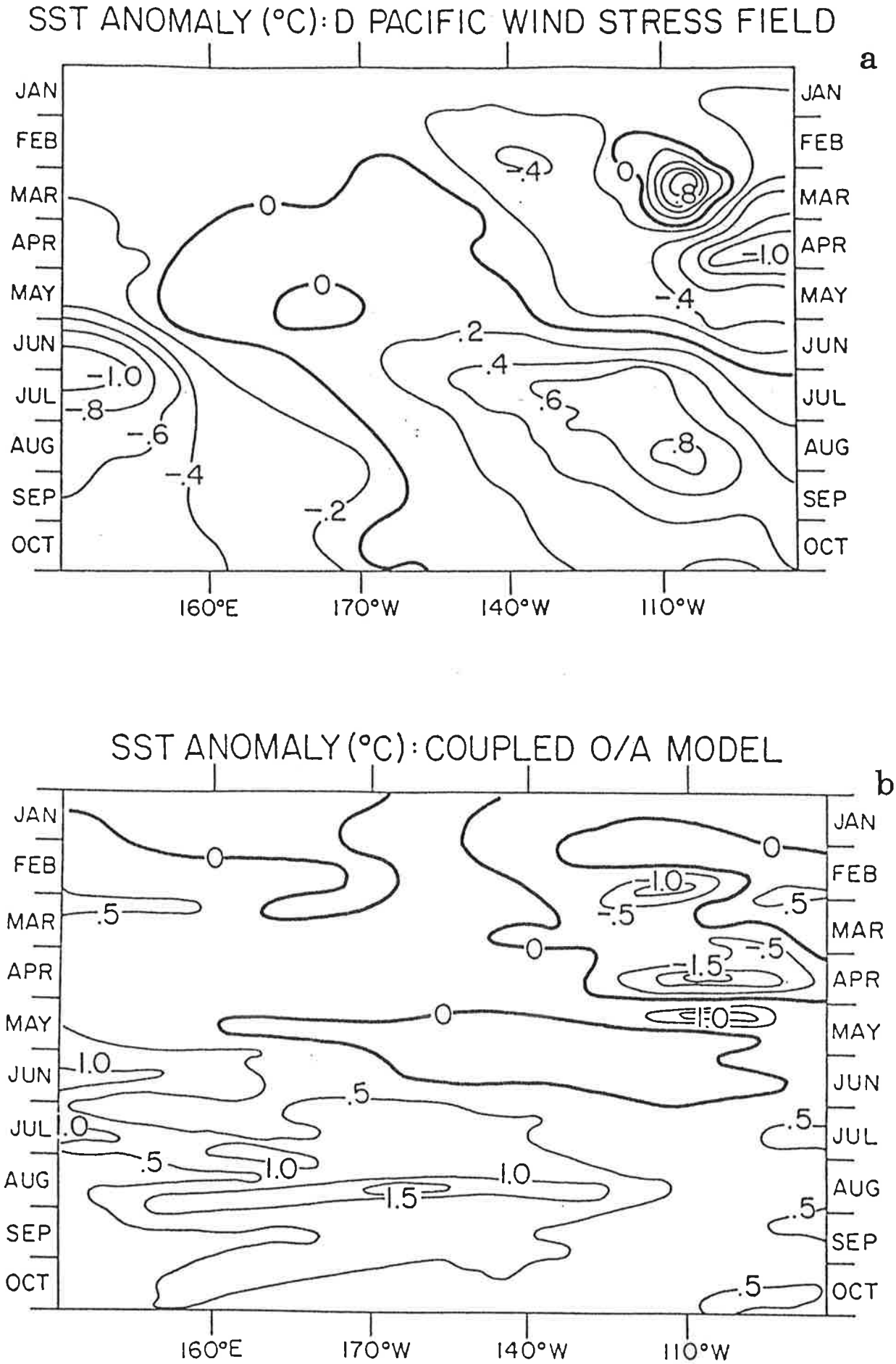

FIGURE 10: Evolution of SST anomalies along the equator; a) Anomalies derived from a run with the ocean model driven with surface wind stress anomalies taken from the uncoupled snow experiment; b) Anomalies derived from the snow experiment performed with the coupled ocean-atmosphere model.

5. ENSO HINDCAST EXPERIMENTS

Although the time scales of ocean and atmosphere become nowhere closer than in the vicinity of the equator, the response of the equatorial atmosphere to disturbances is still much faster than the response of the equatorial ocean. For the hindcast experiments described below a simplified ocean-atmosphere model was therefore applied, where the atmosphere is represented by a simple feedback model which computes surface wind stress anomalies from a given SST anomaly field. The oceanic component consists of the OGCM described in section 3. The coefficients relating SST anomalies to stress anomalies have been determined locally using a run with the ocean model driven with observed winds for the period 1970 to 1985. Initial conditions for the hindcast experiments have been taken from the same run.

Such a coupled system gives a realistic hindcast of the 1982/1983 ENSO event (Fig. 11). The hindcast started on 1 April 1982 successfully simulates the onset and the evolution of this particular event. However, the SST in the Niño 3 region of the Eastern Pacific is hindcasted about 1°C lower than in the run with observed winds. An inspection of the spatial patterns of SST (not shown) shows that the coupled model realistically reproduces the fields for individual months.

It should be pointed out that the hindcast shown above was performed with feedback coefficients derived from a time period including the 1982/1983 ENSO event. In the next step this hindcast will be repeated with coefficients determined from a time period excluding this particular event.

6. SUMMARY AND CONCLUSIONS

It has been shown that boundary forced low frequency variability in the tropics is simulated realistically by the presented ocean and atmosphere model. However, the simulations show also significant errors, so that there arise some problems, when these models are coupled together.

Nevertheless, the individual models have reached a standard where it appears justifiable to use them in a coupled mode for climate studies. As

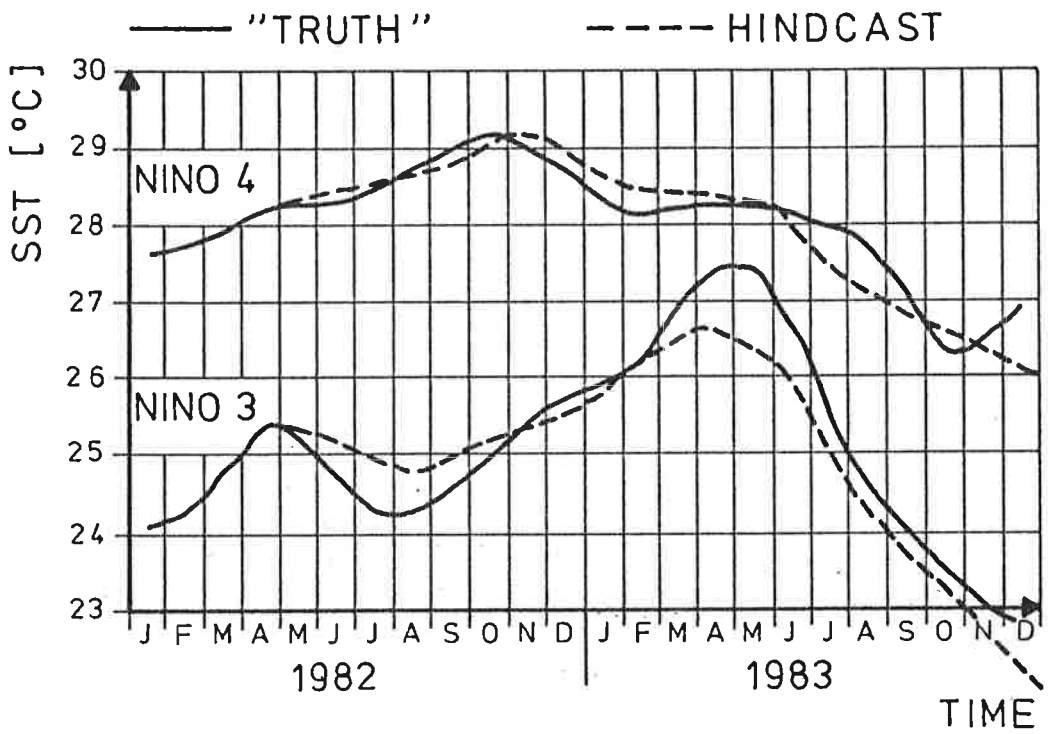

FIGURE 11: Evolution of SST anomalies in the Niño 3 (5° N-5° S, 90° W-150° W) and Niño 4 (5° N-5° S, 150° W-160° E) region during the 1982/1983 ENSO event. Solid lines: Calculated by the ocean model, when forced with observed winds. Dashed lines: Hindcasted by the simplified coupled model initialized on 1st April, 1982.

shown here such coupled models provide interesting results. The high persistence of equatorial SST anomalies, for example, was found only in coupled runs, and the coupled feedback was similar to that found in simpler models of air-sea interactions.

Results from both the uncoupled and the coupled runs provide support for the hypothesis that ENSO is predictable. A simplified coupled system based on the OGCM described in section 3 and a diagnostic atmosphere gave a skillful hindcast of the 1982/1983 ENSO event. This particular hindcast was initialized in April 1982, which is about one year prior to the maximum warming in the Eastern Pacific.

In the next step the coupled GCM presented in section 4 will be used for predictability studies. For this purpose suitable coupling strategies have to be developed which account for the model errors.

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