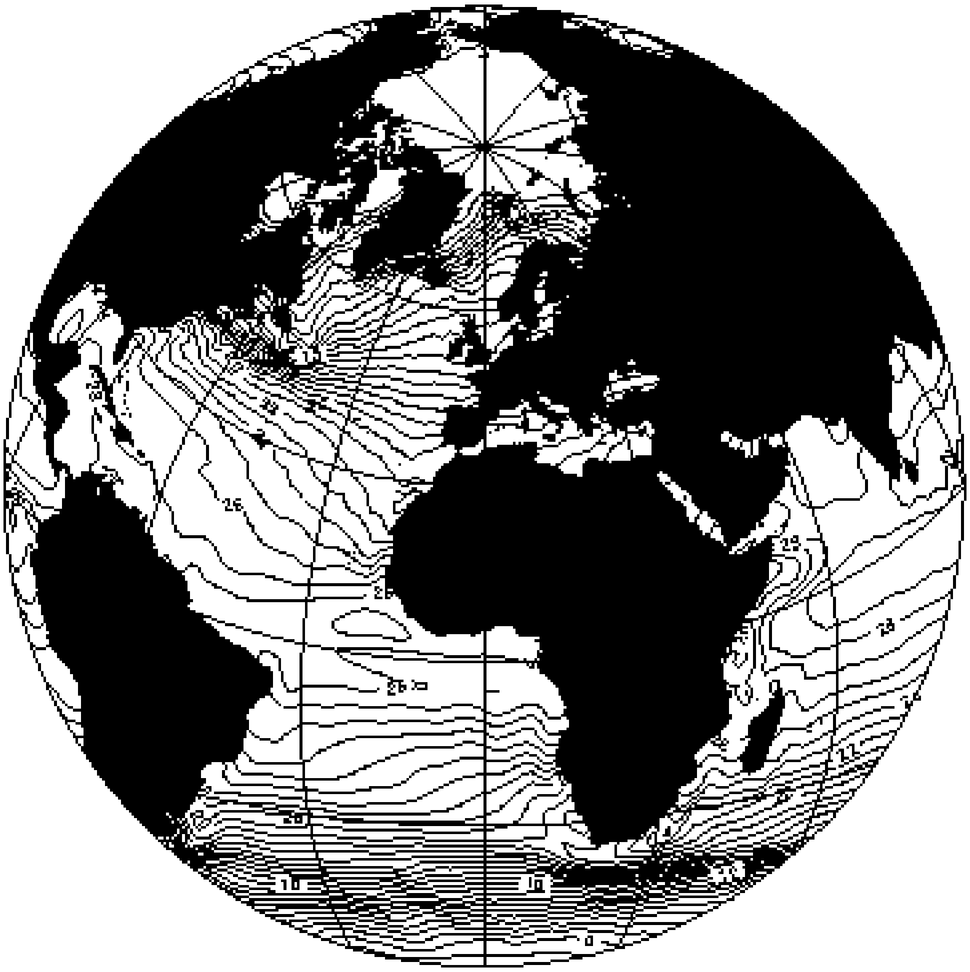
"Climate Modelling & Global Change" Team : 1995/1996 Scientific Report

February 1997



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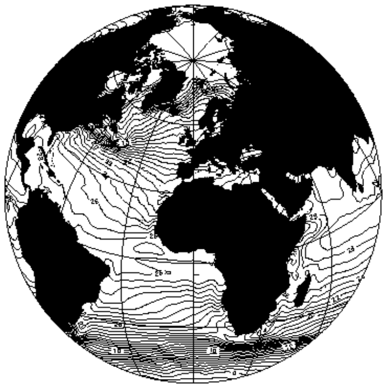

1 INTRODUCTION

1.1 Overview of the team activities

During the first years following its creation, the "Climate Modelling & Global Change" team had to make its proofs in order to achieve its integration into the climate community. It is now part of this community which has appreciated its main achievements: the coupler OASIS, the experiment manager VAIRMER and several pioneer experiments of the ocean-atmosphere climate. This work has been rewarded in 1995/96 by the first prize of the "Concours Seymour Cray France" given to the nine researchers which composed the team at the time of the application. Indeed, such an achievement is only possible through a real team work, and our capacity to work together has been one of our main strength. We intend to preserve it for the future.

The "ocean-atmosphere coupling" activity is now well settled in the team, as can be seen from the richness of the scientific results based upon the team climate experiments. Between 1995 and 1996, we have used the equivalent of 8 000 h mono-processor of a CRAY C98 or 25 000 h mono-processor of a CRAY-2 or CRAY J912. The balance between experiment production and experiment analysis has reached a satisfactory rate. The quality of the results obtained with the coupled model allows detailed analysis such as the study on storm tracks and blocking that we have achieved in the framework of an EDF/DER contract. We have also achieved an older contract with EDF called CATHODe.

We are now ready to launch the first scenario experiment of the French climate community. This big undertaking will benefit from all the improvements that we have contributed to bring to the coupled model, and the expertise that the team has accumulated during these last five years. In the framework of the SIDDACLICH European contract, one of our 3-year goal is to validate the coupled model for anthropogenic climate change studies. This will open the way to its use by METEO-FRANCE for more operational purposes.

In parallel with this ocean-atmosphere coupling activity, we have launched a new program on "data assimilation in general circulation models" which answers to interests formulated by CNES and EDF/DER and enter in the framework of national or european projects such as MERCATOR, AGORA and DUACS. This new activity is likely to follow the same path than the successful one of the ocean-atmosphere coupling activity: concentration of expertise in the team, development of tools for the scientific community, validation through specific scientific studies and contribution to operational uses. This new challenge has generated a new impetus and a flux of new people in the team.

The activities of the team are thus strongly motivated by the interest of three main partners of CERFACS (EDF/DER, METEO-FRANCE and CNES). This is a heavy responsability for the team and we will try to fulfill these expectations as well as possible.

1.2 Team participants in 1995 and 1996

In 1995, there has been 10 participants to the Climate Modelling & Global Change project, including one project leader (Olivier Thual), two senior scientists (Laurent Terray and David Stephenson), five Ph.D. students (Laurence Fleury, Gilles Garric, Marc Pontaud, Eric Guilyardi and Jorge

Macías), one graduate student (Christophe Cassou) and one administrative assistant (Isabelle Moity). We have also welcomed two students for a DEA training period (Christophe Cassou and Bernard Hypolite).

In 1996, three participants (Laurence Fleury, Gilles Garric, and Marc Pontaud) have defended their Ph.D. and have left the team for new positions (two postdoctoral and one permanent position). The team has renewed nearly half of its participants. It now includes 9 participants, including one project leader (Olivier Thual), one senior scientist (Laurent Terray), two research engineers (Andrea Piacentini and Catherine Gaffard, replaced by Sophie Valcke), three post-docs (Pierre Barthelet, Eric Greiner and Philippe Rogel) and two Ph.D. students (Eric Guilyardi and Thierry Lagarde) one administrative assistant (Isabelle Moity). One Ph.D. student (J. Macias) is temporarly on leave and will defend his Ph.D. at CERFACS in 1997. In 1996, we have also welcomed one student for a DEA training period (Thierry Lagarde), one engineer student (Vincent Blohorn) and one ENM/Master student (Edouard Ngakosso).

Name	Position	Period
O. Thual	Project leader	1991/09 —
L. Terray	Senior	1990/10 —
D. Stephenson	Senior	1993/12 — 1996/08
A. Piacentini	Research Engineer	1996/10 —
C. Gaffard	Research Engineer	1996/4 — 1996/12
S. Valcke	Research Engineer	1997/2 —
Ph. Rogel	Post-doc	1996/01 —
E. Greiner	Post-doc	1996/10 —
P. Barthelet	Post-doc	1996/09 —
M. Pontaud	Ph.D. student (IM)	1993/07 — 1995/08
E. Guilyardi	Ph.D. student	1993/10 —
J. Macías	Ph.D. student	1993/10 — 1996/10
L. Fleury	Ph.D. student	1992/10 — 1996/06
G. Garric	Ph.D. student	1992/10 — 1996/06
Th. Lagarde	Ph.D. student	1996/10 —
C. Cassou	Graduate student	1995/03 — 1995/12
V. Blohorn	Engineer student	1996/07 — 1996/09
E. Ngakosso	Master student	1996/09 — 1996/12
I. Moity	Adm. Assistant	1993/10 —

Participants of the Global Change project in 1995 and 1996

2 DEVELOPMENT OF OCEAN-ATMOSPHERE COUPLED MODELS

Ocean-atmosphere interactions play a crucial role in understanding climate variability on a broad range of spatial and time scales. Coupled General Circulation Models (CGCMs) are the most comprehensive and, potentially, the most appropriate tools to simulate and understand the global climate and its present-day fluctuations such as the El Niño - Southern Oscillation phenomenon. The development and validation of such tools are currently carried on in the french climate community. The Climate Modelling and Global Change team has been primarily involved in the development and validation of the ARPEGE-OASIS-OPA CGCM. The atmospheric component is the climate version of the ARPEGE/IFS forecast model developped jointly by Météo-France and ECMWF and the oceanic one is the OPA model developped by the Laboratoire D'Océanographie Dynamique (LODYC). The two components are coupled together with the OASIS software developped at CERFACS. The CGCM has been widely used to simulate regional and global climates with a Pacific and global versions, respectively. Detailed analysis of the different simulations have been performed and have led to sensitivity studies on atmospheric and oceanic physical parametrizations. The new versions of all the components of the coupled system were assembled together (in 1996) in order to realize in 1997 two 100-year simulations of the current and modified (with an increase in CO2 concentration) climate. Other shorter simulations will be realized as well to test the sensitivity of the global model to atmospheric and oceanic parametrizations.

2.1 Initial ocean-atmosphere coupled experiments (95)

The ARPEGE-OASIS-OPA CGCM has been used in several configurations and numerous simulations have been performed; the generated data has been archived for subsequent analysis. They can be separated mostly in two families: the simulations with a Pacific-only ocean model and the ones with a global ocean model. The first family includes the following simulations (the ocean model is the same within this family, OPA version 6 in its Pacific version):

- CO1: a 10-year simulation of the tropical pacific with the beta release of the version 1.0 of the atmospheric model ARPEGE at resolution T42
- CO4: a 3-year control experiment with the version 1.0 of ARPEGE at resolution T42
- CO5, CO7, CO9: 3-year sensitivity experiments with version 1.0 of ARPEGE at resolution T42

The second family contains the global simulations:

- CA1: a 75-year global simulation with version 1.0 of ARPEGE at resolution T21 and OPA7 in its global version at resolution $2^o x 1.5^o$ with a simplistic parametrization of sea-ice
- CG3: a 30-year global simulation with version 1.0 of ARPEGE at resolution T42 and OPA7 in its global version at resolution $2^o x 1.5^o$ with a simple restoring towards sea-ice climatology

- CI5: a 15-year global simulation with version 1.0 of ARPEGE at resolution T42 and the sea-ice and mixed-layer ocean model developped at the University of Louvain-la-Neuve at the same resolution

2.2 Anthropogenic climate change studies: scenario experiments (96)

In the frame of the Simulation, Diagnostic and Detection of the Anthropogenic Climate Change (SIDDACLICH) project of the EC program on Environment and Climate, the Climate Modelling & Global Change Team has to realize two 100 years simulations. The first one, with constant concentration of green house (CO2) gas will be the control run and should be driftless and as close as possible to the observed climate. The second simulation will take into account a constant increase of CO2 concentration (1% per year) and corresponds to one of the scenario proposed by the IPCC. These simulations will use the last versions of the following GCMs :

- ARPEGE V2, developped at Meteo France. This version include a prognostic soil scheme, a gravity wave drag parametrization and an increased convective entrainment. The radiative scheme will be discussed later. A T31 grid (3.75 deg. * 3.75 deg.) with 19 levels over the vertical has been chosen.
- OPAICE, made of the OPA GCM and a thermodynamical sea-ice model, developped at Lodyc.
- OASIS 2.0, the coupler developped at CERFACS, which ensure the interpollation of the coupling variables between the AGCM and the OGCM and the synchronisation of the models.

Intensive work was required in order to prepare these coupled simulations. We had to put together new versions of the models, a new version of the coupler and new interpolation methods. Moreover, in parallel, a work of validation and adaptation to the coupling of the AGCM and OGCM has been realized.
Hereinafter, we describe in particular two specific studies motivated by the above simulations.
Study of radiative scheme for the AGCM ARPEGE V2
In the version 2 of the AGCM ARPEGE, two different radiative schemes can be used : Geylen scheme (G) and Fouquart - Morcrette scheme (FMR). The first simulation in forced mode of OPAICE using fluxes calculated with FMR showed a complete melting of the ice cover in Arctic and Antarctic during summer. This major problem has motivated a comparison between the radiative schemes. We have compared systematically the different components of the heat flux zonally averaged for both schemes. The observation of the total heat fluxes shows that FMR is cooler than G in the tropics (about 10 W/m2) and warmer at mid and high latitudes (about 20 W/m2). The difference between solar component stays essentially in the tropical zone, with G warmer of about 15 W/m2 than FMR, owing to the smaller quantity of clouds in the G simulation. The non solar component is 20 W/m2 warmer in the FMR scheme than in G, in the mid and high latitudes. The latter discrepancy is essentially due to the downward longwave component, and is compensated in the tropical zone because of a stronger cooling due to the latent heat flux. To synthesize this results, we can say that in the tropics G is warmer than FMR(10 W/m2) owing to solar heat flux, and that at mid and high latitudes FMR is warmer than G (20 W/m2) owing to downward longwave component of non solar heat flux. This latter discrepancy seems to explain the melting of ice cover and the strong warming of ocean at mid latitude observed in other coupled simulations with FMR. Nevertheles, the comparison of the results of simulation to the existing observations, shows that, in fact, the radiative component of heat flux is better evaluated with the

FMR scheme. But the turbulent fluxes are strongly biased, and the compensation of error, which allows G to be quit close to the observed total heat flux doesn't work as well with FMR, at least at mid and high latitudes. In conclusion, the G scheme seems more apropriate in the short term to be used for coupled ocean-ice-atmosphere simulations if one wants to avoid the questionable use of flux correction. However, work is in progress to improve the representation of clouds in the FMR version. Initial results with a cloud statistical scheme seems to give much better radiative fluxes.

Calculation of non solar heat flux when open water and sea-ice are simultaneously present

In the frame of ocean-atmosphere coupling, the calculation of non solar heat flux is difficult when open water and sea-ice are simultaneously present under the same mesh of atmosphere. Indeed, strong contrasts of surface temperature and physical propertie s exist between open water and sea-ice. This problem arises particularly when, as for the ARPEGE AGCM developped by Meteo France, only one averaged Sea Surface Temperature for each mesh is seen by the AGCM. The nature of the surface depends on the sea-ice extent, through a simple thresholding. The first problem is to evaluate the quality of calculation of the mean flux generated by the AGCM, using only one mean temperature and one single type of surface. The second problem arises when this estimated mean flux is distributed in the OGCM between open water and ice. The methods used at this moment is a first order extrapollation, using the flux sensitivity of non solar heat flux with respect to the temperatu re. Again, the quality of calculation of fluxes on open water and ice must be evaluated.

These two different problems have been studied by the mean of 1D calculations based on bulk formulae modelisation of the atmosphere. In both cases, the major discrepancy arises in winter conditions.

The estimated mean flux calculated using only one mean temperature and one single type of surface show an error which can reach $\pm$ 20 W/m2. This error is important, if we consider that a sensibility test showed that such a value can lead to the melting o f the whole ice in arctic.

The distribution of this flux using the first order method show an error which can reach $\pm$ 40 W/m2 over open water in winter condition (value which must be compared to a flux of -200 W/m2) and go up to 150 W/m2 over ice (for a flux varying between $\pm$ 20 W/m2). It is worth to notice that the error on ice is always positive, and thus corresponds to underestimate the cooling of the ice surface. The formation of ice can be strongly affected by this problem.

One solution to avoid both problems is to calculate two fluxes in ARPEGE, using a double physic module.

Before to implement such a modification in ARPEGE, forced simulations of OPAICE by ARPEGE fluxes, using a bulk model with a single or a double physic must be done to evaluate the effects of double physic calculations in a 3D dynamic simulation.

2.3 Analysis of coupled models (95/96)

Following the realization of the first global coupled simulations in 1995, an extensive analysis of the results has been performed. In particular, the climatology of the ARPEGE T21/OPA7 50-year experiment has been assessed (Guilyardi and Madec, 1997). The main conclusion are the following. The model reasonably simulates the basic features of the observed mean state and seasonal cycle of the ocean-atmosphere system. As no flux correction techniques are used, a first quality of the model is the good stability of the simulated air-sea interface which is maintained for several decades and for most of the ocean surface. The first contribution to this stability is the balanced radiation budget at the top of the atmosphere (+0.12 Wm^{-2}), already present in the uncoupled AGCM (Déqué et al. 1994). In the tropical ocean, the simulated thermocline is tight (Madec et al. 1996), has a marked **W** meridional structure and realistically acts as a thermal barrier between the

cold interior-ocean waters and the warm mixed-layer waters. This contributes to the stability of the coupled system. Following this stability, the coupled model exhibits a balanced global energy budget and realistic annual-mean northward heat transports in both ocean and atmosphere.
Nevertheless, some systematic deficiencies are identified, including too warm tropical SSTs, a zonalisation and a symmetrization of the ocean-atmosphere circulation, a modified winter atmospheric circulation in the northern mid-latitudes and a warming of the southern ocean. Most of these deficiencies are already present in the uncoupled reference simulations and are further amplified by the coupling. They are mostly due to deficient physical parameterizations (low-level clouds in the AGCM, horizontal diffusion in the OGCM) and illustrate the need for improvements in the physical parameterizations both in the atmospheric marine boundary layer and in the ocean lateral diffusion processes. Besides the deficiencies inherent to the uncoupled GCMs, some strong coupled processes appear and lead to the warmer-than-observed tropical SSTs. Other studies conducted with different versions of the OPA-ARPEGE coupled model show that the warm bias and the stability at the tropical air-sea interface are persistent when the resolution is increased in both GCMs (Terray et al. 1995, Pontaud et al. 1995, Delecluse and Levy, personnal communication 1995). On one hand, this suggests that the model is misrepresenting or even omitting some coupled mechanism which results in the deficiencies described here. But, on the other hand, the tropical stability, obtained with no flux correction, appears robust. It is an encouraging feature for long term climate simulations.
In 1996, new experiments made with an improved version of the AGCM (Arpege V.2) in T31L19 led to a clear improvement of the simulated tropics. This allowed the global atmospheric circulation to remain quite close to the uncoupled simulation and the ocean response was less disturbed than the previous runs. The use of an isopycnal diffusion operator in the OGCM greatly improved the density structure, in particular in the Southern Ocean. Further analysis are underway. In particular, the initial drift of the simulation is explored and diagnostics are applied to understand the heat and salt balance in the ocean.

2.4 Developement of coupled models (95/96)

In the light of the qualities and deficiencies seen in the present coupled simulations some model improvements were prepared. The first category concerns the atmosphere and ocean physical parameterizations. Sensitivity tests to clouds parameterizations (Terray 1997) have shown that the warm tropical bias can be reduced. In the ocean component, the horizontal diffusive scheme, responsible for the (small) remaining trends in the ocean, is currently being replaced by an isopycnal diffusion scheme. Tests in forced mode show significant improvements and, in particular, an increased control of the diffusion accross tight horizontal gradients in the ocean. The second category of improvements concerns the coupling itself and involves energy and fresh water conservation in the global ocean/atmosphere/sea-ice system. It was shown that most of the (moderate) ocean temperature drift (0.4 oC/century) was due to internal heat sources associated to 1) a deep temperature restoring on land, 2) a model coast lines mismatch and 3) the lack of an energy conserving sea-ice model (Guilyardi and Madec, 1997).

2.5 Sensitivity of climate drift to physical parametrizations (95/96)

Major unresolved issues in coupled modelling involve model initialization, coupling strategy and climate drift. The latter does affect the climate mean state but also its variability. Furthermore, it is present in both global and limited domain coupled models. If one wants to avoid the questionable

use of flux correction, the understanding and reduction of climate drift are then one of the highest priority in climate research.
Sensitivity of climate drift to selected convection and cloudiness parameters has been investigated with a coupled ocean-atmosphere general circulation model (CGCM). The dependence of the coupled model climatology upon parameterizations of convective entrainment and strato-cumulus cloud cover is studied in detail. A new diagnostic parametrization of strato-cumulus clouds has been implemented as well as the variation of the convective entrainment rate with height. The methodology relies upon short uncoupled (1 year) and coupled (3 years) simulations. The model climatology as well as the initial drift is very sensitive to both parameterizations. For instance, increase in the convective entrainment rate at low levels result in a much colder mean state for the ocean surface (Figure). More water vapor is available to be exported by the Trades towards the convergence zones, giving a stronger Walker circulation with intense easterlies. These, in turn, generate an enhanced cold tongue through upwelling and thermocline effects, which increases the zonal sea-surface-temperature gradient and feedbacks to the atmosphere. The model sensitivity is generally found to be the result of complex feedbacks between convection, cloud processes, sea surface temperature (SST) and large-scale ocean-atmosphere dynamics.

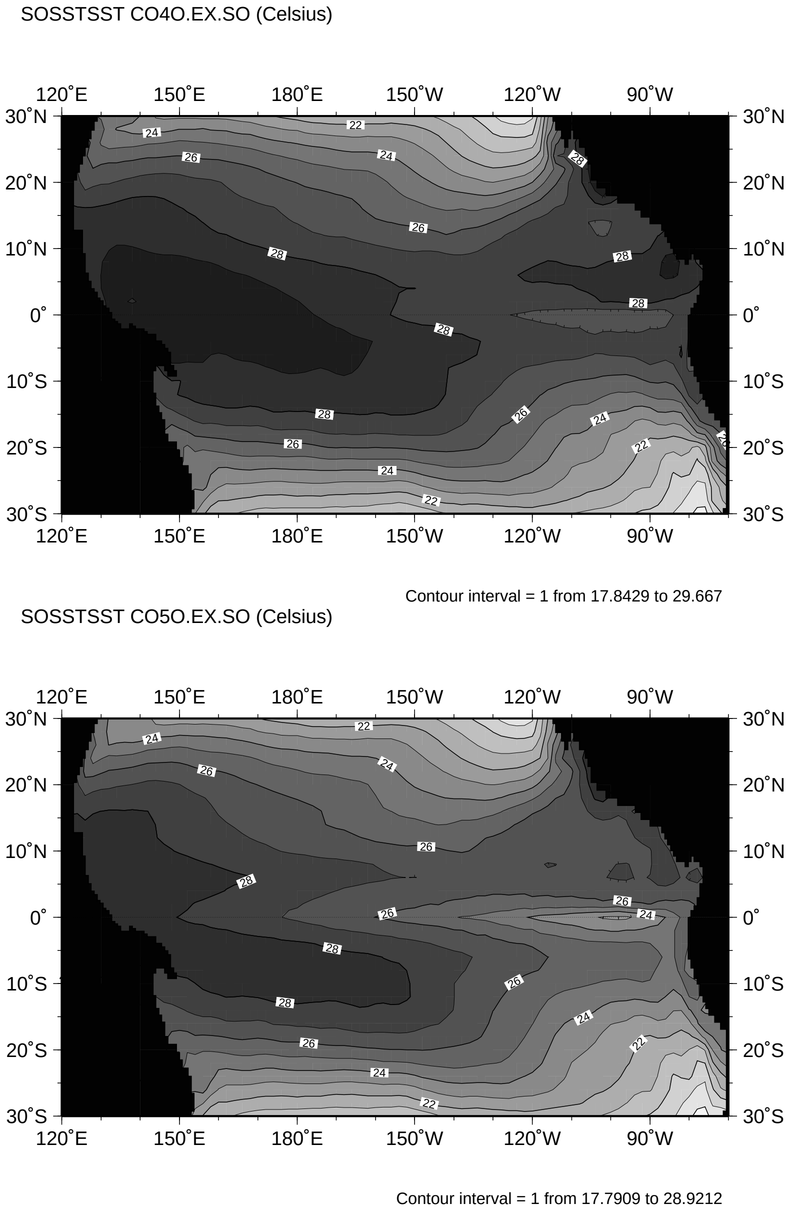

Figure 2.1: Mean sea surface temperature in ^{o} Celsius; upper: the control run and lower: the run with the new convective entrainment rate. The data have been averaged over a 3-year period.

3 FOCUSED ANALYSIS WITH THE COUPLED MODEL

3.1 North Atlantic air-sea interaction and seasonal prediction (95/96)

In January 1995, a project was presented by Dr. D. Stephenson to EDF and was accepted for funding as a 1 year project. The project aims to investigate the short-term predictability of European climate and its relationship to the North Atlantic ocean by using the T42 coupled model at CERFACS and satellite altimetry data.

3.1.1 Seasonal climate prediction

As a necessary first step in using a coupled model for seasonal prediction of European weather, the northern hemisphere circulation of the CERFACS coupled simulation is analysed and compared with both the ECMWF analyses and with the results of an atmosphere-only simulation, with an emphasis on the wintertime circulation. There is a large response to coupling an ocean model especially in the North Atlantic with a more realistic Icelandic low and weaker jet than in the AMIP simulation. This has a beneficial impact on the modelled European wintertime climate which becomes cooler with weaker mean westerlies. The transient behaviour also improves with stormtracks centered correctly over the oceans and increased low frequency variability.
The atmospheric response is due to a dipole SST anomaly in the Atlantic which resembles that found in previous observational and modelling studies due to a weakened thermohaline circulation. The atmospheric heat flux acts as a negative feedback on the SST anomaly and is dominated by the latent and sensible heating. A sub-surface analysis of the North Atlantic behaviour in the coupled GCM is made. The temperature anomalies are in general in the upper 500m of the ocean and are correlated with similar errors in salinity. The mixed-layer is reduced in the central North Atlantic and the thermal structure shows some pathologies such as abrupt jumps which could be due to insufficient vertical mixing. In the western part of the basin, the Gulf stream does not separate at Cape Hatteras but continues northward and flows over the Grand Banks causing a warm anomaly. This is perhaps partly due to a poor representation of the Labrador current in the model.
The atmosphere blocking has been studied and is improved in the coupled model run compared to the atmosphere only run. The blocking frequency is increased and the position improved in the Atlantic sector although blocking is still severely underestimated compared to in the ECMWF analyses.
Analyses of five coupled experiments beginning three month after each other during the year 1992 have been carried out. Though the initial drift is a major drawback of the present coupled experiments for climate prediction, it is found that the model may reproduce some known features of the actual climate predictibility. Indeed, the global temperature difference between those experiments and their corresponding forced experiment shows increases systematically in May-June. Other fields than temperature show that there is a propagation of this signal from atmosphere to subsurface ocean. This may give information about the spring prediction barrier, known in ENSO

forecast activities. This kind of study prefigures what will be done in the DUACS project in order to investigate climate predictability using both coupled model and assimilation schemes.

3.1.2 Model validation using altimeter data

Both Topex/Poseidon observed and model sea level height data have been extracted, calculated and interpolated into Vairmer format thus enabling detailed comparison. Some preliminary altimetric results are presented. Seasonal fluctuations of sea level heights reconstructed from both forced and coupled runs of the OPA model are then analysed. The separation is made between steric height and dynamical contribution to those fluctuations. Steric height is found dominated by the thermal variations of the upper 200 m. Salinity plays a minor role, especially in the coupled experiment and it is not clear whether the forced experiment salinity changes can be trusted. Sea level corrected from steric variations show weak variations, but spatially coherent. Interannual variability in the North Atlantic ocean is investigated, as a function of time and space. In the interior of the gyre, the coupled model show more variability than the forced one.
Interannual variations of sea level heights and sea surface temperature are characterized through a Principal Component (PC) analysis. In general, more variance is explained by the PCs of sea-level than those of temperature. In the forced case, the first PC is related to ENSO variability, whereas the coupled case exhibits a very significant drift. However, the second coupled PC shows very good agreement with ENSO variability, but is also very weak, so that teleconnections can not clearly be evidenced. Results on seasonal teleconnections have been obtained. 200hPa geopotential height and total ozone column are analysed through the same method. Conclusions reached are that the interannual variability of the coupled model is probably too weak to produce teleconnections.

3.2 Water mass analysis (95/96)

This work was initiated in 1995 through a collaboration with Guvan Madec (LODYC) and Kevin Speer (LPO-IFREMER). Water mass formation rates were computed for different forced and coupled experiments following Speer and Tziperman (1982). The next step was to try to related these surface informations to internal processes. This (on-going) work is focused on *mode* waters, first because of the relatively high number of observations available there and second because of their short renewal time scales (several years), which permits their study in multidecadal coupled simulations. The main issue is how are these waters 'consumed' in the ocean interior and what are the associated subduction mecanisms. To try to assess the effect of subgrid scale parameterizations in the OGCM on theses processes, 3 coupled simulations (configuration: Arpege T31L19/OPA8 Global/OASIS2.1 and climatological ice) were carried out with 3 different parameterizations of the lateral diffusion: horizontal operator, isopycnal operator (Redi, 1984) and isopycnal + eddy induced velocity (Gent and McWilliams, 1990). Both the global response of the coupled system and the water masses distribution show significant changes after 40 years. It is expected that this first set of sensitivity experiment will help give some insights on how the energy is redistributed in the modelled coupled system and how this affects its variability.

3.3 Sensitivity to small coupling flux perturbations (95)

In collaboration with EDF/DER, we have examined the sensitivity of coupled simulations to artificial perturbations of the precision of the coupling flux exchanged by the coupler. This study constitutes the second part of the CATHODe project [1], the first part, more technical, being presented below in Subsection (6.3). The coupled experiments were based on the run CG3, i.e. the coupling of ARPEGE T42 (atmosphere) with the global version of the OPA model (ocean).

Perturbations of order 10^{-5} we imposed on the atmospheric flux or the SST, during the first coupling step (1 day) or for all coupling steps, with an exploration of all possible combinations of these options (e.g., perturbation of SST only for all time steps, perturbation of all flux at initial time steps only, etc.). The comparison of these perturbed coupled experiments to the reference simulation provides an interesting evidence of the "butterfly effect" in coupled mode with the following general picture. The atmosphere amplifies the small perturbations of the initial conditions with a doubling time of order 5 days. The upper ocean follows the forcing of the atmosphere with a relaxation time of order 15 hours, and does not seem to amplify the errors, at least for times scales of the order of 10 days. Three perturbed simulations have been continued for one year, and compared to the reference simulations. They all show that discrepencies of several degrees in the SST are observed after several months, due to only 10^{-5} relative errors for the initial conditions. These results raise important issues about seasonnal predicibility.

3.4 Intercomparison of climate experiments (95)

Three coupled simulations have been performed. First, the Pacific OGCM has been coupled with the T42 ARPEGE AGCM for 10 years (experiment named "CO1"). In addition, the global OGCM has been coupled with the T42 ARPEGE AGCM for 25 years (experiment named "CG3"), and with the T21 ARPEGE AGCM for 50 years (experiment named "CA1").

After a short and weak initial warm shock, the Pacific coupled model shows no drift in SST and exhibits a regular seasonal cycle in the equatorial Pacific. The climatological mean state is slightly warmer in the West Pacific and North of the equator, and significantly warmer along the coast of South America but the seasonal cycle of equatorial SSTs captures quite realistically the annual harmonic. The oceanic surface current pattern is accurately depicted and the location and intensity of the Equatorial Undercurrent (EUC) are in good agreement with available data. Some deficiencies remain including a weak zonal equatorial SST gradient, underestimated wind stress over the Pacific equatorial band and an overly strong convergence zone extending south of the equator in northern winter and spring. The atmospheric surface layer over the eastern part of the tropical oceans simulated by the AGCM is too dry. Weak interannual variability is present in the equatorial SST with a maximum amplitude of 0.5^{o}C.

Sensitivity experiments with cloud and convection parameterizations have been performed. Decreasing the entrainment rate with height in the convective parameterization improves the representation of the convergence zones. In addition, not enough low cloud are generated, and the direct solar radiation is roughly 50 W/m^2 too high. When the low cloud parameterization is modified to be more sensitive to low values of humidity, the mean state simulated by the coupled model becomes too cool. It seems possible to fit the cloud parameterizations to simulate a realistic mean state and seasonal cycle in the tropics, but no assurance is given that the tropical improvement will maintain the quality in the extra tropics.

The two global-ocean coupled simulations show an initial tropical warming (within a few months) more pronounced with the T21 AGCM ($+2^{o}$C) than with the T42 AGCM ($+1^{o}$C). Both simulations lead to relatively stable mean states after about 10 years. The drift of the global mean oceanic temperature is between $+0.3$ and $+0.4$ ^{o}C/century. The warm pool is warmer than the observations and the 28^{o}C isotherm is shifted eastward (T42: around 150E ; T21: around 120E). The SST in the eastern Pacific ocean is colder with the T42 AGCM (22^{o}C) in the Northern Hemisphere summer, and reasonable with the T21 AGCM (23^{o}C). The equatorial zonal SST gradient is increased. The simulated thermocline is quite tight and shows a marked latitudinal "W" structure. This positive result comes from the turbulent kinetic energy scheme used for the vertical diffusion. The SST seasonal cycle in the tropical Pacific shows a spurious enhancement of the semi-annual signal with the T42 AGCM and not with the T21 AGCM and the cold phase of the seasonal cycle is very short.

The T42 coupling improves the summer monsoon simulation giving more realistic precipitation over Asia with less precipitation over Sumatra [30]. In both simulations, there is interannual variability in the equatorial Pacific ocean (T42: -3.5 to +2.5 ^{o}C ; T21: -5. to +5. ^{o}C). Cold and warm events appear both in the eastern part of the equatorial Pacific basin and "basin-wide". Events can also appear simultaneously and some coastal events are seen to propagate westward.

In view of long range simulations, energy budgets and transports in the low atmospheric resolution (T21) coupled model are assessed and prove to be within available estimates. The climate drift is on average moderate while significant in some regions: initial tropical warming, lack of formation of intermediate water masses, warming of southern ocean. These regional drifts affect the mean global oceanic and atmospheric circulation. Despite these systemactic biases, the model robustness and stability are quite promising for future studies.

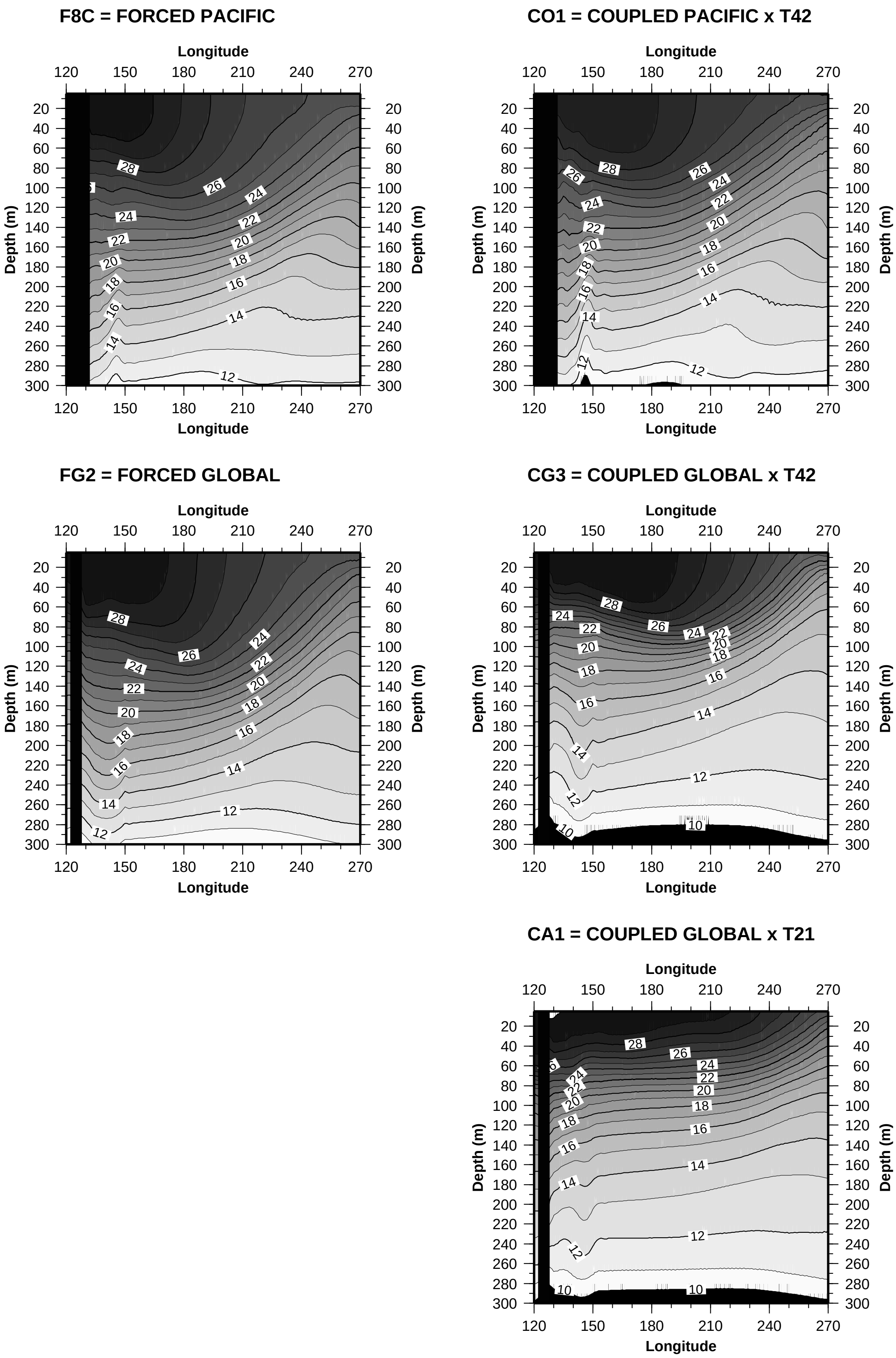

Figure 3.1: Intercomparison of climate models

4 DEVELOPMENTS OF OTHER COUPLED MODELS

Besides the coupling of GCMs of the ocean and atmosphere, the Global Change team has also invested in other kind of coupled models. These models are simplyfied, at least in one of the component of the coupled system, and more localized, tropical Pacific and polar regions, than a completely CGCM. They are intended to understand certain processes that may play an important role in the coupled system. The first of these models is a Hybrid Coupled Model (HCM) of the tropical Pacific. The second is a sea-ice-atmosphere model at high latitudes.

4.1 Coupling of an empirical atmosphere to a Pacific OGCM (95/96)

Simplifying is a way of understanding, and simplyfied models of ENSO have greatly helped to shed light into its complexity. Among these models we find the class of Hybrid Coupled Models (HCMs). They consist of a simplified atmospheric model, which represents the steady-state atmospheric response to oceanic boundary conditions, coupled to an ocean GCM. This design makes used of the fact that the ocean is the important source of memory for the coupled system, while the atmosphere can be treated as the "fast", adjusted component. HCMs have the advantage that they are much cheaper computationally than fully coupled GCMs. Also, for HCMs, the temporal variability in the system is due primarily to the coupling. This aids the understanding of the inherent properties of the coupled system in the abscence of stochastic forcing by noncoupled variability.

The development of a hybrid coupled model (HCM) has been acomplished at CERFACS. In this HCM the ocean component is constituted by the OPA ocean general circulation model. A simplified empirical atmosphere has been constructed by using an Empirical Orthogonal Function (EOF) technique. For developing this empirical atmosphere, a collaboration with Prof. D. Anderson at Oxford University and Dr. M. Balmaseda at Alcalá de Henares University (both presently at the ECMWF) has been established through an ECCN (European Climate Computer Network) project. This project, that covers the period from January 1995 to June 1996, has progressed substantially in 1995. In spring 1995, Dr. M. Balmaseda visited CERFACS for a week and transferred the code for her empirical atmosphere model. Dr. D. Stephenson and Jorge Macías modified this code substantially and developed code to couple it with the OPA6 ocean model. In summer 1995, a first run was made with hybrid coupled model and debugging took place. Over the summer many simulations (50 years) were made with this model as part of the thesis work of Jorge Macías.

At the present moment the following achievements have been accomplished to develop this model:

-Preparation of FSU wind data to force OPA model in its tropical Pacific version. The objective of this forced experiment is to obtain a consistent Sea Surface Temperature (SST) over the period (1961-93) in order to be used, together with the wind data, to construct the empirical atmosphere. This forced experiment will serve as a reference for coupled experiments by being the first forced with observational data.

- The mean state, seasonal and interannual variability simulated in this experiment have been studied in order to validate the model results. This has generated two atlases one containing the mean state and the second the seasonal cycle of this experiment (named OF1). Other atlases were done to compare OF1 results against observations (Levitus Climatology atlas and COLA-CAC observations) and against other experimental results developed at CERFACS: forced experiments (F8C mean state validation atlas) or coupled experiments (CO1 mean state validation atlas). The simulated interannual variability in OF1 experience was summarized in [25].
- Some statistical studies of the results were performed by means of a Principal Component Analysis (PCA) of the SST and wind data in order to examine the interannual variability in the results.
- An Empirical Atmosphere Model (EAM) based on Principal Componenets regressions has been constructed.
- An AMIP test has been performed with the EAM which shows encouraging results.
- More than 50 years of coupled runs have been performed.

It was found that the model was extremely sensitive to the choice of wind-stress coupling factor and to the choice of climatological SSTs used in wind stress parameterisation. Such extreme sensitivity is worrying in a model and necessitates many years of simulation to give confidence in that the results are robust. Some simulations showed the presence of interannual anomalies, it appears that in these cases one modifies the seasonal cycle implying that the seasonal cycle anomalies and interannual anomalies are fundamentally inter-related. These simulations will be further analysed as part of the thesis of Jorge Macías.

It is computationally expensive to run this HCM because of its high horizontal resolution and even with 200 CPU hours on a C90, one can perform less than 60 years of model simulation. We have shown that at least 5 years is needed with the coupled model to see if anomalies do not die out, and another 15 years is desirable to analyse the ENSO anomalies. Hence, with 200 CPU hours on a C90, only three ENSO variability experiments can be feasibly performed. This practical limitation should be kept in mind when considering the possible future experiments.

4.2 Coupling of a sea-ice mixed-layer model the atmospheric CGM (95)

General circulation models of climate predicted that the largest response to changing atmospheric carbon dioxide will occur in the polar regions. A decription of the Earth's climate must take into account the strong feedback mechanisms which link the atmosphere, sea ice and ocean at high latitudes. The poor representation of sea ice in most numerical experiments with coupled models is an important weakness in the modelling of climatic change. An improved representation of sea ice has been performed by using a model with an AGCM coupled to the Louvain large scale sea ice-upper ocean model.

The atmospheric model is the climatic version of the ARPEGE/IFS forecast model, developed jointly by Météo-France and the European Centre for Medium-range Weather Forecasts (ECMWF). The spatial discretization is triangular spectral T42 truncation corresponding to a 2.8° horizontal grid spacing and there are 30 vertical levels including 10 in the troposphere.

The sea ice model, developped at the University of Louvain, is a thermodynamic-dynamic model coupled to an upper layer ocean model. The domain is global and the resolution is the same as that of ARPEGE. Each grid point is subdivided into two kinds of surface : one covered by ice and the other occupied by open water (leads). The thermodynamics is an improved 3-layer model which takes into account the heat capacity of the snow-ice system, and the storage of latent heat within brine pockets. The energy budget of the leads drive the themodynamic variations of ice compactness. The ice velocity field is calculated by a momentum-balance equation using the

viscous-plastic formulation. The upper layer oceanic model is a one-dimensional integral oceanic mixed layer (OML). A 12-layer grid is used down to 300 meters depth. The oceanic heat flux at the sea ice basis is a prognostic quantity.
The OASIS software coupler developped at the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS) ensures the daily time synchronization between the two models. The lack of ocean dynamics is replaced by a restoration of oceanic temperature and salinity to mean annual observations. The coupled model has been integrated for a 15-year period. To optimize the simulation, sea ice parameters were re-adjusted after 10 years and used for an additionnal 5-year simulation.
Although the model has an ice accumulation of roughly +0.1m/year, sea ice extent and sea ice concentration simulated by the experiment show a mean stable state after 2-3 years for both hemispheres. Although a roughly one month lag occurs in winter in both hemisphere, the simulated seasonal cycles are reasonably well in phase with the observed ones. The amplitude of the seasonal cycle is slightly underestimated for both hemispheres throughout the year. As with most sea ice models using lead parameterizations, the model produces a too compact ice cover.
The wintertime sea ice edge is closer to observations than the summertime one. The simulated ice thickness is overestimated during winter. This persists during the melting season and explains a too large summer ice extent. The mean annual ice drift field exhibits many of the observed features of the large-scale ice motion. The thermodynamic net annual ice growth takes place in regions where sea ice diverges in response to winds and oceanic currents. Conversely, net ice melt occurs in zones of convergence and marginal ice zones. This phenomenon emphasizes the key role of sea ice dynamics in the coupled ocean-atmosphere system at high latitudes.
The coupled experiment gives a sea ice surface temperature (SIST) closer to observations and colder ($-5°$C in average) than the SIST simulated by ARPEGE in forced mode. Conversely, the sea surface relative warming in eastern parts of the equatorial and sub-tropical oceanic basins is due to the oceanic model which is not able to reproduce the cold tongues in these regions. There is a well marked meridional gradient of surface temperature in each hemisphere. The equatorial warming induces stronger equatorial convection with intensified Hadley cells. The north polar cell is weakly modified and the south polar cell is appreciably strengthened. The larger release of latent heat in the tropics enhances and shifts tropospheric jets equatorward.
A first coupled experiment with a complete thermodynamic-dynamic sea ice model and an AGCM has been performed. The stability of the surface interface, a reasonable seasonal cycle compared to other coupled models and the presence of good ice dynamic patterns are encouraging results for the future. This coupled experiment constitutes a first and interesting step for understanding the evolution of the coupled atmosphere-ocean-cryosphere system.

5 CONCEPTUAL MODELS FOR TWO CLIMATE PARADIGMS

In the climate research, two complementary approaches exist. Using General Circulation Models allows to study in a realistic point of view the present day climate and its variability. The Simplified Process Models are designed to catch some basic mechanisms involved in a complex phenomenom, such that El Niño. Since the simplified process models are easy to interprete and computationally economical, it is possible to undertake parametric studies and to achieve a better understanding of the phenomenom under scope. Often in the past, some features of a phenomenom were pointed out in a simplified model, before being recovered in a general circulation model. It is, for example, the case for the multiple equilibria of the thermohaline circulation first detected in box models. Moreover, simplified models can provide good information about the diagnosis to apply to the results obtained from general circulation models simulations.

5.1 El Niño: theoretical approach and GCM confrontation (95)

Today, two theories about El Niño still remain. One is the "delay-oscillator" theory which involves the equatorial oceanqic waves. The other one is based on coupled instabilities, but none physical interpretation was proposed. The succes of the "coupled instabilities" comes from Neelin. He conjectures that El Niño was a low frequency oscillation of the coupled system explained by the coupled SST-mode.
A new physical interpretation is proposed by [11]. A simplification of an equatorial coupled model is used to study the ocean-atmosphere coupling. Analytical calculations lead to a quasi-stationary coupled mode, called T_K-mode. The instability comes from the basic zonal and vertical temperature gradients and a damping effect is controled by the basic equatorial upwelling. The seasonal phase lock of El Niño could be explained by the seasonal evolution of the SST: the zonal gradient is maximum between July to November.
To verify this assumption and to complete this theorical approach, the growth rate of this mode is computed from five General Circulation Models simulations: a forced Pacific ocean, a forced global ocean, a coupled Pacific ocean/global atmosphere T42, a global ocean/global atmosphere T42 and a global ocean/global atmosphere T21.

The zonal structures along the equator of the interannual anomalies are shown in a good agreement with the SST, zonal current and wind stress profiles of the T_K-mode. This agreement is particularly striking during the warm "basin-wide" event occurring in the coupled simulation.

When considering a basic state oscillating with the seasonal cycle, these computations confirm that the seasonal phase lock of the ENSO onsets could be explained by an increase of the growth rate between July and November. When considering the interannual variability, these computations show that the interannual occurrence of ENSO is not due to a drift of the mean state.

Meanwhile, the maximum value of the growth rate seems to be not strong enough to allow the development of the warm anomalies within a few months. The westerly wind bursts are mentioned as a possible trigger through the generation of equatorial Kelvin waves. The waves induce a positive sea surface temperature (SST) advection [[10]] which could favor the onset phase of the T_K-mode.

Moreover these westerly wind bursts could explained the interannual occurrence of the warmings. They don't appear periodicilly. To be efficient, they have to generate equatorial Kelvin waves when the zonal SST gradient is maximum. This explain the seasonal phase lock, the interannual occurrence and moreover the spring barrier of previsibility.

This approach provides quantitative diagnostics which allow comparisons between forced and coupled simulations and provides an easy way to point out the deficiencies of the coupled model. The interannual variability of the global coupled model, which is very different from the observed one, seems to be explained by an increased vertical temperature gradient which favors a particular coupled process of the $\mathrm{T_K}$-mode and the predominance of small zonal scales.

5.2 Thermohaline oceanic circulation (95)

The thermohaline ocean circulation is driven by the effects of thermal and freshwater forcing at the ocean surface. Rich dynamical behaviours result from the competition of the two buoyancy components. Multiple equilibria of the thermohaline circulation can exist, as well as thermohaline fronts. The use of simple process models is an essential step towards a better understanding of such dynamical features.
The multiple equilibria of the thermohaline circulation are here investigated through the comparison between numerical results obtained using a bidimensional model and asymptotic predictions in the limit of a thin fluid layer.

The bidimensional (latitude-depth) model is based upon the Boussinesq approximation in a rectangular basin with a flat bottom and is forced by mixed boundary conditions at the surface (temperature field and freshwater flux imposed). It is controlled by five dimensionless parameters and the meridional profiles of the applied surface forcings.
A parametric study was performed, which permitted to locate the domain where multiple equilibria exist in the space of the surface forcing amplitudes. Many profiles of surface forcing were considered, having regard to the topology of the solutions they induce.
An asymptotic expansion of the bidimensional model in the limit of a thin layer results in a single monodimensional evolution equation. It supports multiple equilibria, corresponding to the minima of a Lyapounov functional. But only one of the solutions is globally defined in the basin. A geometric interpretation of the asymptotic solutions enables us to compare them to the numerical results. The asymptotic analysis proved to be a very powerful tool to predict and explain the observed solution. An article about this validation has been submitted to the Journal of Fluid Mechanics.

Regularized by the addition of an hyperdiffusivity term, the asymptotic equation supports multiple equilibria globally defined in the domain. Using a steady solver software (AUTO - Software for continuation and bifurcation problems in ordinary differential equations, written by E. Doedel), the catastrophe structure of the regularized asymptotic equation was exhibited. It is analogous to the one of the bidimensional model.

Parametrizations of momentum forcing and rotation were included in the bidimensional model. The corresponding asymptotic equation was derived. The stationnary solutions of the 1D and

2D models have been studied using respectively AUTO and BAGELS (a software analogous to AUTO, but allowing hundreds of degrees of freedom, developed by H. Dijkstra). In both models, an imperfection exists. It allows the existence of asymmetric solutions under symmetric forcings, without a symmetry breaking transition occurring.

This activity is performed in the framework of an european contract (MAST-CT92-0034) in collaboration with P. Cessi from the FISBAT-CNR Institute (Bologna, Italy).

6 COMPUTER SCIENCE DEVELOPMENTS

New versions of the two main softwares owned by the team have been developped, tested and used extensively in 1995 and 1996. The version 2.0 of the OASIS coupler is a major enhancement of the original program with much stronger modularity and inclusion of a message passing library. The 2.2 and the 2.3 version of Vairmer contain new features such as increased graphics, color mode and new field analysis routines.

6.1 OASIS : the 2.0 version (95/96)

The OASIS coupler is a set of fortran routines which enables the coupling of oceanic and atmospheric general circulation models (GCMs) on a supercomputer. A new version of the software has been developped and tested for several configurations. The main characteristics are as follows:

- Independent models: the models being coupled are separate entities (different processes in the unix sense). There are unchanged in respect to their own main options (like I/O or multitasking) compared to the uncoupled mode. Few routines need to be added to deal with the time synchronization.
- Dynamical definition of models and coupling fields: the models to be coupled and the fields to be exchanged during a simulation are defined ONLY at run-time through the input file. If the number of models or fields change, one needs NOT to recompile or modify the program. One just has to edit and modify the input file. This is done through a pseudo-dynamic allocation (this is standard fortran !) within OASIS.
- Time strategy: the time strategy of the coupling is defined ONLY at run-time through the input file. Models can be run sequentially, in parallel or a combination of both. They can be run synchroneously or asynchroneously.
- Analysis: the set of analysis (i.e interpolation, extrapolation, ordering etc...) to be performed on a given field are defined ONLY at run-time through the input file. They can be different for different fields.
- Computing environment: the CLIM library which is based on the PVM software can be used to run the models in a distributed environment (i.e the AGCM on a Cray C90, the OGCM on a Cray T3D and OASIS on a front-end workstation).

6.2 VAIRMER: the experiment manager (95/96)

The years 1995-1996 have seen 3 new releases of Vairmer (the latest being Vairmer 2.3) which include may new features: enhanced control of the page layout, color mode, superposition of fields and curves, custom subsets in several analysis, enhanced scripting,... The software has now reached a mature level and is routinely used by coupled ocean-atmosphere modellers. Thanks to steadily increasing number of users in the climate community (close to 40 as of Dec 1996), many suggestions are added at each new release and this common tool allows an easy comparison of the models results within the GASTON group.

6.3 CATHODe : a distributed computing project (95)

The CATHODe (Couplage Atmosphère Océan Distribué) project, started in 1994, has been successfully concluded in 1995. The goal of this project was to perform a distributed coupling of the ocean-atmosphere climate model on two different supercomputers communicating through the network (RENATER). This activity has been performed in collaboration with EDF/DER, who initiated the project, METEO-FRANCE and LODYC. The AGCM ARPEGE has been run on the CRAY C-90 of EDF/DER while the OGCM OPA has been run on the CRAY-2 of METEO-FRANCE. We have tested and compared two couplers based on the PVM (Parallel Virtual Memory) software. The first one is the general purpose coupler CALCIUM developed by EDF/DER, that we have applied the climate coupling. The second one is the OASIS coupler in which the software CLIM, developed at CERFACS, has been included. The feasibility of distributed climate coupling have been demonstrated, and the coupler have been valided on 1 year simulations. This activity has motivated a scientific analysis of the sensitivity of the simulations to the precisions of the exchanged flux when shifted from double to single precision during the transfer —see Subsection (3.3).

7 DATA ASSIMILATION

The three major tasks of the Data Assimilation Team, which started his full activity in October 1996, are the contribution to the AGORA project which concerns the Optimal Interpolation, the development of a variational assimilation code for the global ocean and the realization of an assimilation tool which will give raise to the code PALM.
Among the minor tasks, it is not to neglect the collaboration of E. Greiner with S. Arnault (LODYC) aiming to point out the means of a post–analysis of an assimilation (impact, exploitation) in the context of the tropical Atlantic over 1992-1996, through the comparison of the data assimilation system results with ADCP (suspect in intensity), bathysonds, SSS and TOPEX/POSEIDON.

7.1 Optimal Interpolation (96)

In the framework of the AGORA european project, Optimal Interpolation (which is a particular case of the Kalman Filter) of altimeter data into the global OPA model will be performed. For this, the SOFA software, developed by P. De Mey, will be adapted to OPA and documented. Cerfacs contribution will be to provide physical and statistical information in order to take into account the steric sea level variations, which dominate the sea level signal at the large scale. This is based on the calculations mentioned before (Model validation) and on the use of statistical methods. This study is performed in cooperation with GRGS scientists.

7.2 Variational Assimilation (96)

Eric Greiner aims to implement a 4DVAR data assimilation of the global ocean (at least 60°N–60°S). He has first analysed the new points that are the periodisation of the domain, and the use of massively parallel machines. Given the achievement of th eadjoint of OPA8 at the LODYC, O. Thual and E. Greiner have decided to avoid to work on the old OPA4 version, and they are organising a convention for the use of OPA8*. In between, an experience in the Gulf Stream area is started. The objective is to validate the most sophisticated method in conjunction with a model bias (the Gulf Stream is too north). This will clarify the impact of the seasonal forecasting at our latitudes as well.

7.3 PALM (96)

We aim to develop PALM which is a general software of data assimilation. Like OASIS couples atmosphere and ocean, PALM will couple model and observations. Various evaluations and discussion, in the team and with Philippe Courtier, make us progress toward the definition of the software. The main methods are selected for PALM. The search for an united formalism is in progress and it is part of the PhD thesis of Thierry Lagarde. In the frame of his thesis, T. Lagarde will also build a maquette to test PALM on simple models. At the moment he is developing a model governed by the Kuramoto–Sivashinsky equation.
Finally, SOFA, which is P. De Mey's prototype for such a software, is examined through the realization of its help under html.

8 CONFERENCES AND SEMINARS

January 95

Puerto de la Cruz (Tenerife, Spain), NATO Advanced Study Institute, The Mathematics of Models for Climatology and Enviroment, 11-21 January 1995. Invited speaker: "Interannual variability simulated in the tropical Pacific" (J. Macías).

February 95

Les Houches (France), 13-24 February 1995, NATO Advanced Study Institute on Decadal Variability. Attended (D. Stephenson and L. Fleury).

March 95

Saclay (France), CEA, " Réunion simulation et teraflops", March 30, 1995. Invited talk: "Le couplage distribué: l'expérience Cathode" (L. Terray)

Pattaya (Thaïlande), 1995 GEWEX/Game Conference, March 1995. Communication: "The Asian monsoon in a globally coupled ocean atmosphere general circulation model" (D. Stephenson).

April 95

Melbourne (Australia), 2-7 April 1995, conference TOGA-95. Communication: "Coupled ocean-atmosphere simulations", (M. Pontaud).

May 95

Paris (France) EDF/DER Clamart, 9-12 May 1995, Ecole CEA-EDF-INRIA "Modélisations couplées en climatologie". Invited lecturer: " From Ocean-Atmosphere Coupled General Circulation Models (GCMs) to Simple Dynamical Systems: a Hierarchy of Climate Models" (O. Thual).

June 95

Toledo (Spain), DICE-CGSG meeting, June 12-14, 1995. Invited talk: " Sensitivity of the ARPEGE-OPA coupled model to physical parameterizations" (L. Terray). Attended (J. Macías and D. Stephenson).

Mexico-city (Mexico), 21-24 June 1995, conference 2nd UNAM-CRAY supercomputing, Numerical simulations in environmental and earth sciences. "Coupled ocean-atmosphere modelling - computing and scientific aspects", (M. Pontaud).

La Chapelle Aubareil (France), 26-27 June 1995 , "MERCATOR" meeting on data assimilation (O. Thual).

Lyon (France), 28 June 1995, Ecole Normale Supérieure de Lyon, "Pôle Scientifique de Modélisation Numérique". Invited talk: "Ocean-atmosphere coupling at CERFACS" (O. Thual).

Brest (France), 19-20 June 1995, IFREMER, GDR "Couplage d'Equation". Invited talk: "Ocean-atmosphere coupling at CERFACS" (O. Thual).

August 95

Honolulu, (Hawaii, USA), XXI IAPSO Conference, 5-12 August 1995. Communication: "Initial Climate Drift as a diagnotic tool in the OPA-ARPEGE coupled ocean-atmosphere model" (E. Guilyardi).

September 95

Hamburg (Germany), "Third international conference on modelling of global climate change and variability", September 4-8, 1995. Poster: "Simulation and sensitivity studies of the tropical climate with a global coupled ocean-atmosphere GCM" (L. Terray et al.).

Los Angeles (USA), Jet Propulsion Laboratory. Communication: "Coupled ocean-atmosphere modelling at CERFACS" (E. Guilyardi).

Livermore (USA) , PCMDI. Communication: "Coupled ocean-atmosphere modelling at CERFACS" (E. Guilyardi).

Reading (UK), 1995 ECMWF Seminar on Predictability, 4-8 September 1995. Attended (J. Macías and D. Stephenson).

October 95

Venice (Italy), IX International Conference in Finite Elements in Fluids. New Trends and Applications. 15-21 October 1995. Communication: "A finite element multilayer shallow water model. Applications to the numerical modelling of the Albora Sea" (J. Macías).

Tarragona (Spain), MEDCOAST'95. The Second International Conference on the Mediterranean Coastal Enviroment. 24-27 October 1995. Communication: "Modelling Alboran Sea and Starait of Gibraltar dynamics" (J. Macías).

November 95

Carcasonne (France), PNEDC. Communication “La dérive initiale comme outil d’analyse dans un modèle couplé océan-atmosphère” (E. Guilyardi).

Toulouse (France), METEO-FRANCE, “Atelier de modélisation de l’atmosphère”, November 28-30, 1995. Communication: “Validation de simulations couplées et forçées à partir d’observations satellitaires de nébulosité et de flux radiatifs” (C. Cassou). Communication: “Equilibres multiples de la circulation thermohaline” (L. Fleury). Communication:“ Le déclenchement des évènements chauds dans l’océan Pacifique équatorial est-il explicable à l’aide des instabilitées couplées ?” (M. Pontaud). Communication: “ La dérive initiale comme outil d’analyse dans un modèle couplé océan-atmosphère” (E. Guilyardi).

April 96

Den Hague (Netherlands), EGS Conference, Communication: “Initial climate drift as a diagnostic tool in a coupled ocean-atmosphere model” (E. Guilyardi, G. Madec, M. Pontaud, L. Terray, O. Thual M. Imbard and P. Delecluse)

May 96

New-York (USA), Invited Talk at Columbia University: “ Sensitivity of climate drift to physical parameterizations in a coupled CGCM” (L. Terray).

Livermore (USA), Invited Talk at Lawrence Livermore National Laboratory: “ Sensitivity of climate drift to physical parameterizations in a coupled CGCM” (L. Terray).

Los Angeles (USA), Invited Talk at UCLA: “ Sensitivity of climate drift to physical parameterizations in a coupled CGCM” (L. Terray).

July 96

Paris (France), DICE-CGSG meeting, June 10-12, 1996. Invited talk: “ Sensitivity of climate drift to physical parameterizations” (L. Terray).

October 96

Toulouse (France), Journèes PATOM, Communication: “Formation des masses d’eau et ventilation de la thermocline dans un modèle couplé océan-atmosphère” (E. Guilyardi, G. Madec and K. Speer)

Porto (Portugal), 3rd Euroconference on satellite altimetry, Communication: “Sea-level variations in a climate model: an assimilation perspective”, (P. Rogel)

December 96

Toulouse (France), METEO-FRANCE, “Atelier de modélisation de l’atmosphère”, December 3-4, 1996. Communication: “Sensibilité du modèle couplé Océan/Atmosphère ARPEGE/OASIS/OPA aux conditions initiales de couplage” (P. Rogel). Communication: “Dérive initiale et formation des masses d’eau dans le modèle couplé océan–atmosphère OPA–ARPEGE” (E. Guilyardi). Communication: “Modul de “double physique” pour ARPEGE permettant la conservation des flux de couplage a l’interface océan/atmosphère” (T. Lagarde).

San Francisco (USA), AGU 1996 Fall Meeting, 15-19 Dec 1996, Communication: “Water Mass Formation and Thermocline Ventilation in the Coupled Ocean-Atmosphere Model OPA-ARPEGE.” (E. Guilyardi, G. Madec and K. Speer)

9 PUBLICATIONS

9.1 Journals with referees

[1] C. Cassou, P. Noyret, E. Sevault, O. Thual, L. Terray, D. Beaucourt, and M. Imbard, (1996), Distributed Ocean-Atmosphere modelling and sensitivity to the coupling flux precision : the CATHODe project, *Mon. Wea. Rev.*, **submitted**.

[2] L. Fleury and O. Thual, (1996), Stationary fronts of the thermohaline circulation in the low aspect ratio limit, *J. Fluid Mech.*, **submitted**.

[3] L. Fleury and O. Thual, (1997), Stationary Fronts of the Thermohaline Circulation in the Low Aspect Ratio Limit, *J. Fluid Mech.*, submitted.

[4] G. Garric, D. B. Stephenson, and L. Terray, (1996), Seasonal cycle of sea ice in a global coupled ocean-atmosphere simulation, *C. R. Acad. Sci. Paris*, **submitted**.

[5] E. Greiner, S. Arnault, and A. Morlière, (1997a), Twelve monthly experiments of 4D–variational assimilation in the tropical Atlantic during 1987. Part I: method and statistical results, *accepted by Progress in Oceanography.*

[6] E. Greiner, S. Arnault, and A. Morlière, (1997b), Twelve monthly experiments of 4D–variational assimilation in the tropical Atlantic during 1987. Part II: physical results, *accepted by Progress in Oceanography.*

[7] E. Guilyardi and G. Madec, (1997), Performance of the OPA/ARPEGE-T21 global ocean-atmosphere coupled model, *Accepted for Clim. Dyn.*

[8] E. Guilyardi, G. Madec, L. Terray, M. Déqué, M. Pontaud, M. Imbard, D. Stephenson, M.-A. Filiberti, D. Cariolle, P. Delecluse, and O. Thual, (1995), Simulation couplée océan-atmosphère de la variabilité du climat, *C.R. Acad. Sci. Paris*, **t. 320, série IIa**, 683–690.

[9] C. Mechoso, A. Robertson, N. Barth, M. Davey, P. Delecluse, B. Kirtman, M. Latif, T. Nagai, S. Philander, P. Schopf, T. Stockdale, M. Suarez, L. Terray, O. Thual, and J. Tribbia, (1995), The seasonal cycle over the tropical Pacific in general circulation models, *Monthly Weather Review*, **123**, 2825–2838.

[10] M. Pontaud and O. Thual, (1995), Some effects of a mean zonal thermocline gradient on planetary equatorial waves, *Annales Geophysicae*, **13**, 1223–1228.

[11] M. Pontaud and O. Thual, (1997), Coupled Processes for Equatorial Pacific Interannual Variability, *Quart. J. Roy. Meteor. Soc.*, accepted.

[12] L. Terray and O. Thual, (1995), OASIS : Le couplage océan-atmosphère, *La Météorologie*, **8/10**, 50–61.

[13] L. Terray, O. Thual, S. Belamari, M. Déqué, P. Dandin, C. Lévy, and P. Delecluse, (1995), Climatology and interannual variability simulated by the ARPEGE-OPA model, *Climate Dynamics*, **11**, 487–505.

[14] L. Terray, (1996), Sensitivity of climate drift to physical parameterizations in a coupled ocean-atmosphere general circulation model, *submitted to Journal of Climate.*

9.2 Publications in proceedings

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