

Seasonal forecast of tropical climate with coupled ocean-atmosphere GCMs: On the respective role of the atmosphere and the ocean model components in the drifting mean climate.

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Abstract

Seasonal forecasting based on coupled general circulation models is a growing promising avenue for the application of climate research. However, important drift and biases in the state of the art coupled GCM still slow down progress in this field. In order to provide insights on the mechanisms responsible of the errors, a set of four coupled GCM six months long ensemble simulations is taken from ten years of hindcasts of the DEMETER project. Among these models, two different atmosphere GCMs are coupled to three different ocean GCMs, allowing for instructive inter-comparisons between “atmosphere pairs” formed by two different ocean GCM coupled to a given atmosphere GCM. An analysis of the Sea Surface Temperature over the tropics is carried out in term of the impact of changing either the atmosphere or the ocean component of a given coupled GCM.

Our result suggest that six month forecast can be separated in two distinct phases, the initial first month drift, and the remaining longer drift. The initial first month drift appears to result from the combination of forced mode biases of both the atmosphere and the ocean models, of possible comparable amplitude. The second phase of the forecast depends essentially on the forced mode biases of the atmosphere model, the ocean component modulating the drift to the second order. It is shown that, depending on the season, within some localized but key climate regions like NINO3, the first phase bias is persistent throughout the entire forecast whereas the atmosphere merely drift on the given first month bias. Finally, the impact of the method used for constructing initial oceanic conditions is shown to be potentially as important as the forced model biases in the skill of the forecast.

1. Introduction

The improvement of seasonal forecasting currently consists in one of the scientific challenges among the most awaited by the society. Comprehensive climate models, which are generally accepted as the most promising tool for seasonal forecasting, are capable of reproducing important characteristics of the dominant variability modes (e.g., Latif et al., 1993, Ji et al. 1994, Rosati et al., 1997, Kirtman et al. 1997, Vintzileos et al., 1999a,b). The differences and similarities of simulated tropical mean climate and variability has been described in various inter-comparison studies of CGCMs (AchutaRao and Sperber, 2002; Latif et al., 2001; Delecluse et al., 1998; Mechoso et al., 1995; Davey et al., 2001; Schneider et al., 2003, Guilyardi et al., 2004). Many of these groups reported that simulated mean climates were drifting, reaching steady states after many years from initialization. Unrealistic features of simulated interannual modes e.g., quasi-bienniality in the periodicity of ENSO, are most likely related to such climate biases. Stockdale (1997) showed that by removing *a posteriori* this climate drift it was possible to obtain skillful ENSO forecasts at lead times of up to 6 months (more sophisticated methodologies for taking into account this climate drift have also been presented, Yang and Anderson, 2000). However intuition suggests that better models i.e., with no drifting mean state, should present a better skill in seasonal forecast. In fact, numerous studies indicate a direct connection between mean climate and ENSO characteristics. A major task then is a better understanding of the way the state of the art coupled general circulation models (CGCM) function, and

particularly the interactions between their two main components, the ocean and the atmosphere, and the causes of the errors.

The DEMETER project provides a new opportunity to compare retrospective seasonal forecast, or hindcasts, for several CGCMs and over the entire globe. Of particular interest is the fact that out of the seven CGCMs, four of them form two “atmosphere pairs”, each of them based on a different atmosphere model, IFS and ARPEGE (see the DEMETER project description, Palmer et al., 2003). Three ocean GCM are coupled to them: ORCA, OPA8, and HOPE, forming ocean companions of the atmosphere pairs. It is therefore possible to examine the impacts on the climate drift of changing only the ocean component of the coupled model while keeping the same atmosphere. Furthermore, with these four models, it is also possible to form an “ocean pair”, where the same ocean is coupled to two different atmosphere components, and look at the consequences of changing the atmosphere component. In this study, we consequently manage to interpret the behavior of the hindcast in function of the ocean or atmosphere components used for the coupling. The focus is on the key SST and soil level air temperature climate variable, and the since the coverage of the DEMETER project is global, we generalized the study to the three tropical oceans.

2. Methodology

The DEMETER experiment, for the purpose of improving techniques of seasonal forecasting, gathers seven coupled GCMs and their respective six-month ensemble hindcasts repeated every 4 months during several decades ranging from the 70s to the present. We selected over the same 10 year period (1991-2000) four of these model simulation groups, sharing either the ocean or the atmosphere component: they are the CERFACS, LODYC, ECMWF and CNRM simulations. As seen in Table 1, one can describe the four simulations as pairs: the ECMWF atmosphere model IFS coupled to the most recent version of the LODYC ocean model ORCA8.2 (hereafter IFS/ORCA) or to the Hamburg ocean model HOPE-E (hereafter IFS/HOPE); and the Météo-France atmosphere model ARPEGE coupled to two close versions of the ORCA model again (ARPEGE/OPA8 and ARPEGE/ORCA). It is important to note that, that whilst atmosphere initial conditions are the same for all atmosphere components, ocean hindcast initial conditions are different for all CGCMs but the ARPEGE/ORCA and IFS/ORCA, which share the exact same one; and that none of GCM uses data assimilation or flux correction.

It is necessary to say that various climate key-variables and indexes have been compared and are presented on the DEMETER web site (www.ecmwf.int/research/demeter/verification). Though verification underlines differences between models, it also indicates that all four models perform roughly at the same level of skill for hindcasting tropical climate variations at seasonal scale. It allows us to consider the four CGCMs as appropriate tools of analysis regarding the quality level of current state of the art numerical climate prediction models. In the following, prior to the analysis all the SST and soil level temperature fields were averaged over the nine ensemble members, and the resulting ensemble mean forecasts were averaged by season (February, may, august, and November) over the 10-year period. Hence, for a given CGCM, the following study deals only with the behaviors of horizontal fields of four seasonal 6-month hindcasts.

3. Inter-comparison of the tropical hindcasts.

a. The control by the atmosphere component.

Figure 1 displays the SST time evolution for the four starting times, averaged over each equatorial region (5°N-5°S), the 10-year period and the 9 ensemble members. Starting in the Pacific, the most visible pattern consists in mean hindcasts behaving like pairs, one pair tending systematically to drift towards warmer than observed temperature (IFS/ORCA and IFS/HOPE), the other tending to the opposite (ARPEGE/ORCA and ARPEGE/OPA8). Let outlook for a moment the differences within each pair, and consider this as a first interesting result since each pair is made of two CGCMs using the same atmosphere model. This suggests that the atmosphere component controls almost alone the drift of the ensemble mean from the second to the sixth month. Does this result hold for the other basins? For the Atlantic, one does not see such a divergence between the two atmosphere model pair, even though there is a robust cold bias for the ARPEGE pair. However, the two members of either the

IFS or ARPEGE pair are evolving almost perfectly in parallel, comforting the hypothesis that this is the atmosphere model that controls the hindcast ensemble mean drift. Beside an about 1°C cold bias common to all models, the Indian equatorial basin displays the same systematic pair behaviour, where, for a given atmosphere pair, the companion CGCMs evolve almost perfectly in parallel during the entire six-month period. It is again apparent that the atmosphere component alone controls the month-to-month ensemble mean evolution of the SST, both in term of amplitude variations and phase, starting from the second month.

It could be that this regional average results are dominated by a limited number of narrow equatorial areas with stronger than average signals, it is therefore necessary to examine horizontal maps of the drifts. Figure 2 presents a geographical comparison of the five month drifts, starting from the first month of forecast, for the four models in annual mean between 30°N and 30°S. The IFS/HOPE and IFS/ORCA models display a very similar moderate cold drift in most regions, as seen in equatorial averages, except in the eastern equatorial-southern Atlantic, central and southern America, and to a less extent the Maritime Continent, where the model warm up too much. In contrast, the ARPEGE/OPA8 and ARPEGE/ORCA models show a comparable generally warm drift, but more regional with strong values in the eastern Pacific and Atlantic domains, decreasing towards the west and towards the Indian Continent. The computation of the differences with the respective atmosphere pair companions, IFS/ORCA and ARPEGE/ORCA (not shown) display negligible values almost everywhere compared to the differences between the drifts of the two CGCM with different atmospheres but same ocean models. Since the oceans of the ARPEGE pair derive from the same model, they are much closer to each other than ORCA and HOPE. Consequently, the local relative weaker control by the atmosphere appears principally for the IFS pair. It is interesting to realize then that the regions where changing the ocean component is as important or more than changing the atmosphere seem to be only continental: they are India, sub-saharian Africa and subtropical Northern America. Two of them are monsoon regions, and potentially coupled to the ocean, whereas the sub-saharian African Climate is known to evolve at low frequency in phase with the tropical Atlantic SST. However, prior to draw conclusions from this figure underlying the importance of ocean or/and air-sea coupling for these three regions, it is necessary to recall that the natural standard deviation there is large (not shown) and could likely cause major ensemble mean forecast dispersion, even without changing the ocean component. Nevertheless, this comparison enables us to conclude that coupled models sharing the atmosphere component drift, after one month, in parallel to the first order, regardless of their ocean model. A point to point examination of the drift within the tropics confirms the global aspect of this result (not shown).

The next question is naturally how then, apart from the three continental regions mentioned above, does the role of the ocean component reveal itself in such simulations? To try to answer this question, a second look at Figure 1, now directed at the differences among two companion CGCM of a given atmosphere component pair, leads to the deduction that two companion ensemble means, say ARPEGE/ORCA and ARPEGE/OPA8, do generally stay parallel. Regardless of the basin, and to the noteworthy exception for the IFS pair during the April hindcast in the Pacific and Atlantic, the pairs tend to keep quite steadily the offset settled generally during the first month. We will come back later on situations when the offset is not persistent and trajectories cross each other or diverge significantly, but let us first consider the overall steadiness of the offsets among two pair members. Considering the differences between two such members, the ocean model and the initial ocean conditions, the offset is therefore unequivocally linked to the ocean of each CGCM. More precisely, two ocean factors can be considered and require thorough examination: the offset could be a result of differences in the physics of the ocean models, or be simply interpreted as a mere echo of systematic differences of the ocean initial conditions, between ensemble runs, e.g. introduced by the way perturbed oceanic initial conditions have been constructed. Then, they can be maintained in function of the natural persistence of the SST. We consider these two mechanisms as pertaining to the so-called ocean component of the coupled forecast system.

b. The control by the ocean component and the mechanisms at play

To explore the first possible mechanism, the ocean model physics, one need to compare two ocean models coupled to the same atmosphere model, but with the exact same initial conditions in order to filter their potential impact out. This configuration does not exist in the DEMETER experiment, but it

is possible to draw insights on this matter by looking at the case of the IFS pair (IFS/ORCA and IFS/HOPE, with different initial conditions). On Figure 1 the IFS/ORCA model displays a cold offset compared to its IFS/HOPE pair companion, regardless of the season and the basin. This cold bias, reaching up to 0.4°C in the Pacific, can not possibly be a consequence of initial ocean conditions dispersion since they random character can not result in such a systematic bias. It can only be related to the known tendency, in forced mode, of ORCA to overestimate the intensity of the equatorial upwellings. The ocean model physics differences, and likely their consequences in terms of coupling mechanisms, is responsible for very persistent offsets within the equatorial regions of coupled hindcasts. Hence, still in an ensemble mean and basin scale average perspective, our analysis suggests that the ocean model physics hold a major role at the equator: to establish and then maintain a mean bias or state, visible here as a given offset to the reference observations.

Considering such an apparent persistence of the first month drift later on during the five months left of the forecast, it is necessary to check two aspects of it: first, up to what degree this persistence holds locally, and second, is it everywhere controlled by the ocean component? Figure 3 presents a diagnostics aimed at determining the local persistence of the initial bias. Here, we computed the percentage of deviation of the fifth month offset to the observations from the first month offset. The fifth month deviation was chosen instead of the sixth because it allows the percentage to measure best the time-mean departure of the three last months from the first month. For each season, when the deviation is smaller than 50%, the grid point are assigned the unity, and then summed over the four seasons. The result is a map where darker area represents regions where the changing the ocean has a persistent impact on the surface temperature of the ocean or the continent. It is striking to obtain so many regions where the drifts stay approximately parallel for so long. For the IFS pair, it is interesting to recognize continental regions noticed above (Asia, Mexico, and the subsaharian Africa), suggesting again a role of the ocean for these regions, and some other areas like in particular many equatorial boxes. In the ARPEGE pair, the NINO3.4 box as well as the central Indian ocean emerge in particular, as well as the Indian continent, and the Gulf of Guinea.

In the regions highlighted by this diagnostics, which localization depends rather logically also on the atmosphere model (i.e. the physics of its coupling with the ocean), it is possible to conclude that the coupling is at its simpler level of complexity: above an offset established in one to two months, the atmosphere model determines quasi independently the phase and amplitude of the seasonal SST evolution. Nevertheless the ocean seems to plays a role in setting the offset. In the other regions to the contrary, the coupling is sufficiently active to result in SST differences between atmosphere pair companions which diverge significantly with time. Considering our first result on the control by the atmosphere, these latter regions can be interpreted as regions where the SST evolves as a coupled phenomenon but under the control, to the first order, of the atmosphere component.

Is the role of the ocean model physics the only cause of this first months bias between two atmosphere pair companions, or can it be due to other causes like the ocean initial conditions or even the natural dispersion of the coupled system? An element of answer can be drawn from the examination of the sign and amplitude of the first month drift. In the case of two pair companions, the difference of the short term drift actually confirms the suggestion derived from Figure 1 equatorial averaged: its two dimensional field (not shown) possesses globally the same patterns as the known biases of ORCA (too strong equatorial upwellings, two weak eastern tropical upwellings, etc...). However, it is important to say that the examination of differences between first month drifts of IFS/ORCA and ARPEGE/ORCA, two CGCMs which differ only by their atmosphere component (physics and initial conditions), demonstrates the comparable importance of the atmosphere physics. The patterns are of the same order of magnitude as the patterns visible between two atmosphere pair companions, and they are very similar to the known overall cold bias of the IFS model. We conclude that, for tropical six-month forecasts, the forecast evolution over about one to two month is controlled as much by the ocean model physics as by the atmosphere model physics. These two series of mechanisms (combined when the two coupled model components differ) thus establish quickly an initial offset in a forecast. In the case of ocean physics bias, it will persist over six month in specific regions, in particular in some key equatorial regions, depending on the atmosphere model. In the case of atmosphere physics bias, they correspond to the long term drift that will anyway dominate the forecast to the first order.

Finally, in order to evaluate the role of initial ocean conditions in the forecast, it is to note that for a given CGCM ensemble hindcast, an infinite number of ensemble members (associated to an infinite

number of initial perturbations) would of course tend towards a negligible average initial departure from the observation. Only the specificities of the ocean model physics would emerge as offset in such an ideal procedure. In the present case, they are nine members, yet multiplied by 10 for the 10 years, that is 90 members for each season. A gross estimate indicates that, compared to the much larger number of possible SST initial states (which is related to the number of horizontal grid point in the ocean models) such a forecast procedure allows for only a negligible fraction of the number of ocean states that could initiate the forecast. One must therefore expect mean initial offsets between ensemble mean hindcasts, independently from the ocean model own biases. Furthermore, there is no reason for the ocean model to respond linearly to initial perturbation, therefore the non linearities of the response are likely to result also in some biases. This issue is discussed by Rogel (same issue).

An experiment where the same CGCM hindcast ensemble is initiated with two different set of initial ocean conditions would permit to examine the sole impact of these conditions, without the additional effect of differences in ocean model physics. Such a sensitivity experiment is made possible in the DEMETER experiment by the existence of a parallel set of hindcasts carried out with the IFS/ORCA and ARPEGE/ORCA for the 10-year period 1987-1996. Recall that this two CGCMs share the exact same initial conditions. For the parallel set, erroneous ocean initial conditions have been constructed using forcing fields (i.e. wind stress, heat and water fluxes, and SST) that have been consistently shifted southward by 1.5 degree of latitude. The origin of this shift is simply an error in the target grid definition inside the interpolation method used to transform ERA40 fields into forcing fields compatible with the non-geographic global ORCA grid. As a result, and since no climatological restoring term were applied inside the ocean between 60 degrees north and south, all variables of the model have been changed on average, including dynamical variables. Of course, because of the strong restoring term towards (erroneous) SST, the ocean initial condition bias has a strong hemispheric component, of the order of 1 degree warmer in the south and 1 degree cooler in the north. This bias is strengthened in the regions of strong north south temperature gradients. In the tropical Pacific, because of the shifting of the equatorial upwelling and its strong north south temperature gradients in August and November particularly, the bias is confined in the eastern within 5 degrees north and south. There, it reaches about +2 degrees during the latest two forecast seasons, and moderate negative anomalies during the first two. It is therefore appropriate to look at the effect of such significant changes in initial conditions solely in the NINO3 box.

Figure 4 presents the comparison in this illustrative region. Regardless of the coupled model considered, the results are similarly dependent on the hindcast season. For the february and may ones, the initial condition change after the first month has respectively a -0.2°C and -0.5°C effect, and the time evolution lead closely parallel trajectories. For the August and November hindcast, the impact after one month is stronger, respectively $+0.6^{\circ}\text{C}$ and $+0.8^{\circ}\text{C}$, and in the long term, the offset is slowly dissipated. We draw the conclusion that initial conditions have a fundamental impact on the simulations of the seasonal evolution of the SST in CGCM forecasts, they are capable, apparently as well as the physics of the ocean model, to create a persistent bias over several month. It is clear that the persistence of such a bias for a given season and location, is explained by the persistence of the SST in that frame of space and time. The CGCM skill in the tropics were impacted in a major way by the initial conditions, and so during the entire six-month forecast duration for some seasons. Remember though that there is a seasonal dependence to this behaviour, as discussed previously, here masked in this average. It is moreover interesting to recall that the erroneous initial conditions considered here corresponds to a 1.5 degree in latitude, which is itself less than the resolution of the ARPEGE atmosphere model and about the grid size of the IFS model (about one degree for the T96 IFS/ORCA model and about two degrees for the T63 ARPEGE/ORCA model). Such a scale, even spatially systematic, could be considered as noise for the atmosphere models, and consequently thought as a signal to be quickly forgotten by the system. Again, to understand this result, it is necessary to realize that even such a grid-point scale geographical error in the SST initial conditions, when in strong horizontal gradient regions results in anomalous signals regionally reaching up to $\pm 2^{\circ}\text{C}$ over several degrees in longitude and latitude (depending on the extension of the frontal region, here the NINO3 area, but outside the tropics the subtropical front areas), and over a significant given depth range specified in the initial conditions (generally of the order of magnitude of the mixed layer depth).

3. Conclusions.

The DEMETER project provided us with an rich ensemble of coupled simulations that we analysed in term of the respective control of a hindcast drift, and by extension a forecast drift, by the atmosphere and the ocean components of the models. The study was focused on the tropics and its object was the SST behaviour, average over ensemble members as well as a 10-year period. The seasonal aspect of the hindcast was however kept when understandable. Four CGCMs, forming two distinct atmosphere model pair were compared : the IFS pair with the IFS/ORCA and IFS/HOPE models, and the ARPEGE pair with the ARPEGE/ORCA and ARPEGE/OPA8 models.

The main conclusion of this work is that the drift of the simulated climate can be generally divided into two phases: the first or two months of coupling, where ocean and atmosphere components are of comparable role in setting the characteristics of an initial deviation from the observations, and the five or four remaining months where the atmosphere controls the first order of the signal in term of phase and amplitude. During the initial phase, an offset is created which, in many key regions for climate forecast, can persist over most or the entire duration of the forecast. In such regions, improving the biases measured in forced mode for the atmosphere and ocean models will proportionally improve the realism of the forecast. During the second phase, the SST drifts over the initial offset, and only the details of the signal are evolving in functions of interactions specific to the coupling. Again, the phase and amplitude of the drift over the offset are essentially set by the atmosphere physics, that is the bias of the model in forced mode. For this second phase, the correction of the errors of the atmosphere model in forced mode is from far the task that has priority if order to improve forecast quality. Finally, we took advantage of a parallel ensemble of forecast to demonstrate that a grid scale systematic error in the ocean initial conditions can impact as much the first phase as the bias in the atmosphere or ocean components. This is essentially true in regions of strong SST gradients where small perturbation will have larger consequences. The necessity for improving the quality of the way initial ocean conditions are constructed is in this sense an important conclusion of our paper.

Except for the control to the first order by the atmosphere of the second phase drift, the results are generally very seasonally dependent. This paper thus presents an analysis of phenomenon that would require ideally a seasonal approach. Also, it is natural to wonder whether the drifts are possible to anticipate in function of the atmosphere model biases in forced mode, or if they correspond to errors that appear only when the AGCM is coupled to the ocean. In the first case, the improvement of the forecast drift depends only on correcting the errors of the AGCM in forced mode, in the second case the task is more complicated since the consequences of a change in a given parameterization are much more difficult to anticipate and understand in the coupled system. Even if we cannot completely discard the possibility that some or a portion of the CGCM 2-6 month drifts are atmosphere biases which appear only in coupled mode, it is likely the forced mode biases that still dominate the drift. Here for example, the cold drift of the IFS pair is consistent with known biases of the AGCM (Anderson et al., 2002) that were attributed to the atmosphere physics independently of the coupling with the ocean.

The interpretation of these results in term of the physics of the ocean-atmosphere interactions is tempting but delicate. For example, the control of the second phase by the atmosphere could be considered as a sign of minor role of the ocean in the coupled system at this time scale in the tropics. But it is fundamental to realize that it could as well be interpreted as the mere consequence of the existence of much larger differences in the parameterizations among state of the art AGCMs than among equivalently good OCGMs. Similarly, the fact that in some regions, depending on the physics of each component, changing the ocean model simply shift the forecast (of a local value equal to the ocean bias in forced mode), and result in SST evolving almost in parallel, is exciting for the understanding of the coupling. But it is difficult to decipher between the possibility of a real lack of interactions, or of parameterizations flaws.

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TABLE:

	Météo-France (ARPEGE/OPA8)	CERFACS (ARPEGE/ORCA)	LODYC (IFS/ORCA)	ECMWF (IFS/HOPE)
atmosphere component	ARPEGE	ARPEGE	IFS	IFS
resolution	T63 31 Levels	T63 31 Levels	T95 40 Levels	T95 40 Levels
ocean component	ORCA 8.0	ORCA 8.2	ORCA 8.2	HOPE-E
resolution	2.0° x .5°-2.0° 31 Levels	2.0° x .5°-2.0° 31 Levels	2.0° x .5°-2.0° 31 Levels	1.4° x 0.3°-1.4° 29 Levels

Table 1: Description of the simulations in terms of atmosphere and ocean components.

LEGENDS:

Figure 1. Hindcast ensemble mean during the 1991-2000 period. The geographical averages are computed between 5°N-5°S in each basin.

Figure 2. Spatial comparison of the 5-month drifts for all models computed by subtracting the first month to the last. Color shading correspond to the time-average of the drifts, contours correspond to the average of the four absolute time average seasonal drifts. a) IFS/HOPE, b) ARPEGE/OPA8, c) IFS/ORCA, d) ARPEGE/ORCA.

Figure 3. The persistence of the first month offset between two atmosphere pair companions is estimated by the change from month 1 and month 5 of the temperature difference divided between the two companion CGCM, and divided by the initial difference. For each hindcast season, the unity is assigned to the grid point when the percentage of change is smaller than 50% and the first and fifth month differences have the same sign. The results are summed over the four season a) IFS pair b) ARPEGE pair.

Figure 4: Effect of different ocean initial conditions for two CGCMs sharing the same ocean component. SST mean drifts in the NINO3 box, with the observed climatological seasonal cycle removed. _B indicates the ensemble mean with biased ocean initial conditions.

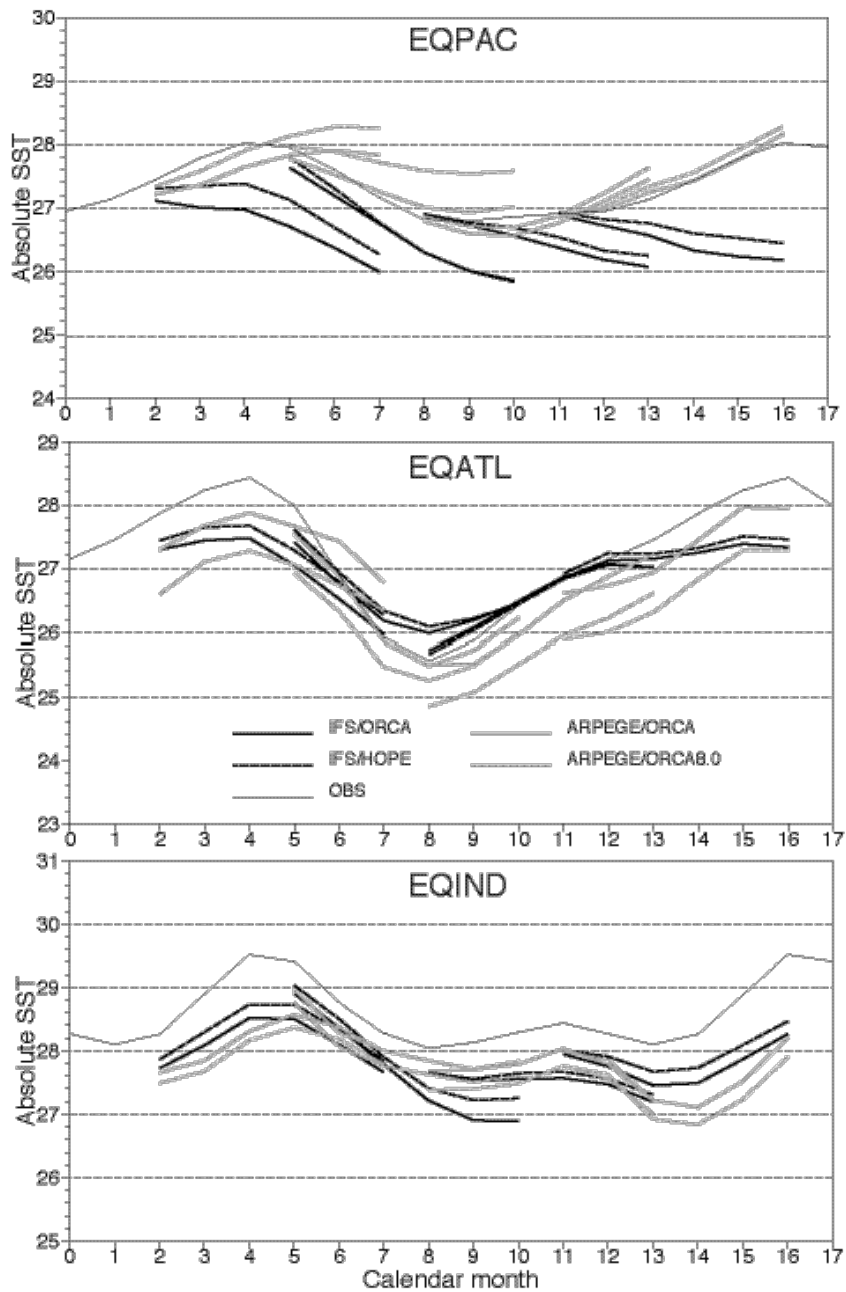


FIGURE 1

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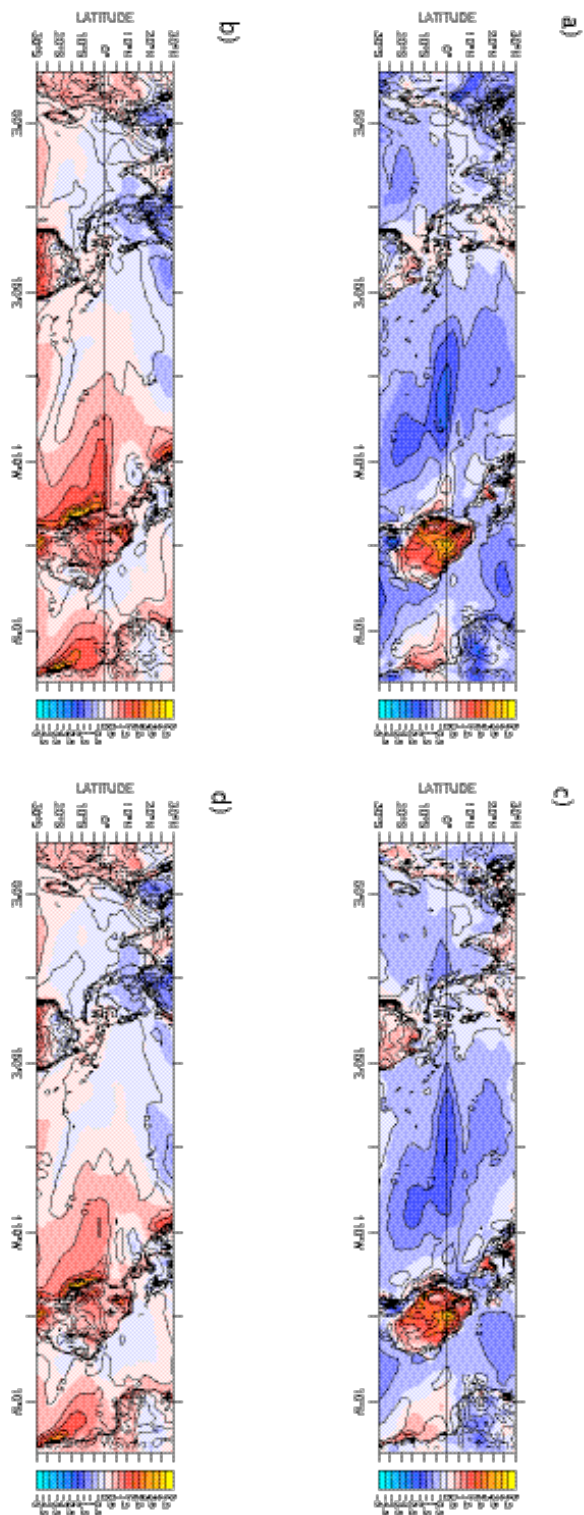


Figure 2

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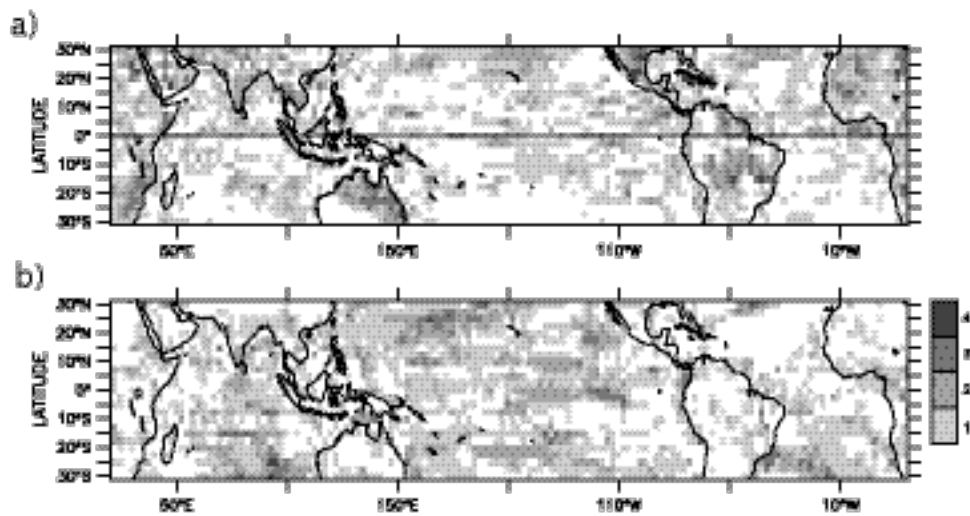


Figure 3

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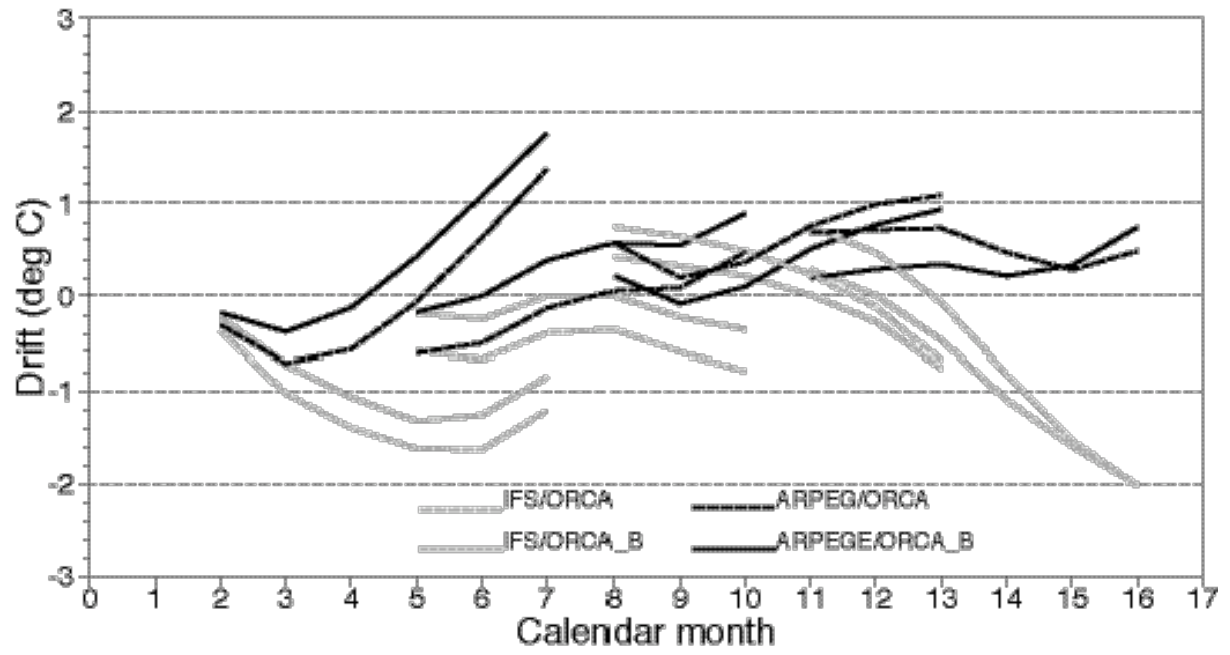


Figure 4

Figure 4: Effect of different ocean initial conditions for two CGCMs sharing the same ocean component. SST mean drifts in the NINO3 box, with the observed climatological seasonal cycle removed. _B indicates the ensemble mean with biased ocean initial conditions.