ROLE OF OCEANIC AND LAND SURFACE TEMPERATURES IN THE RESPONSE OF THE ITCZ TO EXTRATROPICAL THERMAL FORCING

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RESUMEN

Este estudio investiga la respuesta de la Zona de Convergencia Inter-Tropical (ZCIT) a un forzante térmico extra-tropical a través de la utilización de un modelo de circulación general de la atmósfera acoplado con modelos de océano y superficie continental de tipo slab.

El forzante aplicado consiste en enfriamiento en un hemisferio (hemisferio Sur) y calentamiento en el otro (hemisferio Norte) desde 40º hacia los polos, con media global nula y aplicado únicamente sobre puntos oceánicos. Se realizaron tres experimentos: en el primero ambos modelos slab son aplicados globalmente; en el segundo las temperaturas de superficie de mar (TSMs) tropicales se mantienen fijas mientras que el modelo slab de superficie continental es aplicado globalmente; por último, en el tercer experimento, se adicionó la condicionante de temperaturas superficiales sobre África fijas. Las condiciones de borde superficales utilizadas son realistas.

Encontramos que la ZCIT se desplaza hacia el hemisferio más cálido. Cuando se impone la restricción de TSMs tropicales fijas la respuesta de la ZCIT se debilita fuertemente aunque sigue siendo no despreciable, en particular, sobre el Océano Atlántico y África. Finalmente, cuando se incorpora la restricción sobre las temperaturas de superficie en el continente africano encontramos que la respuesta de la ZCIT se desvanece completamente, indicando que la reacción de la ZCIT al forzante extra-tropical no es posible a través de procesos puramente atmosféricos, sino que la participación de la TSM tropical o de las temperaturas superficiales continentales es necesaria.

ABSTRACT

This study investigates the Intertropical Convergence Zone (ITCZ) response to extratropical thermal forcing applied to an atmospheric general circulation model coupled to slab ocean and land models.

The forcing consists in cooling in one hemisphere (Southern hemisphere) and warming in the other (Northern hemisphere) poleward of 40°, with zero global average and applied only over oceanic grid points. Three experiments are performed: in the first the slab ocean and land models are applied globally; in the second the tropical sea surface temperatures (SSTs) are kept fixed while the slab land model is applied globally; in the third, in addition, surface temperatures over Africa are kept fixed. Realistic boundary surface conditions are used.

We find that the ITCZ shifts toward the warmer hemisphere. When the constraint of fixed tropical SST is imposed we find that the ITCZ response is strongly weakened, but it is still not negligible in particular over the Atlantic Ocean and Africa. Finally, when the constraint of the African land surface temperature is incorporated we find that the ITCZ response completely vanishes, indicating that the ITCZ response to the extratropical forcing is not possible just trough purely atmospheric processes, but needs the involvement of either the tropical SST or the continental surface temperatures.

Keywords: ITCZ shift, extratropical forcing, African surface temperature.

1) INTRODUCTION

Paleoclimatic studies, 20th century observations and numerical simulations suggest that the extratropics have the capability to affect the tropical climate through the development of, both, atmospheric and oceanic teleconnections. Simulations with either atmospheric or coupled models, in aquaplanet mode or with realistic surface boundary conditions, have all shown to shift the position of the Inter Tropical Convergence Zone (ITCZ) to the anomalously warm hemisphere.

In particular, Cvijanovic and Chiang (2013) analyse the ITCZ response to a North Atlantic high latitude cooling applied to an AGCM coupled to a slab ocean, using realistic surface boundary conditions. They investigate the relative roles of tropical Sea Surface Temperature (SST) and energy flux changes. The results show only partial local energy flux compensation to the extratropical perturbation and, by means of idealized simulations with fixed tropical SSTs, they argue that the ITCZ shifts are not possible without the tropical SST changes, therefore suggesting that the tropical SSTs are a more suitable driver of tropical precipitation shifts than the atmospheric energy fluxes.

In this study we examine the ITCZ response to an extratropical thermal forcing applied to an AGCM coupled to slab ocean and land models. Our simulations are performed with realistic surface boundary conditions and the extratropical forcing pattern consists in warming in one hemisphere and cooling in the other with zero global mean. In that sense this work can be seen as a continuation of that of Cvijanovic and Chiang (2013). Furthermore, the relative roles played by the atmosphere, the tropical SSTs and the continental surface temperatures in the ITCZ response are investigated in a series of experiments designed to separate these influences.

The manuscript is organized as follows: In Section 2 we introduce the model and the experiments. Results are presented in Sections 3, 4 and 5. In Section 3 we present the experiments where the slab ocean and land models are applied globally. In Section 4 we analyse the role of the tropical SST. In section 5 the role of the African surface temperature is studied. Finally, in Section 6 we summarize the conclusions.

2) MODEL AND EXPERIMENTS

The model used in this study is the Abdus Salam International Centre for Theoretical Physics (ICTP) AGCM (Molteni, 2003; Kucharski et al., 2005), which is a full atmospheric model with simplified physics. We use the model in its 8-layer configuration and T30 (3.75ºx3.75º) horizontal resolution. Over ocean and land slab models are coupled. Present-day boundary surface conditions, orbital parameters and greenhouse gas forcing are used. In addition, a monthly-varying ocean heat flux correction is imposed in order to keep the simulated climatological SST close to present-day conditions.

We perform 3 experiments. In the first experiment the slab ocean is applied globally. In the second, the tropical (30ºS-30ºN) SSTs are kept fixed, while the slab ocean is applied elsewhere, the slab land model is applied globally. Finally, in the third experiment the tropical SSTs are kept fixed, the slab ocean model is applied elsewhere in the ocean and, also, the continental surface temperature over the African continent is kept fixed. In the experiments with fixed tropical SST, the prescribed tropical SST is the monthly climatology obtained in the control run with the global application of the slab ocean model. In the experiments with fixed surface temperature over Africa, the prescribed temperatures are the climatological temperatures of the land model. All the climatological fields consist are calculated as 10 years means and, therefore, do not include interannual variability. In Table I we summarize the three experiments named *global_slabs*, *fix_trop_SST* and *fix_trop_SST_fix_Africa*, respectively. In all the simulations the model was run for 40 years and the last 10 are used for averaging.

For each experiment we perform two runs: a control and a forced run. In the control we run the model without any external forcing. For the forced run we apply an external oceanic heat flux forcing (described in the next paragraph).

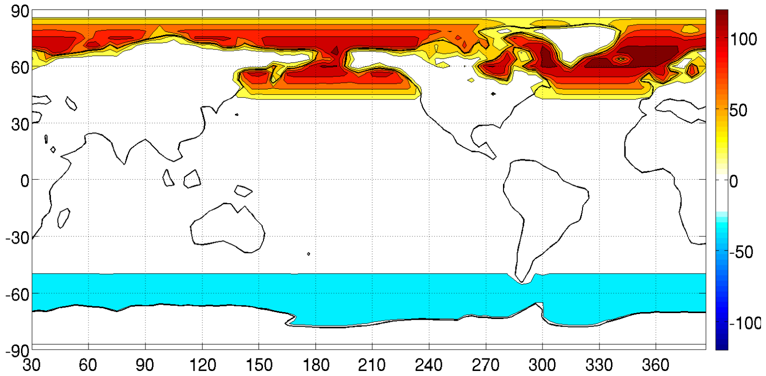

Figure 1: Forcing pattern (positive out of sea). Contour interval: 20 W/m^2. The forcing has the shape of a sinusoidal function with maximum/minimum over 65ºN/65ºS.

The applied forcing pattern (Figure 1) consists in cooling in one hemisphere and warming in the other poleward of 40°, applied only over ocean grid points, and with a resulting global average forcing equal to zero. The forcing pattern is superposed to a background state. The sign convention selected is positive out of sea. Therefore, positive values of the forcing could be thought as representing a situation where the atmosphere is dry and colder than the ocean below it. This type of forcing represents the asymmetric temperature changes associated with glacial-interglacial and millenial-scale climatic variability. The selection of which hemisphere to warm or cool is arbitrary, although the result shown in this paper are, in general terms, reversed if the cooling/warming conditions of the hemisphere are reversed (not shown).

Experiment name	Tropical SST fixed	Africa surface temperature fixed
global_slabs	No	No
fix_trop_SST	Yes	No
fix_trop_SST_fix_Africa	Yes	Yes

Table I: Experiment summary

3) TROPICAL SENSITIVITY TO EXTRATROPICAL FORCING

In this section we present the results of the experiment where the slab ocean and land models are applied globally: *global_slabs.*

SST anomalies are displayed in Figure 2a. The response is a generalized warming in the NH and a generalized cooling in the SH, with the intensity of the warming/cooling largest towards high latitudes. Maximum warming is about 18ºC in the northern Atlantic while the maximum cooling can be found in the Southern Ocean with a value of -16ºC in the Amundsen Sea and -14ºC in the Weddell Sea. The SST anomalies in extra-tropics are quasi zonally symmetric. In the tropical region the main departures from the zonal symmetry can be found in the regions 20ºN-30ºN and 20ºS-30ºS in the Pacific Ocean where the zonal SST gradient is about 6ºC and 4ºC, respectively.

As is the case with SST, the response over land is a generalized warming in the NH and a generalized cooling in the SH, with the largest departures from the control run in high latitudes (Figure 2b). There, the most extreme anomalies are seen over North America (up to 16ºC) and over

Antarctica (around -8ºC). In latitudes lower than 30º the land response is most visible over the NH where the most extreme response is seen over the African continent (anomalies up to 9ºC centered at 25ºN, 30ºE), followed by the responses over North America (up to 5ºC anomalies) and Asia (up to 3ºC); in the SH low latitudes the signal is evident only over the Australian continent with negative anomalies of magnitude of the order of 1ºC.

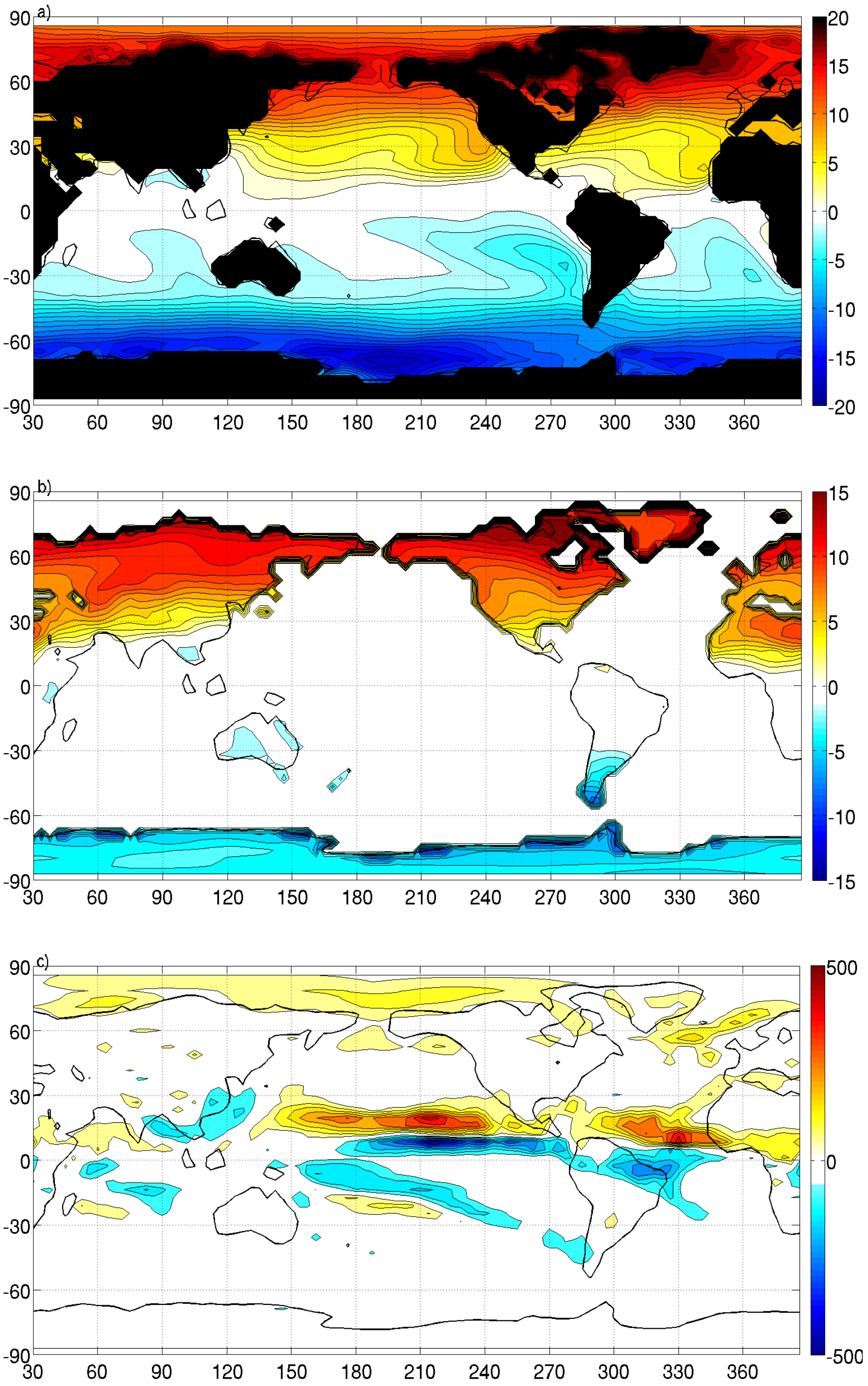

Figure 2: Annual mean anomalies of: a. SST (contour interval: 1ºC) b. Surface Temperature over land (contour interval: 1ºC) c. Precipitation (contour interval: 50 mm/month) for the experiment with global slab ocean and land models: *global_slabs*.

Precipitation anomalies are shown in Figure 2c. In the tropical Pacific and Atlantic oceans there is an increase (decrease) of precipitation north (south) of ~10ºN, indicating a northward shift of the oceanic ITCZ. The increase/decrease of precipitation is maximal toward the centre of the Pacific Ocean where it reaches ~350 mm/month. In the Indian Ocean there is no clear shift of the precipitation pattern. Continental precipitation is also affected, although in a weaker manner. A continental ITCZ displacement is also evident over both the African and the South American continents, with anomalies around 100mm/month over Africa and 200mm/month over South America. Extratropical precipitation changes are only important northward of 50ºN (positive anomalies) and to the west of South America around 45ºS (negative anomalies).

Next we show zonal averages, which will be denoted by square brackets. Temporal means will be denoted by an over bar and deviations from the temporal mean by primes.

To get insight into the mean meridional circulation it is useful to consider the mass streamfunction. In Figure 3b we present the changes with respect to control of the mean meridional overturning circulation stream function. Negative anomalies in the tropical region indicate a northward displacement of the uplift region along with an intensification of the southern Hadley cell and a weakening of the northern Hadley cell. Although much weaker there is also a response in the Ferrel cells: the southern cell is intensified and the norther cell weakened.

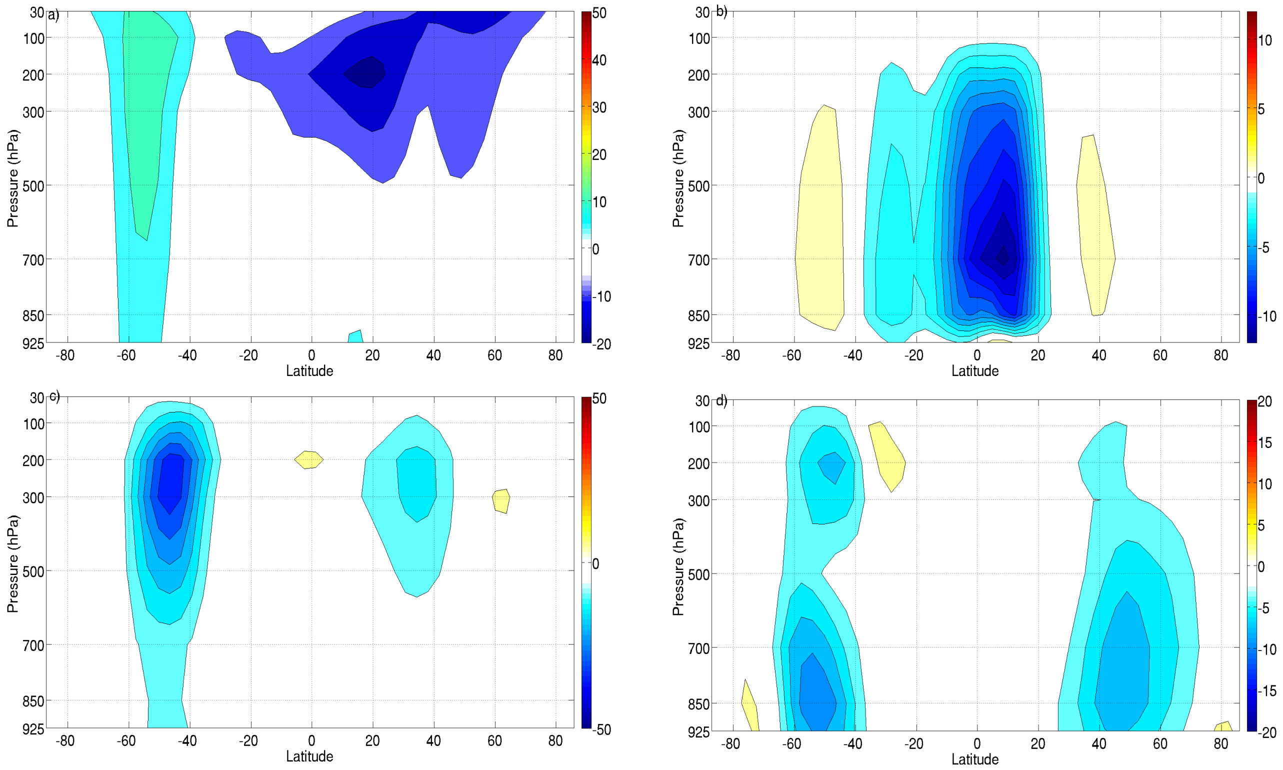

Figure 3: Annual means of: a. Zonally averaged zonal wind with height $[\bar{u}]$ (contour interval: 5 m/s) b. Mean Meridional Overturning Circulation Stream Function $[\overline{\Psi_M}]$ / 1010 (contour interval: 1 kg/s) c. Mean Meridional Momentum Transport by eddies $[\overline{u'v'}]$ (contour interval: 5 m2/s2) d. Mean Meridional Heat Transport by eddies $[\overline{v'T'}]$ (contour interval: 2 mK/s) for the experiment with global slab ocean and land models, *global_slabs.*

Anomalies of meridional momentum transport performed by eddies are only of importance above 700 hPa and mostly negative, with one maximum in each hemisphere (Figure 3c). In the SH the anomalies are maximum between 60ºS and 40ºS, while in the NH the maximum anomalies are weaker and located closer to the Equator. These negative anomalies imply an an intensification (weakening) of the transport from the tropics to high latitudes in the SH (NH). In addition, it is worth noting that such fluxes drive a poleward intensification of the zonal flow in the SH: as (e.g. Holton 2004) $\frac{du}{dt}\alpha-\frac{d[\overline{u'v'}]}{dy}$ in the case shown by Figure 3c, the meridional gradient of $[\overline{u'v'}]$ is positive (negative) on the equatorward (poleward) side of the minimum centered at (50ºS, 250 hPa), forcing a poleward shift of the mid-latitude jet in the SH. The latitude of strengthening of the mid-latitude jet coincides with the latitude of maximum SST gradient anomaly (50ºS-60ºS) consistent with the driving role of the lower atmosphere temperature gradient in the behaviour of the jet (e.g. Lorenz and Hartmann 2001).

Finally, in Figure 3d we show the anomalies of the meridional heat transport by eddies. The anomalies are fundamentally negative, maximal in the latitude bands 60ºS-40ºS and 40ºN-60ºN close to surface and also at the jet level. The SH anomaly is stronger than the northern counterpart.

As was the case with momentum transport, these negative anomalies imply an intensification (weakening) of the eddy heat transport form the tropics to high latitudes in the SH (NH).

4) ROLE OF THE TROPICAL SST

In this section we present the results of the experiment where the tropical SST are kept fixed and the slab ocean model is applied elsewhere, the land model is applied globally: *fix_trop_SST*. The anomalies are calculated with respect to the corresponding control case.

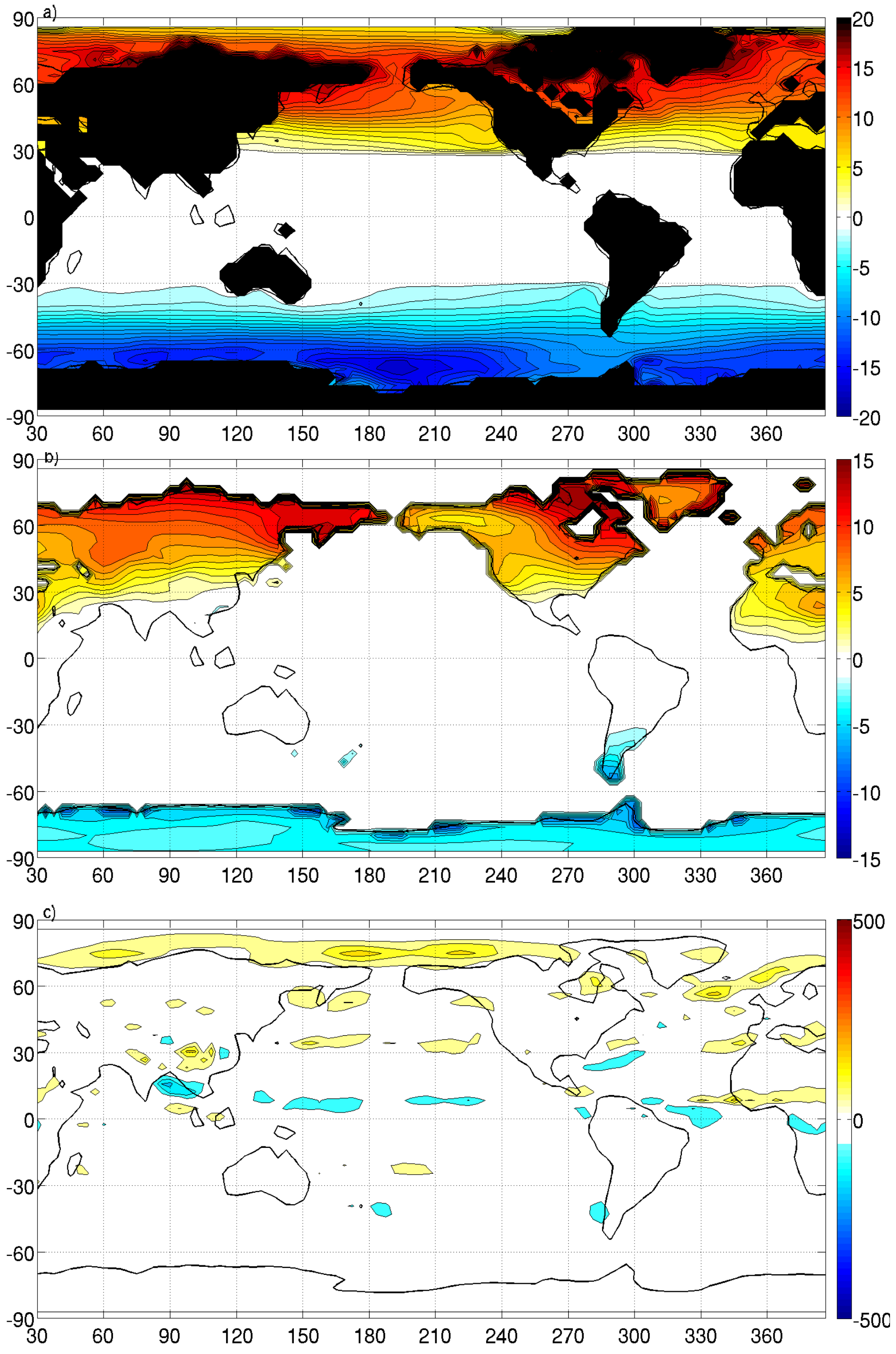

Figure 4: Same as Figure 2 for the experiment with fixed tropical SST, global slab land: *fix_trop_SST.*

SST anomalies are depicted in Figure 4a. Evidently, anomalies in the tropics are zero given that the prescribed SST for that region coincides with the SST of the corresponding control case. The anomalies are positive (negative) in the northern (southern) extra-tropics, with increasing absolute magnitude toward the poles. For both hemispheres the anomalies are very close to being zonally symmetric although there are some asymmetries in the Southern Ocean and to the west of the North American continent. The positive anomalies in the northern Atlantic reach the 16°C and the 14°C in the northern Pacific; in the SH the negative anomalies have a minimum in the Amundsen Sea of -16°C.

As was the case with the experiment *global_slabs* there is a generalized continental warming (cooling) in the NH (SH). In extra-tropics the response is very similar to the one obtained in the previous experiment (compare Figures 2b and 4b). However, some differences are seen in particular with the extent of the continental warming in the region equatorward of 30ºN: in Asia now the warming only reaches 1ºC, in North America 3ºC and in Africa 7ºC, hence, indicating a 2ºC lower response than in the experiment with the global slab ocean model.

Precipitation anomalies in extratropics are very similar to the ones obtained when the tropical SST restriction was not imposed (Figure 4c). On the other hand, the tropical response is very different: the only place where there are signs of a northern shift in the ITCZ is to the east of Africa and over the Atlantic Ocean, with anomalies of the order of 50 mm/month. To better quantify the changes in precipitation we select three tropical precipitation indices: precipitation anomalies over the Sahel (8°N-15°N, 350°E-30°E), precipitation anomalies over northern (8°N-10.5°N, 320°E-340°E) minus southern (5.5°N-8°N, 320°E-340°E) tropical Atlantic and precipitation anomalies over South America (10°S-Eq, 300°E-320°E). In Table II we calculate the values of those indices for the experiment *fix_trop_SST* relative to the same indexes for the experiment *global_slabs*. We see that over Africa the response in the experiments with fixed tropical SST represents more than half (58%) of the response obtained when the slab ocean model is applied globally, indicating that for this region the tropical SSTs are important but not crucial in determining changes of precipitation forced by an extratropical source. On the other hand, over the Atlantic Ocean and South America the response in the experiments with restricted tropical SST has a magnitude of 19% and 13%, respectively, of the response obtained without such restriction, therefore indicating that for these regions the role of the tropical SSTs is much more important.

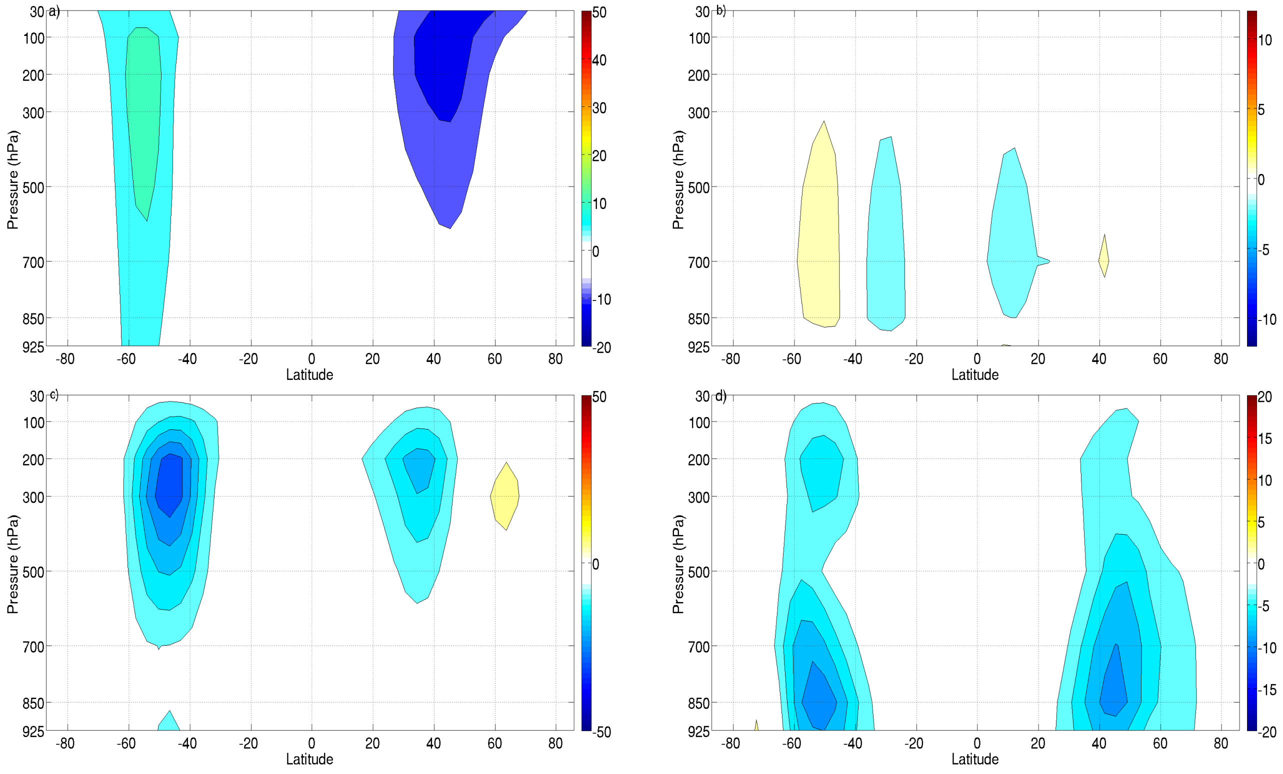

Figure 5: Same as Figure 3 for the experiment with fixed tropical SST, global slab land: *fix_trop_SST.*

Figure 5a shows the zonally averaged zonal wind anomalies respect to the corresponding control run. Once again, the main difference with the experiment applying the slab ocean model globally is that the tropical anomalies almost vanish. In extratropics, the SH barotropic and positive anomaly pattern is still present showing an increase in the mid latitude jet; in the NH extratropics the negative anomaly is slightly stronger and evidences the weakening of the jet.

	Sahel	**Atlantic**	**South America**
fix_trop_SST	58%	19%	13%
fix_trop_SST_fix_Africa	15%	4%	11%

Table II: Value of the Sahel, Atlantic (Northern tropical minus Southern Tropical) and South America precipitation indexes for the experiments *fix_trop_SST* and *fix_trop_SST_fix_Africa* relative to the values for the experiment *global_slabs*.

Regarding the mean meridional circulation changes, seen through $[\overline{\Psi_M}]$ anomalies, it is evident that the Hadley circulation is almost not affected with the tropical SST constraint imposed in this experiment (Figure 5b).

The eddy meridional momentum and heat fluxes are displayed in Figures 5c and 5d, respectively. In both transports there is a subtle weakening of the transport from the tropics to the Poles, with respect to the experiment with global slab ocean model application.

In summary, from the results of this sub section, we can conclude that when the extratropical forcing is applied and the tropical SST is not allowed to react in consequence, the tropical precipitation response is weak but still not negligible, specially over Africa and the Atlantic Ocean where the ITCZ shows a northward displacement. This tropical response is more important over the continent than over the ocean and seems related to the fact that the surface temperature over the African continent is greatly affected by the forcing while the SSTs are maintained fixed. With this motivation to the next section, we show the results for a series of experiments where, in addition, we do not allow the surface temperature over Africa to react to the extratropical forcing.

5) ROLE OF AFRICAN CONTINENTAL TEMPERATURE

In this section we present the results of the experiment where the tropical SST are kept fixed, (the slab ocean model is applied elsewhere) and the surface land temperature over Africa is kept fixed, applying the slab land model elsewhere:*fix_trop_SST_fix_Africa*. As was the case before, anomalies are calculated with respect to the corresponding control case. For this experiment we will focus on the fields: SST, surface land temperature and precipitation, as the other fields investigated previously show little change with respect to the experiment where the tropical SSTs were fixed.

In Figure 6a we show the SST anomalies. As can be seen comparing with Figure 4a, the differences of this case (tropical SSTs and African temperature fixed) with the previous experiment (tropical SST fixed) are almost unnoticeable.

Figure 6b displays the land surface temperature anomalies. As was expected, the anomalies over Africa are exactly zero. Elsewhere the difference with the previous experiment are very small.

Finally, in Figure 6c, we show the precipitation anomalies. For this experiment tropical precipitation changes are almost not present, in particular the anomalies over Africa and the tropical Atlantic are essentially zero. On the contrary, in the extratropics, the anomalies are very similar to those obtained without constraining the African land temperatures. For a more quantitative vision in Table II we calculate the values of the precipitation indices (Sahel, Atlantic and South America) for the experiment *fix_trop_SST_fix_Africa* relative to the same indexes for the experiment *global_slabs.*

For this experiment we see that the precipitation responses are very weak compared with the experiment in which the two slab models are applied globally and never exceed 15% in magnitude, indicating that when both the tropical SSTs and the surface land temperatures are not allowed to react to the extratropical forcing, the precipitation response almost vanishes. Moreover, comparison among the indices clearly indicates that rainfall over the Sahel is the one that is most influenced by the surface warming over Africa. The Atlantic ITCZ shift is also controlled by the African temperatures, while precipitation over South America shows almost no response.

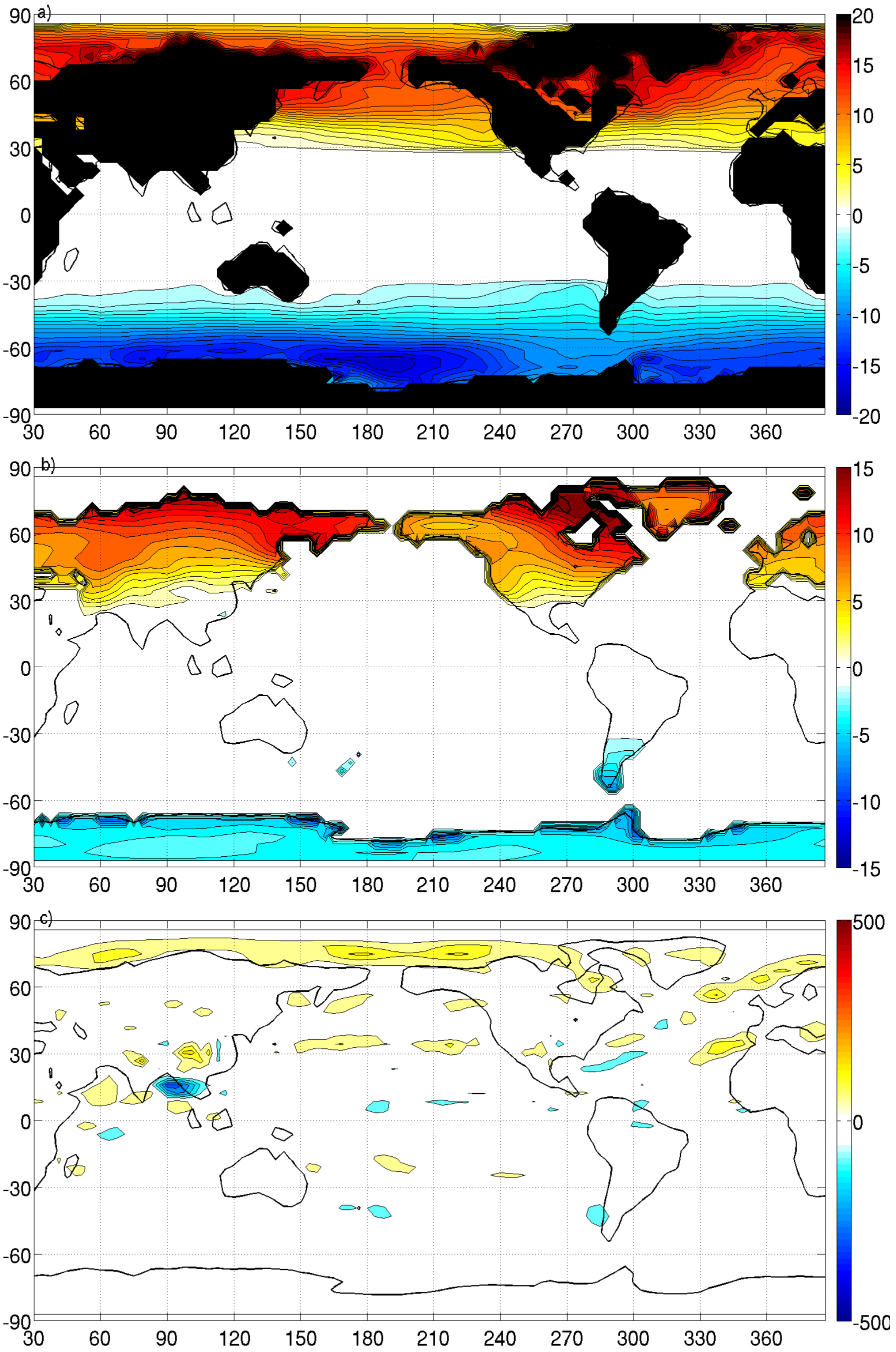

Figure 6: Same as Figu2 for the experiment with fixed tropical SST and fixed surface temperature over Africa: *fix_trop_SST_fix_Africa.*

6) SUMMARY AND CONCLUSIONS

We investigated the response of the ITCZ to extratropical forcing in an AGCM coupled to slab ocean and land models, with realistic surface boundary conditions. We imposed an oceanic heat flux forcing, with zero global mean, consistent in a warming of the NH and cooling of the SH and analysed the changes obtained when averaging over a 10-year period. The relative roles of the atmosphere, tropical SSTs and continental surface temperature were investigated in three experiments.

Regarding the simulations in which the slab ocean and land models are applied globally our results are consistent with previous results in the sense that the ITCZ shifts toward the warmer hemisphere. In this case we also attribute the ITCZ displacement mainly to the tropical cross-equatorial SST gradient, as previous studies did. With respect to heat and momentum atmospheric transports we found that both react to the extratropical forcing by increasing (decreasing) the amount transfered from the tropics to the SH (NH) in order to compensate the anomalous cooling (warming) of the Hemisphere. Transports performed by the mean circulation respond to the forcing with an intensification (weakening) of the southern (northern) Hadley and, to a lesser extent, Ferrel cells in the SH (NH). Meanwhile the changes in the fraction of the transport performed by transient eddies are found to be stronger in the SH, where they drive a poleward intensification of the zonal flow in the SH.

In the simulation in which the slab land model is applied globally but in the ocean the tropical SSTs are not allowed to change we found that the ITCZ response notably weakens. However, there is still some non negligible ITCZ response in particular over the Atlantic Ocean and Africa. In these regions the magnitude of the precipitation anomalies is of the order of 20% and 60%, respectively, of that obtained when the tropical SST constraint was not applied. Cvijanovic and Chiang (2013) performed a similar experiment and also found that by disabling the tropical SST reaction the ITCZ response almost disappears, although in their results significant tropical precipitation changes were essentially not present in any location. This discrepancy in the ITCZ response could be caused by the use of different AGCMs. Based on our results the tropical SSTs are extremely important but not necessary in order to obtain a shift of the ITCZ to the warmer hemisphere, in particular over the Atlantic Ocean and Africa. With respect to atmospheric transports, as a direct consequence of the stillness of the tropical SSTs, the mean meridional circulation shows almost no response in the tropical region while the effect over the Ferrel cells and the transports performed by eddies is similar to the obtained without the SST constraint. Regarding the physical mechanism we hypothesize that, in the absence of an inter-hemispheric SST gradient in the tropical region, the continental surface temperature gradient over Africa is the one responsible for the ITCZ displacements, following a similar process to the one occurring when a SST gradient is present. The relevance of the surface air temperature over the Sahara desert as a driver of the Sahel rainfall variability has been previously highlighted, both in observations and model simulations, by Haarsma et al. (2005).

With this motivation in mind we performed the third and last simulation in which fixed surface temperatures over Africa are imposed as an additional constraint. In this case we found that the ITCZ response completely vanishes, indicating that the ITCZ response to the extratropical forcing is not possible just trough purely atmospheric processes, but needs the involvement of either the tropical SST or the continental surface temperatures.

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