

We thank the reviewer for his/her constructive comments and suggestions.

We have given full consideration to the comments in the revised manuscript which includes: a discussion of the results of Green and Marshall (2017) and Schneider (2017) as well as figure modifications to make them easily interpreted by the reader.

Please find below a point-by-point reply to the questions raised. A marked-up manuscript version (with tracked changes) converted into a pdf is also uploaded as a supplement.

10

Anonymous Referee #1 Received and published: 24 December 2017

15 General Comments

The main motivation of this manuscript titled “Sensitivity of the tropical climate to an interhemispheric thermal gradient: the role of tropical ocean dynamics” is to understand how the addition of a simple dynamic ocean model in the tropics affects the climate response to idealized extratropical forcing with different signs in each hemisphere. Four coupled simulations are presented, two that are coupled to a slab ocean model (SOM) and two that are coupled to a reduced gravity ocean (RGO) model. The extratropical forcing is applied to one simulation in each of these model pairs. The main results are that the tropical precipitation shift in response to the forcing is weaker in the model with the RGO and that the seasonal cycle in the tropics has large change in response to the forcing in the model with the RGO but not the SOM. To my best knowledge, the examination of ITCZ shifts to extratropical thermal forcing with a climate model coupled to a reduced gravity ocean has not been done yet. This examination is timely given the results presented in Kay et al. (2016) and Hawcroft et al. (2017) that show a clear role for ocean dynamics in affecting tropical precipitation shifts. That said, this manuscript misses a few key studies from the past year that are very relevant: Green and Marshall (2017) and Schneider (2017). These two studies provide a mechanistic explanation for how tropical ocean circulation damps an ITCZ shift through coupling of the ocean and atmosphere by wind stress (see comments below). The results in this manuscript support the arguments in these two papers, and I believe that further discussion in light of Green’s and Schneider’s arguments would strengthen this manuscript. Otherwise, I find this manuscript clearly argued and written, and I only have a few other minor comments, mostly regarding figure quality and additional related literature. I recommend this paper for acceptance pending a major revision to include discussion of Green and Schneider and the minor issues listed below.

35 Specific Comments

Major comment 1:

Green and Marshall (2017) (DOI: 10.1175/JCLI-D-16-0818.1) and Schneider (2017) (DOI: 10.1002/2017GL075817) have
40 both shown that an ITCZ shift is damped by tropical ocean circulation, specifically by meridional heat transport through
Ekman transport by the subtropical cells. Because the Ekman transport is driven by the trade winds, the ocean circulation is
coupled to the Hadley circulation and the ITCZ. The heat transport by the subtropical cells decreases the amount of heat that
needs to be transported by the Hadley circulation because both are transporting heat in the same direction. Green and
Schneider have both quantified (in their model frameworks) how much the ocean circulation damps the atmospheric
45 circulation. Here, comparing the models with the SOM and the RGO (which includes a representation of Ekman
transport) is an additional test of Green's/Schneider's arguments. Green/Schneider's work suggests that the model with the
RGO should have less of an ITCZ shift in comparison to the model with the SOM, and that is exactly the result presented
here. This manuscript provides a nice confirmation of these previous results, and should be presented as such. If possible, it
would be useful to calculate how much the ocean damps the atmospheric heat transport in the RGO as compared to the SOM
50 (a factor of 4 in Green and 3 in Schneider). I also suggest adding discussion of Green's/Schneider's results to the
introduction and summary/conclusions, and possibly to a couple of these other relevant sections in the text: L168-169, L171-
172, L181-183, L270-274.

55 Agreed. Discussions about the results of the two mentioned papers have been included in the Introduction and Summary and
Conclusions sections.

Also, the damping of the atmospheric heat transport and energy flux equator shift have been calculated (1.9 and 1.5,
respectively) and included in the text, in section "Results, annual means".

60

Minor Comment 1 (Figure quality): Please make the figures more easily digestible for the reader by placing key information
about what is displayed in each panel both on the panel itself and in the caption. The closer the visual information is to a
description of what it is, the less hunting the reader needs to do and the less likely the reader will become confused or give
up. This includes: labels with units on the colorbars themselves (all colorbars lack this) and labels on the panels that state
65 which experiment and model are shown in that panel (e.g., for Fig 1a. could have a label that says "NOAA SST, Pacific" or
Fig 4a. could have a label that says "Forced_slab"). Also, in figures with maps it appears that much of Central America is
missing. Is this missing in the model or just an artifact of the plotting?

70 Agreed. All the Figures have been modified to include: headings with experiment name or other key relevant information and the corresponding units in the colorbars.

Regarding the longitude-latitude maps: The land-sea mask plotted is the one that the model uses (Central America is missing with this model resolution). We added 1 sentence in the text clarifying this.

75

Minor Comment 2 (L23-26): A bit deeper explanation of the mechanism behind this heuristic would be useful for the readers who are not familiar with this energetic constraint on tropical precipitation. This will probably be useful when adding the explanations in Green/Schneider. There are also numerous additional citations that could (should?) be added here. A couple are: Zhang and Delworth (2005) (DOI: 10.1175/JCLI3460.1), Broccoli et al. (2006) (DOI: 10.1029/2005GL024546),
80 Schneider et al. (2014) (DOI: 10.1038/nature13636), Bischoff and Schneider (2014) (DOI: 10.1175/JCLI-D-13-00650.1), Seo et al. (2014) (DOI: 10.1175/JCLI-D-13-00691.1), Woelfle et al. (2015) (DOI: 10.1002/2015GL063372). Additional relevant references can be found in these papers.

85

Agreed. A couple of sentences have been added to clarify this in the Introduction section. Also, the references of Broccoli et al. (2016) and Schneider et al. (2014) have been incorporated to the manuscript.

90 Minor Comment 3 (L59-60): This sentence is slightly misleading – there has been much work done using a hierarchy of atmospheric models to test these ideas. A couple are: Shaw et al. (2015) (DOI: 10.1002/2015GL0660270), Seo et al. (2014) (DOI: 10.1175/JCLI-D-13-00691.1), Maroon et al. (2014) (DOI: 10.1175/JCLI-D-14- 00188.1). Please rephrase to state more clearly that fewer studies have examined this topic in a hierarchy of ocean models.

95

Agreed, the sentence has been rephrased.

100 Minor Comment 4 (L60-65): There are an additional two studies that have tested similar ideas as Kay and Hawcroft: Mechoso et al. (2016) (DOI: 10.1002/2016GL071150) and Tomas et al. (2016) (DOI: 10.1175/JCLI-D-15-0651.1)

Agreed, Tomas et al. (2016) has been added as reference.

105

Minor Comment 5 (L79): Please state in a bit more depth exactly what the simplified atmospheric physics are. As the complexity of atmospheric physics affect the magnitude of an ITCZ shift to extratropical forcing, an additional sentence briefly stating what these simplifications are is warranted.

110

Agreed. The following text has been added to the model description:

“The model includes parameterizations of: large-scale condensation, shallow and deep convection, shortwave radiation (using 2 spectral bands), longwave radiation (using 4 spectral bands), surface fluxes of momentum, heat and moisture, and vertical diffusion”

115

Minor Comment 6 (L84,87): What are the ocean heat flux corrections derived from? Observational datasets? A fully-coupled version of this model?

120

The correction is derived from a previous model simulation in which all the parameters and settings are identical but in which observed SSTs are prescribed (in this case observed SSTs for the 30-years period 1979-2008).

In the text the sentence has been modified to include this informations in the following way:

“We analyze the outcomes of coupling the AGCM with two ocean models of different complexity. In the first configuration the AGCM is coupled with a slab ocean model; a monthly-varying ocean heat flux correction (derived from a previous 30-year model integration with identical settings but with prescribed observed SSTs) is imposed in order to keep the simulated SST close to present-day conditions.”

125

130

Minor Comment 7 (L210-211, Figure 9/10): Because of the chosen figure scale, the eastward/westward anomalies referenced in this sentence are not visible, which makes this statement confusing.

135 Disagreed. The anomalies referred in the text are easily seen in the mentioned Figures.

Technical Corrections

140 L241, 243, 246: Incorrect figure references

Agreed

145

L249, 298: extra commas in citations

Agreed

150

L270- 271: awkward grammar

155 Agreed

L291: be careful using the word significant if not conducting statistical significance tests

160

Agreed

Figure 11: The caption incorrectly identifies 2 panels when there is only 1.

165

Agreed, the caption has been modified.

We thank the reviewer for his/her constructive comments and suggestions.

170

We have given full consideration to the comments in the revised manuscript which includes: a discussion of the results of Green and Marshall (2017) and Schneider (2017) as well as figure modifications to make them easily interpreted by the reader.

175 Please find below a point-by-point reply to the questions raised. A marked-up manuscript version (with tracked changes) converted into a pdf is also uploaded as a supplement.

180

Anonymous Referee #2 Received and published: 1 January 2018

General Comments: In this paper, the authors employ a climate model hierarchy to understand the climate response to an
185 idealized interhemispheric thermal gradient (ITG). The model hierarchy consists of an atmospheric general circulation model (AGCM) under two coupled configurations. In the first configuration, the AGCM is coupled to a slab ocean model everywhere on the globe. In the second configuration, the AGCM is coupled to a slab ocean model everywhere except in the tropics where it is coupled to a reduced gravity ocean model to yield a total of four simulations. The two configurations are run under two scenarios: a scenario in which no forcing perturbation is applied and in a scenario in which the idealized ITG
190 is imposed to yield a set of four simulations. Using the four simulations, the role of ocean dynamics in the climate response to extratropical forcing perturbations is studied. The authors demonstrate that including tropical ocean dynamics mutes ITCZ shifts in response to imposed ITGs. Further, the authors show that the tropical seasonal cycle is intensified and in response the ENSO is weakened when ocean dynamics are included.

195 The paper nicely complements the recent results of Kay et al (2016) who showed a similar climate response to an imposed extratropical forcing in a climate model hierarchy and emphasizes the importance of ocean dynamics in determining the ITCZ response to forcing perturbations. The paper is structurally and logically well organized. I suggest publication with the following revisions.

200

Specific Comments:

Major Comment

205 My major comment on this paper pertains to the lack of discussion on the recent relevant results of Green and Marshall (2017) and also, as pointed by Reviewer 1, of Schneider (2017) that provide a physical pathway for how ocean coupling mutes the ITCZ response to interhemispheric energy perturbations. The findings of these papers and their relevance to this study are described adequately in Major Comment 1 by Reviewer 1, so I will skip repeating the discussion here. I however have a few minor and a number of technical comments that I list below.

210

Agreed. The results of the two mentioned papers have been included in the Introduction and Summary and Conclusions section.

215

Minor Comments

Line 79: Consider including a sentence or two describing the simplified physics

220

Agreed. The following text has been added to the model description:

“The model includes parameterizations of: large-scale condensation, shallow and deep convection, shortwave radiation (using 2 spectral bands), longwave radiation (using 4 spectral bands), surface fluxes of momentum, heat and moisture, and vertical diffusion”

225

Lines 51, 128, 150, 216, 291: Consider using the word ‘significant’ only when referring to statistical significance. Otherwise, I suggest replacing with synonyms like ‘considerable’ etc., Technical comments

230

Agreed

235

Line 33: trough -> through

Agreed

240

Line 46: being -> with

245

Agreed

Line 63: being -> with

250

Agreed

Line 74: find -> found

255

Agreed

260 Line 90: validate its results comparing -> validate its results by comparing

Agreed

265

Line 106: That means that, for momentum and heat fluxes, the oceanic and atmospheric components of the model exchange anomalies computed relative to their own model annual mean → In this strategy, the oceanic and atmospheric components of the model exchange momentum and heat flux anomalies computed relative to their own model annual mean

270 *****
Agreed

Line 108: superimposed to -> superimposed on

275 *****
Agreed

280 Line 108: wide -> width

Agreed

285 Line 113: analogous -> analogues

Agreed

290 *****

Line 116: in the Control the simulated annual mean SST -> the annual mean SST in the control simulation

295 Agreed

Line 125: than the observed and with the -> than the observed, with the

300 *****
Agreed

Line 126: as do in the observations -> as it does in the observations

305 *****
Agreed

310 Line 132: pattern consists in cooling -> patterns consists of cooling

Agreed

315 Line 136: .asymmetric -> asymmetric

Agreed

320 *****
Line 136: is superposed to a -> is superposed on a

325 Agreed

Line 155: focus in -> focus on

330 *****
Agreed

Line 155: produced to → produced in Line 201: being September-November (SON) the period of strongest cooling and the
335 June-August (JJA) period the one -> September-November (SON) being the period of strongest cooling and June-August
(JJA) being the period

Agreed

340 *****

Line 202: this negative -> the negative

345 Agreed

Line 270: being the signal produced with the RGO coupling weaker in terms of annual means -> with the signal produced in
the RGO coupling case being weaker in terms of annual means

350

Agreed

355 Line 215: Figure 10a shows SST anomalies and not wind anomalies. Please refer to appropriate figure. [Disagreed, the Figure reference is correct.](#)

Line 255: Timmermann et al., (2007) is missing from the list of references.

360 *****

[Agreed, the reference has been added.](#)

All figures: Please include headings for figure panels as visual aids

365

[Agreed, headings indicating the experiment or key information has been added.](#)

370 Figure 1 and 2: increase font size for x and y labels in figures 1 and 2.

Agreed

375

Figure 11: The figure panel corresponding to Forced_slab (Figure 11a) is missing

380 No panel is missing, as there is no thermocline anomaly in the case of slab ocean model. However, the figure caption was incorrectly referring to 2 panels. The caption has been corrected now.

|

Sensitivity of the tropical climate to an interhemispheric thermal gradient: the role of tropical ocean dynamics

Stefanie Talento^{1,2}, Marcelo Barreiro¹

¹Department of Atmospheric Sciences, Institute of Physics, Universidad de la República, Montevideo, 11400, Uruguay

²Department of Geography, Climatology, Climate Dynamics and Climate Change, Justus Liebig University of Giessen, 35390, Giessen, Germany

Correspondence to: Stefanie Talento (stefanie.talento@geogr.uni-giessen.de)

Abstract. This study aims to determine the role of the tropical ocean dynamics in the response of the climate to an extratropical thermal forcing. We analyse and compare the outcomes of coupling an atmospheric general circulation model (AGCM) with two ocean models of different complexity. In the first configuration the AGCM is coupled with a slab ocean model while in the second a Reduced Gravity Ocean (RGO) model is additionally coupled in the tropical region. We find that the imposition of an extratropical thermal forcing (warming in the Northern Hemisphere and cooling in the Southern Hemisphere with zero global mean) produces, in terms of annual means, a weaker response when the RGO is coupled, thus indicating that the tropical ocean dynamics opposes the incoming remote signal. On the other hand, while the slab ocean coupling does not produce significant changes to the equatorial Pacific sea surface temperature (SST) seasonal cycle, the RGO configuration generates a strong warming in the centre-east of the basin from April to August balanced by a cooling during the rest of the year, strengthening the seasonal cycle in the eastern portion of the basin. We hypothesize that such changes are possible via the dynamical effect that zonal wind stress has on the thermocline depth. We also find that the imposed extratropical pattern affects El Niño Southern Oscillation, weakening its amplitude and low-frequency behaviour.

1. Introduction

Paleoclimatic data (Wang et al., 2004), 20th century observations (Folland et al., 1986) and numerical simulations (Chiang and Bitz 2005; Broccoli et al. (2006), Kang et al., 2008, 2009; Cvijanovic and Chiang 2013; Talento and Barreiro 2016, 2017) have all suggested the capability of an extratropical thermal forcing to affect different features of the tropical climate. While Chiang and Bitz (2005) and Broccoli et al. (2006) were among the first to propose an atmospheric bridge mechanism connecting an extratropical forcing with a tropical response, by performing experiments with AGCMs thermodynamically coupled to a motionless ocean, the other studies deepen into these ideas and the physical mechanisms involved in the remote linkage.

The general picture emerging from these studies is that the Inter Tropical Convergence Zone (ITCZ) tends to shift toward the warmer hemisphere at the same time that the atmospheric energy transport is modified to favour the transmission of energy

to the colder hemisphere. For example, if the net energy input into the Northern Hemisphere (NH) is higher than into the Southern Hemisphere (SH) an interhemispheric thermal contrast is generated. This interhemispheric thermal gradient (ITG) triggers an atmospheric response through changes in the Hadley circulation, leading to a partially compensating cross-equatorial southward energy flux and a southward shift of the ITCZ. Schneider et al. (2014) analyse the ITCZ displacements from an energy flux perspective, and find an anti-correlation between the latitude of the ITCZ and the cross-equatorial atmospheric energy transport.

~~In particular,~~ Talento and Barreiro (2016) use an atmospheric general circulation model (AGCM) coupled to a slab ocean model to quantify the relative roles of the atmosphere, tropical sea surface temperatures (SST) and continental surface temperatures in the ITCZ response to an extratropical thermal forcing. They find that if the tropical SSTs are not allowed to change, then the ITCZ response strongly weakens although it is not negligible, in particular, over the Atlantic Ocean and Africa. If, in addition, the land surface temperature over Africa is maintained fixed the ITCZ response completely vanishes, indicating that the ITCZ response to the extratropical forcing is not possible just through purely atmospheric processes, but needs the involvement of either the tropical SST or the continental surface temperatures. With the same model configuration, Talento and Barreiro (2017) focus on the South Atlantic Convergence Zone (SACZ) and show that, during its peak in austral summer, its response to a warming in the ~~Northern Hemisphere (NH)~~ extratropics and a cooling in the ~~Southern Hemisphere (SH)~~ extratropics consists of a weakening, mostly due to the NH component of the forcing. Both studies showed strong changes in the tropical band where SST, surface winds and precipitation are strongly coupled. Nevertheless, in these studies important ocean dynamics are missing as the slab ocean can only simulate the thermodynamic exchange between the atmosphere and the ocean.

Chiang et al., (2008) explore the impact of an ~~interhemispheric thermal gradient (ITG)~~ on the tropical Pacific climate through simulations performed with an AGCM coupled to a medium-complexity ocean model: a Reduced Gravity Ocean (RGO) model. They find that when the NH is warmer than the SH the annual mean equatorial zonal SST gradient strengthens, associated with an earlier onset and a later retreat of the seasonal cold tongue together with an intensification during the peak cold season. They also find that El Niño Southern Oscillation (ENSO) activity is sensitive to the ITG, being with small ITG optimal for the development of ENSO activity.

Lee et al., (2015) also use an AGCM coupled to a RGO model and analyse the impact of the glacial continental ice sheet topography on the tropical Pacific climate. They suggest that the thickness of the ice sheets, separate from the ice albedo effect, has a significant considerable impact on the tropical climate. They identify two types of responses: a quasi-linear response directly associated with the topographic changes and a nonlinear response mediated through the tropical thermocline adjustment. They find that increasing the thickness of the continental ice sheets produces a southward displacement of the ITCZ and a weakening of the equatorial zonal SST gradient, caused by cooling (warming) in the western

(eastern) equatorial Pacific, together with a thermocline deepening to the east. They note that the energy flux approach proposed in Kang et al., (2008, 2009) and Cvijanovic and Chiang (2013) does not appear to explain the ITCZ shifts in these experiments because even though the northern cross equatorial energy transport increases with the ice thickness, the mid-latitude transport decreases.

Although most of the simulation studies on extratropical to tropical teleconnections focus on just one ocean model at a time, there is recent literature analysing the subject. Studies that analyse the extratropical to tropical teleconnection in a hierarchy of ocean model configurations, are scarce, as most of the literature on the subject focuses on just one ocean model at a time. One exception is the work by

Kay et al., (2016) in which the authors study the effect of a Southern Ocean cooling on the tropical precipitation, coupling an AGCM either to a slab or to a full oceanic model. They find that with dynamic ocean heat transport the tropical precipitation response is weaker with being, in this case, most of the cross-equatorial heat transport carried out by the ocean and not by the atmosphere. Similar conclusions are obtained by Hawcroft et al., (2016) and Tomas et al. (2016) with a different fully coupled models, suggesting that the results are not model specific. In the same direction, Green and Marshall (2017) perform a series of idealized simulations in aqua-planet mode with an AGCM coupled either to a dynamic or to a slab ocean model while an ITG is applied. They find that the oceanic circulation dampens the ITCZ shift in response to the ITG by a factor of 4 compared to the case when the ocean circulation is not allowed to respond to the forcing. They find that with a dynamic ocean the mechanical coupling of the tropical atmospheric and oceanic energy transport (through Ekman balance) ensures that the ocean circulation always transports energy across the Equator in the same direction as the atmosphere does, therefore helping offset the imposed thermal contrast and not requiring for the atmosphere to transport as much energy as when the ocean circulation is fixed.

From a theoretical perspective, Schneider (2017) confirms the simulation results and derives a quantitative framework that shows that the Ekman coupling of atmospheric and oceanic energy fluxes dampens the response of the ITCZ and calculates that, in the current climate in the zonal and annual mean, the factor of damping by Ekman coupling is in the order of 3.

To complement the results of the previously mentioned studies here we propose to analyse the tropical response to an extratropical thermal forcing in a hierarchy of ocean model configurations, but using an intermediate-complexity ocean model coupled only in the tropical oceans: a RGO model. This simulations, therefore, represent an additional and intermediate step into understanding the tropical ocean dynamics' role in the extratropical to tropical communication process.

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~~In this study we propose to further examine the role of equatorial ocean dynamics in the tropical response to an extratropical forcing in a hierarchy of model configurations. To isolate the tropical ocean dynamics' effect we will analyse and compare the response generated when an AGCM is coupled to a slab ocean model to that obtained when a RGO model is additionally coupled in the tropical oceans.~~

485

The paper is organized as follows. In section 2 we describe the models used, with special emphasis in the description of the RGO model and its validation against observational data. The experiments performed are explained in section 3. The results can be ~~found~~ in section 4, discriminated as regarding to changes in annual mean, seasonal cycle or ENSO. A summary and conclusions are presented in section 5.

490

2. Model Description

The atmospheric model used in this study is the Abdus Salam International Centre for Theoretical Physics (ICTP) AGCM (Molteni 2003; Kucharski et al., 2006) which is a full atmospheric model with simplified physics. We use the model version 40 in its 8-layer configuration and T30 (3.75°x3.75°) horizontal resolution. The model includes parameterizations of: large-scale condensation, shallow and deep convection, shortwave radiation (using 2 spectral bands), longwave radiation (using 4 spectral bands), surface fluxes of momentum, heat and moisture, and vertical diffusion. Present-day boundary surface conditions, orbital parameters and greenhouse forcing are used.

495

We analyze the outcomes of coupling the AGCM with two ocean models of different complexity. In the first configuration the AGCM is coupled with a slab ocean model; a monthly-varying ocean heat flux correction (derived from a previous 30-year model integration with identical settings but with prescribed observed SSTs) is imposed in order to keep the simulated SST close to present-day conditions. In the second configuration, and in order to better reproduce the tropical ocean dynamics, a RGO model is coupled in the tropical region (30°S-30°N), while a slab ocean model is applied elsewhere. In this setup an annual-mean ocean heat flux correction is imposed in order to keep the simulated SST close to present-day conditions.

500

505

We proceed to describe the RGO model and to validate its results by comparing with observational analogues.

2.1 RGO Model Formulation and Validation

510 We use an extension of the classical 1 ½ layer RGO model, introduced by Cane (1979) to study the ENSO phenomenon. The extension of the model, as in Chang (1994), includes thermodynamics of the upper ocean and allows the prediction of the SST.

The model consists of a 50 m depth upper layer in which mass, heat and momentum obey the conservation laws and a lower
515 layer of infinite depth in which the velocity must be null so that the kinetic energy is finite. The approximation is reasonable for the tropical ocean because of the existence of a sharp thermocline which inhibits the downward propagation of waves generated in the upper ocean (Zebiak, 1985). To better predict changes of the SST a linear and homogeneous frictional layer (assumed to concentrate most of the induced Ekman transport) is added to the model. The subsurface temperature is parameterized in terms of the thermocline depth, the observed annual mean temperature at 50 m depth (from Levitus 1982)
520 and the annual mean thermocline depth when the model is forced by observed wind stress.

The resolution of the RGO model is 1° in latitude and 2° in longitude, applied in the 30°S-30°N tropical band. The model is run using an anomaly coupling strategy. In this strategy, the oceanic and atmospheric components of the model exchange
525 That means that, for momentum and heat fluxes anomalies, the oceanic and atmospheric components of the model exchange anomalies computed relative to their own model annual mean. The modeled anomalies are then superimposed ~~to~~on the observed annual mean. Sponge layers of 5° width~~the~~ are introduced at the northern and southern boundaries to eliminate artificial coastal Kelvin waves.

A 70-years Control simulation in which the AGCM is coupled to the RGO in the tropics and to the slab ocean model
530 elsewhere is produced. The last 50 years of the Control run are used for averaging and comparison with observational analogues. We use the NOAA Extended Reconstructed SST V3b (Smith et al., 2008) and the near-surface winds from the NCEP-NCAR Reanalysis (Kalnay et al., 2006), for the period 1979-2013.

With the imposed heat flux correction, ~~in the Control the simulated~~the annual mean SST in the Control simulation strongly
535 resembles the observed pattern (not shown). In addition, the model reasonably captures the main characteristics of the seasonal cycle in the equatorial (2°S-2°N) Pacific and Atlantic oceans (Figure 1), although in the equatorial Pacific the de-meaned (annual mean removed) simulated SST seasonal cycle is weaker than in the observations. Also, the Pacific cold tongue is not well developed during SH summer.

540 The Control simulation also reproduces the main mode of variability in the tropical Pacific Ocean quite realistically both in the spatial and temporal domains (Figure 2; please note that in all the latitude-longitude maps in the manuscript the land and

~~sea mask used by the model is the one depicted~~). The first coupled pattern arising from a Singular Value Decomposition (SVD) of the monthly SST and surface wind characterizes ENSO and explains 81% (62%) of the variability in the observations (simulation). The simulated pattern is weaker than the observed, ~~and~~ with the SST anomaly maximum located too far eastward. The phase-locking to the seasonal cycle of the simulated pattern peaks during the end of the calendar year as ~~it does~~ in the observations, but its distribution is more uniform throughout the year. Both simulated and observed spectra show statistically significant peaks relative to a red noise null hypothesis from 16 to 60 months.

2.2 Experimental Design

For each model configuration two runs are produced: a Control run (in which no forcing is applied) and a forced run (in which an extratropical forcing is imposed). The applied forcing pattern consists ~~of~~ 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. This pattern is similar to the one used in Kang et al., (2008) and in Talento and Barreiro (2016) and it is intended to represent the asymmetric temperature changes associated with glacial-interglacial and millennial-scale climate variability as well as the asymmetric SST pattern characteristic of the global warming trend. The forcing pattern is superposed ~~onto~~ a background state and is obtained as explained in Talento and Barreiro (2016).

The forcing pattern is shown in Figure 3, in which sign convention is positive out of sea and, 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 so that there is a strong ocean-to-atmosphere net heat flux. This forcing generates a near surface temperature (NSAT) anomaly response of up to 16°C (-20°C) over the north Atlantic Ocean at 70°N (over the Ross Sea), as shown in Figure 4. For comparison, in a climate simulation of the last 21.000 years (TRACE2k experiment, He 2011) anomalies of about -10°C (6°C) are obtained over the North Atlantic (Antarctica) during Heinrich Stadial 1, 18.000 to 15.000 years ago.

As mentioned before we use two ocean models. When the AGCM is coupled to a slab ocean model, the experiments are named: *Control_slab* and *Forced_slab*. If an RGO is used in the the tropical band while the slab ocean model is applied elsewhere, the corresponding experiments are named: *Control_slab+rgo* and *Forced_slab+rgo*. In all the simulations the model was run for 70 years and the last 50 are used for averaging. Running the simulations for 70 years proved to be more than enough to reach the equilibrium; a time scale of 10 years was estimated to be the time span necessary for adjustment. In Table 1 we summarize the experiments.

3. Results

First we analyse and compare the annual mean anomalies generated by the extratropical forcing with the two configurations implemented. Second, we will focus on the tropical Pacific climate and study the changes produced into the seasonal cycle for both setups. Finally, we will briefly investigate possible changes in ENSO activity when the RGO is coupled in the tropical oceans.

3.1 Annual means

In this subsection we compare the results obtained with the two implemented configurations in terms of annual means of different fields. The results are presented in the form of anomalies with respect to the corresponding Control case.

Figure 4 shows the near surface air temperature (NSAT) changes with respect to the corresponding Control for the two configurations. In both experiments there is a generalized warming (cooling) in the NH (SH), while in the southern tropics a strengthening of the zonal gradient is evident. The most pronounced differences between the two configurations are seen in the tropical region, in which the slab+rgo configuration anomalies tend to be up to 1°C weaker than the slab configuration anomalies. In particular, the equatorial Pacific cooling seen in the slab configuration is no longer present in the rgo+slab configuration, and the southeastern ocean basins do not cool as much. This suggests that, overall, tropical ocean dynamics tends to oppose changes in the annual mean conditions. In the extratropics the differences between the two configurations are almost not noticeable, although regions of up to 2°C are noted in the vicinity of the Antarctic Peninsula and Greenland.

As a consequence, tropical changes in precipitation are weaker when using the RGO: while in both experiments the most pronounced feature is a northward shift of the ITCZ, anomalies for the slab+rgo configuration are much weaker (Figure 5). Also, in the slab configuration strong changes of tropical precipitation are found equally over the three ocean basins, but for the slab+rgo setup the most intense anomalies are seen over the Atlantic Ocean concurrent with a still relatively strong cross-equatorial SST gradient and suggesting a larger role for continental temperatures in controlling the position of the ITCZ (as in Talento and Barreiro, 2016). Changes in the subtropical convergence zones are also weaker in the slab+rgo configuration, differently from the southward shift seen in the slab configuration. In particular for the case of the South Atlantic Convergence Zone, this result is consistent with Talento and Barreiro (2016), which showed that during southern summer the weakening of the SACZ is related to the development of a region of strong rainfall in the tropical north Atlantic.

As expected from the above results, both experiments present similar patterns of near surface (950 hPa) wind anomalies (Figure 6): anomalous northward winds associated with the ITCZ northward displacement in the tropics, and anomalous westerly winds over the Southern Ocean. The *Forced_slab+rgo* response is weaker in the tropics but stronger over the

Southern Ocean, compared to the *Forced_slab* response. Similar pictures of a weaker response in the case of slab+rgo configuration can be seen in upper-level winds, mean sea level pressure and mass stream-function (not shown).

To summarize, in Figure 7 we present the northward atmospheric energy transport for the Control and forced runs in the two configurations implemented. As can be seen, while the Control runs display almost an identical transport, the forced runs significantly disagree in magnitude in the tropical region, with the slab+rgo configuration producing the **strongweakest** changes with an **increase** of the transport toward the southern high latitudes, **representing a damping by a factor of 1.9**. In the perturbed runs, the energy flux equator is located around 127°N (~~813°N~~) for the slab (slab+RGO) configuration, **equivalent to a damping in the shift by a factor of 1.5**.

3.2 Seasonal Cycle

As the previous subsection showed, the most pronounced differences between the two implemented configurations are found in the tropical band. Therefore, for the analysis of variations in the seasonal cycle we will focus on the 30°S - 30°N region.

Three-month means of SST and near-surface wind changes for the tropics are shown in Figure 8. In the Pacific Ocean, for the *Forced_slab* experiment negative SST anomalies are seen reaching the Equator (or even more to the north) in all 4 seasons, **being** September-November (SON) **being** the period of strongest cooling and ~~the~~ June-August (JJA) **being the** period ~~the one~~ in which ~~the~~ negative anomalies have the weakest penetration onto the NH. Meanwhile, for the *Forced_slab+rgo* experiment the negative SST anomalies barely reach the Equator and, in fact, positive anomalies are the ones penetrating onto the SH for the seasons March-May (MAM) and JJA. Consistent with these changes in response, the equatorial anomalous winds in the slab configuration are mainly easterlies throughout the year, while in the slab+rgo configuration they have a marked northward component and are eastward during MAM season. Also, the equatorial Atlantic tends to warm up during most of the year when using the RGO model.

Equatorial (2°S - 2°N) de-meaned seasonal cycles for near-surface zonal wind and SST anomalies in the Pacific basin for the two experimental configurations are shown in Figures 9 and 10, respectively. In *Forced_slab* there are eastward (westward) near-surface wind anomalies from December to May (June to November) distributed along the basin. The positive wind anomalies in the *Forced_slab* are quite uniform along the basin, although there are maximums in the western and eastern ends during December-February (DJF). The negative anomalies during the second half of the year are maximal in the central-eastern basin. In the slab configuration, the equatorial SST response to these wind anomalies is, however, very weak (Figure 10a). On the other hand, when the RGO is coupled (and although the annual mean anomalies were even weaker than for the slab configuration, Figure 4) there are **significantsubstantial** changes occurring to the seasonal cycle of SST in the

center-east of the basin: from April to August (October to December) the forced run produces a warming (cooling) of up to 1°C (-0.8°C). The location and timing of these anomalies lead to a substantial strengthening of the SST seasonal cycle in the eastern Pacific Ocean (overlap Figure 10b on the *Control_slab+rgo* SST seasonal cycle showed in Figure 1c).

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The thermocline depth shows consistent changes when the RGO is used (Figure 11): a deepening in the east of the basin starting around March and finishing in July, consistent with the warmer SSTs seen in the region (with 1 month lag). Considering the wind anomalies of the slab setup (Figure 9a) as the forcing pattern for the ocean dynamics derived from the extratropical signal, this thermocline deepening pulse appears to be initiated during the SH summer in the west of the basin (due to a weakening of the trades) and is propagated eastward as a Kelvin wave, reaching the eastern boundary 2-3 months later. The deepening of the eastern Pacific thermocline is concurrent with a shallowing in the western Pacific particularly from May to July, and vice versa (but less obvious) in other seasons of the year. In the second half of the year the strengthening of the trades locally shallows the thermocline in the eastern Pacific and the western Pacific recovers its mean depth.

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In summary, the equatorial near-surface zonal wind changes caused by the extratropical forcing seen in the slab configuration induce dynamical ocean-atmosphere coupling that generates seasonal changes in the SST field when the RGO is used. This results in a late austral fall warming and a cooling in spring and summer in the equatorial eastern Pacific, leading to a strengthening of the SST seasonal cycle with consistent changes in the thermocline depth.

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3.3 ENSO

In this subsection we investigate how the interannual variability in the tropical Pacific is affected by the interhemispheric SST gradient induced by the imposed forcing.

660 The leading pattern of co-variability of SST and near-surface wind in the tropical Pacific basin when the extratropical forcing is applied is weaker than that obtained when no forcing is implemented (Figure 12 a and Figure 2 a), and explains a smaller percentage of the total variability (46% compared to 62%). The phase-locking to the seasonal cycle (Figure 12 b and Figure 2 c) is also modified being more uniformly distributed and with a peak season going from July to the end of the calendar year. The frequency spectrum of the ENSO pattern under the effect of the extratropical forcing is characterized by shorter periods than in the absence of the forcing and has a peak at 24 months (Figure 12 c and Figure 2 e).

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The weakening of the ENSO activity can be understood in relation to the changes produced by the extratropical forcing on the SST seasonal cycle in the eastern Pacific Ocean. According to the non-linear frequency entrainment mechanism (Chang et al., 1994) ENSO amplitude is anticorrelated with the strength of the SST seasonal cycle. The frequency entrainment

670 implies that a self exciting oscillator (like ENSO) will give up its intrinsic mode of oscillation in the presence of a strong external forcing (like a strong seasonal SST cycle) and acquire the frequency of the applied oscillating forcing. Therefore, in our case, as the extratropical forcing generates a significant strengthening of the east Pacific SST seasonal cycle, a weakening of ENSO is expected according to this mechanism.

675 | Assuming a linear behaviour holds, our result of ENSO weakening is also in agreement with Timmermann et al. (2007). These authors analyse fully coupled GCMs in the context of an Atlantic Meridional Overturning Circulation (AMOC) slowdown, producing a generalized cooling of the NH and warming in the SH, and find that most of the models predict a ENSO intensification attributed to a seasonal cycle weakening. The weakening of ENSO activity in the presence of a northward ITG is also consistent with the work of Chiang et al., (2008) who use a model configuration similar to ours: an
680 AGCM coupled to a RGO model. Although they do not attempt to explain the causes, they find that ENSO is sensitive to ITG with maximal activity when the ITG is close to zero and a weakened performance as the gradient increases in any direction.

4. Summary and Conclusions

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We investigated and compared the response of the tropical climate to an extratropical thermal forcing in a hierarchy of models in which an AGCM was coupled either to a simple slab ocean model (just thermodynamic coupling) globally or with a combination of a RGO model in the tropical oceans and a slab ocean model elsewhere.

690 | First, we found that the two model configurations lead to considerable different climate responses. In particular, in tropical regions the responses produced by the two types of configurations greatly differ in the tropical regions, being the signal produced within the RGO coupling case is weaker in terms of annual means, indicating that regional dynamical air-sea interaction opposes to the remote signal. This result is in agreement with the quantitative framework proposed by Schneider (2017), who calculates an expression for the damping of the ITCZ shift in case of an atmospheric-ocean mechanical coupling. In addition, our result also agrees with the simulation experiments performed by Kay et al., (2016) and Green and Marshall (2017), who also obtained a weaker tropical response to an extratropical thermal forcing when using a fully coupled model than when the AGCM is only coupled to a slab model, therefore indicating that the ITCZ shift damping is also seen when an intermediate-complexity ocean model is coupled only in the tropics. In our experiments the energy flux equator (which can be regarded as an approximation for the ITCZ latitude) shift dampens by a factor of 1.5 in case the
695 tropical ocean dynamics is included, while the southward atmospheric energy transport experiences a damping by a factor of
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1.9. In the simulations by Green and Marshall (2017) and in the quantitative work of Schneider (2017) the damping factors for the ITCZ shift were 4 and 3, respectively.

705 However, although the annual mean anomalies produced by the RGO setup are weaker, we find that the changes in the SST seasonal cycle are larger. In particular, over the equatorial Pacific Ocean, while the slab configuration produces no changes to the SST seasonal cycle, the RGO addition generates a profound warming in the centre-east of the basin from April to August balanced by a cooling in the rest of the year, yielding an almost null integration in the annual mean but also implying a significant strengthening of the seasonal cycle in the eastern Pacific. The response of the seasonal cycle to the imposed extratropical forcing is qualitatively similar to the one obtained by Chiang et al., (2008) in similar experiments, although in
710 our case positive SST anomalies reach the eastern boundary of the basin not permitting an earlier onset of the seasonal cold tongue as these authors find in their simulations. We hypothesize that the changes in the SST seasonal cycle are possible via the effect that the zonal wind stress has on the thermocline depth: the remote forcing produces positive anomalies of zonal wind stress to be exerted in the first half of the calendar year; in particular, the significant weakening of the trades over the western portion of the basin around February and March induces a thermocline deepening pulse that propagates eastward in
715 the form of a Kelvin wave, reaching the eastern boundary 2 months later, and generating a warming of the SST over that region as a result. In the second half of the year stronger trades in the central-eastern basin shallow the thermocline producing a local cooling of the SST. Since these mechanisms are not available under the slab configuration, the wind stress seasonal cycle changes are not able to produce any SST changes.

720 Finally, we briefly analysed within the RGO setup, possible changes in ENSO activity and found that under the effect of the extratropical forcing significantconsiderable changes are produced both in the spatial and temporal domains with a weaker SST pattern and a time series that lacks low-frequency variability. We hypothesized that the weakening of the ENSO activity concurrent with the intensification of the SST seasonal cycle in the eastern equatorial Pacific Ocean, could be due to the frequency entrainment mechanism. As future climate projections tend to agree in the fact that global warming will have an
725 important northward ITG component (NH warming faster than the SH; Friedman et al., 2013), the possible sensitivity of ENSO to ITG is of primary relevance. However, current state of the art fully coupled climate models do not seem to agree in the projected future changes in ENSO characteristics and no clear evidence for a correlation with ITG has been detected in future climate projections (Stevenson, 2012; Taschetto et al., 2014).

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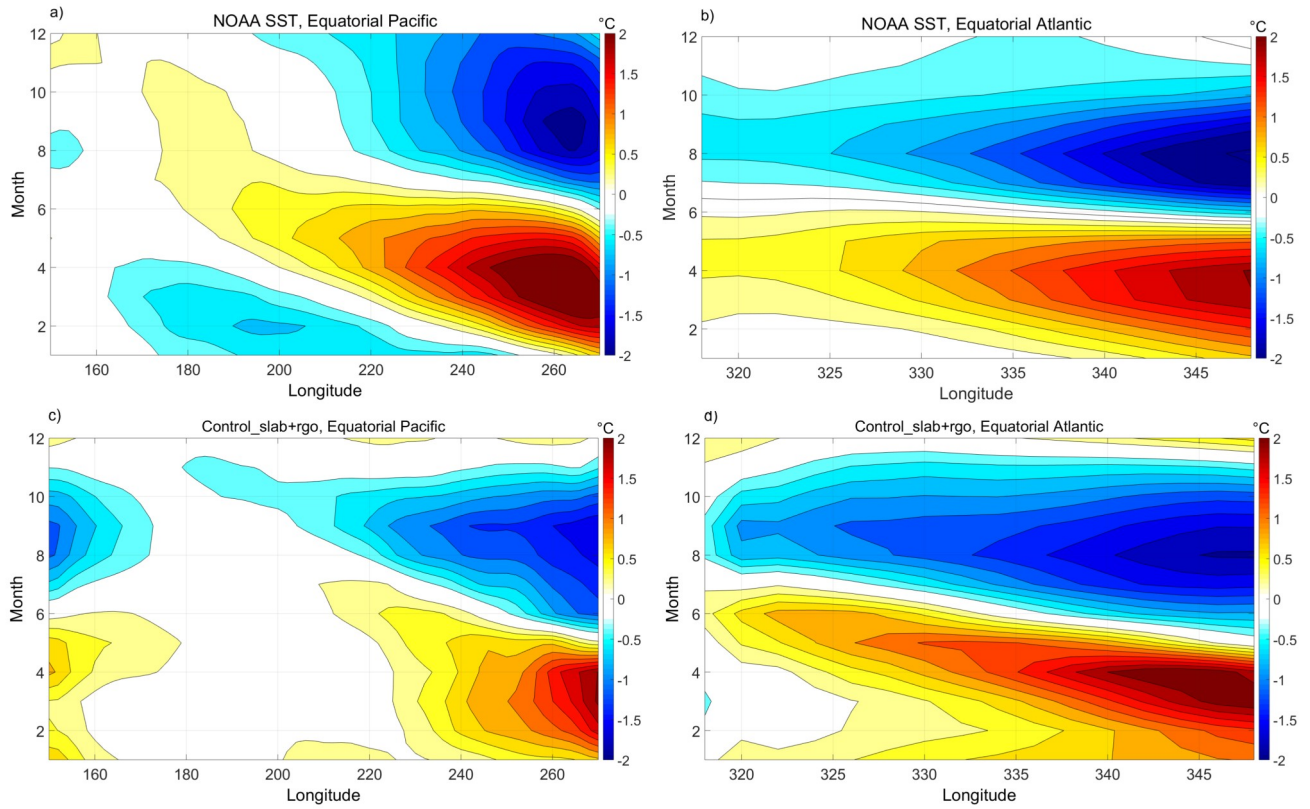
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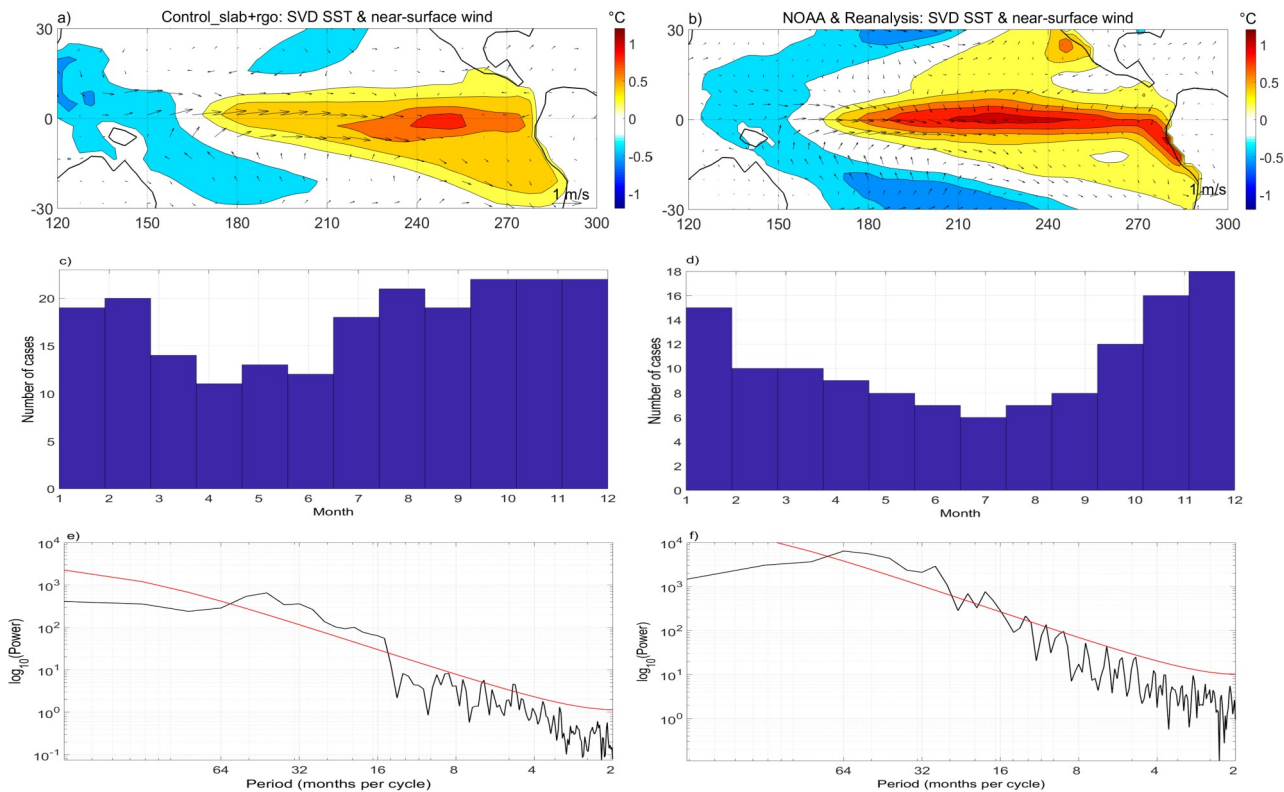
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Table 1: Experiment summary.

Experiment Name	Ocean model	Forcing pattern H
<i>Control_slab</i>	Slab ocean model globally	No forcing
<i>Forced_slab</i>	Slab ocean model globally	Extratropical forcing, as in Figure 3
<i>Control_slab+rgo</i>	RGO model in 30°S-30°N, slab ocean model elsewhere	No forcing
<i>Forced_slab+rgo</i>	RGO model in 30°S-30°N, slab ocean model elsewhere	Extratropical forcing as in Figure 3

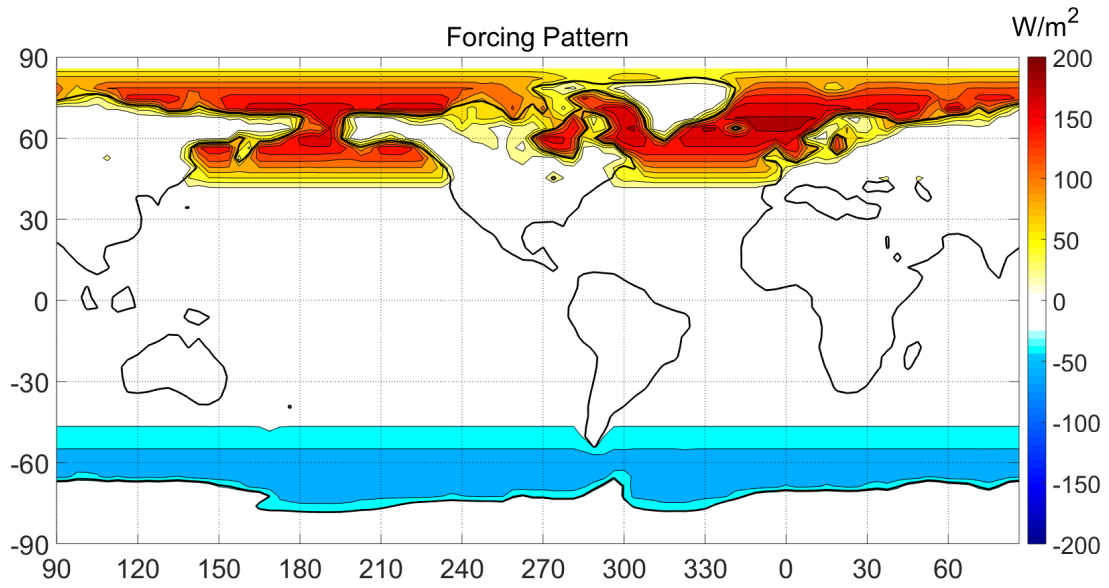


830 **Figure 1: a. and b.: De-meaned SST seasonal cycle from NOAA SST data (Smith et al., 2008) in the Equatorial Pacific (2°S- 2°N, 150°E-270°E) and Atlantic (2°S-2°N, 320°E-345°E), respectively. c. and d.: De-meaned SST seasonal cycle for *Control_slab+rgo* in the Equatorial Pacific and Atlantic, respectively. Contour interval: 0.2°C.**



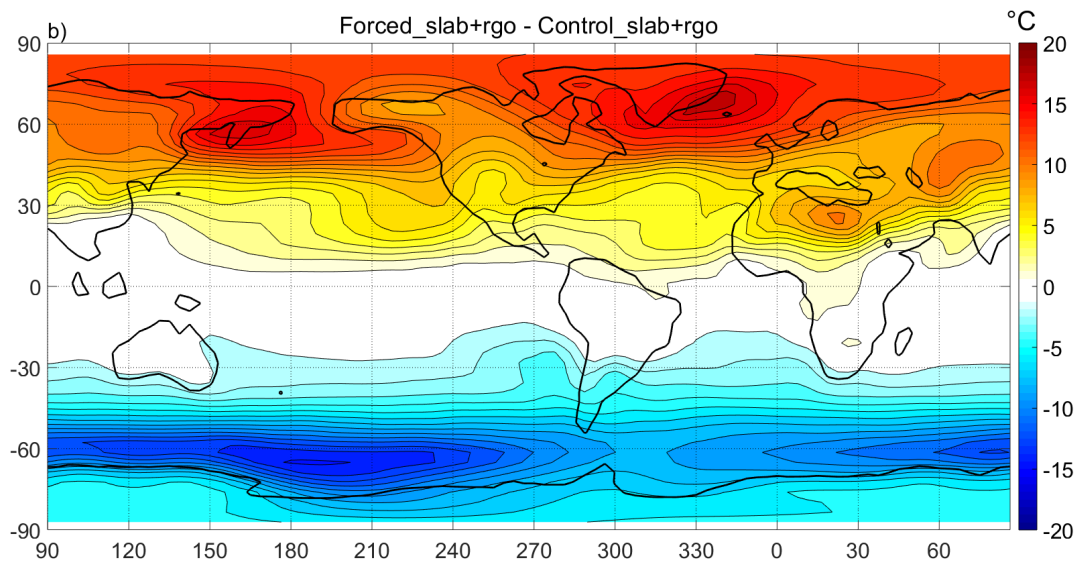
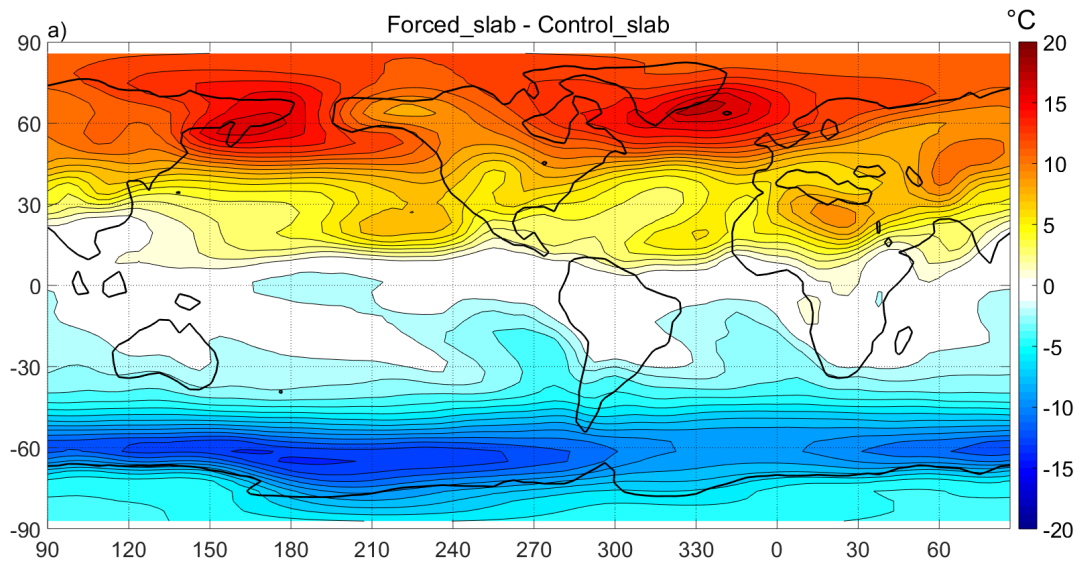
835 **Figure 2: First SVD pattern of SST and near-surface winds in the tropical Pacific Ocean (30°S-30°N, 120°E-300°E) for the *Control_slab+rgo* experiment (left) and NOAA SST and reanalysis data (right; Smith et al., 2008; Kalnay et al., 2006). a. and b.: Spatial pattern; contour interval 0.2°C. c. and d.: Histogram showing phase- locking to the seasonal cycle. e. and f.: Spectral analysis, the red line indicates the red noise spectrum.**

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Figure 3: Forcing pattern. The sign convention is positive out of sea. Contour interval 20 W/m^2 .



850 **Figure 4: Annual mean anomalies with respect to the control of NSAT for: a. *Forced_slab* and b. *Forced_slab+rgo*, respectively. Contour interval 1°C.**

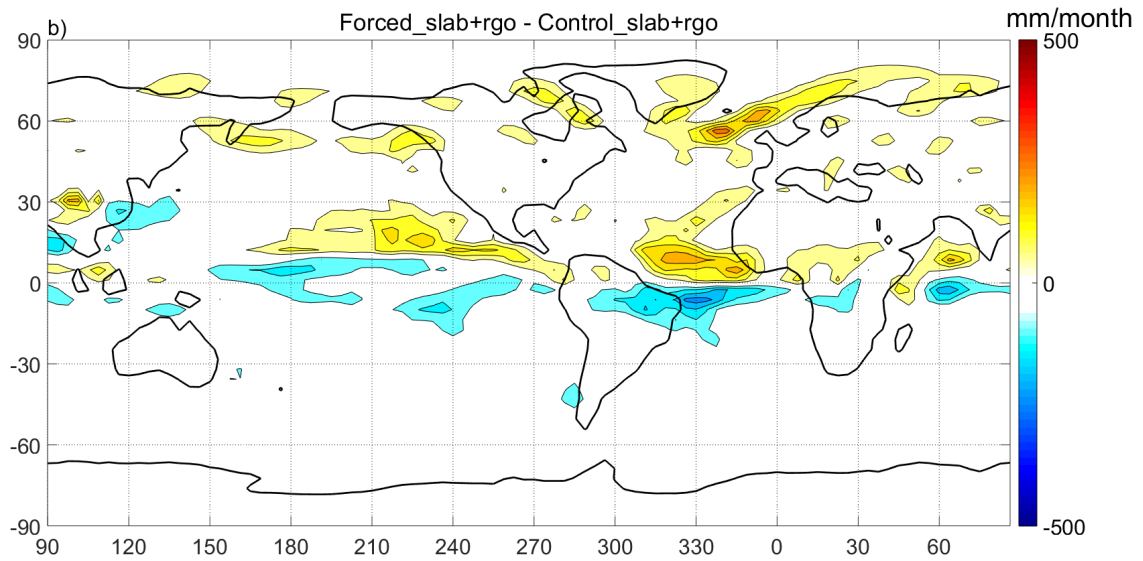
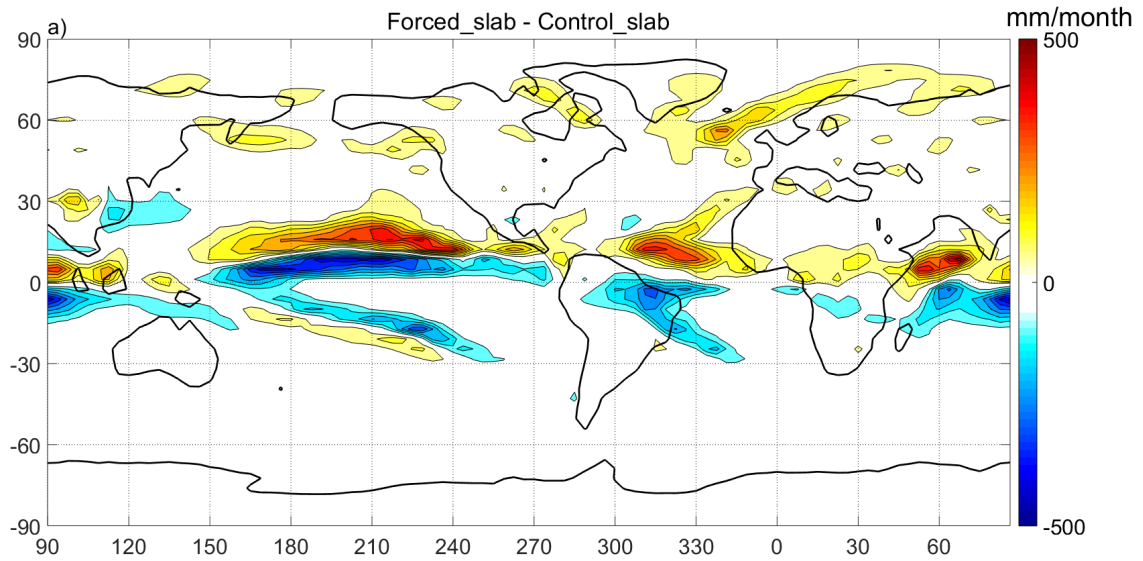
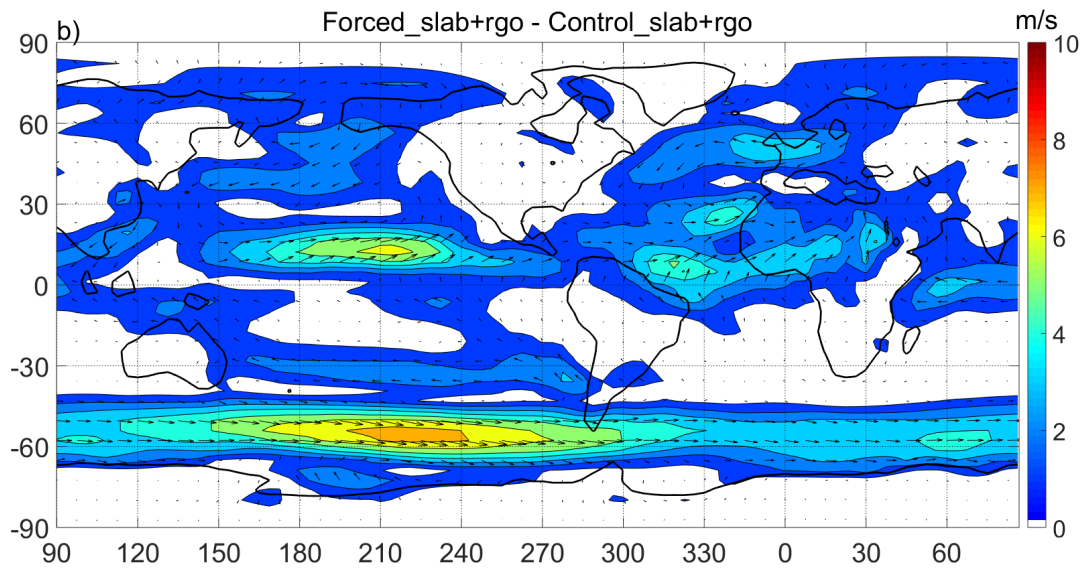
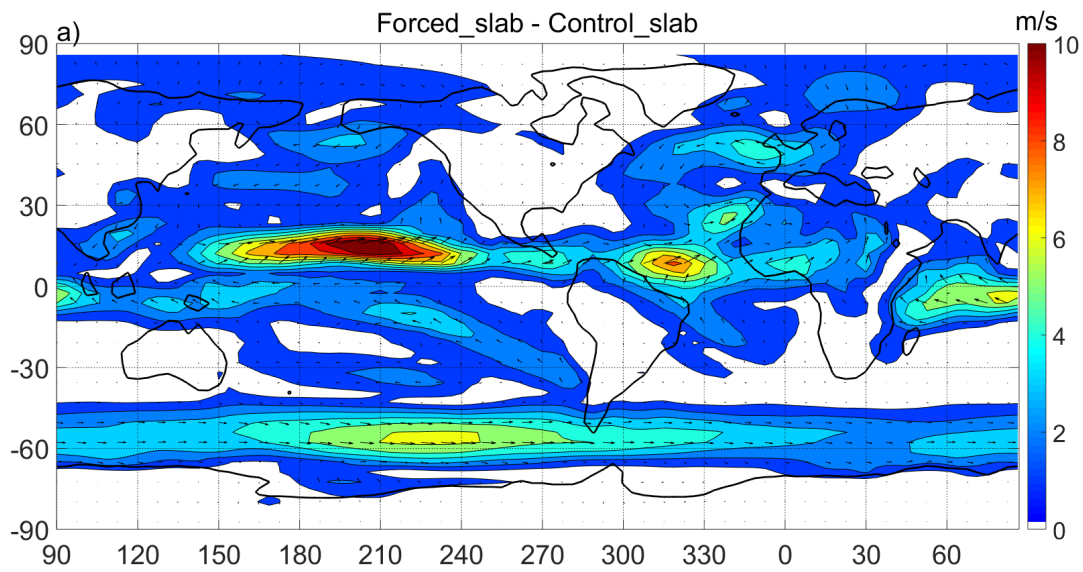


Figure 5: Annual mean anomalies with respect to the control of precipitation for: a. *Forced_slab* and b. *Forced_slab+rgo*, respectively. Contour interval 50 mm/month.



860 **Figure 6: Annual mean anomalies with respect to the control of near-surface (950 hPa) wind for: a. *Forced_slab* and b. *Forced_slab+rgo*, respectively. Contour interval 1 m/s.**

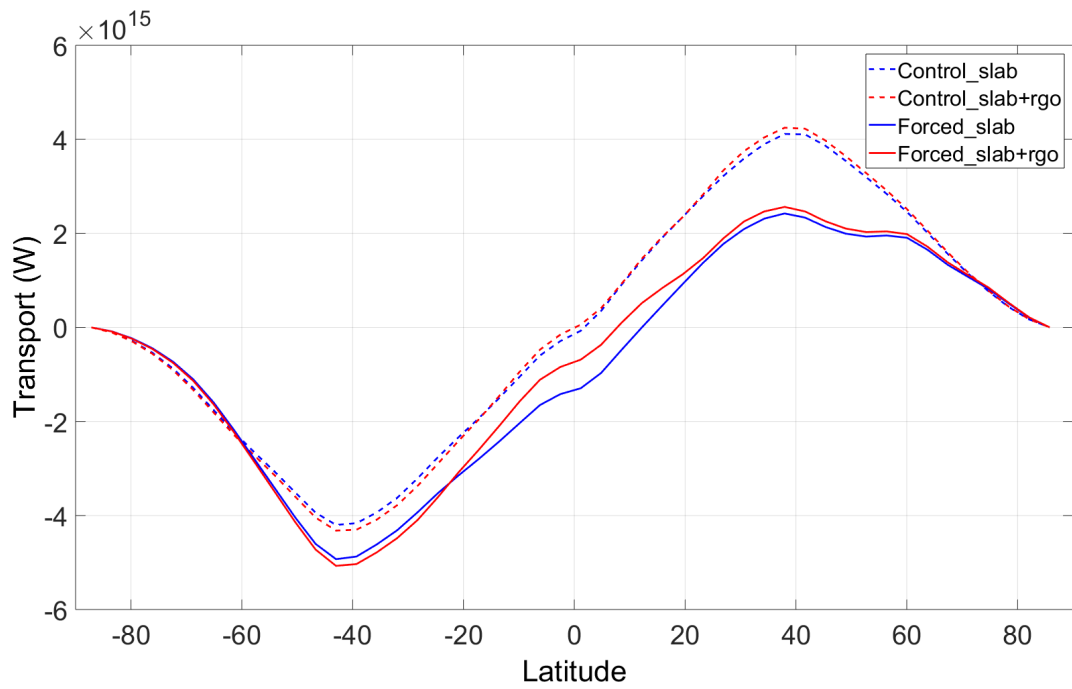
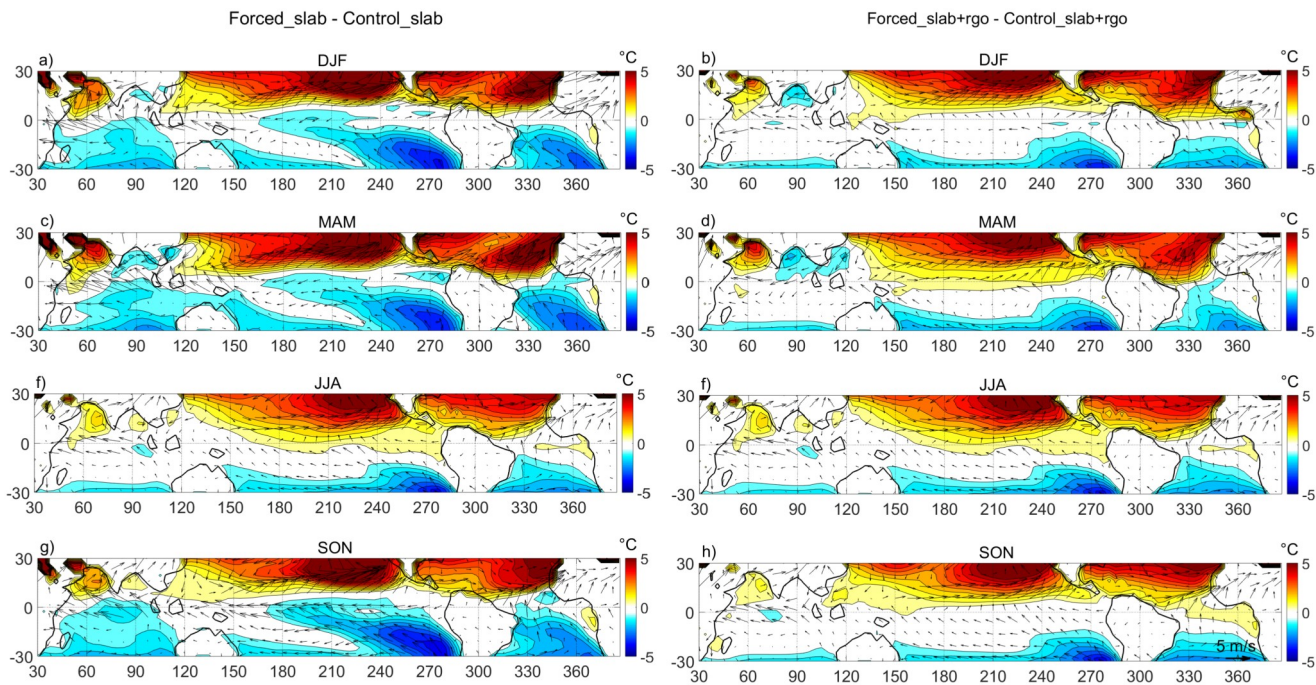
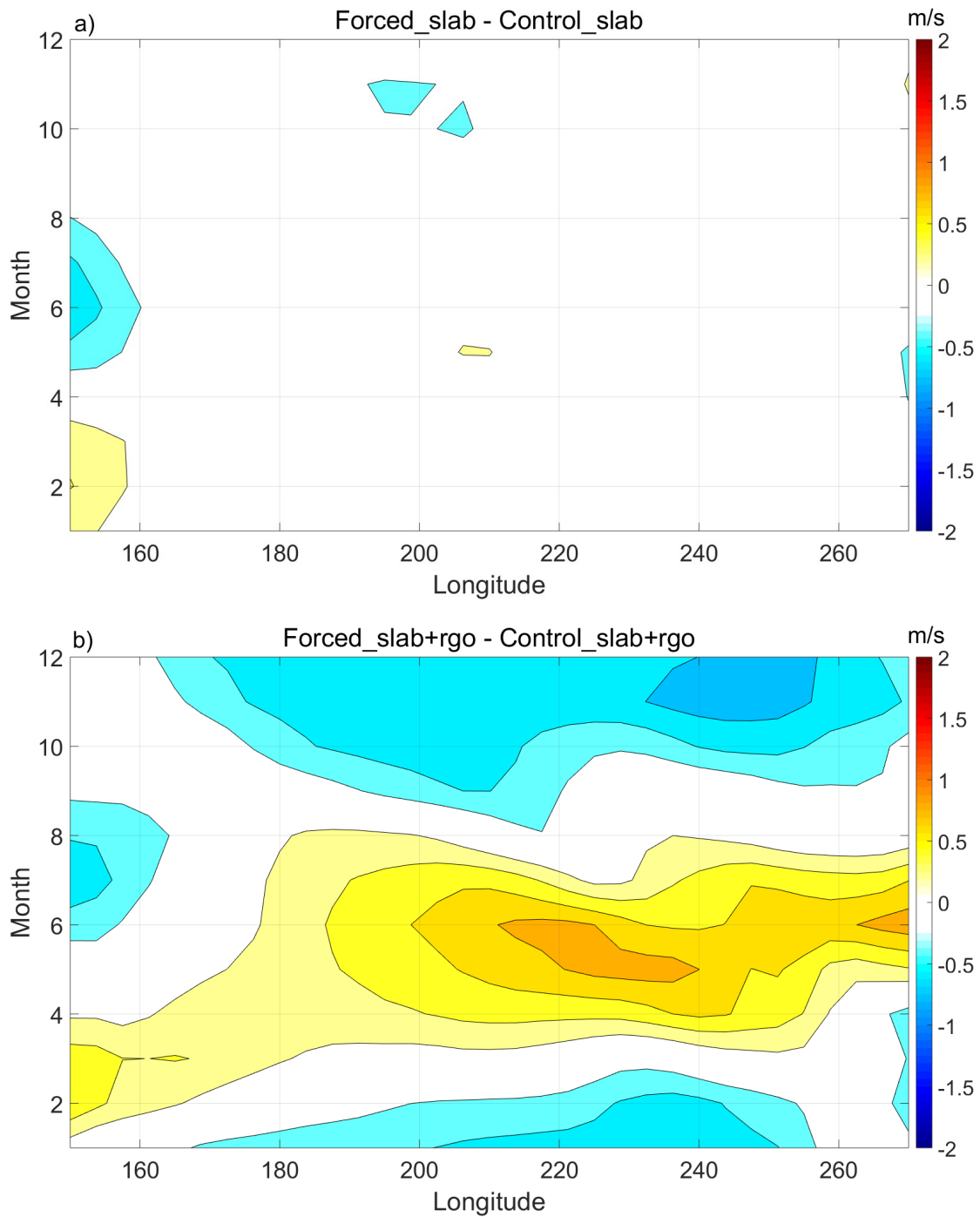


Figure 7: Northward atmospheric energy transport for the experiments: *Control_slab*, *Control_slab+rgo*, *Forced_slab* and *Forced_slab+rgo*.

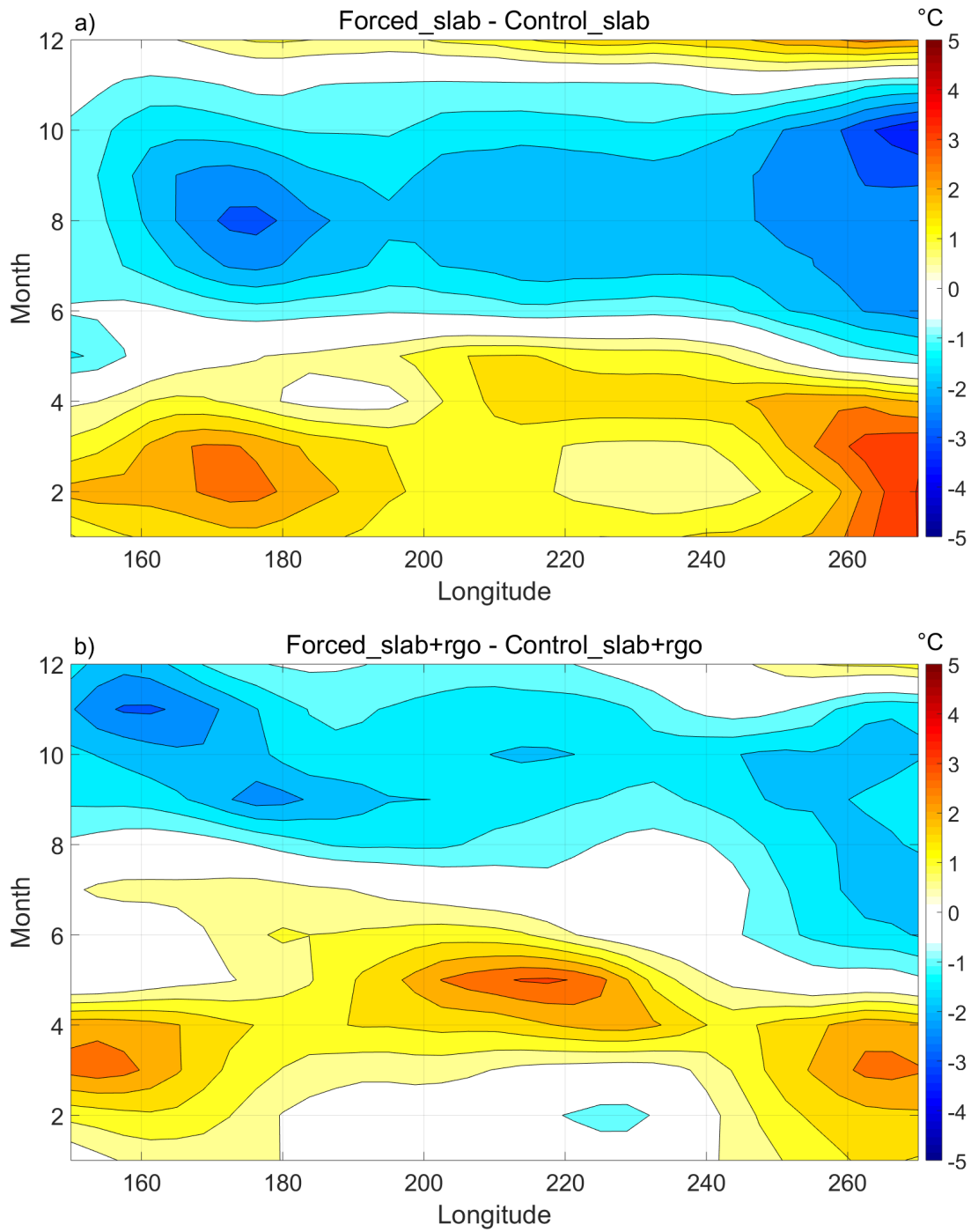
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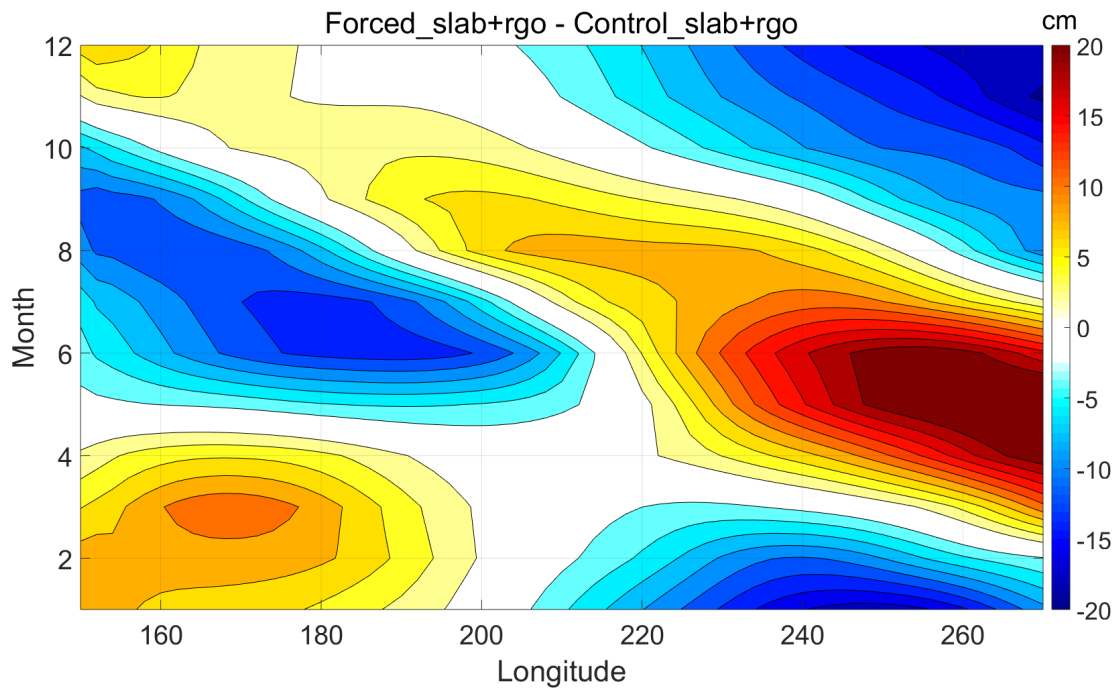
870 **Figure 8: Seasonal SST and near-surface wind anomalies with respect to the control for Forced_slab (left) and Forced_slab+rgo (right). a. and b.: December-February; c. and d. March-May; e. and f.: June-August; g. and h.: September-November. Contour interval 0.5°C.**



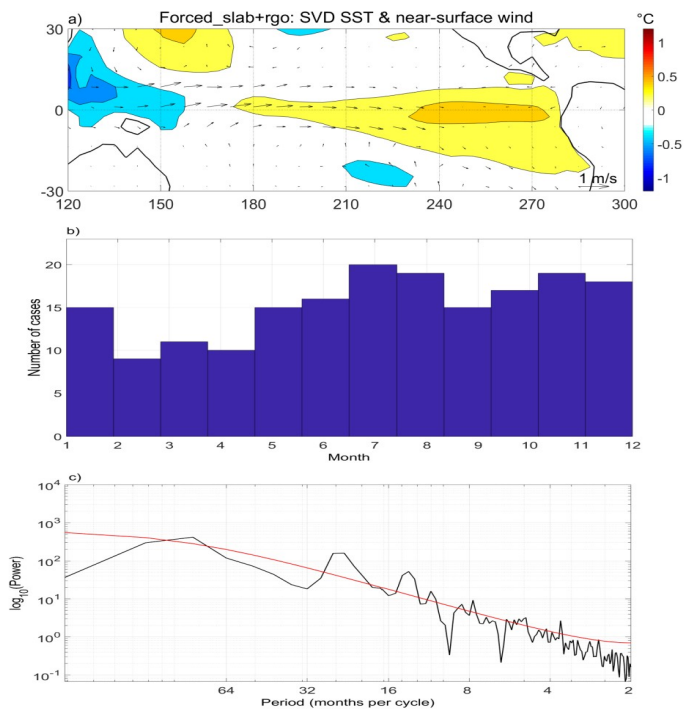
875 **Figure 9: Equatorial Pacific Ocean (2°S-2°N, 150°E-270°E) de-meaned near-surface (950 hPa) zonal wind anomalies seasonal cycle for: a. *Forced_slab* and b. *Forced_slab+rgo* experiments, respectively. Contour interval: 0.5 m/s.**



880 **Figure 10: Equatorial Pacific Ocean (2°S-2°N, 150°E-270°E) de-meaned SST anomalies seasonal cycle for: a. *Forced_slab* and b. *Forced_slab+rgo* experiments, respectively. Contour interval: 0.2°C.**



885 | **Figure 11: Equatorial Pacific Ocean (2°S-2°N, 150°E-270°E) de-meaned thermocline depth anomalies seasonal cycle for the : a. Forced_slab and b. Forced_slab+rgo experiments, respectively. Contour interval: 2 cm**



890 **Figure 12: First SVD pattern of SST and near-surface winds in the tropical Pacific Ocean (30°S-30°N, 120°E-300°E) for the *Forced_slab+rgo* experiments. a.: Spatial pattern; contour interval 0.2°C. b.: Histogram showing phase-locking to the seasonal cycle. c.: Spectral analysis; the red line indicates the red noise spectrum.**