EUCLIPSE

EU Cloud Intercomparison, Process Study & Evaluation Project

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Deliverable D2.6 Diagnostic of the climate feedbacks, including global and regional spreads, produced ESMs and of cloud and precipitation responses to climate change for CMIP5 runs; comparisons with estimates from the CMIP3 models.

Delivery date: 24 months

SEVENTH FRAMEWORK PROGRAMME

EUCLIPSE WP2 Deliverable D2.6:

Diagnostic of the climate feedbacks produced by the different models in some CMIP5 simulations; Report on the spreads of feedbacks and of cloud and precipitation responses to climate change and their comparison with estimates from the CMIP3 models

Main contributors to this report:
Sandrine Bony, Florent Brient, Jean-Louis Dufresne, Jessica Vial, LMD/IPSL, France
Mark Webb, MetOffice/Hadley-Centre, United Kingdom

WP2 coordinator:
Sandrine Bony (CNRS/LMD/IPSL)

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WP2 is focused on the analysis and the evaluation of climate simulations from CMIP5 (the 5th Phase of the Coupled Models Intercomparison Project). An important component of WP2 is the analysis of the climate response to anthropogenic perturbations, especially the changes in temperature, clouds and precipitation induced by the increase of greenhouse gases in the atmosphere. This deliverable reports on the spread of climate sensitivity produced by CMIP5 models, and interprets it in terms of global climate forcings and feedbacks. It also reports on the spread of cloud-radiatives responses and regional precipitation projections in the Tropics. Whenever possible, a comparison with CMIP3 results is discussed.

EUCLIPSE research currently aims at interpreting further the physical reasons for the spread of temperature, clouds and precipitation responses in climate change projections. This is done in close collaboration among three EUCLIPSE workpackages (WP2, WP3 and WP4).

1 Analysis of climate sensitivity estimates from CMIP5 models

We quantify forcing and feedbacks across available CMIP5 coupled atmosphere-ocean general circulation models (AOGCMs) using several methodologies. First, we analyze simulations forced by an abrupt quadrupling of atmospheric carbon dioxide concentration and apply the linear forcing-feedback regression analysis of Gregory et al. (2004) to the ensemble of AOGCMs. We show that the range of equilibrium climate sensitivity is 2.1-4.7 K, i.e. close to that derived from CMIP3 models, and that differences in cloud feedbacks continue to be important contributors to this range. Then, using the so-called kernel approach proposed by Soden and Held (2006) we assess the role of inter-model differences in climate feedbdacks associated with water vapor, temperature lapse rate, clouds and surface albedo in the spread of climate sensiitivty. This analysis confirms the role of cloud feedbacks in the climate sensitivity uncertainty. It also shows that fast tropospheric adjustments to CO_2 contribute to the spread, but to a much lesser extent than climate feedbacks.

1.1 Climate sensitivity estimates

Equilibrium climate sensitivity (ECS) is defined as the global equilibrium surface-air-temperature change in response to instantaneous doubling of atmospheric CO_2 concentration. Although this is clearly not a realistic scenario,

AOGCM	Radiative Forcing (Wm^{-2})		Climate Feedback Parameter $-\alpha$ ($Wm^{-2}K^{-1}$)				$2xCO_2$ Eqm Climate Sensitivity (K)
	Fixed-SST	Regression	Net	LW Clear-Sky	SW Clear-Sky	Net CRE	
CanESM2	7.35	7.67	−1.04	−1.88	0.71	0.13	3.69
CNRM-CM5	n.a.	7.43	−1.14	−1.73	0.78	−0.20	3.25
CSIRO-Mk3-6-0	6.20	5.17	−0.63	−1.70	0.84	0.23	4.08
GFDL-CM3	n.a.	5.98	−0.75	−1.94	0.70	0.48	3.97
GFDL-ESM2G	n.a.	6.18	−1.29	−1.65	0.61	−0.26	2.39
GFDL-ESM2M	n.a.	6.72	−1.38	−1.63	0.58	−0.33	2.44
HadGEM2-ES	6.99	5.85	−0.64	−1.66	0.65	0.37	4.59
INM-CM4	6.24	5.95	−1.43	−1.98	0.67	−0.12	2.08
IPSL-CM5A-LR	6.49	6.20	−0.75	−1.99	0.53	0.70	4.13
MIROC-ESM	n.a.	8.51	−0.91	−1.93	0.83	0.19	4.67
MIROC5	n.a.	8.25	1.52	1.85	0.84	0.51	2.72
MPI-ESM-LR	8.63	8.18	−1.13	−1.79	0.71	−0.04	3.63
MPI-ESM-P	n.a.	8.62	−1.25	−1.80	0.65	−0.10	3.45
MRI-CGCM3	7.19	6.49	−1.25	−1.99	0.83	−0.09	2.60
NorESM1-M	n.a.	6.21	−1.11	−1.86	0.86	−0.11	2.80
Model mean	7.01	6.89	−1.08	−1.83	0.72	0.02	3.37
Standard Dev.	0.85	1.12	0.29	0.13	0.11	0.32	0.83

Table 1: Forcing, feedback and equilibrium climate sensitivity values from CMIP5 models. The 4xCO2 adjusted radiative forcing has been diagnosed via two independent methods: regression and fixed-SST. The $-\alpha$ and equilibrium climate sensitivity values are derived from ordinary least-squares regression. From Andrews et al. (2012).

ECS is a convenient way of quantifying the joint effect of forcing and feedback, which are separately quantities of practical interest for understanding and predicting transient climate change. Recently, a new generation of climate models, participating in CMIP5, has been developed. Diagnosing the forcings, feedbacks and ECS in each of these models is a first step to identifying and understanding sources of uncertainty in their climate projections. For this purpose, we apply the regression method of Gregory et al. (2004) to an ensemble of AOGCMs using the CMIP5 so-called "abrupt4xCO2" experiment. Another estimate of the forcing is derived from CMIP5 4xCO2 equilibrium experiments.

The ECS of each model is given in Table 1 and shown in Figure 1, increasing from left to right. Based on the available CMIP5 model simulations, the ECS spans the range from 2.1 K to 4.7 K, which is similar to the 2.1-4.4 K range diagnosed from equilibrium 2xCO2 slab-ocean experiments performed with the earlier CMIP3 generation of models (Randall et al. 2007).

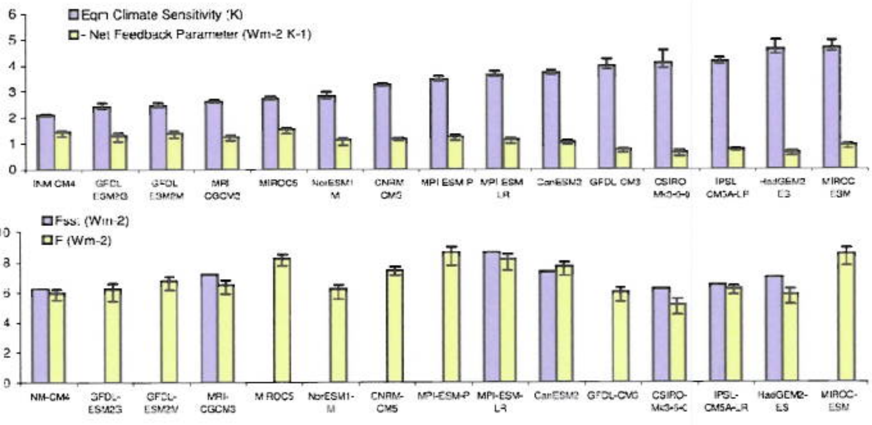

Figure 1: Comparison of the 2xCO2 equilibrium climate sensitivity, 4xCO2 adjusted radiative forcing (from fixed-SST, Fsst, and regression, F) and various climate feedback terms. The models are ordered from left to right in order of their equilibrium climate sensitivity. Note that in the top panel, α is reported as the climate feedback parameter, rather than $-\alpha$, to maintain the same scale. Errors bars represent 95% (2.5-97.5%) confidence interval on the fit. From Andrews et al. (2012).

There are some differences in forcings across models, which might be expected from differences in their treatment of radiative transfer and differences across models in rapid tropospheric and land surface adjustment processes (e.g. Gregory and Webb, 2008). In the previous generation of models, differences in feedbacks contributed more to the uncertainty in ECS than forcing (Webb et al., 2006, 2012). This also appears to be the case in CMIP5.

Although the multi-model mean CRE (cloud-radiative effect) feedback is close to zero (Table 1), large differences between models are noticeable (Table 1). The models span a wide range (-0.5 to +0.7 W/m2/K), which explains most of the range in the net feedback parameter, as in CMIP3 (Ringer et al. 2006). Such values are consistent with near neutral or positive cloud feedbacks of CMIP5 models (like CMIP3 models) when defining cloud feedbacks relative to the Planck response and thus taking into account the cloud masking effects (Soden et al. 2008).

The spread of ECS can to a certain extent be explained by differences in CRE feedbacks, i.e., those models with a more positive CRE feedback tend to have a larger ECS. As with the older generation models (Webb et al. 2006), this spread mostly comes from inter-model differences in SW CRE feedback processes.

1.2 Interpretation of the spread of climate sensitivity estimates

The spread of CMIP5 climate sensitivity estimates is analyzed further by using another methodology consisting in decomposing the global-mean surface temperature change into climate feedbacks associated with radiative forcing, water vapor, temperature lapse-rate, surface albedo and cloud changes (Dufresne and Bony 2008). For this purpose, we use the radiative kernel approach (Soden and Held 2006) to diagnose climate feedbacks and tropospheric adjustments from CMIP5 models (Vial et al., submitted). Recognizing that the increase of CO_2 induces fast adjustments in the atmosphere and at the land surface (Gregory and Webb 2008), we define the radiative forcing of each model from atmosphere-only experiments in which the CO_2 concentration is increased but sea surface temperatures are kept unchanged.

For each model (11 models have been considered so far, including 3 EUCLIPSE models), we compute the contributions to climate sensitivity associated with each feedback parameter and with the fast response to CO_2 (Figure 2). From a methodological point of view, we find that considering the tropospheric adjustments to CO2 as part of forcings rather than feedbacks (like at the time of CMIP3) reduces the strength of cloud feedbacks by about 20%, but does not substantially affect their spread.

The contributions of the Planck response, tropospheric adjustments, and feedbacks to the multi-model mean estimate of climate sensitivity show than on multi-model average, the Planck response and the combined water vapor plus lapse rate feedback provide the largest contributions to the climate sensitivity (their sum contributes for two third of the multi-model mean climate sensitivity), and that the sum of the cloud feedback, surface-albedo feedback and CO2 adjustments contributes for about one third.

In terms of inter-model differences, on the other hand, the relative contributions of the different components is very different. Cloud feedbacks are responsible for about 70% of the spread of climate sensitivity estimates amongst models, with a large contribution from the tropics. The combined water vapor + lapse rate feedback is found to also provide a non negligeable contribution to the spread of climate sensitivity.

This work will be updated in the next few months by adding models to the analysis, as soon as they become available on the CMIP5 multi-model archive.

2 Analysis of tropical cloud feedbacks

In CMIP3, tropical cloud feedbacks exhibited a large spread amongst models, which primarily resulted from

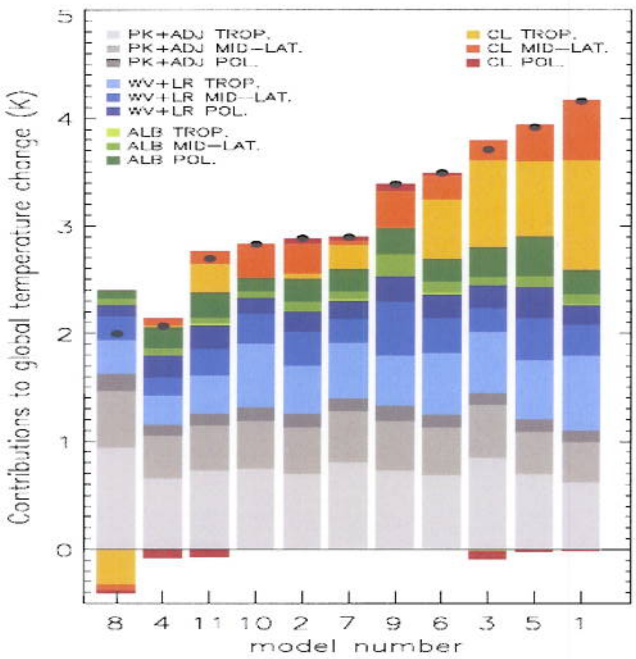

Figure 2: Decomposition of the climate sensitivity estimate (indicated by black dots) of each CMIP5 model into different contributions (the sum of all contributions equals the climate sensitivity): the Planck response to the non-adjusted forcing and the adjustments (PK+ADJ, in grey), the combined water vapour + lapse rate feedback (WV+LR, in blue), the albedo feedback (ALB, in green) and the net could feedback (CL, in red). Each contribution is also decomposed into the three different regions: the tropics (light shading), the mid-latitudes (medium shading) and the poles (dark shading). From Vial et al. (submitted).

inter-model differences in the response of low-level clouds to global warming (Bony and Dufresne 2005). We show that the spread of tropical cloud feedbacks has not narrowed among CMIP5 models (Vial et al, submitted), and that it is still dominated by inter-model differences in the (low) cloud response predicted by the models in regimes of weak subsidence and shallow convection. By analyzing the cloud response to global warming in a range of model configurations (coupled ocean-atmosphere, atmosphere-only, aqua-planet, single-column), we are able to interpret the physical mechanisms underlying the strongest positive cloud feedback estimate from CMIP5 models (predicted by the IPSL-CM5A-LR model).

2.1 Spread of tropical cloud radiative responses

Figure 3 shows that the spread of tropical cloud-radiative responses amongst CMIP5 models has not reduced compared to CMIP3 (Bony and Dufresne 2005, Vial et al. submitted). CMIP5 experiments now allow us to assess the relative contributions of temperature-mediated responses (feedbacks) and tropospheric adjustments to the spread of cloud-radiative responses under climate change. We find that both feedbacks and adjustments contribute to the spread, with however a much larger role of feedbacks.

We find that the spread of tropical cloud-radiative responses and cloud feedbacks arises from a larger range of dynamical regimes in CMIP5 than in CMIP3, but that it remains dominated by inter-model differences in the SW component of cloud feedbacks and by the cloud response in regimes of weak subsidence and shallow convection (Vial et al submitted). Current analyses now focus on determining the role of different cloud types and physical processes in the inter-model spread of cloud radiative reponses under climate change.

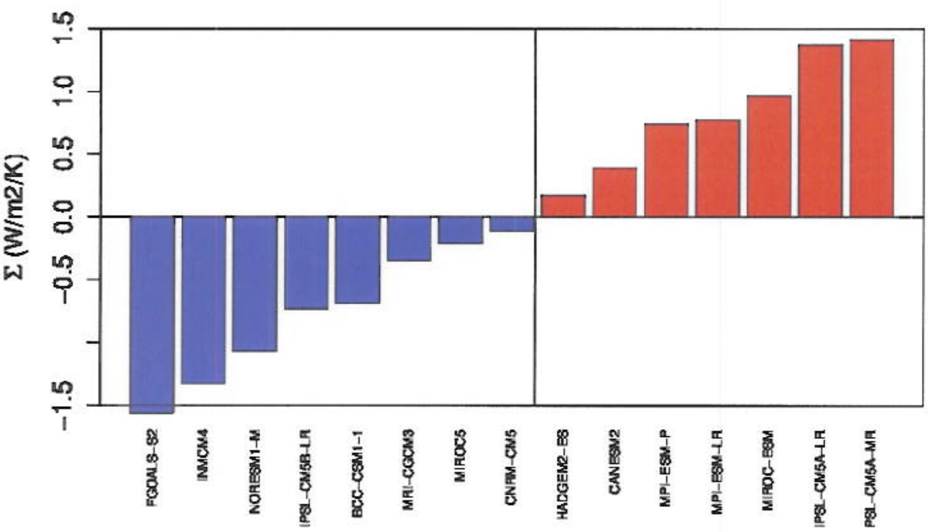

Figure 3: Sensitivity (in W/m2/K) of the Net Cloud Radiative Forcing to Sea Surface Temperature changes predicted by 15 CMIP5 coupled ocean-atmosphere climate models over tropical ocean. Low-sensitivity models are shown in blue, and high-sensitivity models in red. This figure is an update of Bony and Dufresne (2005).

2.2 Interpretation of the positive cloud feedback predicted by the IPSL-CM5A-LR model

The response of low-level clouds to climate change has been identified as a major contributor to the uncertainty in climate sensitivity estimates among climate models. Figure 3 shows that the IPSL-CM5A-LR coupled ocean-atmosphere model is the model that predicts the strongest positive cloud feedback in the tropics.

By analyzing the behaviour of low-level clouds in a hierarchy of models (coupled ocean-atmosphere model, atmospheric general circulation model, aqua-planet model, single-column model) using the same physical parameterizations, we propose an interpretation of the strong positive low-cloud feedback predicted by this model under global warming (Brient and Bony 2012).

In a warmer climate, the model predicts an enhanced clear-sky radiative cooling, stronger surface turbulent fluxes, a deepening and a drying of the planetary boundary layer, and a decrease of tropical low-clouds in regimes of weak subsidence. We show that the decrease of low-level clouds critically depends on the change in the vertical advection of moist static energy from the free troposphere to the boundary-layer. This change is dominated by variations in the vertical gradient of moist static energy between the surface and the free troposphere just above the boundary-layer. In a warmer climate, the thermodynamical relationship of Clausius-Clapeyron increases this vertical gradient, and then the import by large-scale subsidence of low moist static energy and dry air into the boundary layer. This results in a decrease of the low-level cloudiness and in a weakening of the radiative cooling of the boundary layer by low-level clouds.

We are currently investigating the extent to which the energetic framework proposed in this study helps to interpret the spread of tropical cloud feedbacks exhibited by CMIP5 models (Figure 3) under climate change.

We also studied the influence of uncertain model parameters on the low-cloud feedback predicted by this model (Brient and Bony, submitted). For this purpose, sensitivity tests were carried out in a range of model configurations (atmospheric GCM, aqua-planet GCM, single-column model). We show that the physical mechanism and the sign of the IPSL-CM5A-LR feedback is robust, but that the strength of the feedback can vary considerably depending on the model tuning parameters. Moreover, the strength of the low-cloud response to climate change exhibits a strong correlation with the strength of the low-cloud radiative effects predicted in the current climate. We show that this

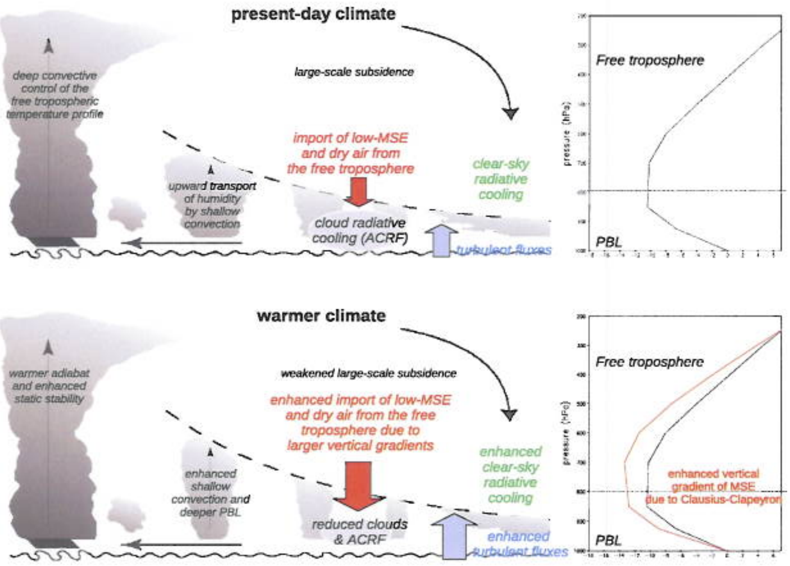

Figure 4: Schematic of the physical mechanisms controlling the positive low-cloud feedback of the IPSL-CM5A-LR OAGCM in climate change. In the present-day climate, tropical marine lowclouds primarily occur in regimes of large-scale subsidence. In these regimes, the moist static energy (MSE) of the PBL is increased by surface turbulent fluxes, and decreased by clear-sky radiative cooling, cloud-radiative cooling, and by the downward advection of low MSE from the free troposphere (the typical profile of MSE deficit on the right -defined as the difference between the MSE profile and the 1,000 hPa MSE- shows that the MSE minimum occurs around 700850 hPa in weak subsidence regimes). Shallow cumulus clouds contribute to the vertical transport of humidity from the PBL to the lower free troposphere, and deep convection controls the free tropospheric temperature profile of the tropical belt. In a warmer climate, the change in the moist-adiabatic stratification of the tropical atmosphere, the enhanced vertical transport of humidity by shallow convection and the deeper PBL due to enhanced surface fluxes all tend lead to a decrease of the vertical gradient of MSE. However, the non-linearity of the Clausius-Clapeyron relationship leads to a larger increase in specific humidity at high temperatures and low altitudes than at lower temperatures and higher altitudes. This leads to an enhanced vertical gradient of specific humidity and MSE between the PBL and the lower free troposphere, and thus an enhanced import of low-MSE and dry air from the free troposphere down to the PBL. This decreases the low-level cloud fraction and weakens the cloud radiative cooling within the PBL. From Brient and Bony (2012).

correlation primarily results from a local positive feedback (referred to as the beta feedback) between boundary-layer cloud radiative cooling, relative humidity and low-cloud cover. Based on this correlation and observational constraints, it is suggested that the strength of the tropical low-cloud feedback predicted by the IPSL-CM5A model in climate projections might be overestimated by about fifty percent.

We showed that CMIP5 models still exhibit a "too few, too bright" low-cloud problem in the tropics and that the models systematically over-estimate the optical thickness of low-level clouds (Nam et al. submitted). This bias potentially over-estimates the strength of the "beta feedback". In the future, in collaboration between WP2 and WP4, we will investigate further the role that the beta feedback may play in the simulation of the current climate and in climate change cloud feedbacks, based on coordinated model experiments.

3 Analysis of tropical precipitation projections

Large uncertainties remain about the future evolution of rainfall, particularly in the tropics and at the regional *scale. Understanding the factors that control the regional distribution of tropical precipitation and its response to anthropogenic activities would help to assess model projections and to inform policy decisions about adaptation and mitigation. In the original EUCLIPSE proposal, we had planned to analyze the spread of regional precipitation responses to climate change. However, when analyzing CMIP5 precipitation projections, we were struck by the resemblance of the regional pattern of tropical precipitation change predicted by CMIP5 models with that predicted by CMIP3 models under different scenarios. For this reason, we decided to understand first the reasons for this robustness before investigating the reasons for inter-model differences. In this report, we thus focus on the understanding of the CMIP5 multi-model mean pattern of tropical precipitation changes at the regional scale.*

The increase of carbon dioxide concentration in the atmosphere is expected to affect the hydrological cycle through surface warming (e.g. Held and Soden 2006). However, recent studies have shown that carbon dioxide could also impact the atmosphere through fast adjustments independent of surface temperature changes (e.g. Gregory and Webb 2008). To assess the actual dependence of tropical precipitation projections on surface warming, we analyze a large suite of CMIP5 model outputs from a range of experiments (realistic, idealized, RCP scenarios) and configurations (coupled ocean-atmosphere model, atmosphere-only, aqua-planet, single-column), and we decompose the regional precipitation changes into thermodynamical and dynamical components (Figure 5).

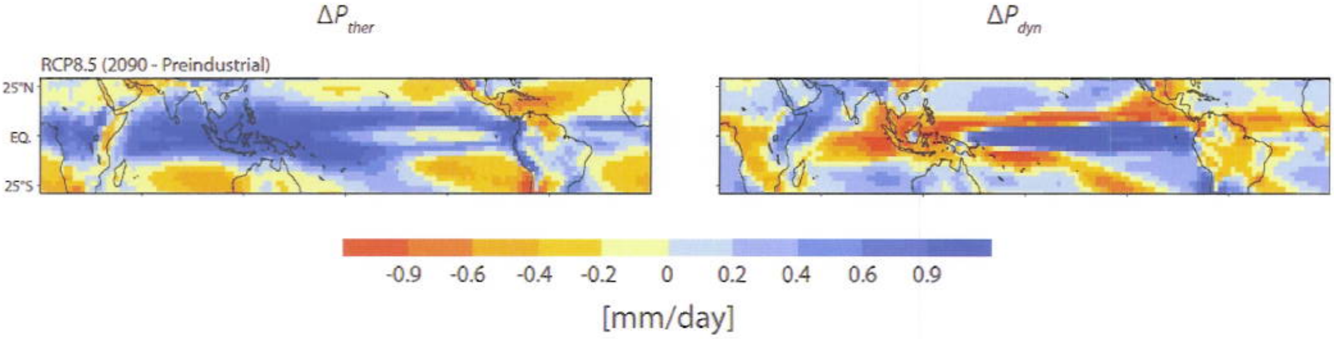

Figure 5: Interpretation of the multi-model mean regional pattern of tropical precipitation projections. The annual-mean precipitation change predicted by CMIP5 coupled ocean-atmosphere models in a non-mitigated climate change scenario (RCP8.5) at the end of the century (around 2090) is decomposed into thermodynamical (ΔP_{ther}) and dynamical (ΔP_{dyn}) components ($\Delta P = \Delta P_{ther} + \Delta P_{dyn}$). The thermodynamical component is dominated by the Clausius-Clapeyron relationship and thus exhibits a "wet get wetter, dry get drier" regional pattern, while the dynamical component is related to the change in large-scale atmospheric vertical motions. From Bony et al. (submitted).

We show that in the tropics, a substantial fraction of the long-term precipitation changes projected by climate models by the end of the century, and particularly the dynamical component, does not depend on surface warming but results from the fast and direct impact of increased carbon dioxide concentrations on the large-scale atmospheric circulation. This effect is explained by the radiative impact of greenhouse gases on the internal cooling of the atmosphere, which affects tropical convection and the strength of atmospheric vertical motions. It is predicted by multiple state-of-the-art climate models in a large spectrum of configurations, and by an operational Numerical Weather Prediction model (we performed weather forecasts in $4xCO_2$ conditions with the ECMWF-IFS model). These findings suggest promising strategies for improving the assessment of regional rainfall projections, and highlight the limitations of geo-engineering strategies that would aim at weakening global warming and regional precipitation changes without removing carbon dioxide from the atmosphere.

Over the next years, we plan to exploit these findings and this methodology to better understand inter-model differences in regional precipitation projections in the tropics.

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