Horizon 2020 Societal Challenge 5:
Climate action, environment,
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CONSTRAIN

CONSTRAIN: 'Constraining uncertainty of multi-decadal climate projections'

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Work Package: WP2
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Deliverable title: End-of-project KGSIR on robust circulation responses to climate change in the tropical Atlantic sector and in the mid-latitude European sector

Key messages:

- Models used to project climate change show recalcitrant biases in their representation of tropical precipitation. A new generation of models, which explicitly represent convective processes at km-scales, couple convection to circulation (rather than surface fluxes) and re-duce many of these biases. Their fundamentally different behavior calls into question our understanding and expectation for the response of tropical precipitation to perturbations, in-cluding warming.
- Observations show strong coupling between clouds and mesoscale circulations absent in models used to project climate changes. Models that explicitly represent cloud scale process-es can capture many of these couplings and hence the imprint of circulation on cloudiness.
- Convective (self-)aggregation has a strong influence on the mean humidity. New studies show how the climate sensitivity depends on the mean humidity, a form of state dependence. Hence convective aggregation can modify the climate sensitivity irrespective of whether it increases or decreases with warming.
- Anvil cloud amount reduces substantially with upper tropospheric stability, which increases with warming. This identifies a mechanism for inducing circulations that increase convective self-aggregation, a hypothesis that can be tested observationally using synoptic variability, and with a new class of models capable of representing this large and small scale coupling globally.
- Storm strength has a strong influence on cloud amount, so that the southern hemispheric storm tracks, with its stronger storms are cloudier on average. This asymmetry counterbal-ances hemispheric asymmetries in the surface albedo.
- Both by increasing stability, in response to amplified upper tropospheric warming, and by reducing temperature gradients, by amplified polar warming, mid-latitude storms are ex-pected to weaken

with warming, leading also to reduced cloudiness. This would constitute a new, positive cloud feedback on warming.

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Knowledge Gains Summary and Implication Report: Robust (Atlantic/European sector) circulation responses to climate change

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- Storm strength has a strong influence on cloud amount, so that the southern hemispheric storm tracks, with its stronger storms are cloudier on average. This asymmetry counterbalances hemispheric asymmetries in the surface albedo.
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Context

As Earth warms, attention is turning toward how global warming translates into changes of weather on the regional scale. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), addressed the magnitude of the knowledge gaps in this area. Over the past seventy years of warming, it concluded (Figure SPM.3 panels b and c) that signals of regional changes in hydro-meteorology (droughts and heavy precipitation) are difficult to identify. Even where signals could be identified, almost nowhere could they be attributed to warming with a high degree of confidence. Knowledge gaps, as manifest in the poorly developed expectation of what regional changes to expect with warming, hinder efforts to attribute observed changes to warming, and make it difficult to know how to identify signals from sparse data.

Changes in regional hydro-meteorology that link to changes in major circulation features, such as the tropical rain belts or the extra-tropical storm tracks, should be the easiest to understand. But even this rather prescribed view of possible circulation changes encompasses a vast area of inquiry, that integrates our understanding of the climate system as a whole, and is something that CONSTRAIN could only begin to touch upon. Even so, given the societal importance of these topics, small advances in understanding confer tremendous benefit. CONSTRAIN, addressed this knowledge gap by exploring factors thought to influence the circulation response to warming across a hierarchy of models and observations, using a variety of novel analysis techniques. It also paired with other European projects, notably NextGEMS to begin developing and applying a new generation of tools to help explore these issues.

The present KGSIR builds on the Mid-term KGSIR on the link between tropical circulation changes (changing patterns of rain and storm potential) and convective aggregation processes and their implications for regional (Caribbean) climate change. It extends on those previously reported efforts, which focused on cloud-circulation coupling in the tropics, to study how large-scale circulation and cloudiness is coupled in the extra tropics, and how this influences global climate.

Summary of Knowledge Gains

Robust (Atlantic Sector) tropical circulation changes and their origin

CONSTRAIN investigators showed how model large biases over the tropical Atlantic sector, particularly over land, are structural features of the standard (CMIP) modelling paradigms used to project climate changes. They collected novel observations through large-scale field campaigns to identify the importance of mesoscale circulations for cloudiness — circulations that do not exist in the standard models, and they developed new classes of models, which allow a more physical coupling between clouds, convection and circulation, to test their ideas. These and related studies make a strong case that progress in understanding requires empiricism from the new, more physical models, which CONSTRAIN, together with a sister project, NextGEMS, has been helping to pioneer.

Comparing tropical precipitation biases, Fiedler et al (2020) identified a substantial southward bias (displacement) of the Atlantic ITCZ that remained mostly unchanged over three generations of CMIP models. Linked to this bias, the central Amazon was systematically too dry, while southeastern Brazil and the austral African monsoon were too moist across models and CMIP phases. The models did not capture the observed response to El Nino over the bulk of the South American continent, and the diminishment of precipitation in the northern tropical Atlantic during El Nino years was only weakly represented in the models. While simulated dry anomalies, as measured by the standardized precipitation index, progressively improved across CMIP phases, the models deteriorated in their representation of wet anomalies across progressive development cycles. Taken as a whole, the study demonstrates that the CMIP models are not fit to the purpose of projecting tropical precipitation changes.

CONSTRAIN contributed to the development of a new generation of more physical models. The first coupled storm resolving climate models (Hohenegger et al., 2023), were used by CONSTRAIN investigators to demonstrate an improved ability to represent many precipitation features in the tropics. Paccini and Stevens (2023) demonstrated a better representation of organized convection, consistent with past studies using regional models over smaller domains, and a much-improved representation of the diurnal cycle and its variation across the Amazon basin. Segura et al., (2023) showed that despite considerable variability in the spatial distribution of tropical precipitation over the ocean, and some remaining biases particularly over the equatorial warm pool region, the new generation of models shows a robust and accurate representation of precipitation over land, which they interpreted as indicative of a negative feedback between soil moisture and precipitation. Using a large, but still regional, scale storm resolving representation of the Atlantic sector under climate change, Heim et al, (2023) further demonstrates substantial improvements in the seasonal cycle of albedo and the structure of the Atlantic ITCZ. Studies of global warming using this regional storm resolving model coupled to the pseudo-global warming approach suggest a less pronounced contraction of the ITCZ, and less pronounced Caribbean drying. The results suggest that new and more physical modelling approaches may yield a picture of tropical hydro-meteorological changes to warming that differ fundamentally from past projections, and new insights.

Also on the mesoscale, CONSTRAIN contributed to new insights into cloud-circulation coupling in the tropical Atlantic sector. Through its support of EUREC^{4}A (Stevens, et al., 2020) it helped collect observations that were used by George et al., (2023) to document the ubiquity of shallow meso-β (200 km) scale circulations that Vogel et al., (2022) showed strongly co-varied with cloudiness. Standard (CMIP) climate modelling approaches are based on the assumption that circulations on these scales play no role in the climate system. Schulz et al., (2020) demonstrated how variations in shallow clouds could be explained by changes in large-scale circulations, i.e., the northward migration of the ITCZ, versus the tropical intrusion of mid-latitude fronts. Schulz and Stevens (2022) further demonstrated how the new modelling approaches could represent these signals, as well as major elements of the mesh-scale variations in cloudiness as identified in earlier studies.

Link between circulation changes and convective aggregation processes

CONSTRAIN investigators studied convective self-aggregation — a particular form of coupling between meso-β circulations and cloudiness — in some detail. These studies were facilitated by the Radiative Convective Equilibrium Model Intercomparison Project (RCEMIP, Wing et al, 2020), with support from CONSTRAIN.

showed that the stability effect, and therefore stability and vertical motions around anvil clouds, explains the observed behavior of anvil clouds with surface temperature variations at the interannual time scale, their response to volcanic eruptions — which Fiedler et al., (2020) showed was more muted in climate models as compared to observations — and their response to anthropogenic forcings (Saint-Lu et al. 2020, Saint-Lu et al. 2022). If the shrinking of anvil clouds with rising surface temperatures make the atmospheric cloud-radiative effects more concentrated, and helps strengthen shallow circulations, this could contribute to enhance aggregation in a warming climate (cf. Coppin and Roehrig, 2020).

Models, whether they are based on an explicit or statistical representation of convection, mostly agree that self-aggregated states correspond to warmer and drier atmospheres with reduced high cloudiness and increased cooling to space, compared to unaggregated counterparts. Bourdin et al (2020) and Kluft et al., (2021) identify and explain how climate sensitivity depends on base-state?

humidity and temperature. This implies that even if convective aggregation does not depend on warming, the degree of convective self-aggregation will affect the climate sensitivity, and the variability of self-aggregation across models will be a source of difference in model based estimates of climate sensitivity. The lack of a systematic response of self-aggregation to warming across, or even within classes of models, may be a result of the very large degree of symmetry in the RCEMIP set-up, which makes it susceptible to small differences among models. For this reason CONSTRAIN has contributed to new approaches, involving both more comprehensive modelling frameworks, and observations to help narrow this knowledge gap.

Observationally, the idea that “drivers” of natural variability involve some of the same processes that link clouds to warming and thus may make the question of the response of convective aggregation to warming amenable to constraints from observations, e.g., as introduced by Vial et al. (2023) and Vogel et al., (2022) to constrain cloud feedback processes using diurnal, respectively synoptic variability. In terms of modelling, CONSTRAIN investigators have partnered with NextGEMS to obtain an extremely large allocation of computing time through EuroHPC. This will allow us to investigate the coupling between circulations and cloudiness and its ability to influence convective self-aggregation, in more realistic global warming experiments and contribute to CONSTRAIN’s legacy.

Physical mechanisms associated with mid-latitude cloud feedbacks

CONSTRAIN investigators identified the mechanism by which clouds help symmetrize the planetary albedo, and linked this to mid-latitude circulation features. Other studies, analyzing the extended record of CERES measurements, showed that the southern hemisphere compensates for its reduced surface albedo relative to the Northern hemisphere through a greater prevalence of clouds in the storm-tracks over the ocean. CONSTRAIN investigators showed how this worked, identifying a potential dynamical mechanism that could communicate inter-hemispheric temperature differences.

In CONSTRAIN two different approaches were taken to understand why the storm tracks of the southern hemisphere are brighter than their counterparts in the northern hemisphere. Lagrangian tracking of storms identified a systematic increase of cloudiness with storm strength (Hadas et al., 2023). By virtue of having stronger storms, the southern hemisphere has cloudier storm tracks. Likewise Blanco et al (2023) showed the importance of surface winds as a cloud controlling factor, and how the stronger winds and colder SST (presumably in association with, respectively a driver of, stronger storms) explain the enhanced southern hemisphere storm track cloudiness. This cloud controlling factor analysis is used by Datseris et al., (2022) to demonstrate that global cloudiness can be captured by a very small number of cloud controlling factors, one of them related to storm strength. The hypothesis that land leads to stationary eddies, which studies by others have been shown to contribute to most? of the equator to pole heat transport, may also explain the reduced baroclinicity of the northern hemisphere. This suggests that the stronger storms of the Southern Hemisphere do not arise by chance, but are linked to the source of the surface albedo symmetry. Why, however, this should balance so well, remains a mystery.

Blanco et al., (2024, in press) explores whether CMIP models identify similar drivers and responses. They find that yes, the models on average show greater cloud albedo in the SH than in the NH, but are not quantitatively skillful, as the absolute albedo values in each hemisphere suffer from large biases. Nonetheless, in the models these differences also correlate with SST and surface winds, suggesting that observations of synoptic variability could, as was done by Vogel et al., (2022), be used to constrain the cloud representations in the models.

Yuval and Kaspi (2020) explore the drivers of baroclinicity, and hence storm strength, under global warming to better anticipate how storms will respond to warming. The question is not trivial, because the sign of the meridional temperature gradient differs at the surface, where it is expected to weaken storms, as compared to in the upper troposphere, where it is the sense of driving stronger storms. Overall an increase in the dry static stability with warming, (following the moist adiabat) dampens eddy kinetic energy, and weaker surface temperature gradients damp eddy heat fluxes, leading to the expectation of weaker storms and reduced cloudiness with warming, thereby identifying a new positive cloud feedback mechanism. Raiter et al. (2024) have begun to explore how these anticipated changes in the extra tropics influence the tropics, and tropical circulations.

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