Horizon 2020 Societal Challenge 5:
Climate action, environment,
resource efficiency and raw materials

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

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Work Package: WP2
Deliverable number: D2.4
Deliverable title: End-of-project KGSIR on the improved physical understanding and quantification of tropical low-cloud feedbacks

Key messages:

- New observations from the EUREC4A field campaign make it possible to assess for the first time the physical mechanisms through which the low-cloud amount varies with environmental conditions: we show that the specific mechanism that is responsible for high climate sensitivities in climate models is not supported by observations, which renders large positive tropical low-cloud feedbacks implausible and refutes an important line of evidence for a high climate sensitivity.
- Using observations and a hierarchy of numerical models, we have advanced our knowledge and understanding of the mesoscale organisation of shallow convection: mesoscale cloud patterns can now be characterized by a handful of interpretable metrics; their dependence on environmental conditions has been revealed by observations; mesoscale cloud patterns have been shown to be closely associated with the development of shallow mesoscale overturning circulations (SMOCs); and the ubiquity of SMOCs in the tropical atmosphere has been explained through a conceptual model and theory.
- The role of the mesoscale organisation of shallow convection in tropical low-cloud feedbacks remains a vivid subject of research: a modeling study suggests that this role is of secondary importance for the low-cloud feedback; to assess the robustness of this result, new modeling frameworks and model intercomparisons have been developed to further investigate this issue with a hierarchy of models.
- Theory, observations and simulations have helped to further understand and constrain cloud feedbacks and climate sensitivity: clear-sky radiative cooling and static stability in the upper troposphere explain the responses of the anvil cloud area to natural and anthropogenic perturbations; the present day climatology constrains a major part of the cloud feedback provided

that the feedback decomposition is performed in the right measurement space; by using such a framework together with observations, the clear-sky sensitivity is well constrained, and the anvil area feedback is shown to be many times weaker and more constrained than previous assessed. However the anvil cloudy albedo feedback remains much less constrained.

Cite as:

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Deliverable D2.4 (CNRS, MPG, TU Delft), October 2023
End-of-project KGSIR (*Knowledge Gains: Summary and Implication Report*) on the improved physical understanding and quantification of tropical low-cloud feedbacks and their implications for WP-4 by revisiting the plausible range of climate sensitivity estimates in the light of new observational constraints.

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- Theory, observations and simulations have helped to further understand and constrain cloud feedbacks and climate sensitivity: clear-sky radiative cooling and static stability in the upper troposphere explain the responses of the anvil cloud area to natural and anthropogenic perturbations; the present day climatology constrains a major part of the cloud feedback provided that the feedback decomposition is performed in the right measurement space; by using such a framework together with observations, the clear-sky sensitivity is well constrained, and the anvil area feedback is shown to be many times weaker and more constrained than previous assessed. However the anvil cloudy albedo feedback remains much less constrained.

Introduction

The overarching objective of WP-2 was to use new observations, models and experimental strategies to transform knowledge gaps in our understanding of clouds, circulation and climate sensitivity into knowledge gains.

One of the targeted knowledge gaps was our physical understanding and assessment of tropical low-cloud feedbacks, especially the feedback associated with shallow cumuli, which has been a leading source of uncertainty in climate sensitivity for more than 15 years. This uncertainty was decomposed into two components: one related to key known uncertainties, including the role of the mixing-dessication mechanism in the feedback (cf deliverable D2.1), and one related to the unknown role of the mesoscale organisation of convection in the feedbacks (cf deliverable D2.3). We summarize below how CONSTRAIN has successfully addressed these two issues (sections 1 and 2, respectively).

During the course of this project, another key source of uncertainty for climate sensitivity was pointed out as part of an highly influential community assessment on climate sensitivity in which CONSTRAIN scientists played a primary role (cf deliverable D2.15): the tropical anvil cloud feedbacks. In addition, recent advances in our understanding of radiative transfer suggested new physically-based frameworks to decompose climate feedbacks and constrain climate sensitivity. Although it was not planned in the original CONSTRAIN proposal, these findings motivated additional research on the anvil cloud feedback and on the clear-sky climate sensitivity that further contributed to the overarching objective of WP-2 (section 3).

These advances have important implications, including the ability of CONSTRAIN to revisit the plausible range of climate sensitivity estimates in the light of new physical understanding and observational constraints, to highlight the power of using a hierarchy of models and observations to address challenging science questions, to highlight new directions of research and to provide guidance for the future of climate modelling (sections 4 and 5).

Summary of knowledge gains:

1. Reduction of the known uncertainty in tropical low-cloud feedbacks (see also D2.1)

CONSTRAIN publications: Radtke et al. (ACP, 2021), Stevens et al. (ESSD, 2021), Vogel et al. (Nature, 2022), Vial et al (PNAS, 2023)

For more than 15 years, the response of tropical low clouds, and more specifically of shallow cumuli, has been a leading source of uncertainty in model estimates of climate sensitivity. In climate models, the trade cumulus cloud feedback is primarily governed by changes in cloud fraction near cloud base, and high climate sensitivity models suggest a strong decrease in the cloud-base cloud fraction due to the desiccation of the cloud layer by enhanced lower-tropospheric mixing. The EUREC^{4}A (Elucidating the role of cloud-circulation coupling in climate) field campaign led by two CONSTRAIN scientists (Bony, Stevens) was specifically designed to test the plausibility of this feedback mechanism. It took place over the tropical Atlantic near Barbados in Jan-Feb 2020 (Stevens et al. 2021).

The analysis of EUREC^{4}A observations showed that entrainment at the top of the subcloud-layer and mesoscale motions contribute equally to the variability in lower-tropospheric mixing, but have opposing effects on humidity around cloud-base. As a result, mixing does not desiccate clouds, which refutes the mixing-desiccation hypothesis (Vogel et al. 2022). Observations show that clouds are more dynamically controled by convective and meso-scale vertical motions than thermodynamically controled by humidity variations, but the climate models that predict a large positive trade-cumulus feedback under climate change predict the opposite, which makes their cloud radiative feedback implausible. We further show that the daily cycle of trade cumuli constitutes an excellent benchmark to assess the cloud-circulation coupling in the trades, and that the models that predict a strong low-cloud feedback are those that use a cloud parameterization uncoupled to the convective mass flux (Vial et al. 2023). Our project thus provides the first observational test of the trade-cumulus feedback at the process level, supports a weak shallow-cumulus feedback, and refutes an important line of evidence for a high climate sensitivity.

In addition to the physical evaluation of tropical low-cloud feedback processes, we investigated the dependence of the feedback on the horizontal resolution of the model (varying from 100 m to 5 km) in the absence of mesoscale organisation. The conclusion is that the magnitude of the decrease in low-cloud fraction correlates with the present-day cloud fraction, while the change in cloud optical thickness is resolution independent. This result suggests that refining the resolution leads to convergence to a near-zero shallow cumulus feedback, and that storm-resolving models may exaggerate the strength of this feedback (Radtke et al. 2021).

In conclusion, CONSTRAIN observational, modeling and analysis studies have i) improved our physical understanding of the tropical low-cloud feedback at the process level, ii) reduced the long-standing uncertainty in the shallow cumulus cloud feedback and refuted an important line of evidence for a high climate sensitivity, and iii) clarified how the cloud parameterization and horizontal resolution of the models influenced the strength of the feedback, thus providing guidance for future model development.

2. Improved understanding and assessment of the unknown impact of the mesoscale organisation of convection on tropical low-cloud feedbacks (see also D2.3)

CONSTRAIN publications: *Bony et al. (GRL, 2020), Janssens et al. (GRL, 2021), Schulz et al (JGR, 2021), Beucher et al. (QJRMS, 2022), Dauhut et al. (QJRMS, 2022), George et al. (Nature Geosci., 2023), Janssens et al. (GRL, 2021), Janssens et al. (J. Atmos. Sci., 2023a), Janssens et al. (JAMES, 2023b), Brogli et al. (GMD, 2023), Jansson et al (JAMES, 2023), Bony et al. (in prep), Janssens et al. (in prep), Maury et al. (in prep).*

One of the lessons of the EUREC^{4}A field campaign was that the clouds associated with shallow convection tend to organize at the mesoscale, that this organisation is more the norm than the exception, and that it leads to a wide diversity of cloud patterns. CONSTRAIN studies have shown that trade-wind clouds exhibit four prominent patterns of mesoscale organisation (named Sugar, Gravel, Fish and Flowers, Stevens et al. 2020, Bony et al. 2020) that correspond to the tails of a 4-dimensional distribution of 4 objective and interpretable metrics (Janssens et al. 2021). Further observational analyses revealed the vertical structure of the cloud patterns, how the patterns depend on environmental conditions and how they affect the Earth radiation budget (Bony et al. 2020, Schulz et al. 2021). Finally, EUREC^{4}A observations revealed the ubiquity of shallow mesoscale overturning circulations (SMOCs) in the trade-wind atmosphere, and the role of these circulations in controlling the mesoscale moisture variability (George et al. 2023).

The ubiquity of cloud mesoscale patterns and SMOCs in the trades deserved a physical explanation. It was provided by a conceptual model and theory developed as part of CONSTRAIN: non-precipitating cumulus convection is intrinsically unstable to length-scale growth owing to the ability of spatial heating fluctuations related to condensation in cumulus clouds to generate SMOCs and spontaneously grow into mesoscale clusters (Janssens et al. 2023a). The link between SMOCs and cloud clustering was further investigated at the process level: the analysis of EUREC^{4}A observations and large-eddy simulations suggests that shallow mesoscale circulations influence cloud clustering by modulating the density of subcloud-layer thermals and then the size distribution of cloud-base widths (Bony et al., in prep; Maury et al., in prep).

The ubiquity of shallow cloud organisations in the trade-wind atmosphere raised two major questions: (1) How well do models represent the mesoscale cloud organisation? and (2) To what extent does the mesoscale organisation influence the low-cloud feedback and climate sensitivity?

To answer the first question, CONSTRAIN has assessed the capability of a hierarchy of models (four Large-Eddy Simulation models with a resolution ranging from 100 m to 600 m and five Storm Resolving Models with a resolution ranging from 1.25 km to 2.5 km) to simulate the observed mesoscale cloud organization observed over the Northern subtropical Atlantic Ocean during the EUREC^{4}A field campaign (Beucher et al. 2022, Dauhut et al. 2023, Janssens et al. 2023b, Schulz and Stevens 2022). CONSTRAIN also initiated the EUREC^{4}A-MIP model intercomparison (https://eurec4a.eu/motivation) to consider an even larger range of models worldwide. In addition, a parametric ensemble of LES simulations was created for a range of environmental conditions (Jansson et al. 2023). Early results show that the different mesoscale patterns are unequally reproduced by LES and SRM models, and suggest that a km-scale resolution is needed to simulate the four main mesoscale patterns observed in the trades.

Several modeling studies were developed to address the second question. One such study suggested that in the presence of mesoscale organisation, global warming was leading to a redistribution of cloudiness from many small clouds to fewer, larger and deeper mesoscale cloud structures, but that this had a negligeable impact on cloud-radiative effect because of a compensation between changes in cloud fraction and cloud optical thickness (Janssens et al., in prep). This result is in line with observational evidence for a small shallow cloud feedback (e.g. Vogel et al. 2022). Nevertheless, to assess the robustness of this result and explore its dependence on model specificities, a model intercomparison (named EUREC^{4}A-MIP) has been initiated as part of CONSTRAIN, that will use the Pseudo-Global Warming framework (Brogli et al. 2023) to investigate the impact of global warming on the mesoscale organisation of shallow clouds and cloud feedback in a hierarchy of models ranging from Large-Eddy Simulation models to Storm Resolving Models.

In conclusion, CONSTRAIN has advanced our ability to characterize the diversity of cloud mesoscale organisations in models or simulations, to interpret the ubiquity of shallow mesoscale circulations and cloud organisations in the trade-wind atmosphere, to understand the physical processes leading to mesoscale cloud clusters, and to assess the response of the cloud organisation to global warming and its implications for cloud feedback and climate sensitivity.

3. Further understanding and assessment of climate feedbacks and climate sensitivity.

<u>CONSTRAIN publications:</u> Sherwood et al. (Rev. Geophys., 2020), Saint-Lu et al. (GRL, 2020), Saint-Lu et al. (Nature Clim. Atmos. Sci, 2022), McKim et al. (Nature Geosci., in revision), Stevens and Kluft (ACP, in press).

CONSTRAIN scientists have been involved in a very influential community assessment on Climate Sensitivity (Sherwood et al. 2020, deliverable D2.15). As part of this assessment, the tropical anvil cloud feedback was pointed out as one of the leading sources of climate sensitivity uncertainty in the latest generation of climate models. In addition, recent advances in our understanding of radiative transfer suggested new approaches for assessing and constraining cloud feedbacks and climate sensitivity. Although it was not planned in the original proposal, these findings encouraged CONSTRAIN scientists to use a combination of theory, observations and simulations to advance our understanding and evaluation of the anvil cloud feedback and climate sensitivity.

Based on limited observational evidence, Sherwood et al. (2020) suggested a strongly negative anvil cloud feedback associated with a large uncertainty (-0.2 +/- 0.2 W/m^2/K). Among the possible mechanisms leading to a decrease of the anvil cloud area with warming was the stability iris effect, that was shown to be at work in a hierarchy of numerical models. CONSTRAIN showed that the basic physical mechanism underlying the stability iris effect was supported by satellite observations, meteorological reanalyses and climate models, and that it explained the response of anvil clouds to a wide range of natural and anthropogenic perturbations, including explosive volcanic eruptions, interannual surface temperature variability, and the direct and surface-mediated effects of increased CO_2 in the atmosphere (Saint-Lu et al. 2020, 2022).

Then, a novel feedback analysis combined with a conceptual model and a storyline approach allowed us to put physical and observational constraints on the anvil cloud area feedback. It led to a new estimate of the feedback of 0.02 +/- 0.07 W/m^2/K, which is many times weaker and more constrained than the overall anvil cloud feedback suggested so far (McKim et al., in revision). The feedback decomposition also allowed us to show that in comparison, the anvil cloudy albedo feedback is much less constrained, both theoretically and observationally, and thus poses an obstacle for further narrowing the uncertainty in climate sensitivity.

Finally, Stevens and Kluft (2023) built on new approaches using a line-by-line treatment of radiative transfer to develop new frameworks for assessing and constraining climate sensitivity. They show that a major contribution of clouds depends on their present day climatology, which can be constrained by measurements, and that assessments of cloud feedbacks is better preformed in the measurement space of cloud emission temperature and reflectivity.

In conclusion: CONSTRAIN has advanced our physical understanding of cloud feedbacks and climate sensitivity, and our ability to constrain them with physical and observational constraints.

Implications:

4. New constraints on the plausible range of climate sensitivity

The most recent assessments of climate sensitivity point out two main sources of uncertainty in tropical cloud feedbacks: the shallow cumulus feedback and the anvil cloud feedback. CONSTRAIN provided observational, modelling and physical support for a weak shallow cumulus feedback and a weak anvil cloud area feedback. These findings refute important lines of evidence for a high climate sensitivity. Moreover, new constraints were put on the assessment of clear-sky sensitivity. However, some uncertainty remains regarding the role of the mesoscale organisation of convection in the shallow cumulus feedback and the magnitude of the anvil cloud albedo feedback, although early studies suggest that the former feedback is also weak. These findings will be used in WP-4 to constrain the plausible range of climate sensitivity.

5. Demonstration of the value of using a hierarchy of models and observations to address challenging science questions, and guidance for the modelling

CONSTRAIN advances in our physical understanding and observational constraint of tropical cloud feedbacks have only been possible thanks to the combined use of a hierarchy of models (Large-Eddy Simulation Models, Storm-Resolving Models, General Circulation Models, conceptual models) and observations (EUREC^{4}A field campaign, Barbados Cloud Observatory, satellites, reanalyses). CONSTRAIN will certainly be remembered as being one of the best demonstration of the power of using a hierarchy of models (of differing complexity) to tackle challenging questions of climate science.

Regarding modelling, CONSTRAIN provided an experimental framework, and observations, to evaluate the ability of a range of atmospheric models to simulate the mesoscale organisation of shallow convection and SMOCs (Stevens et al. 2021, Beucher et al. 2022, Dauhut et al. 2022, Schulz and Stevens 2023, Jansson et al. 2023, Janssens et al. 2023b) and its response to climate change (Brogli et al. 2023, Janssens et al, submitted). CONSTRAIN then explored the implications of the mesoscale cloud organisation for parameterizations. It showed that the ‘superparameterization’ framework was not a useful benchmark for representing SMOCS (due to the lack of exchange of coherent structures between the model grid cells), and hence demonstrated how difficult, if not impossible, it was to design a SMOC parameterization. CONSTRAIN results also pointed out the importance of refining the vertical resolution of mesoscale models to improve the representation of cloud stratiform layers near the inversion level.

Finally, CONSTRAIN motivated the use of a new generation of km-scale climate models for climate change studies related to cloud feedbacks and convective organisation. It led CONSTRAIN scientists to write a EuroHPC proposal (accepted and now ongoing) to perform a series of climate experiments with the ICON Global Storm Resolving Model that will help CONSTRAIN scientists to further develop their research and insights, and constrain even better our understanding and assessment of climate feedbacks and sensitivity.

Open science:

CONSTRAIN produced many modeling and observational datasets that are accessible in open access, including the ‘Botany’ dataset (http://143.178.154.95:3141/botany-7-1536/index.html) and the EUREC^{4}A dataset (https://howto.eurec4a.eu/intro.html, https://eurec4a.aeris-data.fr/).

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