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

CONSTRAIN

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

GA number 820829
H2020-LC-CLA-2018-2

More information: cordis.europa.eu/project/id/820829
Project archive: zenodo.org/communities/constrain-project-820829

Work Package: WP3
Deliverable number: D3.2
Deliverable title: End-of-Project KGSIR on interaction of ocean heat uptake and radiative feedback change via SST-pattern change

Key messages:

- Post 1980 the Earth warmed with a configuration of SST patterns (cooling in the eastern Pacific and Southern Ocean) that results in feedbacks that are uncorrelated with – and indicating much lower equilibrium climate sensitivity than—that expected for long-term CO2 increase.
- Satellite observations of changes in top-of-atmosphere radiative fluxes since 1985 are in agreement with Atmospheric General Circulation Model (AGCM) simulations forced with observed SST and sea-ice, and are suggestive of a relationship between the pattern effect and ocean heat uptake efficiency.
- The 2015/16 El-Nino had a substantial impact on the Earth's diagnosed feedback parameter, reducing it by ~25% due to a large warming of the eastern Pacific. Since then three La Nina's in a row have been observed. The impact of this on radiative feedback is yet to be assessed. Continuity of satellite record radiation budget crucial to monitoring this.

Cite as:

Andrews T., Mauritsen T., Olonscheck D., Smith D. and Toniazzo T. 2022. Interaction of ocean heat uptake and radiative feedback change via SST-pattern change over recent decades. Knowledge Gains: Summary and Implication Report. The CONSTRAIN Project. DOI: 10.5281/zenodo.10125154.

CONSTRAIN

CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

D3.2 Knowledge Gains: Summary and Implication Report

Interaction of ocean heat uptake and radiative feedback change via SST-pattern change over recent decades

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December 2022

Key messages

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Context

Since the late 1970s regions of deep convection in the western Pacific have warmed by about 50% more than the tropical-mean (Fueglistaler & Silvers, 2021), while the eastern Pacific and Southern Ocean have cooled (see Figure 1a; also Power et al., 2021; Wills et al. 2022) despite temperatures increasing globally at ~ 0.19 K dec^{-1}. This configuration of warming in the tropical Pacific and Southern Ocean is in stark contrast to proxy reconstructions of past equilibrium climates and Atmosphere Ocean General Circulation Model (AOGCM) simulations of long-term climate change and Equilibrium Climate Sensitivity (ECS), which show a more "ENSO-like" temperature pattern with enhanced warming in the eastern Pacific as well as the Southern Ocean (e.g. Sherwood et al., 2020).

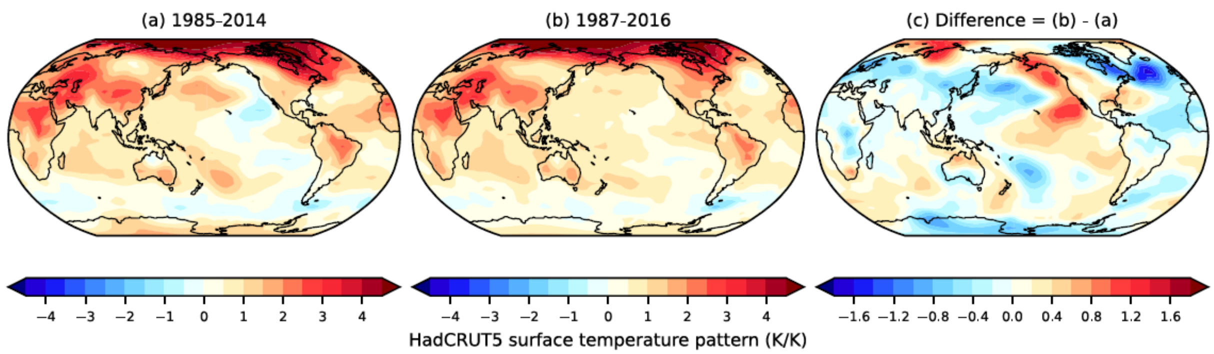

***Figure 1: Pattern of near-surface temperature change** (local dT per global-mean dT) for the time-periods (a) 1985-2014 and (b) 1987-2016, and (c) shows the difference (b minus a). Data is the HadCRUT5 analysis dataset (Morice et al. 2021). Taken from Andrews et al. (2022).*

Here, we summarize key recent improvements in our understanding and quantification of (i) how the pattern of surface temperature change over the last few decades has affected radiative feedback (termed the 'pattern effect') both in models and observations, (ii) how this may have interacted with ocean heat uptake, and (iii) what the implications are for the near-future. We predominantly summarize CONSTRAIN's contributions to the peer reviewed literature.

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Summary of Knowledge Gains

1. Radiative feedback and pattern effect over recent decades

Andrews et al. (2022) estimated the Earth's radiative feedback from observations between 1985 to 2014 using the Earth's global-mean energy budget, i.e. $\lambda = d(F - N)/dT$, where T is the surface temperature change (HadCRUT5), N the planetary energy imbalance from a merged satellite reconstruction (DEEP-C) and F the effective radiative forcing (IPCC AR6). Figure 2a and 2b show the dT, dN and dF timeseries over this period. The 1985-2014 'observed' feedback estimate is $-\lambda = d(F - N)/dT \sim 2.0 \pm 0.7$ [5-95%] W m^{-2} K^{-1} (Figure 2c).

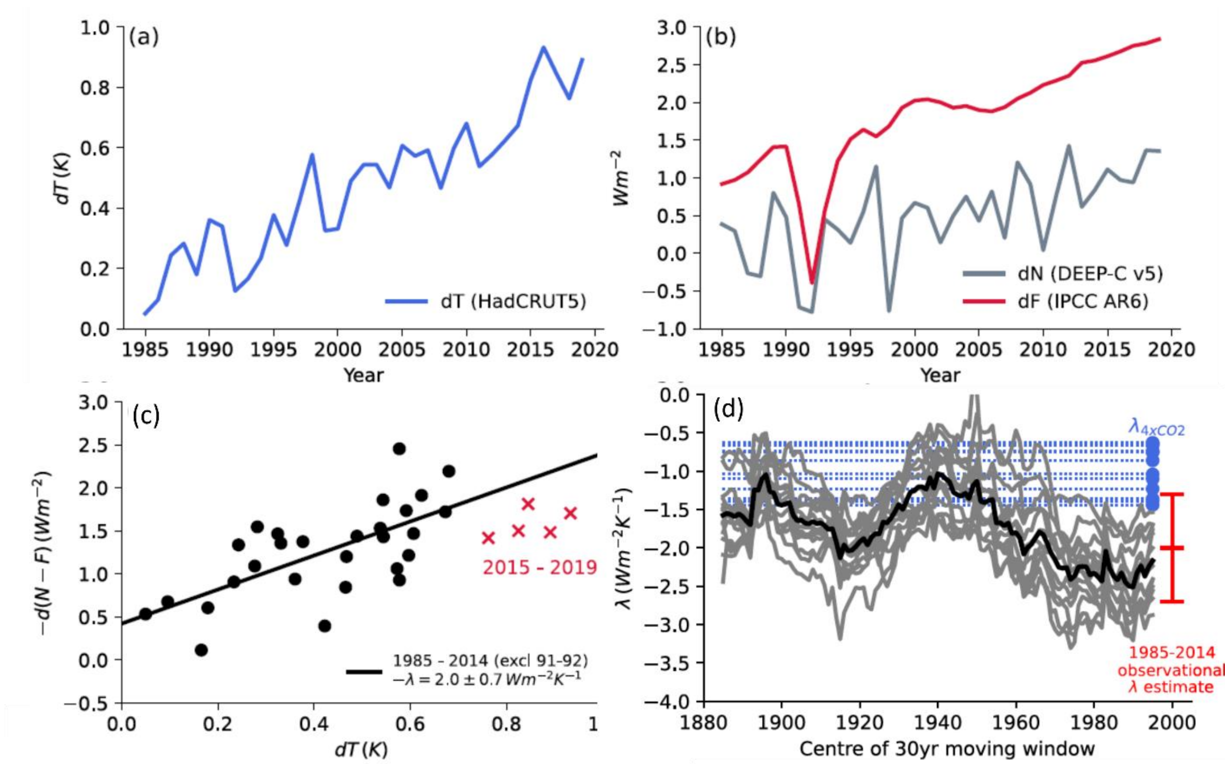

Figure 2: Observational estimate of the Earth's 1985-2019 energy balance*. All points are global-annual-means. (a) dT (HadCRUT5 analysis dataset; Morice et al., 2021), (b) dN (DEEP-C v5; Allan et al., 2014; Liu and Allan, 2022) and dF (IPCC AR6). (c) $-\lambda_{hist}=-d(N - F)/dT$ relationship over years 1985-2014. Black dots are global-annual means over years 1985-2014 excluding years 1991-2 which are strongly influenced by the Pinatubo explosive volcanic eruption (see red line panel b). The stated 5-95% uncertainties are $\pm 1.645\sigma$ from the standard error of the linear fit.* (d) *Decadal variation in the feedback parameter λ from 1871 to 2010 in 14 amip-piForcing simulations. Each grey line represents a single AGCM. Thick black is the ensemble-mean of the results, blue is the equivalent model's feedback from abrupt-4xCO_2. Taken from Andrews et al. (2022).*

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Andrews et al (2022) also summarised the equivalent feedback calculation in fourteen AGCMs forced with observed SST (from both HadISST1 and AMIP II reconstructions) and sea-ice variations. The observed 1985-2014 λ estimate is shown on Figure 2d (red line) in comparison to the AGCM decadal variations in λ (grey). The observed λ best estimate agrees exceptionally well with the AGCM multi-model mean, and nearly all models are within the 5-95% uncertainty estimate as they approach the 1985-2014 value. It is important to note that this is only true for AGCMs. Accounting for internal climate variability, Olonscheck and Rugenstein (in review) show that over 2001-2020, AOGCMs systematically underestimate the observed top-of-atmosphere radiation response to surface warming, adding uncertainty to climate projections.

In contrast to the observed and simulated feedback, AOGCM feedback of long-term climate change (blue lines, Figure 2d) are less stabilizing (implied ECS higher). This pattern effect is consistent with previous studies (e.g. Zhou et al. 2016; Gregory and Andrews, 2016). Here however Andrews et al. (2022) were able to quantify this pattern effect with a wider set of models with a more diverse range of atmospheric physics and climate sensitivities, as well the structural dependence on the underlying SST reconstruction (see also Modak and Mauritsen, 2022, who take this further). For 1981-2010 they found a pattern effect of ~1.4 ± 0.8 [5-95%] Wm^{-2} K^{-1} when the models were forced with AMIP II SSTs (~0.2 Wm^{-2} K^{-1} smaller when forced with HadISST1 SSTs).

A key result is that the feedback over 1981-2010 in AGCMs forced with observed SST and sea-ice variation had little correlation with the corresponding AOGCM feedbacks under long-term CO2. This suggest recent decadal climate change is not only unrepresentative of the long-term feedbacks (i.e. the pattern effect) but also not correlated.

Extending the observational feedback analysis post 2014 includes the major El-Nino event of 2015/2016 that was associated with eastern-pacific warming and marked changes in the observed radiation budget (Loeb et al. 2020; 2021). Figure 1b,c illustrates the impact of this event on the pattern of decadal surface warming. Over 1985-2014 there is marked cooling over the eastern Pacific (Figure 1a) which is much reduced when the pattern is calculated over 1987-2016 (Figure 1b) to include the peak 2015-16 El-Nino years. The difference (Figure 1c) shows the warming event of the 2015-16 El-Nino on the eastern Pacific, while cooling in the western Pacific, as well as a slight reduction in Southern Ocean cooling.

Such a shift in tropical Pacific SST patterns (a shift to warming in the eastern Pacific) should favour more positive feedbacks (Loeb et al., 2020). Indeed, Andrews et al. (2022) showed in their analysis including these post 2014 years (up to and including 2019) reduced the magnitude of the observed λ estimate by up to ~25%, from ~ 2.0 to 1.5 Wm^{-2} K^{-1} (see also Figure 2a – all red points falling below the line) This suggests a much-diminished pattern effect over the most recent data. Whether this continues into the future is an open research question depending on the evolution of the tropical Pacific (see Section 3 and Implications), for example, since the 2015/2016 El-Nino there have been three La Nina's in a row (Jones et al., 2022).

2. Interaction with ocean heat uptake?

To understand transient climate change one must also consider the efficiency of ocean heat uptake. Using passive ocean uptake experiments wherein ocean circulation cannot change, Newsom et al. (2020) found that ocean heat uptake efficiency is smaller when warming is enhanced in the tropics (where deep ocean ventilation is small) and larger when warming is enhanced in the high latitudes

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(where deep ocean ventilation is large). With relatively small warming in the southern high latitudes, this suggests that the surface/ocean-mixed layer might have been less efficient at fluxing heat into the deep ocean over the same period as the large pattern effect over recent decades, potentially enhancing global surface warming and muting some of the impact of feedback changes. Hence variations in both radiative feedbacks and ocean heat uptake appear to be physically linked through SST patterns and may even to some extent co-vary (Newsom et al. 2020).

Andrews et al. (2022) investigated such a possibility in the recent satellite data by showing that while λ reduced by ~25% over recent years (see previous Section), the climate resistance, $\rho = \mathrm{d}F/\mathrm{d}T = \kappa - \lambda$ remained approximately constant, suggesting that κ and λ must have co-varied. They estimated $\kappa = \mathrm{d}N/\mathrm{d}T \sim 0.4 \pm 0.8$ W m^{-2} K^{-1} over 1985-2014, which is smaller (but not necessarily inconsistent) with AOGCM simulations of steady increasing CO_2 ($\kappa = 0.73 \pm 0.18$ W m^{-2} K^{-1} for years 61-80 of CMIP5 1%CO2 AOGCM simulations, Gregory et al. 2015). It raises the possibility that the pattern of surface warming and/or atmospheric circulation may also change the efficiency of global heat uptake, thus both λ and κ might vary and to some extent be related (Newsom et al., 2020). If an anti-correlation existed, it could buffer the impact of a large pattern-effect on transient climate change. Such processes have been seen in AOGCMs (e.g. Hedemenn et al. 2017).

3. Discussion: how will the pattern-effect evolve in the near-future

Having established how the pattern of surface warming over recent decades has affected climate feedback and ocean heat uptake, the remaining question is how it will evolve in the near future. This is important for constraining near-term projections, yet is a difficult and multi-varied task. Three principal approaches could be used:

(i) Leveraging decadal forecasting systems to produce a range of near-future SST patterns conditioned on observed (initialized) conditions.
(ii) AOGCM scenario simulations (e.g. from CMIP6) of SST variations to produce a likelihood or bound of possible future patterns.
(iii) Develop a mechanistic understanding of what caused the pattern observed over the last 30 years, and use this understanding to say how it will evolve in the future.

A principal issue with (i) is the inherent unpredictability of the tropical Pacific, which CONSTRAIN has helped identify as a key region to informing radiative feedback and pattern effects (e.g. Hedemann et al., 2022). For example Power et al. (2021) showed that the 2-9yrs prediction skill score is extremely poor in the eastern Pacific in initialized decadal predictions (see their Figure 6).

Similarly, the principial issue with (ii) is that AOGCMs find it extremely difficult to simulate the recent observed decadal SST pattern in the Pacific (Olonscheck et al, 2020; Fueglistater and Silvers, 2021; Wills et al., 2022). Hence AOGCMs are generally biased in their simulation of the recent decadal feedbacks and the pattern effect (Gregory et al., 2020; Dong et al., 2021).

However recent CONSTRAIN research as made considerable progress on (iii), For example:

- Mauritsen et al. (2022) showed how high resolution global coupled simulations (ICON-Sapphire, 5km) in response to increased CO2 can be utilized to learn about such processes,

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even if the simulations are necessarily short. For example they found a much more diversified spatial pattern of warming compared to the lower resolution MPI-ESM1.2-LR CMIP type model. This early result could suggest that forced pattern effects in contemporary models are somewhat underestimated, perhaps resolving the biases found in them discussed above.

- Annan et al. (2022) presented a new reconstruction of surface temperatures for the Last Glacial Maximum. Such paleo reconstructions are useful for informing long-term SST pattern response and the fidelity of the long-term AOGCM response.
- Hedemann et al. (2022) showed that apparently discrepancies in literature relating to which regions (e.g. tropical Pacific, Southern Ocean) contribute to the global feedback variation can be explained by differences in local v global temperature definitions of feedback, recommending a global framework which showed the tropics being the dominant influence. This helps identify a region of key interest for predicting and understanding.
- Olonscheck and Rugenstein (in review) showed that AOGCMs systematically underestimate the top-of-atmosphere radiation response to surface warming. This is in contrast to the AGCMs response and points to a systematic bias in the ocean-atmosphere coupling of AOGCMs, which will bias climate projections.
- Huusko et al. (2022) showed how aerosol-cloud-interactions produce different SST pattern responses and feedbacks than direct aerosol effect, over the Pacific amongst other regions. This is consistent with other work (e.g. Dittus et al. 2021) in implicating aerosol-cloud-interactions as a potential driver of Pacific SST patterns.
- Toniazzo (in prep) utilized an alternative formulation to show how the pattern effect can be usefully represented as due to surface flux heating anomalies independent of global radiative forcing. The results show that cloud feedbacks are controlled by the tropical circulation, but the global-mean temperature response tends to follow the response of the cool subtropics where local radiative feedbacks and non-local advection both play a role.

Andrews et al. (2022) pulled much of the mechanistic understanding together to give an outlook for the near-future. They discuss the various hypothesis (which we reproduce here) for the recent tropical Pacific configuration over recent decades that drove such a large pattern effect (e.g. strong warming in the western Pacific while cooling in the eastern Pacific and Southern Ocean):

1. *Natural variability:* It could represent a mode of unforced coupled atmosphere-ocean variability (e.g. Watanabe et al. 2021), albeit an unusual one is that is rarely simulated by AOGCMs (Olonscheck et al, 2020; Fueglistaler and Silvers, 2021). In this scenario, we might expect the pattern effect to reduce in the near-future as the configuration of tropical SST patterns shift to more warming in the east than the west. There is some evidence (Loeb et al. 2020; 2021) this has already begun in the most recent years. We might therefore, expect an acceleration of warming trends (unless buffered by changes in heat uptake efficiency or a shift to more La Nina like conditions which has potentially already been observed).

2. *Forcing*: Spatiotemporal variations in anthropogenic forcings such as aerosols (e.g., Smith et al., 2015; Dittus et al. 2021; Heede and Fedorov, 2021) or explosive volcanic eruptions (Smith et al. 2015; Gregory et al. 2020) have been implicated in driving tropical Pacific SST patterns. In these scenarios, the pattern effect may decline with the reduction in aerosol emissions in the future, or continue to have decadal variations associated with future volcanism. In addition, Hartmann (2022) suggests a link between the onset of the Antarctic

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ozone hole, Southern Ocean cooling and impacts on tropical Pacific, which is expected to persist for another ~50yr.

3. *Thermostat:* While not explaining cooling per se, delayed warming in the eastern Pacific is an expected transient response to forcing due to the upwelling of (as yet) unperturbed waters from below (Clement et al., 1993; Heede and Fedorov, 2021). The implication of this is that eventually the eastern Pacific will warm, and hence we might expect the pattern effect to reduce and the estimated ECS to increase.

4. *Teleconnections:* from either the Atlantic Ocean (McGregor et al. 2018) or Southern Ocean (Hwang et al. 2017) have potentially driven the tropical Pacific SST patterns. Under the scenario of a Southern Ocean influence, we might expect the pattern effect to reduce as the Southern Ocean surface warms; this could take years to decades if the Southern Ocean temperature trends have been largely mediated by internal variability (e.g., Zhang et al. 2019) but could take centuries if related to freshwater input (e.g., Sadai et al. 2020).

Each of the above interpretations imply different futures, and therefore untangling them is critical for informing both near-term and long-term climate projections. Usefully, Smith et al. (2022) has developed a protocol for a Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP) designed to isolate the impacts and mechanisms of different external drivers on regional climate change. In the future this large ensemble of AOGCM simulations could be used to isolate the mechanisms (such as aerosol and volcanic forcing) on pacific SST gradients, as well separate forced and unforced response.

Implications

- Substantial progress has been made in quantifying and understanding the recent decadal pattern effect and how it may evolve in the future. However it is still incomplete and so it remains an uncertainty in projections of both near and long-term climate change.

- Given recently observed changes in the radiation balance and feedback parameter post 2014/15, associated with the large El-Nino and shift in the PDO index, the pattern effect may potentially wane and the Earth enter a period of sustained positive feedbacks & accelerated warming relative to recent decades. In the most recent data however, three La Nina's in a row have been observed. The impact of this on radiative feedback is yet to be assessed.. Continuity of satellite record radiation budget crucial to monitoring this.

- Given that radiative feedback in models over recent decades has been shown to be (i) different and (ii) uncorrelated with the same model's long term feedbacks and ECS, this suggests caution in using recent decadal climate change to inform long-term predictions. Doing so may understate future warming.

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About this Knowledge Gains: Summary and Implication Report

CONSTRAIN's Knowledge Gains: Summary and Implication Reports outline CONSTRAIN's contributions to the peer reviewed literature (knowledge gains), and summarise the implications for both the scientific community and broader society. This report and other CONSTRAIN publications are available at http://constrain-eu.org.

Acknowledgements

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How to cite

Andrews, T., *et al.* (2022), Interaction of ocean heat uptake and radiative feedback change via SST-pattern change over recent decades. Knowledge Gains: Summary and Implication Report. The CONSTRAIN Project, doi: XXXX.

About CONSTRAIN

The 2015 Paris Agreement sets out a global action plan to avoid dangerous climate change by limiting global warming to well below 2°C, whilst pursuing efforts to limit warming to 1.5°C. However, predicting how the climate will change over the next 20-50 years, as well as defining the emissions pathways that will set and keep the world on track, requires a better understanding of how several human and natural factors will affect the climate in coming decades. These include how atmospheric aerosols affect the Earth's radiation budget, and the roles of clouds and oceans in driving climate change.

The EU-funded CONSTRAIN project, a consortium of 14 European partners, is developing a better understanding of these variables, feeding them into climate models to reduce uncertainties, and creating improved climate projections for the next 20-50 years on regional as well as global scales. In doing so, CONSTRAIN will take full advantage of existing knowledge from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) as well as other Horizon 2020 and European Research Council projects.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820829.