Key messages:

- The ocean plays a key role in setting the climate response to cumulative emissions thanks to its capacity to absorb heat and carbon from the atmosphere.
- The interplay between the ocean heat and carbon uptake, also known as the “ocean heat-carbon nexus”, governs the future response of the ocean to rising CO2 emissions (and other climate forcers).
- We show that existing modelling platforms that are widely used in IPCC assessments can disagree over the representation of the ocean heat-carbon nexus. One of the key means of future modelling improvements is in the representation of key driving processes such as ocean mixing and stratification.
- An improved representation of the ocean heat-carbon nexus in simple climate models increases global mean surface warming by about 0.1-0.2°C in future projections, having the potential to impact the overall scenario classification of the corresponding emissions pathway.
- Through the geographical structure of sea surface temperature (SST) trends and its coupling with the atmosphere, the ocean can also influence cloud-climate feedbacks.
- Recent work shows that coupled climate models struggle to capture the observed pattern of SST trends since the 1980s.
- Nonetheless, recent ocean observations suggest that mixing and stratification can also be a potential candidate to explain the lack of model-data agreement in the representation of the pattern of SST trends. This document maps possible future research in this area.

Cite as:
Role of the ocean in setting the transient climate sensitivity to cumulative emissions

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• The ocean plays a key role in setting the climate response to cumulative emissions thanks to its capacity to absorb heat and carbon from the atmosphere.

• The interplay between the ocean heat and carbon uptake, also known as the “ocean heat-carbon nexus”, governs the future response of the ocean to rising CO2 emissions (and other climate forcers).

• We show that existing modelling platforms that are widely used in IPCC assessments can disagree over the representation of the ocean heat-carbon nexus. One of the key means of future modelling improvements is in the representation of key driving processes such as ocean mixing and stratification.

• An improved representation of the ocean heat-carbon nexus in simple climate models increases global mean surface warming by about 0.1-0.2°C in future projections, having the potential to impact the overall scenario classification of the corresponding emissions pathway.

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Context

How does the ocean influence the transient climate response?

The transient climate response to cumulative greenhouse gas emissions (TCRE) is a key emergent property of the Earth system (see KGSIR D4.8). This property is driven by several key components of the Earth system such as the atmosphere, the ocean, the land surface, etc. These components interact with each other through complex feedback processes, influencing the Earth's energy balance and climate response to cumulative emissions.

Within this global picture, the ocean plays a crucial role in the Earth’s climate system, particularly in terms of regulating the climate response to cumulative greenhouse gas emissions. On the one hand, the oceans absorb more than 25% of anthropogenic CO₂ emissions annually (Friedlingstein et al. 2022). Because of this, the oceans exert a strong control on the airborne fraction of CO₂ in the atmosphere. On the other hand, the oceans absorb most of the additional heat resulting from the radiative forcing induced by the accumulation of greenhouse gases in the atmosphere (Figure 1).

Through the combined control on the accumulation of CO₂ and heat in the atmosphere, the oceans play a key role in linking the responses of the Earth’s climate and carbon cycle to cumulative CO₂ emissions. The interplay between the uptake of heat and carbon by the oceans is generally referred to as the “ocean heat-carbon nexus” (Canadell et al. 2021).

The ocean heat-carbon nexus arises from a combination of well-understood processes. The exchange of heat and carbon across the sea-air interface, which governs the partitioning of anthropogenic CO₂ emissions and additional heat, emerges as the primary driver of the nexus (e.g., Frölicher et al. 2015, MacDougall et al. 2017). The other driver of the ocean heat-carbon nexus arises from the suite of processes controlling the capacity of the oceans to store heat and CO₂ such as ocean circulation, mixing and stratification (Figure 2).

The recent IPCC AR6 WGI report (Canadell et al. 2021) emphasizes the overall contribution of the ocean heat-carbon nexus in controlling the near-constancy of the TCRE: this emergent property arises from the compensation between the diminishing sensitivity of radiative forcing to increasing CO₂ at higher atmospheric concentrations, and the diminishing ability of the ocean to take up heat and carbon at higher levels of cumulative emissions.

The ocean also plays a significant role in setting the climate response through its interactions with the atmosphere. One of the key players in this interaction is the sea surface temperature (SST, Figure 2).
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.

Figure 1: Proportion of heat and carbon excess absorbed by the ocean over the historical period.

Figure 2: Major ocean processes driving the climate response to cumulative greenhouse gas emissions. The figure has been adapted from Palazzo-Corner et al. (in revision).

von Schuckmann et al. (2020)  Friedlingstein et al. (2019)
The amount and distribution of low clouds also strongly depends on the spatial pattern of SST – a phenomenon known as the “SST pattern effect” (Stevens et al. 2016). This tight ocean-atmosphere interaction is responsible for a climate feedback that can either amplify or dampen the initial climate perturbation, with the tropical Pacific region identified as a key area for global cloud feedbacks. Coupled climate models typically simulate a decrease in the tropical Pacific SST zonal gradient under sustained CO2 forcing, resulting in more amplifying low cloud feedback over time (albeit with large uncertainty), acting to enhance surface warming.

While a number of studies have focused on the pattern effect from the perspective of atmosphere-ocean coupling, only a very limited number have investigated the role of the ocean contribution in setting this pattern (Fox-Kemper et al. 2021). Current knowledge suggests that ocean mixing and stratification are key overarching drivers of the change in geographical distribution of SSTs because they integrate the complex contribution of wind stress and buoyancy fluxes over space and time (Figure 3). CONSTRAIN has paid further attention to these processes.

![Figure 3: Schematic of an idealized meridional section across the world ocean illustrating the ocean’s three-layer structure, emphasizing key ocean processes contributing to changes in the geographical distribution of sea surface temperatures. The figure has been adapted from Sallée et al. (2021).](image)

**Summary of Knowledge Gains**

**Revealing the difference in the representation of the ocean heat-carbon nexus across modelling platforms**

One of the approaches used to estimate the climate response to cumulative greenhouse gas emissions is to use Earth system models (ESMs) (Jones and Friedlingstein 2020). The modelling paradigm of ESMs primarily addresses the process understanding of the flow of energy, moisture and chemicals through the atmosphere, ocean and land surface, which govern the Earth’s climate. These processes are either
explicitly resolved or parameterized in ESMs. The latest generation of ESMs describes these processes in unprecedented detail.

On the other hand, Simple Climate Models (SCMs) are parametric models designed to be CPU-efficient, flexible and easily tuneable in order to emulate the response of complex ESMs within a certain domain of validity. Thanks to their flexible framework, SCMs can account for multiple lines of evidence (Nicholls et al. 2022) that counter known biases of the current generation of ESMs and hence result in improved future projections. Because of these properties, SCMs have played a key role in the latest IPCC AR6 assessment, expanding the WG1 physical assessment by ESMs and allowing a wider range of emission pathways to be assessed by WG3.

Virtually all of these climate models are assumed to capture the key features of the ocean heat-carbon nexus. This is particularly because all models simulate a near proportional relationship between cumulative emissions of CO$_2$ and change in global mean temperature (the so-called transient climate response to cumulative CO$_2$ emissions) that mainly arises from the interplay between the heat and carbon uptake by the oceans (MacDougall and Friedlingstein 2015, Williams et al. 2016, MacDougall et al. 2017). However, recent work (Séférian et al. in review) conducted under CONSTRAIN shines a light on the physical inconsistency between SCMs and ESMs (Figure 3) arising from the structure of SCMs, which only crudely account for the coupling between the ocean thermal and carbon cycle modules.

Séférian et al. (in review) show that the physical inconsistency between SCMs and ESMs may have important consequences for future warming as modelled by the SCMs, in terms of both magnitude and timing. It shows that a more realistic heat-to-carbon uptake ratio exacerbates the projected warming by 0.1°C in low overshoot scenarios, and up to 0.2°C in high overshoot scenarios.
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 820829.

Figure 4: Comparison of projected warming and ocean heat-carbon nexus between ESMs and SCMs under an idealized set-up. Panels a), b) and c) show the temporal evolution of the projected warming, ocean heat uptake and ocean carbon uptake as simulated by both ESMs and SCMs. Panel d) display the representation of the ocean heat carbon nexus between ESMs and SCMs. SCMs are given in coloured solid lines, individual ESMs in thin grey lines and ESM multi-model mean in black lines. Coloured boxes highlight 20-year window centred around the year 70 and 140 where atmospheric CO₂ is doubled (2xCO₂) or quadrupled (4xCO₂). The thick vertical red lines in panel a) indicated the IPCC AR6 1-sigma range for the transient climate response at CO₂ doubling (Forster et al. 2021).

The oceanic origin of the intermodel difference in SST pattern

Recent work by Dong et al. (2021) analysed coupled ocean-atmosphere CMIP6 simulations to show that the ‘pattern effect’ causes the transient climate response (that is, the physical component of the climate response to cumulative emissions) to be slightly biased low when derived from (simulated) historical periods.
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This is consistent with the work of Andrews et al. (2022) performed within CONSTRAIN: both works show that coupled climate models struggle to capture the particular pattern of SST warming since the 1980s, suggesting either that this period was affected by a rare mode of variability, or that models systematically fail to capture some of the forced response over that period. Interestingly, recent work by Sallée et al. (2021) shows a deepening of the summertime mixed-layer depth from 1970 to 2018 from oceanographic observations, finding that, in contrast with previous work, the summertime mixed layer deepened by 2.9 ± 0.5 percent or several metres per decade (depending on region).

Comparison of both ocean features, the SSTs on one hand and the mixed-layer depth on the other, shows a strikingly similar geographical distribution (Figure 5). Such a comparison has motivated further investigations into the relationship between changes in SST and stratification patterns.

![Figure 5: Comparison between the latest estimates of SST trend patterns from 1979–2014 (a, with models and observations from Dong et al. 2021), and trends in summer mixed-layer depth (b, from Sallée et al. 2021).](image)

The top panel in Figure 6 shows that, for most models, there are two timescales associated with the ocean response to forcing: a short/decadal timescales for ocean adjustment where the correlation between change in mixed-year depth (MLD) and SST increases with time; and then a stable long-term regime where the pattern of MLD and SST are tightly correlated.

This is explained by the ocean stratification: when ocean mixed-layer depth becomes shallower the water-volume directly impacted/interacting with the atmosphere decreases. The heat storage capacity of this smaller water volume saturates sooner than that of a large water volume and hence drives the pattern of ∆SST and the pattern of ocean heat fluxes (∆HFLX) (Figure 6 bottom panel).

This diagnostic sheds light on the fact that some ESMs (e.g., CanESM5, CMCC, E3SM-1-0) display no correlation between ∆MLD and ∆SST in spite of global warming. Although this might be for various reasons (e.g. spurious ocean deep convection, unrealistic MLD, etc.), it shows an unphysical ocean response to global warming and hence a potential source of disagreement between models in their capacity to accurately represent changes in SST patterns.
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Figure 6: Temporal evolution of the spatial correlation between SST pattern and mixed-layer depth (MLD, top) and Ocean heat fluxes (HFLX, bottom) in idealized warming experiments. Pattern, or Δ, are diagnosed from abrupt-4xCO2 minus long-term average over the piControl. In the top panel, correlation is multiply by -1. From Séférian et al. (in review).

Implications

Improved climate projections

The work conducted by CONSTRAIN focusing on the representation of the ocean heat-carbon nexus has several potential implications for the assessment of temperatures outcomes but also on scenario classification.
The application of the geophysical constraint in the ocean heat-carbon nexus in the Pathfinder SCM (Bossy et al. 2022) increases the simulated warming by about +0.1°C for both high-mitigation/low overshoot scenarios, and up to 0.2°C for the high overshoot scenario (Figure 7). The constraint also results in a slightly smaller spread in projected warming (about 5-8% with respect to the reference simulations). Pathfinder simulates a mean warming of 1.75°C at peak warming with a range of 0.99–2.91°C in SSP1-1.9 and 2.06°C with a range of 1.14–3.52°C for SSP1-2.6. Under the high-overshoot scenario the peak warming ranges between 1.57°C and 4.72°C with a mean estimate of 2.76°C.

A similar difference of 0.1°C in MAGICC temperature outcomes was also found in Nicholls et al. (2022) when comparing IPCC SR1.5 (Rogelj et al. 2018) and AR6 (Riahi et al. 2022) due to the increase in assessed historical warming between SR1.5 and AR6, and an improved (i.e., weaker) response to emissions. As stated in this work, such a difference is enough to cause all the “1.5°C no overshoot” scenarios to be reclassified as “1.5°C low overshoot” scenarios. Here, our finding has a stronger implication as it concerns a geophysical feature commonly misrepresented in all SCMs, potentially inducing in systematic biases in the projected warming.

The implication for the recent categorization of scenarios (Schleussner et al. 2022) might be stronger as the additional warming could result in emptying the C1 category that limits warming to 1.5 °C in 2100 with a greater than 50% chance.

![Figure 7: Implications of the representation of the ocean heat-carbon nexus on projected global warming. Projected warming as simulated by PATHFINDER with (red) and without (blue) accounting for the ratio between heat and carbon uptake at 2xCO2 of complex ESMs under various emission scenario. The difference in warming between both set-ups is given at the peak warming for SSP1-1.9 and SSP5-3.4-over.](image-url)
The role of the ocean processes in setting the Zero Emission commitment (ZEC)

As shown in the recent work of MacDougall et al. (2020, Figure 8a) there is a significant correlation between the transient climate response to cumulative emissions and the magnitude of the zero emission commitment (ZEC) after 50 years.

This relationship emerges between these metrics because, as with the TCRE, the ZEC is determined by the difference in warming caused by reduction in ocean heat uptake and cooling caused by continued land and ocean carbon uptake after the cessation of emissions.

![Figure 8: Contribution of ocean processes in setting the ZEC. Panel a) shows the relationship between the transient climate response to cumulative emission (TCRE) and the zero emission commitment at 50 years (ZEC\textsubscript{50}). Panel b) shows the breakdown of the energy fluxes following cessation of CO2 emissions. \( \Delta N \) is the change in ocean heat uptake relative to the time that emissions ceased. A reduction in ocean heat uptake will cause climate warming, hence \( -\Delta N \) is displayed. \( F_{\text{ocean}} \) is the change in radiative forcing caused by ocean carbon uptake, and \( F_{\text{land}} \) is the change in radiative forcing caused by terrestrial carbon uptake. Vertical black lines are estimated uncertainty ranges. Models are arranged in ascending order of ZEC\textsubscript{50}.]

Therefore, the same suite of ocean processes that controls the ocean heat-carbon nexus is susceptible to the overall climate response to emission cessation (Figure 8b). However, the relative contribution of each process in setting the regional and global response to emission cessation across
time-scales remains largely uncertain; this latter aspect may also depend on the state (level of warming and atmospheric CO₂) at which emissions are brought to zero.

An ongoing synthesis effort is currently being conducted, involving several CONSTRAIN scientists (Palazzo-Corner et al., in revision). Figure 9 highlights where the expert assessment on the relative contribution of ocean processes across time-scales may impact the magnitude of ZEC. This work will map the overall uncertainty across time-scales and highlight future research needs to better understand ZEC and, if possible, constrain it.

Figure 9: Overview of the expert assessment on ZEC unknowns from Palazzo-Corner et al. (in revision).
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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.

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How to cite

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 in 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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