The Active Role of the Ocean in Transient Climate Sensitivity

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Key Points:

• Pure atmosphere-driven "passive" and ocean-driven "active" climate responses are isolated using a novel partial coupling method.
• The spatial pattern evolution of surface temperatures and ocean heat uptake is attributable to the active ocean-driven component.
• The active ocean response is largely responsible for reduced transient sensitivity compared to that at equilibrium.

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Abstract

Transient climate sensitivity has been shown to be influenced by the changing pattern of SST and Ocean Heat Uptake (OHU), which in turn have been attributed to ocean circulation changes. A set of novel experiments are performed to isolate the active role of the ocean by comparing a fully-coupled CO$_2$-quadrupling CESM simulation against a partially-coupled one, where the effect of the ocean circulation change and its impact on surface fluxes are disabled. The active OHU is the main factor responsible for the reduced transient climate sensitivity and weaker surface warming response in the fully-coupled simulation. The passive OHU excites qualitatively similar feedbacks to CO$_2$ forcing in a slab ocean model configuration due to the similar SST spatial pattern response in both experiments. Additionally, the non-unitary forcing efficacy of the active OHU (1.7) explains the very different net feedback parameters in the fully-and partially-coupled responses.

1 Introduction

Climate sensitivity is a transient metric that increases with time after a forcing is applied [Murphy, 1995; Senior and Mitchell, 2000; Williams et al., 2008; Winton et al., 2010]. The transient climate sensitivity is smaller than the equilibrium climate sensitivity, as the effective feedback parameter $\lambda$ is always more stabilizing than the equilibrium feedback parameter $\lambda_{eq}$. Accordingly, the emergent climate sensitivity tends to increase with time toward the equilibrium value. The transitory feature of climate sensitivity has been interpreted to be the result of a time evolving pattern of Ocean Heat Uptake (OHU) and its efficacy [Armour et al., 2013; Rose et al., 2014; Andrews et al., 2015; Rugenstein et al., 2016; Rose and Rayborn, 2016]. Climate models robustly show that the OHU response has an efficacy greater than 1 [Winton et al., 2010, 2013], causing weaker surface warming and the transient sensitivity to be smaller than the equilibrium one. This non-unitary OHU efficacy has been associated with local and global radiative feedbacks induced by the evolving spatial pattern of SST and OHU, and ocean circulation changes have been suggested to play an important part in these patterns [Winton et al., 2013; Trossman et al., 2016]. However, it is not yet clear how much of the fully-coupled transient climate sensitivity reduction, or SST and OHU pattern change, can be attributed to ocean circulation change or to other processes. Here, we isolate the contributions of the pure atmosphere-driven "passive" response, from the ocean dynamics-driven "active" response to the transient climate sensitivity, by separat-
ing SST and OHU patterns, and the associated radiative feedbacks due to each component, in a fully-coupled simulation.

Under abrupt CO$_2$ increase, ocean circulation changes redistribute ocean reservoir temperature, causing weaker global SST warming and deeper heat anomaly penetration into the ocean [Banks and Gregory, 2006; Xie and Vallis, 2012; Garuba and Klinger, 2016]. Using ocean-only models, Xie and Vallis [2012] and Garuba and Klinger [2016] showed that this process also changes the pattern and magnitude of OHU and increases the effective heat capacity of the ocean. By modifying the SST, ocean redistributive processes also modify radiative feedbacks and global surface temperature, thereby changing the efficacy of OHU. Winton et al. [2013] studied the impact of changes in the ocean circulation by comparing simulations in which ocean circulation is fixed and free to change, and demonstrated that the efficacy of ocean heat uptake is greater than one only when the circulation is free to change but is equal to one when held fixed. Trossman et al. [2016] concluded that interactions between cloud radiative feedbacks and ocean circulation change slows global surface warming. The influence of ocean circulation change on the transient climate response is therefore two-fold: (i) changing the effective heat capacity of the ocean; (ii) and changing atmospheric radiative feedbacks.

In this study we isolate the passive and active SST and OHU components to quantify the climate feedbacks associated with each in a coupled system. To this end, we use a novel experimental design, in which ocean temperature response is decomposed into surface- and oceanic dynamics-forced components, and the ocean is only partially-coupled through the surface-forced SST anomalies; the atmosphere does not interact with SST anomalies due to changes in the ocean circulation. We further compare the radiative feedbacks due to the passive and active OHU components using a slab ocean model framework. Our approach is in the spirit of the fixed-circulation experiment of Winton et al. [2013] and Trossman et al. [2016], and the ocean-only passive and active OHU decomposition by Garuba and Klinger [2016]. The method presented here, however, allows us to isolate the SST and OHU pattern change, as well as the radiative feedbacks, due to the passive and active components of the fully-coupled response.
2 Model and experimental design

We use the fully-coupled and slab ocean versions of the community Earth System Model version 1.1 (CESM 1.1 and CESM-SOM). The fully-coupled CESM consists of the following active components: Community Atmospheric Model version 5 (CAM5) [Neale et al., 2010], Parallel Ocean Program version 2 (POP2) [Danabasoglu et al., 2012], Community Land Model version 4 (CLM4) [Oleson et al., 2010], and the Community Ice CodE (CICE) [Hunke et al., 2010]. In the CESM-SOM, the ocean model POP is replaced by a slab ocean model [SOM; see Bitz et al., 2012]. The horizontal resolution used for CAM5 and CLM4 is 2.5° X 1.9°, with the atmospheric component having 30 vertical levels. CICE, POP and SOM run on a nominally-1° resolution displaced-pole grid (with the north pole singularity centered over Greenland); POP has 61 vertical levels.

The fully- and partially-coupled simulations are both branched from a 1000-yr pre-industrial control run, forced by abrupt CO$_2$-quadrupling, and integrated for 150 years. The slab simulations use ocean heat flux convergences computed from either the pre-industrial control, partially-coupled 4xCO$_2$, or fully-coupled 4xCO$_2$ simulations, as described in §2.2.

2.1 Partial coupling

The design of the partial coupling method is inspired by fully-coupled and ocean-alone tracer experiments of Banks and Gregory [2006], Xie and Vallis [2012], Marshall et al. [2015], and Garuba and Klinger [2016], in which the ocean temperature anomaly is decomposed into what we will call "surface-forced" and "ocean dynamics-forced" components. The evolution equation for the ocean temperature response to an external forcing can be expressed symbolically as:

$$\frac{DT'}{Dt} = F' - \nu' \cdot \nabla \bar{T}$$  \hspace{1cm} (1)

where overbars represent the control variables, primes denote anomalies from the control, and $\frac{D}{Dt} = \frac{\partial}{\partial t} + \nu \cdot \nabla$ (i.e, the total derivative following the ocean circulation, $\nu = \bar{\nu} + \nu'$).

Equation (1) implies that the total ocean temperature response can be thought of being forced by surface flux anomalies, ($F'$) and the advection of the background mean temperature by the circulation change ($\nu'$). The temperature anomalies due to the latter are often referred to as the redistributive temperature anomaly, as they conserve heat content globally. The physical meanings of the "surface-forced" and "ocean dynamics-forced" components of the temperature response become much clearer via the following decomposition of equation (1):
This decomposition shown above, however, does not cleanly isolate the (atmospherically-driven) "passive" ocean temperature response from the (ocean dynamics-driven) "active" ocean temperature response. To see this, we write the fully-coupled surface fluxes as

\[ F' = \alpha (T_S' - SST') \]  

where \( T_S' \) is the surface air temperature anomaly induced by CO\(_2\) increase and the \( SST' \) is the ocean surface temperature response. Writing \( SST' = SST'_F + SST'_O \), we see that \( F' \) is not only driven by atmospheric changes through \( T_S' \) and \( SST'_F \), but also by the active, ocean dynamics-driven temperature anomaly \( SST'_O \). Therefore, we can further decompose the surface flux anomaly \( F' \) into passive and active components, \( F' = F'_P + F'_A \), where \( F'_P \) is the surface heat flux anomaly solely due to changes in the atmosphere (CO\(_2\)-quadrupling in this case), and \( F'_A \) is the active component due to the impact of \( SST'_O \) on the surface heat flux anomaly. Note, however, that this active surface heat flux component is not included in equation (3), where \( T'_O \) has no surface forcing; instead, it is rolled into \( F' \), the forcing for \( T'_F \) evolution in equation (2). This represents a major drawback of prior decompositions of the ocean temperature anomaly, since \( T'_F \) and \( T'_O \), as written in equations (2) and (3), are not truly the atmospheric-driven and ocean dynamics-driven ocean temperature anomalies.

Through our partial coupling framework, we isolate \( F'_P \) by coupling the atmosphere only to the "surface-forced" component of the ocean temperature anomaly, thereby preventing the "ocean dynamics-forced" component from interacting with the atmosphere. Therefore, the partially-coupled surface heat flux anomaly is the passive component \( F'_P \); the active surface heat flux component can be computed as the difference between the fully-coupled and partially-coupled surface heat flux anomalies: \( F'_A = F' - F'_P \). The partially-coupled "surface-forced" component \( T'_{F,\text{part}} \), analogous to the fully-coupled \( T'_F \), represents the purely atmosphere-driven "passive" ocean temperature anomaly component, since it excludes the ocean-forced surface heat flux component \( F'_A \). We hereafter refer to this as \( T'_P \), which evolves as:

\[ \frac{DT'_P}{Dt} = F'_P \]
The fully-coupled "active" ocean temperature anomaly component $T'_A$ is similarly derived from the difference $T' - T'_p$. The evolution of $T'_A$ is thus equation (1) minus (5):

$$\frac{DT'_A}{Dt} = F'_A - \nu' \cdot \nabla T$$

From (6), we see that the total active ocean temperature anomaly consists of a part owing directly to the circulation change $\nu'$ (thus similar to $T'_O$) plus a part forced by the difference between the surface heat flux in the fully-coupled and partially-coupled experiments ($F'_A$).

We argue that the attribution of $T'_A$ through equation (6) is self-contained to the extent that $F'_A$ itself is attributable to the ocean circulation change.

In contrast, the partially-coupled ocean dynamics-forced component $T'_{O_{part}}$, analogous to the fully-coupled $T'_O$, is the uncoupled ocean dynamical response and only captures the direct part of the "active" response by the ocean circulation change ($\nu'_{part}$) in the partially-coupled response (note that $\nu'$ and $\nu'_{part}$ also differ, due to additional surface flux changes arising from coupling to $T_{O_{part}}$). Nevertheless, the atmospheric coupling to $T'_{O_{part}}$ in the fully-coupled simulation is the cause of the active surface fluxes and temperature anomalies.

Comparing the uncoupled $T'_{O_{part}}$ with the derived active surface heat flux and SST components verifies the validity of our derived decomposition (see discussion in §3.1).

$$\frac{DT'_{O_{part}}}{Dt} = -\nu'_{part} \cdot \nabla \tilde{T}$$

In practice, the decomposition of the full temperature (or SST) anomalies into a "surface-forced" and "ocean-dynamics-forced" components is realized through implementing two temperature tracers, formulated in the same spirit as in Xie and Vallis [2012] and Garuba and Klinger [2016] (see Supplementary information for tracer formulation). The two decomposed components add up reasonably well to the total temperature anomaly (see Fig S1). The corresponding fully- and partially-coupled experiments, their associated flux configurations, and the decomposition of ocean temperatures and SST anomalies are listed in Table 1.

2.2 Slab simulations

The slab simulations use q-flux (mixed layer ocean heat convergence) anomalies diagnosed from the partially- and fully-coupled simulations, and are used to isolate the radiative feedbacks due to the passive and active ocean components and to estimate the efficacy of
Table 1. Summary of fully-coupled, partially-coupled and SOM Experiments. See text for details

<table>
<thead>
<tr>
<th>Name</th>
<th>Run (yr)</th>
<th>Description</th>
<th>Tracer temperature decomp.</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>150</td>
<td>Fully cpld 4xCO2 abrupt inc.</td>
<td>$T = \bar{T} + T'_F + T'_O$</td>
<td>$F' = \alpha(TS' - SST')$</td>
</tr>
<tr>
<td>Partial</td>
<td>150</td>
<td>Partially cpld 4xCO2 abrupt inc.</td>
<td>$T = \bar{T} + T'<em>P + T'</em>{O_{part}}$</td>
<td>$F'_p = \alpha(TS' - SST'_p)$</td>
</tr>
<tr>
<td>Slab$_{P-OHU}$</td>
<td>50</td>
<td>4xCO2 inc. + Passive Q-flux anom</td>
<td>$T = \bar{T} + T'$</td>
<td>$Q = \bar{Q} + Q'_p$</td>
</tr>
<tr>
<td>Slab$_{A-OHU}$</td>
<td>50</td>
<td>Active Q-flux anom</td>
<td>$T = \bar{T} + T'$</td>
<td>$Q = \bar{Q} + Q'_A$</td>
</tr>
<tr>
<td>Slab$_{4xCO2}$</td>
<td>50</td>
<td>4xCO2 inc.</td>
<td>$T = \bar{T} + T'$</td>
<td>$Q = \bar{Q}$</td>
</tr>
</tbody>
</table>

the active OHU component. The passive OHU slab experiment, slab$_{P-OHU}$, is forced with CO$_2$-quadrupling together with the q-flux anomaly diagnosed from the mixed layer heat content anomaly due to passive temperature component, $T'_P$. The active OHU slab experiment, slab$_{A-OHU}$, is forced with q-flux difference between the fully-coupled q-flux anomaly and passive ones, (equivalent to active mixed layer heat content anomaly due to $T'_A$). Note that because there is no CO$_2$ forcing anomaly between the fully-coupled and partially-coupled experiments, the slab$_{A-OHU}$ experiment is not forced with the 4xCO$_2$ increase. These experiments are compared to a 4xCO$_2$ experiment with only the climatological q-flux forcing from the control experiment, slab$_{4xCO2}$. See Table 1 for a summary of experiments.

3 Results

3.1 SST and Ocean heat uptake pattern

We first compare the fully-coupled OHU pattern $F'$ and its passive and active components ($F'_P$ and $F'_A$ respectively), with the latter being derived from the difference between the fully- and partially-coupled surface fluxes ($F' - F'_P$). During the first decade or so, the full OHU, $F'$, is globally uniform, because the oceanic mixed layer is absorbing heat in response to CO$_2$-induced atmospheric warming. This feature is fully captured by the passive component of the uptake during the same period. Soon, this uniform uptake pattern is overtaken by a meridional structure with a strong sub-polar uptake in both hemispheres and a heat release in the tropics. Interestingly, sub-polar uptake in the southern hemisphere (SH) is attributable largely to the passive OHU (Fig 1b), in agreement the ocean-alone tracer experiments of Armour et al. [2016], whereas the sub-polar uptake in the northern hemisphere (NH) is mainly the result of the active OHU, and is due to the ocean circulation change (Fig 1c). Moreover,
the time scales for the establishment of the passive and active OHU patterns are different: the former only takes a few decades, while the latter continues to evolve after half a century. We examine the slow evolution of the OHU spatial pattern, using the difference between the yr 20 to 50 average and the yr 50 to 150 average (excluding the mixed layer adjustment period). Figure 1d-f shows that the slow evolution of the OHU in the fully-coupled case is almost identical to that of the active OHU (Fig 1j-l), whereas the passive OHU exhibits little change in its pattern (Fig 1g-i). The evolution of the fully-coupled surface air temperature, TS, and SST are likewise dominated by the active components (Figs S2 and S3).

**Figure 1.** Zonally averaged net surface heat flux anomalies in the fully-coupled experiment (a), in the partially-coupled experiment (passive; (b)), and the difference between the fully-coupled and partially-coupled experiments (active; (c)). Surface heat flux anomaly evolution shown for the annual mean over years 20 to 50 (left column) and years 51 to 150 (middle column), and the difference between these two time periods (right column), in the fully-coupled experiment (d, e, and f respectively), in the partially-coupled experiment (passive; g, h, and i respectively), and the difference between the fully-coupled and partially-coupled experiments (active; j, k, and l respectively). Units=Wm$^2$

Although the passive OHU pattern is forced by the air-sea interfacial flux, its pattern is determined ultimately by the structure of the mean ocean circulation, as implied by the nature of the governing equation for tracer $T'_p$. By design, $F'_p = \alpha(TS' - SST'_p)$; and for the slow time scale of interest, $TS'$ and $SST'_p$ always follow each other closely (as also confirmed in the actual simulations). Therefore, $F'_p$ is strongly shaped by $SST'_p$ through the mean ocean
circulation pattern. Large passive uptake occurs at upwelling regions or regions of large heat divergence due to strong ocean currents, such as at western boundaries and the equatorial Pacific. In agreement with the study of Armour et al. [2016], the relatively weak Southern Ocean surface warming response is caused by the deep downwelling in the Southern Ocean (compare Figs 1b and 2b). Reduced ocean surface warming there creates a large air-sea temperature difference, driving the large passive uptake. Being ultimately driven by the advection of the mean ocean circulation, which is fixed in time, the passive OHU does not change much in time, a feature with interesting implications for the OHU efficacy (to be elaborated upon later).

The active OHU pattern, $F'_A$, on the other hand, is consistent with the uncoupled ocean dynamics-forced pattern, $SST'_{O\text{part}}$, inducing it (Fig 2c). A comparison of the active OHU and $SST'_{O\text{part}}$ reveals a strong compensating effect between them: whenever the ocean circulation change acts to warm (cool) the SST, the induced active surface heat flux would work against it to cool (warm) the SST. The active tropical heat release is due to tropical warming in $SST'_{O\text{part}}$, while the active NH high-latitude uptake comes largely from Atlantic sub-polar gyre cooling, caused by AMOC weakening in the partially-coupled experiment (compare Figs 1c and 2c, j-l). The derived active SST pattern, $SST'_A$ is the residual surface temperature anomaly resulting from the compensating effect of $F'_A$ on $SST'_{O\text{part}}$, and the additional circulation changes due to all the surface flux changes (including $F'_A$) arising from the coupling to $SST'_{O\text{part}}$ (Fig 2d; also compare equations (7) and (6)). Accordingly, $SST'_A$ shows much reduced warming in the tropics and greater cooling the NH high-latitudes, in comparison to $SST'_{O\text{part}}$. The Pacific El Niño - like warming pattern seen in $SST'_A$ has been shown to be a robust feature of global warming experiments in CESM, and shown to be partly due to the weakening of the shallow subtropical overturning cell [Luo et al., 2016]. The large active uptake in the sub-polar Atlantic would have caused anomalous warming there if acting in isolation, and therefore appears to be at odds with the extra cooling of the active SST pattern in this region. However, this wide spread NH cooling is due to the larger cooling effect caused by a much weaker AMOC in the fully-coupled compared to the partially-coupled (see Fig 2e). This extra cooling due to the AMOC weakening in the two experiments can be seen by comparing their respective ocean dynamics-forced components, $SST'_O$ and $SST'_{O\text{part}}$, neither of which are subject to any surface forcing (see Fig S4).

The uncoupled ocean dynamics-forced component, $SST'_{O\text{part}}$, warms the ocean surface in the global average (Fig 2f thin blue line) because of the dominance of tropical warming
Figure 2. Surface temperature anomaly (average for the final 50 years; in K) in the fully- and partially-coupled experiments: (a) Fully-coupled total surface temperature anomaly, $SST'_{A}$; (b) Partially-coupled surface-forced or passive component $SST'_{P}$; (c) Partially-coupled ocean dynamics-forced component, $SST'_{O_{part}}$; (d) Fully-coupled active component, $SST'_{A} = SST' - SST'_{P}$. (e) Atlantic meridional overturning (AMOC) index in the fully-coupled (red) and partially-coupled (blue) experiments. (f) Global averaged SST anomaly and its components: fully-coupled $SST'$ (red), the passive component $SST'_{P}$ (blue solid), the active $SST'_{A}$ (blue dashed), and the partial ocean dynamics-forced $SST'_{O_{part}}$ (thin blue solid). (g) Effective depth of temperature anomaly penetration in the fully-coupled (red) and partially-coupled (blue) experiments.

Garuba and Klinger [2016] showed that the over NH high-latitude cooling in this pattern, and thus resulting in a decrease in the ocean heat capacity. However, the atmospheric coupling to this ocean dynamics-forced surface warming, leads to a net cooling in the global surface temperature due to the widespread NH high-latitude cooling in the active SST pattern (Fig 2f dashed blue line; compare also Figs 2b and d). This net global surface cooling implies an increase in ocean heat capacity (shown by the effective depth in Fig 2g), and, therefore, an increase of the OHU in the fully-coupled simulation compared to partially-coupled one. Garuba and Klinger [2016] showed that the
rearrangement of ocean reservoir temperature by the circulation change would cause a deep-
ening (shallowing) of the effective depth of uptake, when it cools (warms) the surface. We
find, however, that this deepening effect in the fully-coupled response is not an ocean-only
effect as suggested in these studies (see, e.g., Xie and Vallis [2012] and Garuba and Klinger
[2016]), but that the ocean by itself does the opposite. This different conclusion, however,
may be because the boundary forcings used in these studies are derived from fully-coupled
experiments which already include the coupling effect between ocean circulation changes
and the atmosphere.

3.2 Climate sensitivity and radiative feedbacks

Climate sensitivity in the partially-coupled experiment, which permits coupling solely
between the passive ocean response and the atmosphere is compared to climate sensitivity in
the fully-coupled experiment where the full (active + passive) ocean response is coupled to
the atmosphere. Making use of the relation $N = R - \lambda \Delta T$, where $N$ is the OHU, $R$ is the ra-
diative forcing and $\Delta T$ is the surface temperature response, we estimate the effective climate
feedback parameter $\lambda$ as the regression coefficient in the partially- and fully-coupled simula-
tions. The fully-coupled simulation has a smaller climate sensitivity (larger climate feedback
parameter) than the partially-coupled simulation (Fig 3a). Reduced climate sensitivity of the
fully-coupled simulation is consistent with the net cooling effect of the active ocean response
(recall Fig 2f). The smaller climate sensitivity in the fully-coupled simulation suggests that
the active component must contribute to this reduced transient climate sensitivity.

We use slab ocean model experiments to estimate how much of the reduction in the
fully-coupled transient climate sensitivity is caused by the passive and active components
because the partially- and fully-coupled simulations are still far from reaching equilibrium.
CO$_2$-forcing experiments using slab ocean models have been shown to provide a good ap-
proximation of coupled equilibrium climate sensitivity [Danabasoglu and Gent, 2009]. Our
slab$_{P-OHU}$ and slab$_{A-OHU}$ experiments are able to reproduce the respective passive and ac-
tive SST patterns (Fig S5). Comparing the global feedbacks in the slab$_{4xCO_2}$ and slab$_{P-OHU}$,
which are 0.75 and 0.83 respectively, suggests that the passive ocean response contributes
very little to the reduced transient climate sensitivity or the enhanced transient climate feed-
back parameter (Fig 3b). Furthermore, the equilibrium sensitivity of the partially-coupled
experiment, approximated by that in the slab$_{P-OHU}$ experiment, shows that the partially-
coupled transient climate feedback (0.88) is not very different from its equilibrium value es-
estimated from the slab experiment (0.83). This is consistent with the stationary passive ocean heat uptake pattern in the partially-coupled simulation, and the very similar SST responses in slab$_{4xCO_2}$, slab$_{P-OHU}$ and the passive surface change $SST_p'$ (see Fig S5). Indeed, the meridional structure of the global feedbacks and its components in slab$_{4xCO_2}$ and slab$_{P-OHU}$ are also very similar (Fig 3c-g black and blue dashed lines).

Figure 3. Global climate feedback parameter ($\lambda$, Wm$^{-2}$ K$^{-1}$) in the partially-coupled (passive component) (blue) and fully-coupled (red) experiments. (b) Climate feedback components in the slab, partially-coupled and fully-coupled experiments, and (c) meridional pattern of the global feedback parameter, and its components: (d) longwave clear-sky, (e) longwave cloud, (f) shortwave clear-sky, and (g) shortwave cloud.

Compared to the partially-coupled feedback, the fully-coupled feedback (1.18) is significantly larger than $\lambda_{CO_2}$, as estimated from the slab$_{4xCO_2}$ (0.75), suggesting that the enhanced efficacy in the fully-coupled case is largely due to the active ocean response. Using
the slab$_{A-OHU}$ (where the active ocean heat convergence is the only forcing), we estimate
the efficacy of the active OHU, defined as $\epsilon = \lambda_{CO_2}/\lambda_{A-OHU}$ to be 1.7, which is comparable
to the fully-coupled estimate (1.6) in Winton et al. [2013]. Accordingly, the meridional pat-
ttern of the feedbacks due to the active OHU is likewise distinct from those of the slab$_{A-CO_2}$
and slab$_{P-OHU}$ (Fig 3c-g compare dashed and solid red lines).

Analysis of the radiative feedback components shows that the shortwave (SW) clear-
sky component is the primary cause of the large efficacy of the active ocean response. The
reduced feedback $\lambda_{A-OHU}$ is due to the large SW clear-sky feedback offsetting the LW clear-
sky feedback effect. This result is, however, different from those of Trossman et al. [2016]
and Rugenstein et al. [2016], in which the SW cloud feedback is pointed to as the leading
factor in mediating the atmospheric response to changes in ocean dynamics. Here, because
of the large cancellation between the the LW and SW cloud components, they are not the
primary cause of the large feedback efficacy in slab$_{A-OHU}$. Further inspection of the sea ice
field indicates that the enhanced SW clear sky feedback is the result of the increased sea ice
associated with major cooling in the north Atlantic in slab$_{A-OHU}$ (Compare the SST in Fig
S5).

4 Summary and Discussion

Here we have considered the role of ocean circulation changes on the transient cli-
mate sensitivity by formulating a novel partially-coupled framework using temperature-like
passive tracers. The decomposition of the total OHU into passive and active components is
achieved by comparing the response to CO2-quadrupling in the fully- and partially-coupled
experiments. The passive component can be attributed solely to atmospheric changes, while
the active component is due to the interaction of ocean circulation changes with air-sea fluxes.
When uncoupled, the ocean dynamics-forced SST pattern, which includes NH sub-polar
cooling and tropical warming, warms the surface on the global average. Through coupling
to the atmosphere, this ocean-forced pattern induces a slowly evolving active OHU pattern
which is characterized by tropical heat release and NH sub-polar uptake, and incites a cooler
SST response in the fully-coupled experiment. Further slab experiments reveal that the large
forcing efficacy of the active OHU is the main cause of the reduced transient climate sensi-
tivity in comparison to the equilibrium one. On the other hand, the climate sensitivity asso-
ciated with the passive OHU component is not significantly different from the equilibrium
one. The high efficacy of the active OHU arises from the SW clear-sky feedback through an enhanced ice-snow albedo feedback in the NH high-latitudes.

The decomposition into the passive and active OHU presented here is similar to the ocean-only passive and active OHU decomposition of Garuba and Klinger [2016], and the fully-coupled fixed-circulation experiment of Winton et al. [2013]. The study here, however, is able to isolate explicitly the fully-coupled active component and its associated radiative feedbacks. We have shown that the fully-coupled evolving patterns of the OHU, SST, and TS is due to the active component. Interestingly, the fully-coupled TS pattern evolution here greatly resembles the multi-model surface temperature evolution pattern in the study of Andrews et al. [2015]. Thus, the result here offers a direct verification that the evolving OHU and surface temperature patterns in the fully-coupled experiments are indeed caused by ocean circulation changes. The fully-coupled pattern has often been thought to be evolving towards a more sub-polar pattern with time [Winton et al., 2013; Rose et al., 2014], but our results here suggest that this is only true for the northern hemisphere sub-polar region; the sub-polar uptake in the Southern Ocean does not vary much during the time frame examined. Our results also show that the uncoupled ocean circulation change warms the surface globally; when coupled to the atmosphere, however, it induces net global surface cooling and an increase in the effective ocean heat capacity in the fully-coupled response. This result underlines the need for caution in the interpretation of ocean-only experiments forced by surface fluxes derived from the fully-coupled system, which have often led to the erroneous conclusion that weaker global surface warming is an ocean-only effect [Xie and Vallis, 2012; Garuba and Klinger, 2016].

We have shown that the active OHU component is the main reason why transient climate sensitivity is smaller than equilibrium sensitivity. As the ocean component continues its course of equilibration, we suspect the active OHU will gradually diminish with time as the climate sensitivity gradually increases (i.e the red slope in Fig 3a becomes gentler with time). On the other hand, we speculate the pattern of the passive OHU will remain roughly fixed during this slow adjustment and will contribute little to the increase in climate sensitivity with time. The NH sub-polar region is the primary contributor to the high efficacy of the OHU found in this study, due primarily to the ice-albedo feedback magnifying the active response in this area. The SH sub-polar uptake pattern is passive and stationary in time, and does not contribute to the radiative feedback pattern change in the fully-coupled response. We also found that the SW clear-sky feedback is the greatest contributor to the high efficacy
of the active OHU, a conclusion that differs from previous studies suggesting the importance
of cloud feedbacks [Andrews et al., 2015; Trossman et al., 2016; Rugenstein et al., 2016;
Rose and Rayborn, 2016]. While the result here may be model dependent, we note that sea
ice is not considered in the aquaplanet studies of Rose et al. [2014]; furthermore, the clear-
sky SW feedback associated with idealized high-latitude OHU with active sea ice in Rugen-
stein et al. [2016] also accounts for most of the reduction of the net feedback. Our result here
suggests that there is a physical basis for the SW clear-sky component dominance. Finally,
we point out that the passive and active decomposition here is model dependent and the rel-
ative importance of the radiative feedbacks components may change with different models.
Further studies with several models will be needed to demonstrate the robustness of relative
importance of the passive/active response and clear-sky/cloud radiative components in tran-
sient climate sensitivity.

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