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2015 Environ. Res. Lett. 10 034016

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Environmental Research Letters



LETTER

Atmospheric consequences of disruption of the ocean thermocline

OPEN ACCESS

RECEIVED
10 February 2015

ACCEPTED FOR PUBLICATION
24 February 2015

PUBLISHED
19 March 2015

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Keywords: biogeochemistry, oceanography, ocean pipes, thermocline

Supplementary material for this article is available [online](#)

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**Abstract**

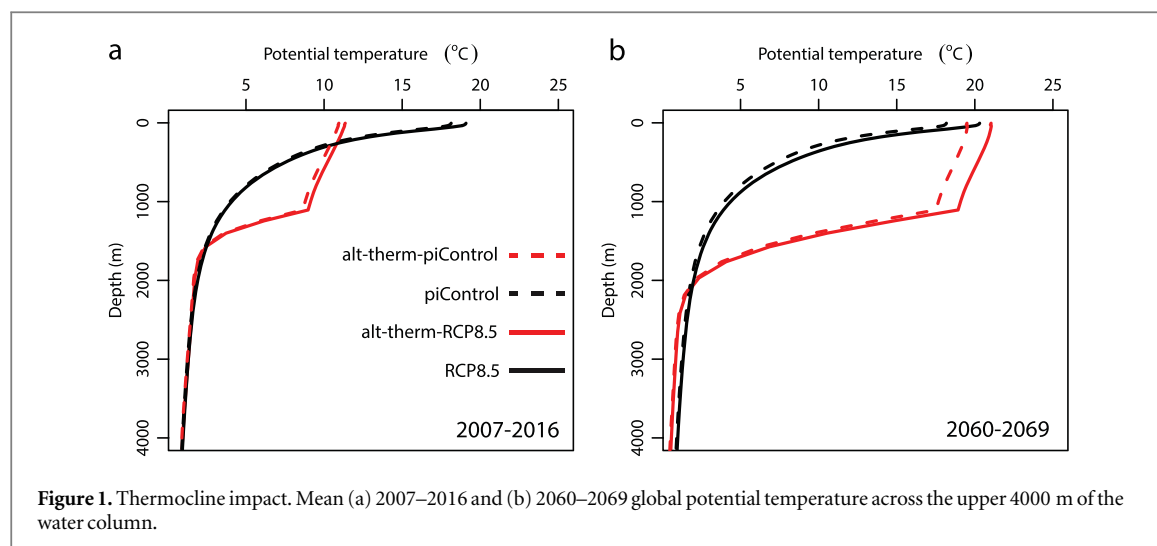
Technologies utilizing vertical ocean pipes have been proposed as a means to avoid global warming, either by providing a source of clean energy, increasing ocean carbon uptake, or storing thermal energy in the deep ocean. However, increased vertical transport of water has the capacity to drastically alter the ocean thermocline. To help bound potential climate consequences of these activities, we perform a set of simulations involving idealized disruption of the ocean thermocline by greatly increasing vertical mixing in the upper ocean. We use an Earth System Model (ESM) to evaluate the likely thermal and hydrological response of the atmosphere to this scenario. In our model, increased vertical transport in the upper ocean decreases upward shortwave and longwave radiation at the top-of-the-atmosphere due primarily to loss of clouds and sea-ice over the ocean. This extreme scenario causes an effective radiative forcing of $\approx 15.5\text{--}15.9\text{ W m}^{-2}$, with simulations behaving on multi-decadal time scales as if they are approaching an equilibrium temperature $\approx 8.6\text{--}8.8\text{ }^{\circ}\text{C}$ higher than controls. Within a century, this produces higher global mean surface temperatures than would have occurred in the absence of increased vertical ocean transport. In our simulations, disruption of the thermocline strongly cools the lower atmosphere over the ocean, resulting in high pressure anomalies. The greater land-sea pressure contrast is found to increase water vapour transport from ocean to land in the lower atmosphere and therefore increase global mean precipitation minus evaporation (P–E) over land; however, many high latitude regions and some low latitude regions experience decreased P–E. Any real implementation of ocean pipe technologies would damage the thermal structure of the ocean to a lesser extent than simulated here; nevertheless, our simulations indicate the likely sign and character of unintended atmospheric consequences of such ocean technologies. Prolonged application of ocean pipe technologies, rather than avoiding global warming, could exacerbate long-term warming of the climate system.

1. Introduction

Ocean thermal energy conversion (OTEC) (Lavi 1980, Pelc and Fujita 2002, Fujita *et al* 2012) uses the temperature gradient between surface waters and deep waters to run a heat engine in either an open or closed pipe system (Takahashi 2000). As thermal gradients are largest in the tropics, it is there that OTEC technologies have the greatest potential per unit area (Takahashi 2000, Pelc and Fujita 2002). It has also been proposed that ocean pipe technologies could increase ocean carbon uptake by bringing nutrient rich deeper waters into nutrient limited surface ocean regions, hypothetically increasing primary production

(Lovelock and Rapley 2007). If the flux of organic carbon into the deep ocean were similarly enhanced, ocean carbon uptake would increase and thus atmospheric concentrations of carbon dioxide would decrease (Shepherd *et al* 2007). Ocean pipe technologies have also been proposed as a means to limit the impact of extreme events such as hurricanes (MacCracken 2009, Salter 2009). All of these technologies have the potential to affect the thermal structure of the ocean and could in theory drastically alter the properties of the ocean thermocline.

In this paper, when we refer to ‘disruption of the thermocline’ we refer to perturbations that would shift the thermocline from the surface to the deep ocean



and diminish temperature gradients in the upper ocean. We make no assumptions about how this process would be energetically driven. Disruption of the ocean thermocline could be expected to have unintended consequences for both the ocean and atmosphere (Yool *et al* 2009, Oschlies *et al* 2010), but our focus here is on consequences for the atmosphere of technologies that would increase vertical transport in the ocean. Our study explores the atmospheric impacts that could be caused by widespread application of these technologies. Smaller deployments might be expected to have similar consequences but at smaller amplitudes.

Previous simulation studies, using simpler models, have focused on the effect of ocean pipe-like technologies on ocean carbon uptake and concluded that ocean primary productivity would increase under an ocean pipe regime, but the effect on CO₂ uptake would be highly variable and often negative (Dutreuil *et al* 2009, Yool *et al* 2009, Oschlies *et al* 2010). Such studies have also indicated that the termination of processes bringing warmer surface waters into the deep ocean has the potential to cause near surface temperatures to rise higher than they would have if pipes had never been implemented (Oschlies *et al* 2010, Keller *et al* 2014).

We extend the work of previous authors by using a full-complexity three-dimensional ocean-atmosphere carbon-climate model to focus on the atmospheric thermal and hydrological effects of greatly increased vertical mixing in the upper ocean. In particular our approach allows us to explore the ‘fast climate adjustments’ due to changes in climate variables such as cloud and the ‘slow climate feedbacks’ due to the climate response associated with gradual changes in surface temperature (e.g. Gregory and Webb 2008, Andrews *et al* 2009, Andrews *et al* 2010).

2. Method

We use the Community Earth System Model, version 1.0.4 (CESM) (Gent *et al* 2011, Lindsay *et al* 2014) to simulate an idealized disruption of the thermocline under both pre-industrial conditions (*piControl*, Taylor *et al* 2011) and the contemporary emissions scenario, Representative Concentration Pathway 8.5 (*RCP8.5*, Riahi *et al* 2011). All simulations were performed diagnostically using the fully coupled (i.e., atmosphere, land, ocean, and sea ice) version of the model at an atmospheric resolution of $1.25^\circ \times 0.90^\circ$ (f09_g16) with 26 vertical layers and an ocean nominal resolution of $1^\circ \times 1^\circ$ with 60 vertical layers. The ocean grid has enhanced horizontal resolution in the tropics and high latitudes; the Northern Hemisphere pole is displaced, residing over Greenland. The vertical grid spacing is 10 m in the upper 160 m, increasing to 250 m by a depth of approximately 3500 m and then remaining constant to the model bottom at 5500 m. Diagnostic simulations used prescribed CO₂ concentrations with computed CO₂ fluxes not affecting radiative forcing or biogeochemistry (Lindsay *et al* 2014). Ocean carbon biogeochemistry in CESM is represented by the ocean Biogeochemical Elemental Cycle model embedded within the CESM ocean component (Long *et al* 2013).

The model was spun up for 1200 years under pre-industrial control conditions before being run under historical (1850–2005) forcing in the case of *RCP8.5* simulations. The initial conditions and duration of all simulations are shown in figure S1. We simulated 66 years of climate for each of our four cases (*piControl* and *RCP8.5*, with and without disruption of the thermocline). Simulations conducted under *RCP8.5* forcing started in January 2005 and finished in December 2070. Simulations conducted under pre-industrial control conditions ran for the same duration.

Vertical diffusion within ocean general circulation models controls the vertical scale of the thermocline (Bryan 1987). Within this study the disruption of the ocean thermocline was simulated by increasing the background vertical diffusivity in the top 1000 m of the water column to $60 \text{ cm}^2 \text{ s}^{-1}$ with the intention of well mixing the upper ocean. This amount of vertical mixing greatly diminishes temperature gradients in the upper ocean (figure 1) and is orders of magnitude higher than the model's background value of $0.1 \text{ cm}^2 \text{ s}^{-1}$. While this level of increased vertical transport may be infeasible with respect to economic and engineering potential (Yool *et al* 2009), these simulations serve to explore the geophysical impacts of disruption of the thermocline within an Earth System Model. To indicate the likely responses to vertical transport increases of lower magnitude, we include two additional simulations in the supplementary material, available at stacks.iop.org/ERL/10/034016/mmedia, that increase background vertical diffusivity in the top 1000 m of the water column to $6 \text{ cm}^2 \text{ s}^{-1}$ and $0.6 \text{ cm}^2 \text{ s}^{-1}$ under pre-industrial conditions.

Although conducted within the context of ocean pipe technologies, our simulations have similarities with the early Cess experiments (Cess and Potter 1988, Cess *et al* 1990) that explored how uniform SST perturbations under perpetual month simulations influenced cloud radiative feedback processes. However in our simulations vertical mixing in the upper ocean is perturbed with global SSTs free to evolve. Whereas Cess *et al* (1990) analyse cloud feedbacks that integrate changes in temperature, moisture distribution and clouds, we separate the 'fast climate adjustments' due to changes in cloud and the 'slow climate feedbacks' due to the climate response associated with gradual changes in surface temperature (Gregory *et al* 2004). Moreover, in addition to analysing impacts on the Earth's radiation budget we also assess the impact of ocean biogeochemistry on atmosphere-ocean CO_2 fluxes as well as impacts on terrestrial hydrology, global sea ice and sea level.

We define two averaging time periods for analysis, the 'initial' period from year 2007–2016 and a 'later' period from year 2060–2069. Simulations of thermocline disruption are referred to as '*alt-therm-piControl*' and '*alt-therm-RCP8.5*'.

3. Global temperature, energy budget and carbon flux

Figure 2 shows that the simulation of thermocline disruption results in dramatic changes to the Earth's energy budget and ocean carbon fluxes. The energy budget and ocean carbon flux effects of disruption of the ocean thermocline are generally far more apparent than the differences between the *piControl* and *RCP8.5* simulations. This is due to the magnitude of enhanced vertical mixing in these simulations and, as discussed

in detail later, the effective radiative forcing that this results in.

The *alt-therm-RCP8.5* simulation initially (2007–2016) results in a global mean temperature decrease of 8.31°C relative to the *RCP8.5* simulation (figure 2(a)). As outgoing top-of-atmosphere energy fluxes are related to mean surface temperatures through a number of processes (Gregory *et al* 2004, Donohoe *et al* 2014), the reduction in surface temperature is consistent with a reduction in outgoing longwave radiation (figure S2). However in addition to this reduction in outgoing longwave radiation that previous simulation studies have found (e.g. Oschlies *et al* 2010), we also see a reduction in outgoing shortwave radiation due to decreases in global cloud fraction and sea ice causing a reduction in mean planetary albedo (figures S2–6). The combination of these shortwave and longwave effects results in net downwelling energy fluxes at the top of the atmosphere of 31.78 W m^{-2} (figure 2(b)) during the initial period of our *alt-therm-RCP8.5* simulation.

The initial (2007–2016) reduction in outgoing shortwave radiation is primarily due to the loss of clouds, with clear sky net shortwave fluxes at the top of the atmosphere relatively unaffected (figures 3 and S2). This is despite a rapid loss of sea ice (figures S3–4) and is a consequence of lower surface albedo in the Southern Ocean being offset by higher surface albedo predominately across Northern hemisphere land masses and to a lesser extent the arctic ocean (figures S4–5). Over the duration of thermocline disruption simulations this enhanced albedo across Northern hemisphere land masses is lost in combination with the accelerated melting of arctic sea ice (figures S4–5). Consequently over time mean clear sky outgoing shortwave fluxes at the top of the atmosphere decrease and contribute to the outgoing shortwave reductions seen under all sky conditions (although these are still largely due to cloud loss). Cloud interactions have limited influence on the reduction in outgoing longwave radiation which is driven by the Planck feedback and therefore mean longwave fluxes at the top of the atmosphere are similar under all sky and clear sky conditions (figure S2).

The impact of thermocline disruption on surface latent and sensible heat fluxes is shown in the supplementary material, with enhanced vertical mixing resulting in large reductions in latent heat flux as would be intuitively expected due to near surface cooling. Impacts on sensible heat fluxes are of a much lower magnitude, with thermocline disruption causing initial increases followed by gradual reductions (figures S8–11).

Under *RCP8.5*, mean carbon fluxes into the ocean are $2.86 \text{ Pg C yr}^{-1}$ during the initial (2007–2016) period. Thermocline disruption, however, causes outgassing of $3.20 \text{ Pg C yr}^{-1}$ during this period (figure 2(c)) as colder CO_2 rich water is transported to the surface. Note that as the model simulations are run

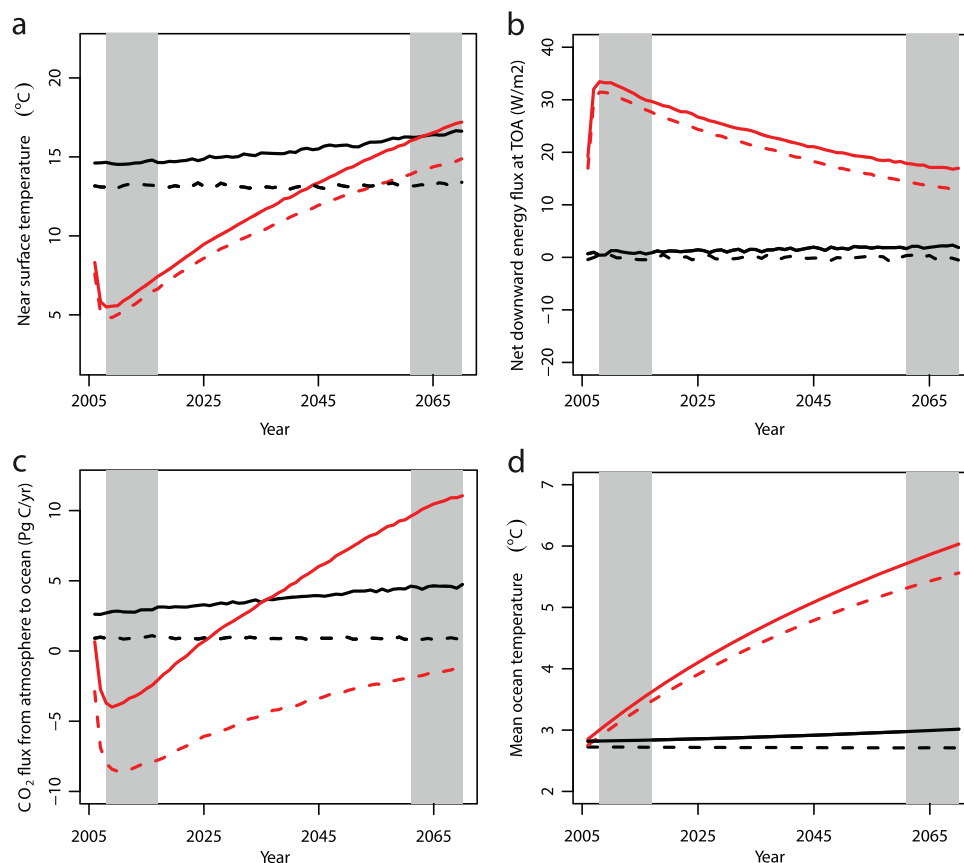


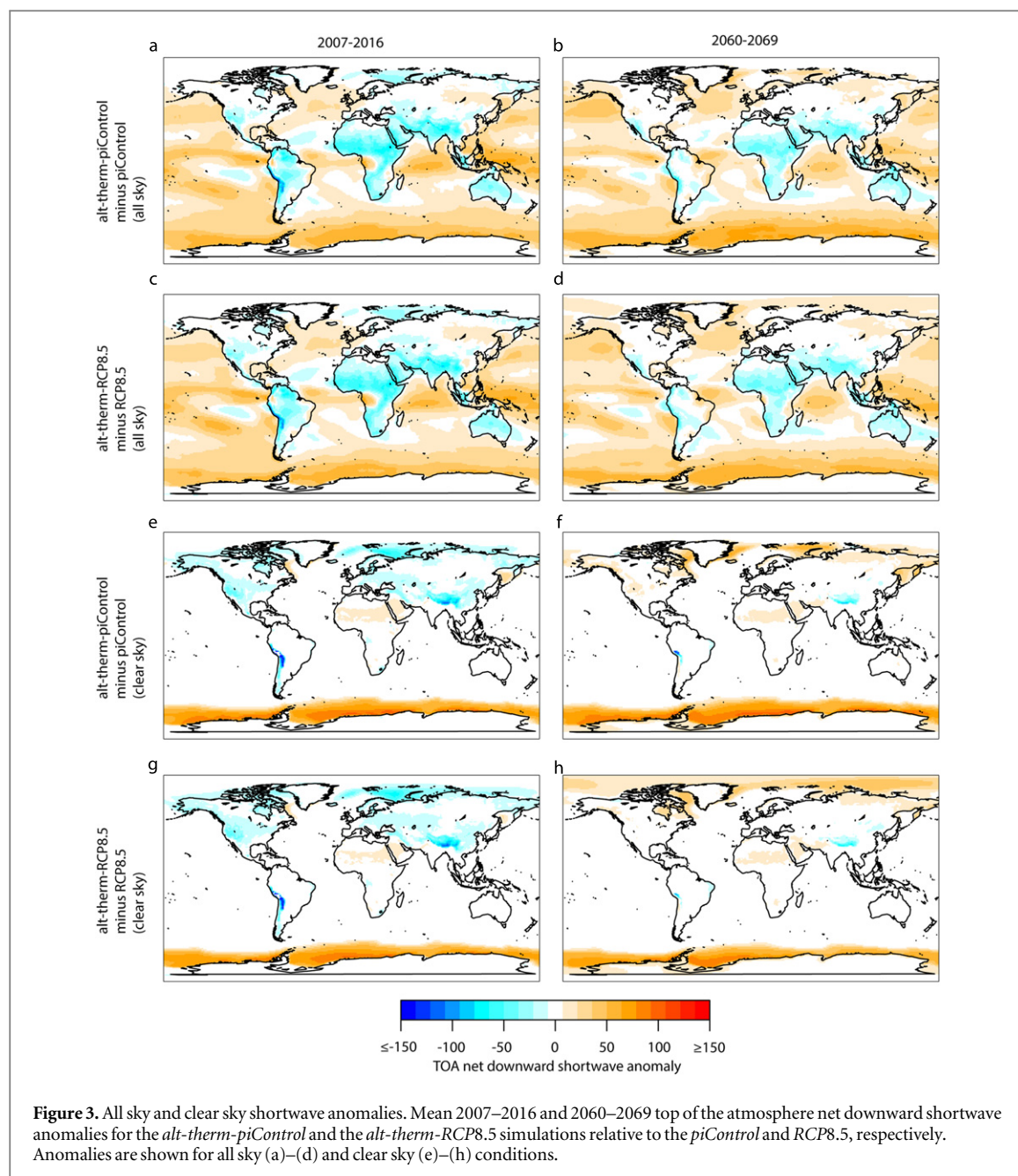
Figure 2. Temperature, energy budget and carbon flux response. (a) Global mean near surface atmospheric temperatures ($^{\circ}\text{C}$), (b) top of the atmosphere net downward energy fluxes (W m^{-2}), (c) dissolved inorganic carbon fluxes from the atmosphere to ocean (Pg C yr^{-1}) and (d) mean ocean temperature ($^{\circ}\text{C}$) for RCP8.5 (bold lines) and pre-industrial control (dashed lines) simulations. RCP8.5 and *piControl* simulations are shown in black and thermocline disruption simulations in red. Grey shading shows the decadal periods of initial impact (2007–2016) and later response (2060–2069).

diagnostically these CO_2 fluxes do not affect radiative forcing or biogeochemistry. Surface ocean dissolved inorganic carbon concentrations increase because upward physical transport of carbon overwhelms increased downward biological transport of carbon (figure S12).

In the later (2060–69) period, the high atmospheric CO_2 concentration of the RCP8.5 scenario causes a substantial increase in dissolved inorganic carbon in the near-surface ocean and the greater vertical mixing in the *alt-therm-RCP8.5* simulation helps transport this carbon to the deep ocean. This effect dominates ocean carbon transport with the result that the disturbed thermocline causes ocean carbon uptake to increase in the later period (figure 2(c)). The ocean becomes a net carbon sink by 2025 under the *alt-therm-RCP8.5* conditions with this sink increasing to $10.44 \text{ Pg C yr}^{-1}$ by 2060–69, (a 127.9% increase relative to the carbon sink in this time period for the RCP8.5 scenario in the absence of increased vertical mixing; figure 2(c)). These fluxes are driven by increasing atmospheric CO_2 concentrations. Note that such effects are not seen when thermocline disruption is implemented in the *piControl* (*alt-therm-piControl*)

scenario because CO_2 concentrations are not increasing.

Over time the cooling due to thermocline disruption declines and by the later (2060–69) period global mean near surface temperature is 0.20°C higher in the *alt-therm-RCP8.5* than in RCP8.5 and 1.14°C higher in the *alt-therm-piControl* than in the *piControl* (figure 2(a)). As described below, this transition from net cooling to net warming over time is a consequence of the limited capacity of the ocean below the mixed layer to store thermal energy, and increased net downward radiative fluxes at the top of the atmosphere (figure 2(b)) continue to be greater in the *alt-therm-RCP8.5* simulation (17.29 W m^{-2}) than in RCP8.5 (2.01 W m^{-2}). Thus, although global near surface atmospheric temperatures are only 0.20°C and 1.14°C higher by 2060–69 in the thermocline disruption simulations (figure 2(a)), the amount of energy stored in Earth's climate system as a whole is substantially higher. This additional energy is primarily stored in the ocean, where average (2060–69) temperatures combined across all depth levels are 2.88°C higher in the *alt-therm-RCP8.5* than in RCP8.5 (figure 2(d)). A consequence of this is that there is



thermal expansion of the ocean and sea level rise. Using an estimated 12 cm sea level rise per additional 10^{24} J of energy stored in the ocean (Kuhlbrodt and Gregory 2012) we compute that thermal expansion would account for mean sea level rise in excess of 1.5 m by year 2060 of thermocline disruption simulations.

An increase in the simulation of ocean vertical mixing drives warm upper ocean water downward and cold deeper water upwards, this would tend to decrease transient near-surface temperatures in the *alt-therm-piControl* simulation relative to the *piControl*. However, within several decades, *alt-therm-piControl* temperatures exceed those of the *piControl*.

A regression analysis (Gregory *et al* 2004) indicates that thermocline disruption imparts a large effective radiative forcing, estimated as the y-intercept of the

regression line (figure 4). A similar linear relationship between top-of-atmosphere net downward radiation fluxes and near surface temperatures is seen in both the *alt-therm-piControl* and the *alt-therm-RCP8.5* simulations (figure 4). Such relationships imply that thermocline disruption results in effective radiative forcing (in the absence of any temperature change) of ≈ 15.5 – 15.9 W m^{-2} (for the *RCP8.5* and *piControl* simulations, respectively) and over the course of simulations the thermocline disruption simulations behave as if they are approaching an equilibrium temperature ≈ 8.6 – 8.8 °C warmer than the respective *RCP8.5* and *piControl* simulations. Under clear sky conditions effective radiative forcing is reduced by ≈ 10.2 – 10.8 W m^{-2} (figure S14) which can be attributed to cloud interactions and changes in atmospheric water vapour. The remaining effective radiative

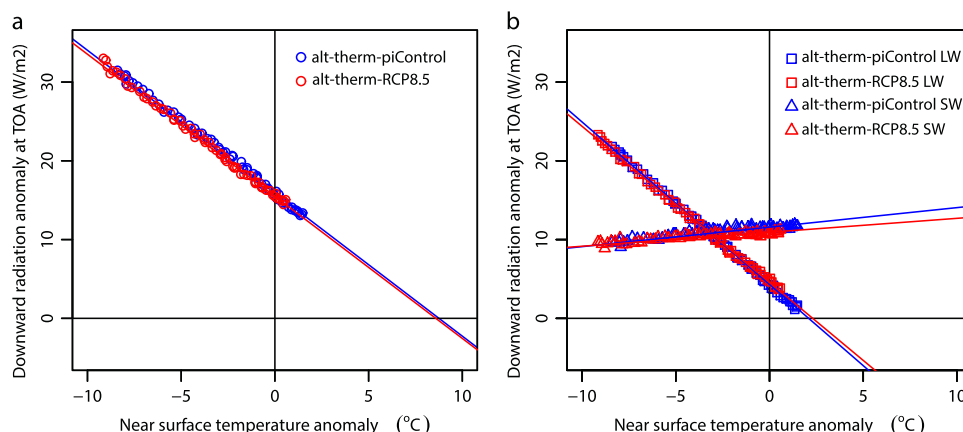


Figure 4. Effective radiative forcing and equilibrium temperatures. Annual near surface temperature anomaly and downward radiation anomaly at the top of the atmosphere for the *alt-therm-piControl* (blue) and *alt-therm-RCP8.5* (red) simulations relative to the respective *piControl* and *RCP8.5* simulations. Downward radiation anomalies are shown for (a) combined fluxes and (b) separable longwave (LW) and shortwave (SW) fluxes.

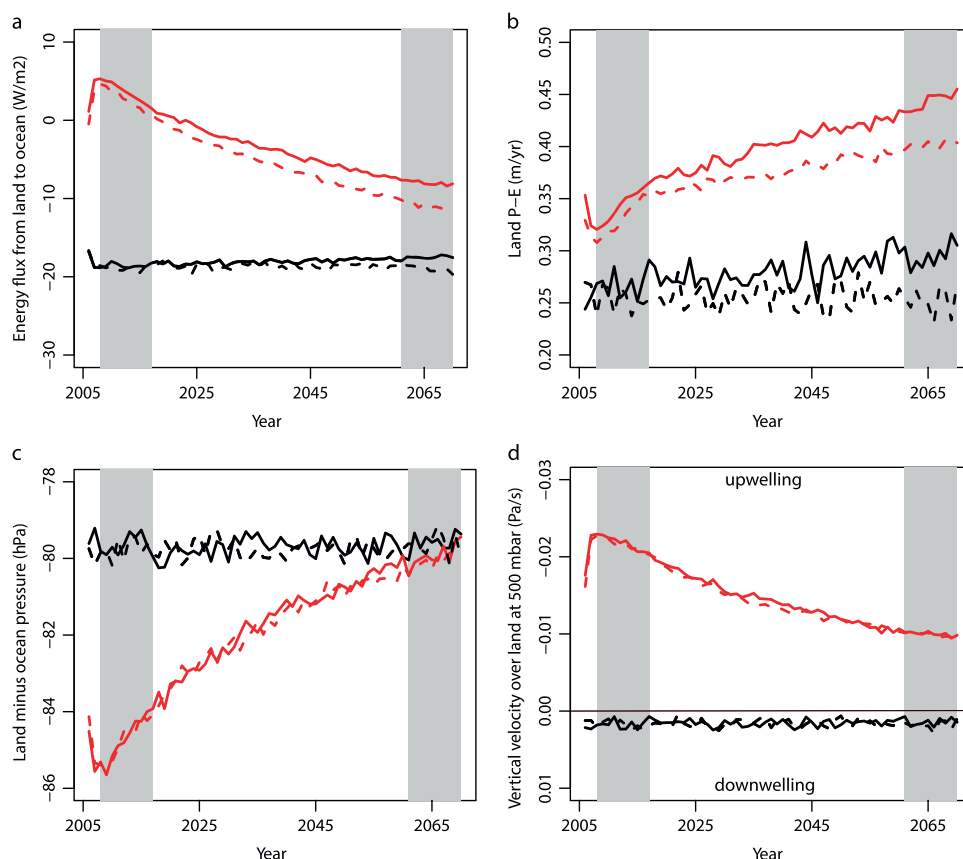
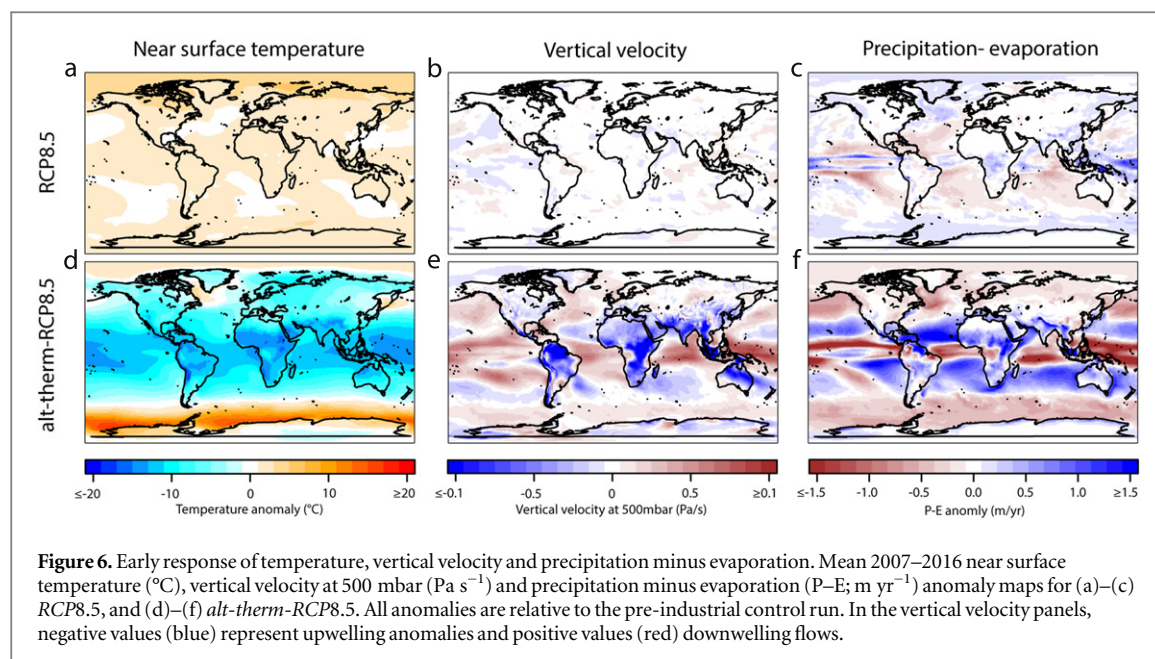


Figure 5. Energy and water vapour transport between land and ocean. (a) Annual energy flux from land to ocean (W m^{-2}), (b) land precipitation minus evaporation ($P-E$) (m yr^{-1}), (c) global mean land-minus mean ocean pressure (Pa) and (d) terrestrial vertical velocity at 500 mbar (Pa s^{-1}) for *RCP8.5* (bold lines) and pre-industrial control (dashed lines) simulations. Negative vertical velocities in units of Pa s^{-1} represent upwelling flows and positive velocities represent downwelling flows. *RCP8.5* and *piControl* simulations are shown in black and thermocline disruption simulations in red. Grey shading shows the decadal periods of initial impact (2007–2016) and later response (2060–2069). Note that values at the nominal 500 mb tracer point are strictly at 510 mb as we do not interpolate within depth levels.

forcing is due to the loss of sea ice and the global changes in surface albedo. We note however that shortwave cloud feedbacks are one of the largest sources of uncertainty in current generation climate models

(Sherwood *et al* 2014) and as such these results are likely to vary between ESMs. Our results show that a change in ocean heat transport can produce a large effective radiative forcing despite not having any direct



effect on Earth's top-of-atmosphere radiative balance, either in the shortwave or longwave. Additional simulations with the enhanced vertical diffusivity decreased by one and two orders of magnitude are given in the supplementary material and the same qualitative behaviour of temperatures and energy fluxes is found across this entire range.

4. Transport of energy and water vapour between land and ocean

Net energy flux from ocean to land is calculated as the difference between the net radiative balance at the surface over land (*surface downwelling shortwave—surface upwelling longwave—latent heat flux—sensible heat flux*) and the net radiative balance at the top of the atmosphere over land (*TOA downwelling SW—TOA upwelling LW*). Under *RCP8.5* (and pre-industrial) conditions net energy flows from the ocean to the land. With the simulation of thermocline disruption this energy flow is initially reversed due to the large thermal sink that is now accessible in the oceans (figure 5(a)).

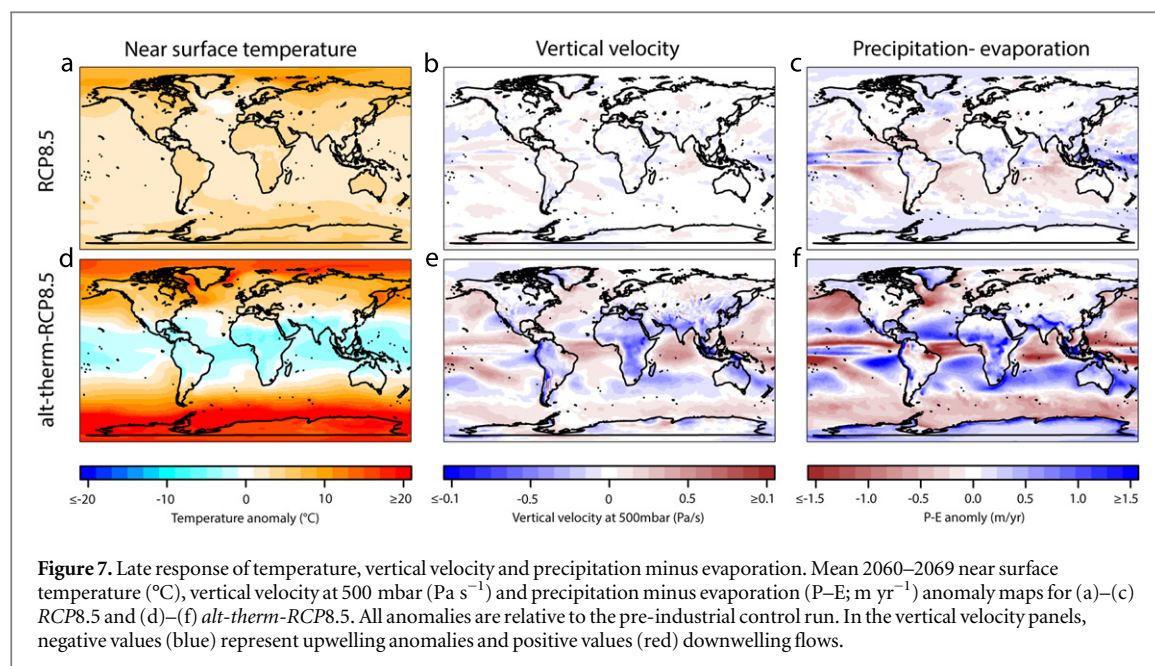
The precipitation minus evaporation (P-E) balance in a region indicates net atmospheric water transport, and, on land, is also a proxy for the sum of river runoff and changes in storage. With thermocline disruption, land P-E increases (figure 5(b)) despite the reduced water-holding capacity of the atmosphere at lower temperatures (Wentz *et al* 2007). This is a consequence of intensified transport from ocean to land in the lower atmosphere, driven in part by greater land-ocean pressure contrast as discussed below (figures 5(c) and S15). This intensified transport results in a large increase in upwelling vertical velocity at 500 mbar over land (figure 5(d)).

Throughout the duration of thermocline disruption simulations, the atmosphere over the ocean warms, resulting in an increase in absolute humidity. The higher absolute humidity of air transported from ocean to land in the lower atmosphere (figure 5(d)) plays a role in the increase in P-E over land, although this effect would be modulated by changes to the surface energy fluxes (Boer 1993, Allen and Ingram 2002).

5. Spatiotemporal variability of temperature and hydrology impacts

The temperature and hydrological impacts of thermocline disruption simulations have high spatial variability. Initially, low latitude ($<30^{\circ}$ latitude) near surface atmospheric temperatures over the ocean are reduced by 12.26°C in the *alt-therm-RCP8.5* simulation compared to *RCP8.5* (figure 6). In the Northern hemisphere high latitudes ($>60^{\circ}\text{N}$) temperatures over the ocean are reduced by 5.34°C while temperatures over land masses are reduced by 8.11°C . As temperatures increase with depth below Southern Ocean sea ice, with colder fresher water overlying warmer saltier water, increased vertical mixing brings this warmer water in contact with the sea ice. The consequent loss of sea ice (figure S4) results in large increases in latent and sensible heat fluxes in the high latitude southern hemisphere (figures S9–11), warming the overlying atmosphere. Mean near surface atmosphere temperatures increase by 0.75°C over Antarctica and by 8.73°C over the Southern Ocean (figure 6).

In the period from 2007–2016, P-E changes resulting from thermocline disruption exhibit a high degree of spatial variability (figure 6(f)). Increases in P-E occur largely in the tropics where thermocline



disruption promotes greater atmospheric pressure contrast between the oceans and land (figure S15), one of the drivers of land-ocean atmospheric transport. This is a result of cooling of the surface ocean by deeper waters, which in combination with the greater temperature sensitivity of moist oceanic adiabats (Joshi *et al* 2008), leads to enhanced cooling of the vertically integrated air mass over the ocean relative to land.

The intensified transport from ocean to land in the lower atmosphere combined with lower relative pressures over land increases upwelling vertical velocities at 500 mbar over most low latitude land regions (figures 6(e) and (f)). Rising air over land draws in air masses from the ocean that generally have a much higher specific humidity. This increases the formation of clouds over low latitude land masses (figure S6), and the net transport of water from ocean to land, consistent with the global scale relationship between mean P-E over land and upwelling vertical velocities illustrated in figure 5.

Increases in P-E can exceed 0.5 m yr^{-1} in regions where thermocline disruption promotes the upward motion of air masses, whereas tropical decreases in P-E are largely seen in regions where thermocline disruption promotes a downward motion of air masses (figure 6). It should be noted however, that there are large uncertainties in current generation ESM precipitation outputs, especially in the tropics (Chadwick *et al* 2012, Rowell 2012), and these uncertainties could have a large impact on the P-E spatial patterns simulated. As such, although beyond the scope of this study, it would be useful to assess the consistency of spatial P-E anomalies within an enhanced vertical mixing multi-model ensemble experiment.

The effects of enhanced vertical mixing on the spatial distribution of precipitation as well as surface

sensible and latent heat fluxes are shown in the supplementary material. As would be expected thermocline disruption reduces surface latent heat fluxes over the low and mid-latitude ocean where there is cooling and increases surface latent and sensible heat fluxes across the high latitude ocean where there is warming. Over land masses, areas that experience increased precipitation under thermocline disruption generally partition heat flux changes into increased surface latent heat fluxes and decreased sensible heat fluxes.

The spatial pattern of near surface air temperature anomalies are much changed in the later period (2060–2069; figure 7(d)) relative to the earlier period (2007–2016; figure 6(d)). In the later period, the tropics are still cooler in the *alt-therm-RCP8.5* simulation than in RCP8.5, albeit not as cool as they were in 2007–2016. The Southern hemisphere high latitudes, however, have land temperatures 13.90°C higher than the RCP8.5 simulation and temperatures over the Southern Ocean are 19.01°C higher. These high polar temperatures are, as previously mentioned, a consequence of the melting of sea ice (figure S4). With the high latitude atmosphere no longer insulated from the warmer ocean sensible heat fluxes and especially latent heat fluxes show large increases in these regions (figures S9–S11) contributing to very high near surface temperature anomalies. Furthermore, the loss of sea ice leads to increased absorption of downward short-wave radiation (figure S9).

In contrast to near surface air temperature anomalies, in the later period, P-E anomalies associated with thermocline disruption simulations are spatially similar to those seen in the earlier period (figures 6(f) and 7(f)) with atmospheric vertical velocities also showing consistent global scale spatial features. An exception to this is seen over the land masses of the mid-high

latitudes where P–E reductions are much less apparent in the later period.

6. Conclusions

We have focused on the atmospheric impacts of an idealized disruption of the ocean thermocline, shifting the thermocline from the surface to the deep ocean via artificially enhanced vertical mixing of the surface ocean. Such an assessment could be viewed as an upper estimate of the geophysical impact of technologies relying on ocean pipes such as OTEC.

Consistent with the results of others (Dutreuil *et al* 2009), we find that the initial direct effect of increased vertical transport in the upper ocean is to cause CO₂ to degas from the ocean to atmosphere. Ocean thermocline disruption is found to initially cause large-scale outgassing of 3.20 Pg C yr⁻¹ as colder CO₂ rich water is transported to the surface. Surface ocean dissolved inorganic carbon concentrations increase as increased upward transport of carbon due to vertical mixing overwhelms any increased export flux. However, the long term evolution of ocean-atmosphere carbon fluxes is highly dependent on atmospheric CO₂ concentration. As downward transport of anthropogenic carbon increases with increased vertical mixing, the ocean becomes a carbon sink by 2025 in the *alt-therm-RCP8.5* simulation yet remains a carbon source throughout the *alt-therm-piControl* simulation.

Initially, the disruption of the ocean thermocline causes a dramatic decrease in near surface atmospheric temperatures due to the large thermal sink that becomes available in the deep ocean. As outgoing top-of-atmosphere energy fluxes are related to mean surface temperatures (Gregory *et al* 2004), the reduction in surface temperature results in net downwelling energy fluxes at the top of the atmosphere and less energy being lost to space. In our simulations, this is a consequence of both a reduction in outgoing long-wave radiation and a reduction in outgoing shortwave radiation associated with decreases in cloud fraction largely over the ocean and a reduction in mean planetary albedo. Thermocline disruption results in effective radiative forcing (in the absence of any temperature change) of 15.5–15.9 W m⁻² and over the course of simulations the thermocline disruption simulations behave on the multi-decadal time scale as if they are approaching an equilibrium temperature 8.6–8.8 °C warmer than the respective *piControl* and *RCP8.5* simulations.

As the disruption of the thermocline is maintained over time the amount of energy stored in Earth's climate system (i.e., atmosphere, land, and ocean) increases. By 2060–69 near surface temperatures are actually higher than would have been reached had such thermocline disruption processes never been implemented. This is largely a consequence of the

effective radiative forcing associated with rapid adjustment to increased ocean vertical mixing. Previously such findings have only been seen upon an abrupt termination of enhanced vertical mixing processes (Oschlies *et al* 2010).

The disruption of the ocean thermocline increases net water vapour transport from ocean to land, and thus on average increases precipitation minus evaporation on land. The greater land-ocean pressure contrast results in a large increase in upwelling vertical velocities over land masses and downwelling vertical velocities over the ocean, with intensified transport from ocean to land in the lower atmosphere. However in addition to such circulation changes, temperature dependent changes in absolute humidity and the surface energy budget also strongly influence global P–E anomalies over land.

There is a high degree of spatial heterogeneity in atmospheric impacts, with the potential for considerable warming in the high latitudes and both increases and decreases in land P–E.

We show in simulations that that disruption of the ocean thermocline could result in initial levels of global mean cooling considerably greater than projected global mean climatic warming this century. However, such temperature responses are shown to not persist in time, with net near surface warming evident after approximately 50 years of simulation. We find that increased vertical mixing increases long-term global mean temperatures. This fundamental behaviour is consistent across two-orders-of-magnitude of applied changes to ocean vertical diffusivity, indicating that our results may apply broadly to increases in vertical heat transport in the upper ocean. Thus, while ocean pipe technologies have often been proposed as means to avoid global warming, our simulations suggest that widespread deployment of such technologies could ultimately add to global warming.

Acknowledgments

Funding for this work was provided by the Fund for Innovative Climate and Energy Research (FICER) and the Carnegie Institution for Science endowment.

Author contributions

LK and KC designed and conducted the research and analysis. LK and KR performed the model simulations. LK, KR and KC wrote the paper.

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