Effects of Ocean Circulation on Ocean Anthropogenic Carbon Uptake

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Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
under the Executive Committee
of the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2020

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Abstract

Effects of Ocean Circulation on Future Ocean Carbon Uptake

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The ocean is the only cumulative sink of atmospheric CO_2 . It has absorbed approximately 40% of the CO_2 from fossil fuel burning and cement production, lowering atmospheric CO_2 and limiting climate change. Here we will examine the regional and global mechanisms controlling the evolution of ocean uptake of this additional carbon from human activities (anthropogenic carbon, $0=\mathbb{C}$) using ocean models and observations. $0=\mathbb{C}$ is rapidly injected into the deep ocean, sequestering it from the atmosphere for centuries. It is currently uncertain whether any of this sequestered $0=\mathbb{C}$ was absorbed from the atmosphere in the subpolar North Atlantic. Here we present evidence that the upper limb of the ocean's overturning circulation supplies the subpolar North Atlantic with capacity to absorb $0=\mathbb{C}$ from the atmosphere. Using a coupled ocean model, we find that surface freshening of the subpolar North Atlantic reduces the volume available for $0=\mathbb{C}$ storage. We also investigate whether global ocean $0=\mathbb{C}$ uptake is reduced due to changing ocean circulation, this time across multiple emission scenarios, including scenarios with aggressive emission mitigation. Though it is clear that emission mitigation will reduce the magnitude of the ocean carbon sink, the mechanisms governing the decline in uptake have not been studied in detail. We find that the ocean sink becomes less efficient due to kinematic effects wherein $0=\mathbb{C}$ escapes from the surface ocean as atmospheric CO_2 plateaus and then declines. In emission scenarios ranging from high to low emissions, projected changes in global $0=\mathbb{C}$ uptake due to ocean circulation are small. This is in contrast with the subpolar North Atlantic, where future circulation change plays a important role in the declining $0=\mathbb{C}$ uptake.

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Introduction

I.I Carbon Dioxide, the Primary Driver of Climate Change

The industrial revolution initiated the largest uncontrolled experiment ever conducted. By perturbing the carbon cycle, fossil fuel combustion, cement production, and land use change (LUC) have resulted in a human-attributable (anthropogenic) increase in atmospheric carbon dioxide gas (CO_2). It has been these changes to the carbon cycle that drive climate change, via an increase in the greenhouse effect. Increasing the greenhouse effect will increase Earth's surface temperature, which then drives sea level rise, increases in drought and heavy rainfall, heat waves, and other changes that can dramatically impact our lives (IPCC 2014).

The greenhouse effect is the ability of trace gases such as CO_2 and water vapor to keep Earth's surface warm. Physical properties of these trace gases allow them to absorb the upwelling longwave radiation emitted by the surface and return that energy back towards the surface. Amplifying the greenhouse effect works to warm the climate by altering how much heat energy leaves Earth's surface. The sun emits shortwave radiation, with about 30% of that energy being re ected back to space by clouds (Figure I.1). Most of the remaining downwelling shortwave radiation is absorbed by the surface and then emitted by Earth's surface as upwelling longwave radiation. The upwelling longwave radiation is absorbed by greenhouse gases and redirected towards the surface, resulting in an elevated surface temperature relative to an atmosphere free of greenhouse gases. Greenhouse gases are quite effective at warming the planet, keeping the surface 33°C warmer (the

greenhouse effect), than if the atmosphere was pure nitrogen (IPCC 1994). Increasing the concentration of greenhouse gases increases this warming effect. Thus, increases in atmospheric CO_2, a greenhouse gas, would act to increase surface temperature by trapping more energy at the surface.

Figure I.1: Schematic of the pathways of shortwave (yellow) and longwave radiation (orange). Numbers show the present day climatological energy uxes in units of W/m^2. Figure originally published in IPCC AR5 (Hartmann et al. 2013)

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The instantaneous effect of increasing CO_2 is a change in the radiative balance at the top of Earth's atmosphere, which is referred to as radiative forcing. This is related to surface temperature because changes in radiative forcing, as discussed above, heat Earth's surface. Radiative forcing can be changed by trace gases other than CO_2, including halocarbons (such as CFCs) and methane, as well as natural variations such as changes in insolation. Positive radiative forcings act to warm the surface, while negative radiative forcings act to cool the surface. Anthropogenic CO_2 is the dominant radiative forcing, contributing 75% of the net positive radiative forcing in 2011, while natural radiative forcings contribute almost nothing (Hartmann et al. 2013). Today, this positive forcing has generated approximately a global average of 1°C of warming since preindustrial times. Having shown the physical link between CO_2 and climate, we will focus on the controls on the future atmospheric concentration of CO_2, and thus future temperature.

I.II Determining the Sources and Sinks of Atmospheric CO_2

In 1896, Svante Arrehnius became the first to pose that fossil fuel combustion would result in a change in atmospheric CO_2, and this increase in atmospheric CO_2 would result in climate change. Arrhenius (1896) was the first to develop a quantitative relationship between temperature and CO_2 concentration. With this derived relationship, one would predict that Earth's climate would warm by approximately 5-6°C for a doubling of atmospheric CO_2, and that the doubling of atmospheric CO_2 due to combustion of coal would take tens of thousands of years. While the fundamental concept was sound, neither the predicted warming for a doubling of CO_2, nor the time it would take to double CO_2, were correct because some important processes were unknown at the time.

These errors in estimating the CO_2 doubling time scale and the magnitude of warming are primarily due to a poor understanding of the carbon cycle and missing radiative feedbacks. The Arrhenius model for CO_2 induced surface warming did not account for cloud feedbacks, the presence of other anthropogenic radiative forcings that could act to cool the climate, and the interaction of aerosols with clouds. Even today, these processes are still a significant challenge to model. Better understanding of these feedbacks suggests a much lower estimate of warming from a doubling of CO_2, 1.5-4.5°C (17-83% CI; IPCC, 2013). Also, Arrenhnius erroneously concluded that the geological sinks of carbon dioxide were so large, and the growth of anthropogenic CO_2 emissions so slow, that the doubling of atmospheric CO_2 would take tens of thousands of years. After approximately 220 years of fossil fuel burning, we're approximately halfway to doubling atmospheric CO_2.

What factors led Arrehnius to be so far off on the CO_2 doubling time scale? In order to accurately predict the change of any quantity inside a control volume one must know the magnitude of the relevant sources and sinks. Today, we are able to use numerical models and an extensive observation network to determine the magnitude of atmospheric sources and sinks. With these tools, we have identified all of the relevant sources and sinks: the land biospheric sink and the sol-

ubility driven ocean sink (Figure I.2). In gure I.2, land uptake refers to only the land biospheric component of land uptake. When combining this term with the other land term, LUC, land uptake is reduced by 47%. We refer to combined LUC and biospheric land uxes as "net land" uptake. This is a useful way to partition uxes because observations of the change in atmospheric CO_2 and ocean CO_2 uptake can be used to estimate the net land sink by residual. Anthropogenic CO_2 emissions (fossil-fuel, industry, LUC) are the dominant source to the atmosphere, and are calculated using reports from individual countries

Figure I.2: Sources (upward arrows) and sinks (downward arrows) of atmospheric CO_2. Reservoir size shown as dots. Figure originally published in the Global Carbon Budget (Friedlingstein et al. 2019).

While calculating fossil emissions were feasible in Arrehnius's time, running the complex numerical models and implementing a global observation network were not. It would take more than 50 years before scientists had the observations to begin revisiting the idea that fossil fuel emissions were altering the carbon cycle. Researchers continue to develop this observation network and improve our understanding of the sources and sinks to the atmosphere, 124 years after Arrehenius

(1896).

Until the late 1950s, it had been assumed that the ocean could absorb all of the CO_2 from fossil fuel emissions, and that this could continue inde nitely (Revelle and Suess 1957). Revelle and Suess 1957 were the rst to provide evidence that the ocean sink would be unable to keep up with future emissions; therefore, fossil fuel combustion would increase atmospheric CO_2 and thus change Earth's climate. The Revelle and Suess 1957 prediction was based on radiocarbon measurements and an estimate of the buffer capacity. In order to estimate buffer capacity, and thus the uptake rate of the ocean, one must consider the chemistry of seawater. When CO_2 enters the ocean it participates in chemical reactions that convert CO_2 into chemical species that do not exchange with the atmosphere, thus hiding CO_2 from the atmosphere and enhancing the CO_2 uptake rate of the ocean by effectively reducing the concentration of CO_2 in seawater. The effectiveness of this chemical process is quanti ed as the buffer capacity of the ocean, which we discuss in more detail in Chapter 3. This buffer capacity allowed past CO_2 emissions to be absorbed almost entirely by the ocean; however, Revelle and Suess 1957 correctly predicted that this would not be the case in the future because CO_2 emissions were projected to increase faster than the ocean could absorb carbon. In summary, this work was the rst to provide evidence that the ocean is a sink, enhanced by the chemical composition of seawater, and that natural sinks alone cannot not mitigate anthropogenic CO_2 emissions. More measurements would be required to determine that fossil fuels were the dominant source to the atmosphere, and that the ocean was the primary sink.

An important advancement towards determining the driver of present CO_2 increase came from Keeling et al. 1976, who made the rst daily measurements of atmospheric CO_2 in 1958 at Mauna Loa. From this point measurement, as well as measurements in Antarctica, Keeling et al. 1976 determined that atmospheric CO_2 was increasing, which would be expected if anthropogenic emissions were driving climate change. Tracking the change in atmospheric CO_2 is possible with only a few observing stations because atmospheric CO_2 is well mixed on inter-annual timescales. Combining the observed change in atmospheric CO_2, with an inventory of CO_2 emissions from fossil fuel combustion and cement production, Keeling et al. 1976 determined that half of an-

thropogenic CO_2 emissions remained in the atmosphere, with the other half being absorbed by sinks. The fraction of emissions remaining in the atmosphere is referred to as the airborne fraction, with continued observations indicating that the airborne fraction has remained relatively constant (Gloor, Sarmiento, and Gruber 2010). The work of Keeling et al. 1976 determined whether atmospheric CO_2 was increasing due to fossil fuels, and proved the existence of a sink of anthropogenic CO_2 emissions.

The increase in anthropogenic CO_2 in atmosphere drives the sequestration of anthropogenic CO_2 in the land biosphere and ocean. Since the land and ocean store CO_2 in various forms, we track the exchange of carbon, not CO_2. The additional human attributable carbon is referred to as anthropogenic carbon (C_{anthro}). Over the industrial era (1765-present), the ocean has been a sink, accumulating 140 ± 25 Pg C_{anthro} (1 Pg C = 10^{15} g C) as of 2009 (Khatiwala, Primeau, and Hall 2009). Over this same time period, cumulative (industrial era) LUC and biospheric uptake have combined to be a small cumulative source (20 ± 36 Pg C_{anthro}; Khatiwala et al. 2009). While land (LUC + biospheric uptake) has cumulatively been a source of C_{anthro}, there is a growing land biospheric sink. Increasing atmospheric CO_2 concentration, in the absence of its radiative effects, enhances plant photosynthesis, and thus storage of CO_2 in plant biomass. Annually, the net land has been a C_{anthro} sink since the 1940s due to CO_2 enhanced biospheric uptake beginning in the 1940s (Houghton 2007), just not enough of a C_{anthro} sink to account for the LUC earlier in the industrial era. Therefore, cumulatively, the net land (land biosphere + LUC) has been close to net zero. That leaves only the ocean as the cumulative sink for ~40% of CO_2 emissions from fossil fuel combustion and cement production.

While today we know that the annual natural sink is roughly equally partitioned between the land biosphere and ocean, observations that could determine this partitioning did not exist in 1976. Our understanding of the land biosphere's response to CO_2 would lag that of the ocean for decades. Observations of the biosphere's response to CO_2 were extremely limited, and the observations that existed led scientists to conclude that it would be difficult to perturb land ecosystems in a way that would allow them to sequester C_{anthro} (Popkin 2015). There is large, plant community driven,

spatial variability that makes the land biosphere more challenging to observe that the ocean. Other scientists, such as Revelle and Suess 1957, concluded that the land biosphere was limited by soil nutrients, therefore the addition of CO_2 to the atmosphere would not result in enhanced growth. Along with the dif culty of obtaining observations, the land biosphere's response to increasing CO_2 is also far more complicated than the solubility driven response of the ocean. As of today, land carbon cycle models are still highly uncertain (Lovenduski and Bonan 2017). The challenges of observing the land biospheric sink allowed ocean models to become the primary tool to constrain the natural sinks.

The expected outcome was that ocean models and anthropogenic emissions inventories would close the atmospheric CO_2 budget. Instead, what the ocean model results suggested, contrary to previous work, was that there was a sink in the land biosphere. Lacking direct observations of the carbon cycle, modellers leveraged other atmosphere and ocean observations to constrain their models. Observations, such as measurements of radiocarbon and other tracers in the ocean (GEOSECS, 1972-1978) for each ocean basin, allowed for quanti cation of the components of the ocean general circulation. Using simple box models like Broecker, Li, and Peng 1971, and with these observations, modellers attempted to model ocean carbon uptake (Siegenthaler and Oeschger 1987). The HILDA (HIgh Latitude-exchange/interior Diffusion-Advection) model (Siegenthaler and Joos 1992; Shaffer and Sarmiento 1995) was the rst box model to realistically simulate ocean uptake of ^{14}C. The model was very simple, consisting of 4 boxes. Using nutrients, radiocarbon, and temperature observations from GEOSECS, the authors tuned the vertical diffusivity of the model so that the modeled vertical pro le matched the observed pro le of these tracers. Others (Maier-Reimer and Hasselmann 1987; Sarmiento, Orr, and Siegenthaler 1992) used ocean General Circulation Models (GCMs), which require far more computational resources to integrate, but provides a three dimensional solution. All of these models gave a consistent result (IPCC, 1990), that there was an unaccounted for sink.

Today, we know that this “missing sink” is in the land biosphere. CO_2 fertilization experiments were conducted and modelling studies continued (IPCC 1994) , that gave us a mechanistic

understanding of the terrestrial sink. The conclusive evidence for the terrestrial sink ultimately would come from the most extensive survey of ocean biogeochemistry ever conducted, the World Ocean Circulation Experiment and Joint Ocean Global Flux Study (WOCE-JGOFS). The necessary observations were conducted from 1987-2003 for the calculation of ocean anthropogenic carbon uptake (Sabine et al. 2004). Accurate estimates of fossil fuel emissions, LUC, and the ocean anthropogenic CO_2 sink, leaves only one unknown, the land biospheric sink (Figure I.2). By constraining the cumulative ocean sink, Sabine et al. 2004 were then able to constrain the cumulative net land sink (LUC + biospheric sink) and resolve the "missing sink" debate.

In summary, the land biosphere and ocean combined, are annually a sink for approximately half of anthropogenic CO_2 emissions (Figure I.2). The annual sink is split evenly between the land biosphere and ocean. The cumulative net land component (LUC + biospheric uptake) is actually a source (Khatiwala, Primeau, and Hall 2009). However, land biosphere uptake is growing: current land biosphere uptake is approximately twice the magnitude of the LUC component of anthropogenic CO_2 emissions (Figure I.2). Ocean models played a critical role in identifying the previously overlooked land biospheric sink. Because of the short period of observations, ocean models are still the best means to gain insight into the history of ocean sink for anthropogenic CO_2 over the historical period, and our only means of projecting the future of the ocean sink.

I.III The Ocean Sink for Anthropogenic CO_2

Using models and observations, the work presented in the following chapters will improve our understanding of the spatial distribution of the anthropogenic CO_2 uptake, and what controls the future of ocean anthropogenic CO_2 uptake. We focus on ocean anthropogenic CO_2 uptake because it is by far the largest change in the evolving ocean CO_2 budget.

Modeling and observation of the ocean anthropogenic carbon sink relies upon a few assumptions. These assumptions are necessary to accurately estimate how carbon is partitioned between various ocean carbon reservoirs. Conceptually, ocean carbon can be separated into three

reservoirs:

$$_{2>=} = \quad _{0=C}, \quad _{=0C} \qquad \text{(I.1)}$$

$_{2>=}$ is the total concentration, and can be measured with high accuracy in seawater. $_{0=C}$ is the carbon that has entered the ocean as a result of increasing atmospheric CO_2, and $_{=0C}$ is the carbon that existed in the preindustrial period.

The global $_{=0C}$ cycle is controlled by a balance between the rate of physical exchange between the surface ocean and deep ocean and biologically mediated removed removal from the $_{0=C}$ surface. Deep waters, high in $_{=0C}$, are upwelled to the surface, where that carbon is released to the atmosphere. This occurs primarily in the Southern Ocean and the Equatorial Paci c. Eventually the photosynthesizers are able to consume the nutrients upwelled along with the $_{=0C}$. The remains of the photosynthesizers eventually sink, returning the $_{=0C}$ to depth. This process is referred to as the biological pump. In the subtropics, thermodynamically driven $_{=0C}$ uptake occurs, balancing some of the equatorial $_{=0C}$ outgassing. As waters move away from they equator, they cool, enhancing the solubility of CO_2 and taking up $_{=0C}$ from the atmosphere. These waters are eventually subducted in the subpolar regions in what is referred to as the solubility pump.

$_{=0C}$ release could result from changes in ocean circulation and the biological bump, and both could change in the future. The biological pump is a series of processes, starting with carbon being removed from the surface by photosynthesizing organisms. These organisms die, and/or are consumed by predators. Almost all of their remains are remineralized before reaching the ocean oor, with approximately 1% is lost to the system in ocean sediments. The gradual remineralization that occurs through the water column allows the biological pump to lower the $_{=0C}$ concentration at surface and enhance the $_{=0C}$ concentration at depth. Therefore, by removing carbon from the surface ocean, a stronger biological pump results in lower atmospheric CO_2. Unlike in the land biosphere where the addition of carbon stimulates new biomass production, photosynthesizers

in the ocean do not strongly respond to CO_2 because phytoplankon communities are limited by nitrogen, phosphorus, light (at high latitudes) and micronutrients such as iron (Moore et al. 2013). Changes to the biological pump due to CO_2 are mostly indirect, acting through climate change driven changes to the delivery of nutrients to the surface ocean by ocean circulation. CO_2 uptake is thus independent of changes to the biological pump.

In order to obtain observation based estimates of CO_2 it is assumed that CO_2 release in the industrial era will remain small relative to the increase in the ocean CO_2 reservoir. Warming related effects are expected to reduce physical exchange, and would act to reduce the strength of the ocean biological pump by reducing the supply of nutrients brought to the surface. At the same time, less remineralized carbon would be brought to the surface. Thus in current carbon cycle models, reduced removal by the biological pump is largely compensated by reduced outgassing of upwelled carbon (Bernardello et al. 2013). Bernardello et al. 2013 estimate the net CO_2 change is an increase in carbon storage of 20 Pg C from 1850-2100. Projected CO_2 uptake is approximately 20 times larger for 1850-2100 under the same projected increase in atmospheric CO_2 (Chapter 2).

I.IV The Distribution of the Ocean Sink for Anthropogenic CO_2

Resolving the spatial distribution allows us to determine the regional mechanisms controlling CO_2 uptake, and thus inform our understanding of the sensitivity of the regional CO_2 uptake to climate change. Observational products are able to resolve the outgassing and uptake regions of the CO_2 cycle, although there remains large uncertainties because there are sparse observations in regions that account for much of the CO_2 flux, such as the Southern Ocean. The air-sea CO_2 flux products, however are far more detailed than estimates of the air-sea CO_2 flux. Beyond broad regions, the spatial distribution of the air-sea CO_2 flux remains unresolved. This is because it is quite difficult to separate the CO_2 and CO_2 signals for one another in observations. Currently, we must rely upon GCMs to determine the spatial distribution of air-sea CO_2 flux.

Unlike the CO_2 cycle, where the spatial distribution of air-sea CO_2 fluxes depends on re-

gional warming and cooling tendencies, ocean circulation, and biological productivity, the air-sea $_{0=C}$ ux distribution depends on where old waters reach the surface (Sarmiento, Orr, and Siegenthaler 1992). This is because the air-sea $_{0=C}$ ux is only dependent on the deviation from the preindustrial ux. The upwelling of old waters, low in $_{0=C}$ act to restore the surface ocean to preindustrial? $ $_{2}^{>2=}$ values and thus support the air-sea $_{0=C}$ ux. It is this quality of the $_{0=C}$ component of the carbon cycle that allows regions that are outgassing $_{2>=}$ to be substantial $_{0=C}$ sinks, because the increase in $ $_{2}^{0C<}$ has reduced $_{=0C}$ outgassing (Gruber et al. 2009).

Resolving regional $_{0=C}$ uxes is important because the mechanisms controlling the air-sea $_{0=C}$ vary regionally, and the response of these mechanisms to climate change is not uniform. For example, the Southern Ocean dominantes ocean $_{0=C}$ uptake (Caldeira and Duffy 2000; Gruber et al. 2009; Frölicher et al. 2014). Ekman driven divergence supports the upwelling of Circumpolar Deep Water (CDW) that are low in $_{0=C}$ and therefore have a high capacity to absorb atmospheric $_{0=C}$ (Ito, Woloszyn, and Mazloff 2010). By understanding this mechanism, we predict that future $_{0=C}$ uptake will continue to increase (Frölicher et al. 2014). In the subpolar North Atlantic, another hot spot of $_{0=C}$ uptake, we have a less clear understanding of what drives uptake, and also lack a conceptual model for the region's vulnerability to future changes. For these reasons, the subpolar North Atlantic region will be the focus of the nal two chapters.

I.IV.I Obtaining the Air-Sea $_{0=C}$ Flux from Observations

Here we outline the assumptions used to obtain the globally integrated air-sea $_{0=C}$ ux from global maps of $_{2>=}$ uxes, such as those from Takahashi et al. 2009 and Landschützer et al. 2014. Describing this process avoids potential confusion, as many readers mistakenly interpret regions of $_{2>=}$ sinks and sources in mapped $_{2>=}$ ux products as important sources and sinks of $_{0=C}$. The globally integrated $_{0=C}$ ux can be determined from $ $_{2}^{>2=}$ observations, however the spatial distribution of $_{0=C}$ uxes cannot. Ocean inversions are used instead to determine the spatial distribution $_{0=C}$ uxes. This method uses an estimate of the circulation from ocean models, and interior ocean carbon measurements, to estimate the $_{0=C}$ ux.