

# Elucidating the role of ocean circulation in changing North Atlantic nutrients and biological productivity

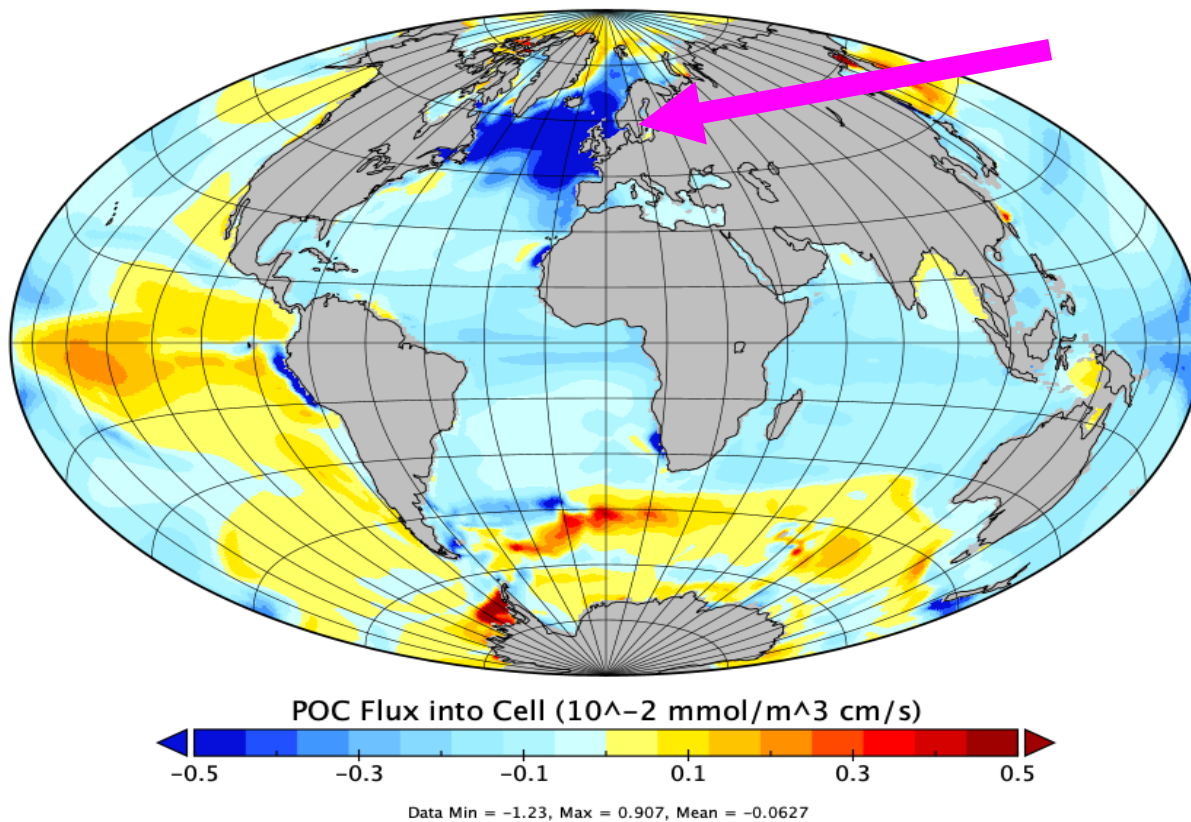
Funded by  
NASA 2020 New Investigator Program in Earth Science  
NASA Physical Oceanography Program



## MOTIVATION

Earth system models show Subarctic Atlantic biological productivity especially vulnerable to global warming

Simulated export at 50 m in CESM/RCP8.5: 2090s minus 2020s



# Four papers... slower CO<sub>2</sub> reduces Natl productivity

# 2019

4

## On the Role of the Gulf Stream in the Changing Atlantic Nutrient Circulation During the 21st Century

Daniel B. Whitt

### ABSTRACT

The Gulf Stream transports macronutrients poleward as a part of the Atlantic meridional overturning circulation (AMOC). Scaling shows that this advective transport is greater than diapycnal transport from deep convection in the North Atlantic and is therefore crucial for sustaining the nutrient supply to the subtropical North Atlantic on interannual timescales. Simulations of the RCP8.5 emissions scenario with the Community Earth System Model (CESM) reveal 25% declines in the Gulf Stream volume transport above the potential density surface  $\sigma_{\theta} = 27.5 \text{ kg/m}^3$  and 35% declines in the associated nitrate transport between 2006 and 2080. The declining Gulf Stream transport largely explains contemporaneous 40% declines in zonally-integrated volume and nitrate transports to the subtropical part of the AMOC. In addition, scaling suggests that the declining Gulf Stream nitrate transport (2.4 kmol/s per year) is the dominant driver of the declining export of particulate organic nitrogen across  $\sigma_{\theta} = 27.5 \text{ kg/m}^3$  in the subtropical North Atlantic (0.57 kmol/s per year), because the declining nitrate entrainment from water with  $\sigma_{\theta} > 27.5 \text{ kg/m}^3$  is only 0.4 kmol/s per year. A review of various small-scale ocean biophysical processes suggests that the projected decline in the Gulf Stream nutrient flux is qualitatively robust to uncertainties associated with ocean physics.

### 4.1. INTRODUCTION

The Gulf Stream is part of the upper limb of the Atlantic meridional overturning circulation (AMOC) and the western boundary current of the North Atlantic subtropical gyre. The Gulf Stream is also a nutrient stream. It transports macronutrients (nitrate, phosphate, silicate) necessary for marine phytoplankton growth along the eastern continental margin of the United States from the Straits of Florida to Cape Hatteras at globally significant rates. At Cape Hatteras, the Gulf Stream separates from the coast and carries its nutrients to the northeast off the continental slope and into deep water. There, waters of recent tropical, subtropical and subtropical origins converge and both the volume and nutrient transport increase in a great junction of the global ocean circulation.

National Center for Atmospheric Research, Boulder, CO, USA

Kawachi Current: Physical, Biogeochemical, and Ecosystem Modeling 2014, First Edition. Edited by Takashi Nagai, Hiroaki Sato, Koji Suzuki, and Motoyuki Takahashi. © 2019 American Geophysical Union. Published 2019 by John Wiley & Sons, Inc.

Further east, near the Grand Banks of Newfoundland, the waters and nutrients of the Gulf Stream diverge again into the subtropical and subtropical gyres. As nutrients and water move northward, they rise along the western boundary current of the North Atlantic and are eventually advected into the surface mixed layer or entrained by seasonal mid-layer deepening. This upward nutrient flux is compensated for by downward nutrient fluxes associated with physical and biogeochemical processes. A significant fraction of the inorganic nutrient entering the mixed layer is transformed directly to denser North Atlantic Deep Water and sinks as the incoming water loses heat to the atmosphere. However, another significant fraction of the inorganic nutrient entering the mixed layer is converted to organic form by phytoplankton. A fraction of this organic nutrient sinks via particles to denser water, where it is remineralized, and the other fraction of the organic nutrient (i.e., the nonmineral dissolved part) is transformed

# 2020

## Slower nutrient stream suppresses Subarctic Atlantic Ocean biological productivity in global warming

Daniel B. Whitt<sup>1</sup> and Malte F. Jansen<sup>2</sup>

<sup>1</sup>Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO 80507; and <sup>2</sup>Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60627

Edited by Edward A. Boyle, Massachusetts Institute of Technology, Cambridge, MA, and approved May 18, 2020 (received for review January 15, 2020)

Earth system models (ESM) project that global warming suppresses biological productivity in the Subarctic Atlantic Ocean as increasing ocean surface buoyancy suppresses two physical drivers of nutrient supply: vertical mixing and meridional circulation. However, the quantitative sensitivity of productivity to surface buoyancy is uncertain and the relative importance of the physical drivers is unknown. Here, we present a simple predictive theory of how mixing, circulation, and productivity respond to increasing surface buoyancy in 21st-century global warming scenarios. With parameters constrained by observations, the theory suggests that the reduced northward nutrient transport, owing to a slower ocean circulation, explains the majority of the reduced productivity in a warmer climate. The theory also informs present-day biases in a set of ESM simulations as well as the physical underpinnings of their 21st-century projections. Hence, this theoretical understanding can facilitate the development of improved 21st-century projections of marine biogeochemistry and ecosystems.

ocean circulation | biogeochemistry | global warming

The Subarctic Atlantic Ocean hosts a highly productive marine ecosystem (1), which contributes to a major regional sink of anthropogenic CO<sub>2</sub> (2) and sustains valuable fisheries along its margins (3). However, earth system models (ESM) project that global productivity will decline rapidly in the Subarctic Atlantic Ocean relative to other oceans as greenhouse gases increase (5, 6). Consistent with these projections, observations suggest that Subarctic Atlantic Ocean productivity has declined during the industrial era (7, 8), but future declines may be far more dramatic (5, 6).

$$\frac{\partial N_i}{\partial t} = \text{PROD}_i - \text{FR}_i \quad (1)$$

where  $N_i$  is the nitrate concentration in the surface mixed layer and  $\text{FR}_i$  is the rate of consumption of nitrate by the ecosystem, i.e., net productivity. As the nitrate is drawn down to relatively low concentrations during summer, new productivity (nutrient supply) is needed.

Global warming drives cascading changes across physical, chemical, and biological systems. However, the coupled dynamics of these systems are difficult to disentangle. Here, we present a simple theoretical model of how these systems respond to the surface buoyancy changes in the Subarctic Atlantic Ocean productivity (5, 6, 9, 10), some studies recently suggested that the slowing meridional transport of nitrate in the North Atlantic Ocean productivity declines in 21st-century projections than shoaling surface mixing layers (16, 17). However, the mechanisms that lead to productivity declines in ESM can be hard to disentangle (5, 6, 10–30), and the relative importance of the physical 21st-century productivity declines in the Subarctic Atlantic Ocean is not well understood.

Here, we use a two-box theoretical model of the physical and biogeochemical dynamics in the Subarctic Atlantic Ocean to predict and understand the physical drivers of biogeochemical change under increasing ocean surface buoyancy, which results from ocean surface warming and freshening as atmospheric greenhouse gas concentrations increase (5, 10). We also use the box model to interpret sophisticated ESM simulations

www.pnas.org/cgi/doi/10.1073/pnas.2008611117

PNAS Lead Article | 1 of 7

Co-author  
Malte Jansen  
UChicago

# 2023

## Global Biogeochemical Cycles

### Subsistence Effects on Changes to Export Production Under Global Warming

Geovany Jay Brant<sup>1,2</sup>, Daniel B. Whitt<sup>1,2</sup>, Matthew C. Long<sup>3</sup>, Frank O. Bryan<sup>4</sup>, Kate Foley<sup>1</sup>, and Keltin J. Richardson<sup>1</sup>

<sup>1</sup>Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; <sup>2</sup>University of Hawaii Manoa, Honolulu, HI, USA; <sup>3</sup>Aronson Research Center, National Aeronautics and Space Administration, Moffett Park, CA, USA; <sup>4</sup>Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

**Abstract** We examine the effects of the subsistence in mediating the response to projected warming of phytoplankton new production and export using idealized biogeochemical tracers in a high-resolution regional model of the Pacific Alaskan Plains region of the North Atlantic. We quantify subsistence effects by comparing our control run to an integration in which subsistence motions have been suppressed using increased viscosity. Annual new production is slightly reduced by subsistence motions in a climate representative of the early 21st-century and slightly increased by subsistence motions in a climate representative of the late 21st-century. The warmer climate at the end of the 21st century reduces resolved subsistence activity by a factor of 3.3. Reducing the subsistence, however, does not strongly impact the projected reduction in annual production under representative warming. Organic carbon export from the surface ocean includes both direct sinking of detritus (the biological gravitational pump) and advective transport mediated pathways; the sinking component is larger than advectively mediated vertical transport by up to an order of magnitude across a wide range of imposed sinking rates. The subsistence are responsible for most of the advective carbon export, however, which is thus largely reduced in a warmer climate. In summary, our results demonstrate that reducing most of the subsistence has a modest effect on present-day export production, a small effect on simulated reductions in new production under global warming, and a large effect on advectively mediated export fluxes.

**Plain Language Summary** We examine the effects of a warmer climate on phytoplankton growth and the sinking of organic matter in the ocean using numerical simulations of a region of the northeastern North Atlantic. We quantify the effects of physical motions at scales below 25 km (subsistence) by suppressing them in some simulations. In this region, annual phytoplankton growth is slightly reduced when including these motions in the current climate and slightly increased when including them in the warmer climate. The subsistence motions are less energetic in the warmer climate at the end of the 21st century. The projected reduction in phytoplankton growth over the 21st century due to climate change, however, is very sensitive to the inclusion of subsistence in our simulation. The transfer of organic matter from surface to depth is due to both sinking of particles and vertical motions of the water. Subsistence are responsible for most of the vertical transfer of organic matter by vertical water movement, which is largely reduced in a warmer climate. Therefore, global climate models do not explicitly represent the subsistence are likely to be accurate for phytoplankton growth but not for the downward transport of organic matter.

**1. Introduction** Global warming over the 21st century is expected to alter the ocean's biological pump, but the sensitivity, and thus magnitude of response of important rates remain uncertain (Henson et al., 2022; Kwiatkowski et al., 2020; Sullivan et al., 2020). The eastern North Ocean is one of the largest and most robust proposed declines in export production of organic matter by global warming in global Earth system models (Theriot et al., 2020; Kwiatkowski et al., 2020), though (Figure 9 and 2, respectively). This robustness may be related to consistent projections of reduced mixed layer depths, which suggest a link between increased upper ocean buoyancy stratification and the fluxes of nutrients in the euphotic zone. In the ocean, these mixed layer depths and nutrient fluxes are strongly affected by physical stirring and mixing in the upper ocean, which are sensitive to mesoscale horizontal stirring and subsistence vertical velocities. However, standard climate projections rarely model low-resolution Earth system models (e.g., Fu et al., 2016). Mesoscale and subsistence physical processes are not resolved in such

BRETT ET AL.

Lead author  
Jay Brett  
JHU/APL

# 2023

## Geophysical Research Letters

### Global Warming Increases Interannual and Multidecadal Variability of Subarctic Atlantic Nutrients and Biological Production in the CESM-1.0

David B. Whitt<sup>1</sup>

<sup>1</sup>NASA Ames Research Center, Moffett Park, CA, USA

**Abstract** Earth system models indicate that the Subarctic Atlantic Ocean ecosystem are uniquely sensitive to global warming. Nutrients, phytoplankton biomass, and phytoplankton production all decline precipitously in global warming scenarios. Superimposed on this forced response is changing internal variability that is not fully understood. Here, a large ensemble of simulations with the Community Earth System Model is used to quantify how global warming affects the interannual and multidecadal variability of phytoplankton production integrated over the Subarctic Atlantic. Surprisingly, it is found that this variability increases non-monotonically with global warming. The increased variability of production is caused by a reduced variability of wintertime surface nutrient concentrations, which is a consequence of a rising sensitivity of these nutrients to winter mixing and overturning fluctuations, which overcomes a reduced amplitude of other physical fluctuations with warming. Future work is needed to fully understand how internal climate variability impacts ocean ecosystems in a warming climate.

**Plain Language Summary** Marine ecosystems are sensitive to natural interannual to decadal climate oscillations. For example, fishery yields wane and wave and population shifts with well known climate variability like El Niño. However, with the intensification of global warming and other anthropogenic impacts on marine ecosystems, it is necessary to investigate how climate-driven variability of marine ecosystems is changing. This study uses global Earth System system simulations of twenty-first century global warming scenarios to quantify how climate-driven fluctuations in North Atlantic Ocean ecosystems might change if anthropogenic greenhouse gas emissions and global warming continue. The study reveals that global warming intensifies the ecological and biogeochemical variability at the regionally integrated scale of the Subarctic Atlantic Ocean due to a rising sensitivity to climate variability under ocean circulation and mixing.

**1. Introduction** The Subarctic Atlantic Ocean currently hosts a highly productive marine ecosystem (Behrenfeld & Falkowski, 1997; Field et al., 1998), which is characterized by a prominent spring phytoplankton bloom (Behrenfeld & Boss, 2014; Swenson, 1953) that supports valuable fisheries around the margin (FAO, 2022; Kwiatkowski et al., 2020) and contributes to the sequestration of carbon in the deep ocean (DeVries & Weber, 2017; Lomas et al., 2000; Mazerov et al., 2020). However, global Earth system models (Bryce et al., 2015; Henson et al., 2022; Kwiatkowski et al., 2020) and observations (Orman et al., 2010) indicate that the Subarctic Atlantic production is especially vulnerable to global warming relative to other regions, and various sources of biological production decline by as little as 50% in this region by the end of twenty-first century high-emissions scenarios (Bryce et al., 2020; Henson et al., 2022; Kwiatkowski et al., 2020). These regional reductions in production occur with significant biogeochemical changes in and below the euphotic zone, including substantial declines in nutrient concentrations, which primarily result from the slowing Atlantic meridional overturning circulation (AMOC), which is an important driver of biogeochemical variability and change in the Subarctic Atlantic on decadal and longer timescales (Orman & Jipson, 2012; Henson et al., 2022; Coney, et al., 2021; Liu et al., 2020; Pelzer et al., 1996; Ridge & McCreary, 2002; Sarin et al., 2004; Schneider, 2005; Tagliari et al., 2020; White, 2016; White & Jansen, 2020; Williams et al., 2006).

Although many models simulate a decline in the surface nutrients and biological production in the Subarctic Atlantic under global warming scenarios (Bryce et al., 2015; Henson et al., 2022; Kwiatkowski et al., 2020), prior studies have not fully quantified how the quasi-variability of nutrients and production change with global warming in the region. Yet, numerous prior studies have observed that the production and nutrients vary

WHITT

Lead author  
Jay Brett  
JHU/APL

1 of 12

# Seasonal cycle

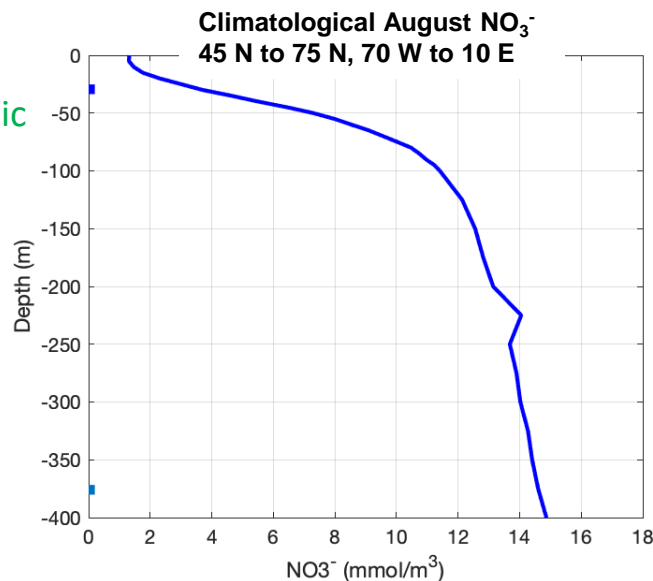
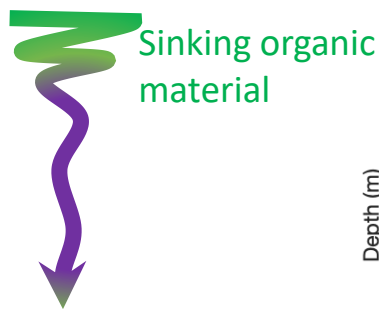
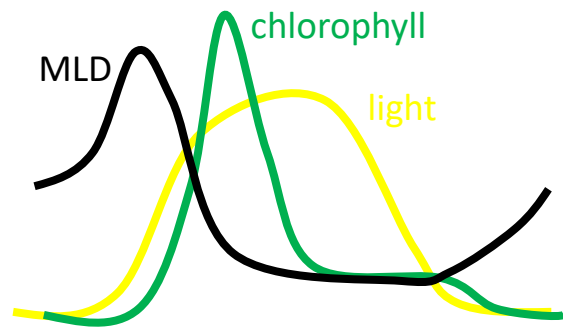
Phytoplankton require light and nutrients such as nitrate ( $\text{NO}_3^-$ ) to grow.

$\text{NO}_3^-$  is low at the surface and replete at depth during summer.

Wintertime vertical mixing replenishes  $\text{NO}_3^-$

Spring solar radiation shoals the mixing layer, and phytoplankton draw down  $\text{NO}_3^-$

Sinking detrital material is remineralized back to  $\text{NO}_3^-$  in the seasonal thermocline or deeper



Dynamics are essentially local/vertical/1-D

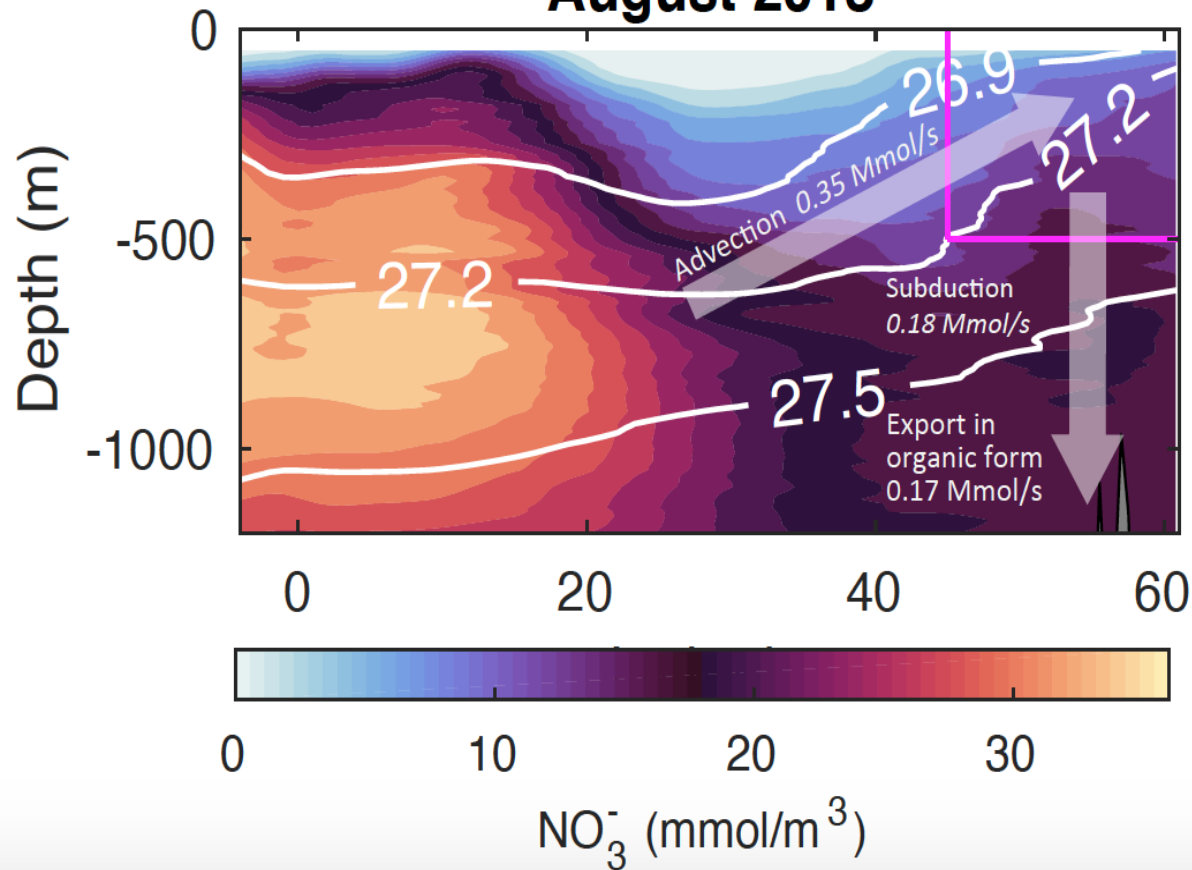
## Annual mean


Export & subduction to depths below the winter mixed layer is replenished by meridional circulation

To put these numbers in perspective:  
**Global** Anthropogenic N fixation  $\sim .475$  Mmol/s  
 (Fowler et al. 2013)

Advective replenishment timescale  
 for Subpolar North Atlantic  $\text{NO}_3^-$  above 1 km:  
 $(200 \text{ Gmol}) / (0.3 \text{ Mmol/s}) \sim 20$  years

**(B) Observed meridional section  
 August 2013**

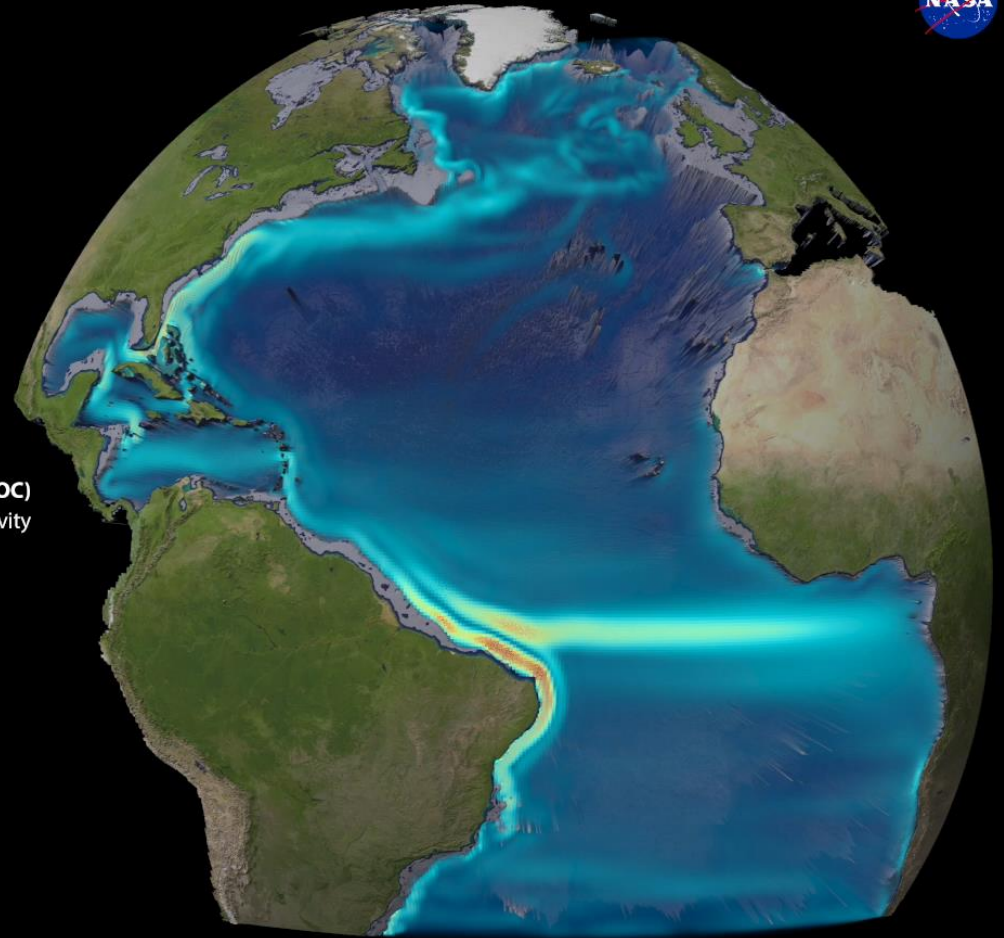




How *does* the MOC participate in North Atlantic biogeochemistry?

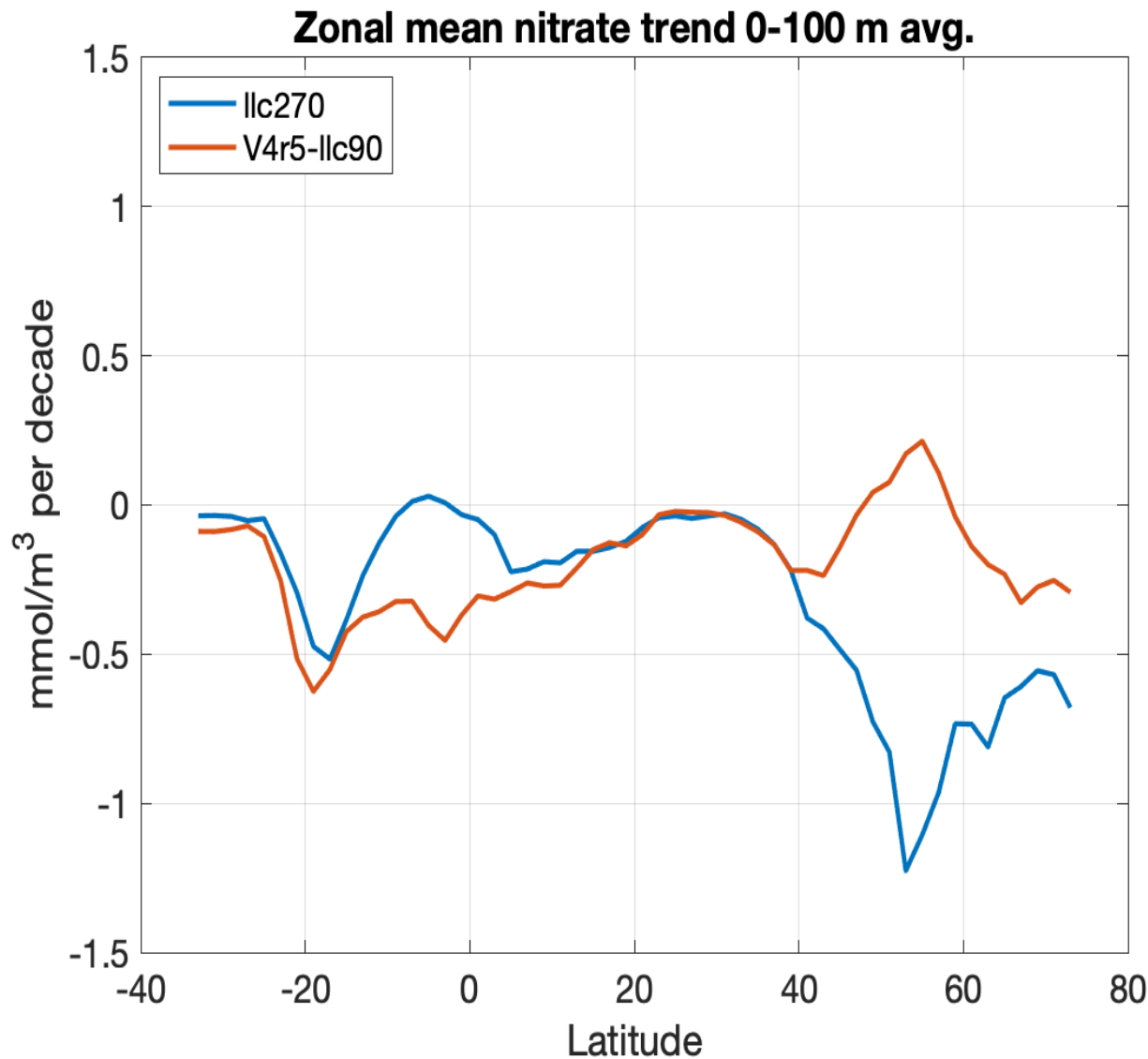


**Nitrate transport by the Atlantic Meridional Overturning Circulation (AMOC)**  
a key governor of marine ecosystem productivity



## Annual mean

Patterns are qualitatively reasonable, but biases and trends are large relative to low background concentrations in the upper ocean.



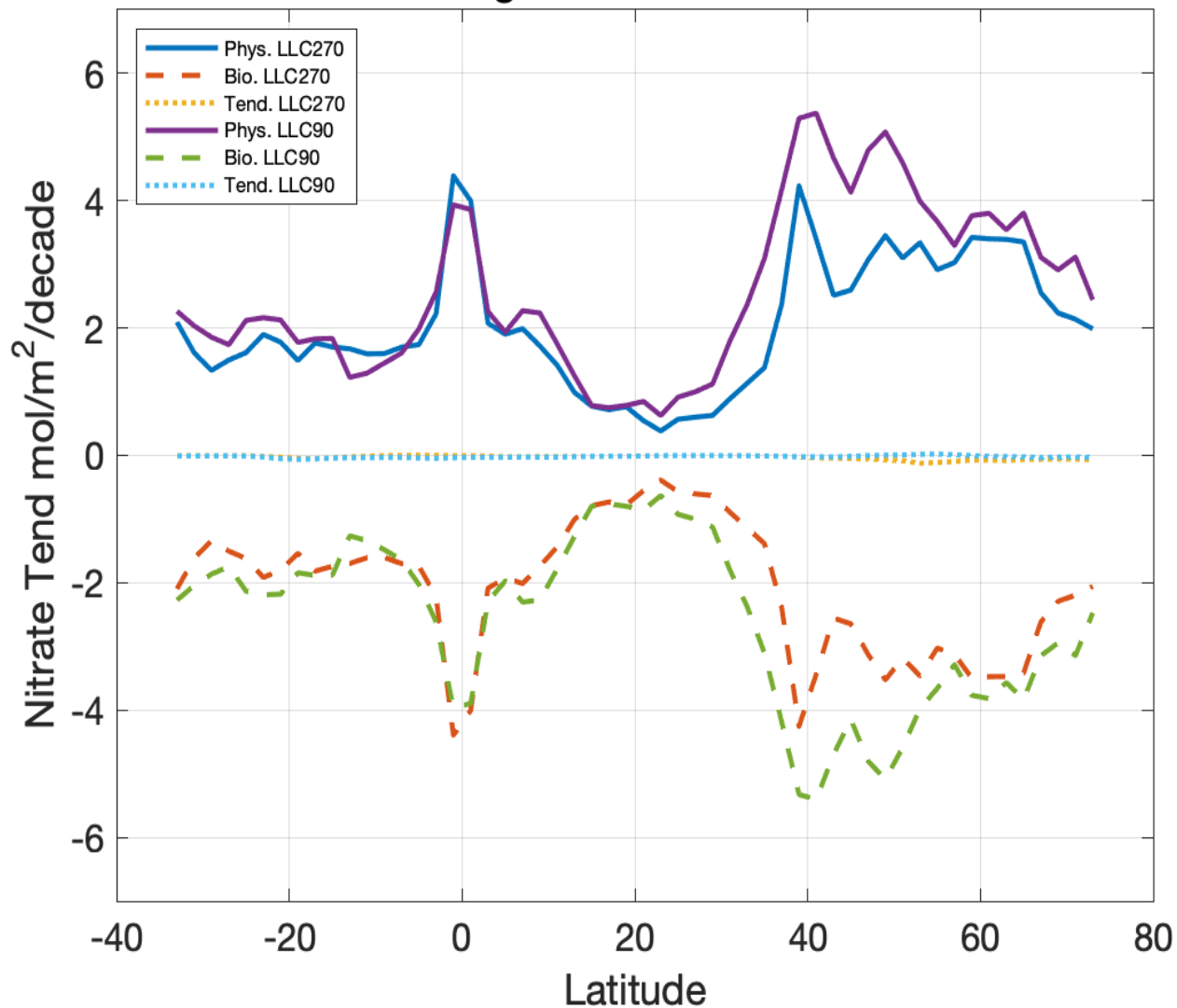


## Top 100 m

Physical transport supplies and biology consumes and exports nitrate in the top 100 m on a timescale  $\sim 1$  year on average.

LLC270 has lower new production, weaker biological pump in the Subarctic Atlantic

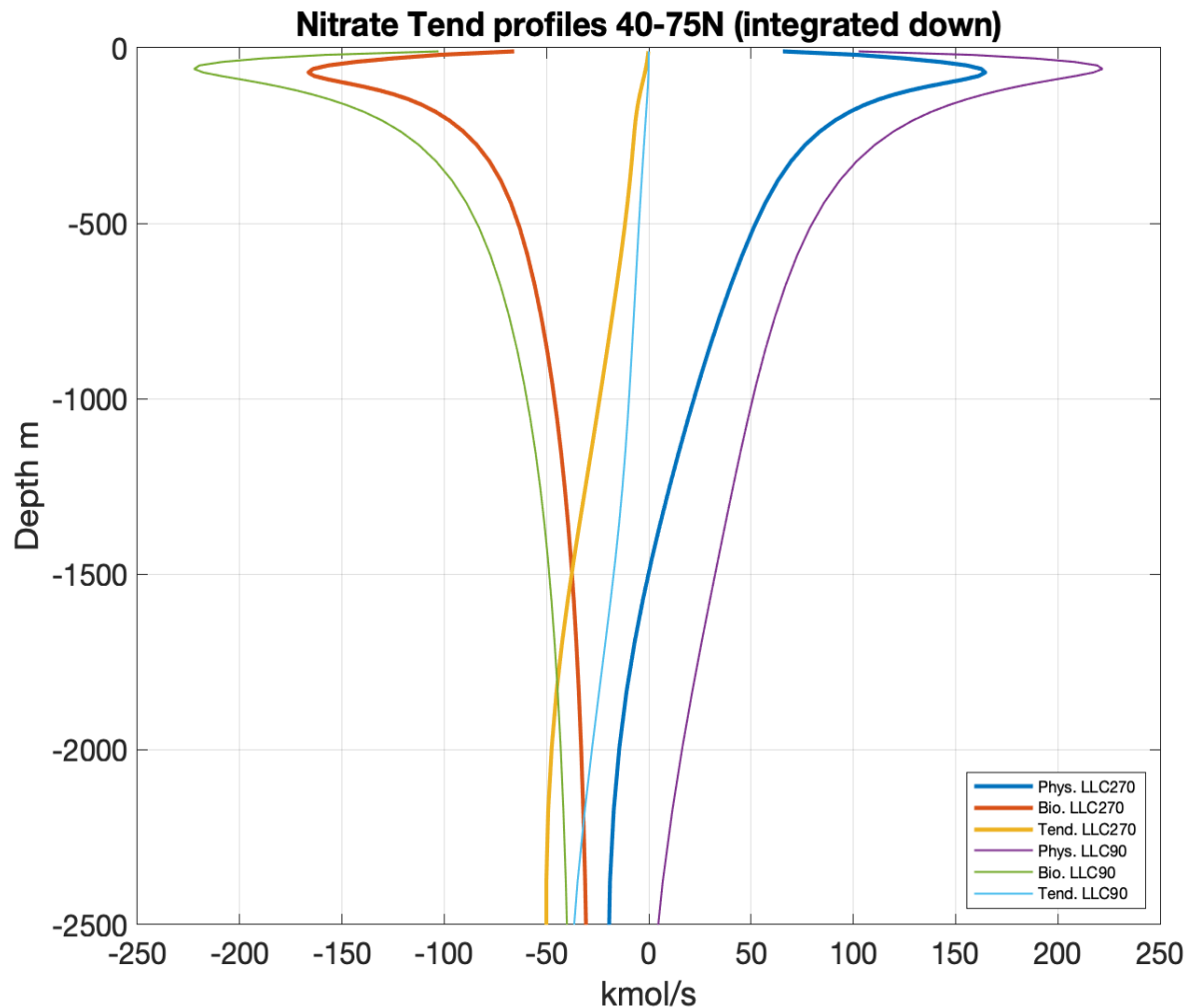
### Nitrate Tendencies integrated 0-100 m V4r5-LLC90 vs LLC270



## Subarctic Atlantic Profile

Nitrate tendency of new productivity in the euphotic zone and remineralization at depth mirrors physical transport

The Subarctic Atlantic biological pump is 30-40% stronger in V4r5 than LLC270

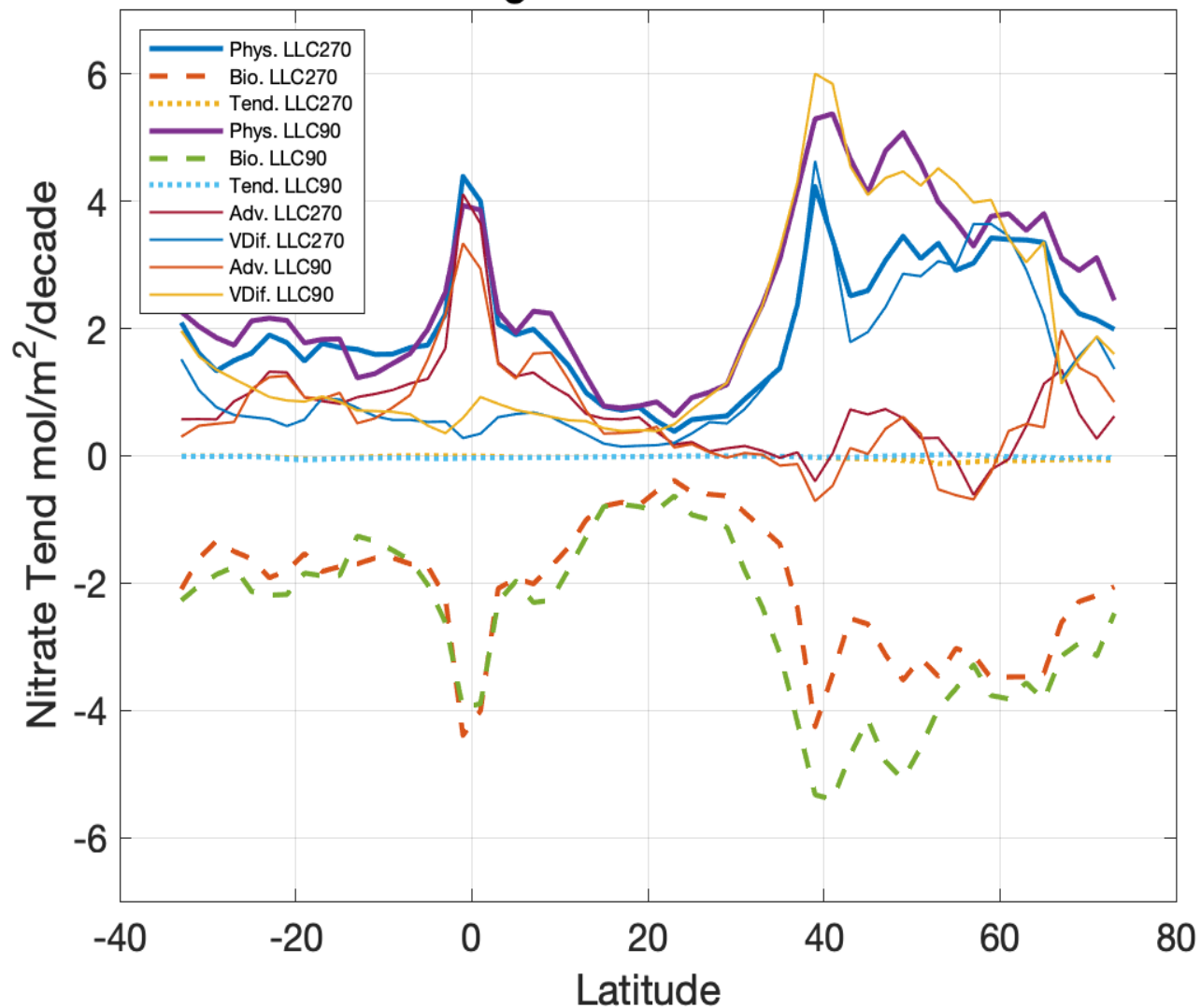


# Separating Physical Contributions to New Production in the top 100 m

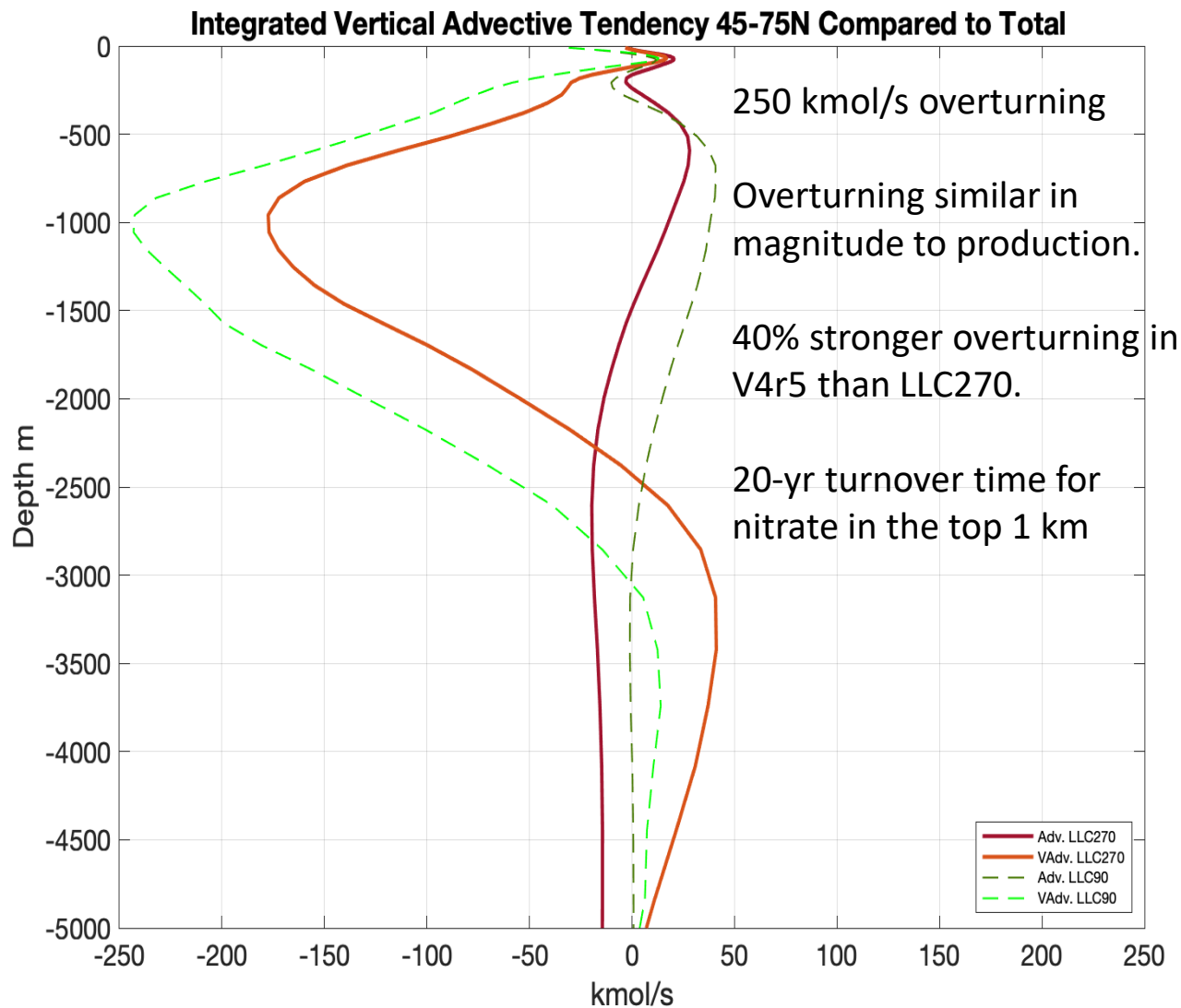
Vertical mixing dominates flux at 100 m poleward of 30°

Upwelling dominates flux at 100 m equatorward of 30°

## Nitrate Tendencies integrated 0-100 m V4r5-LLC90 vs LLC270



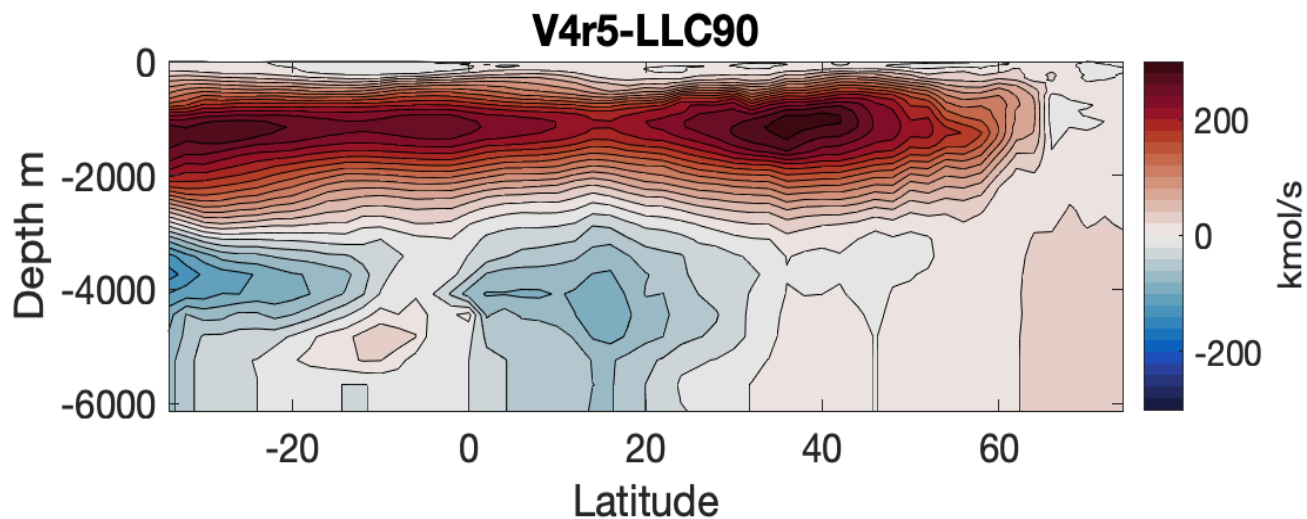
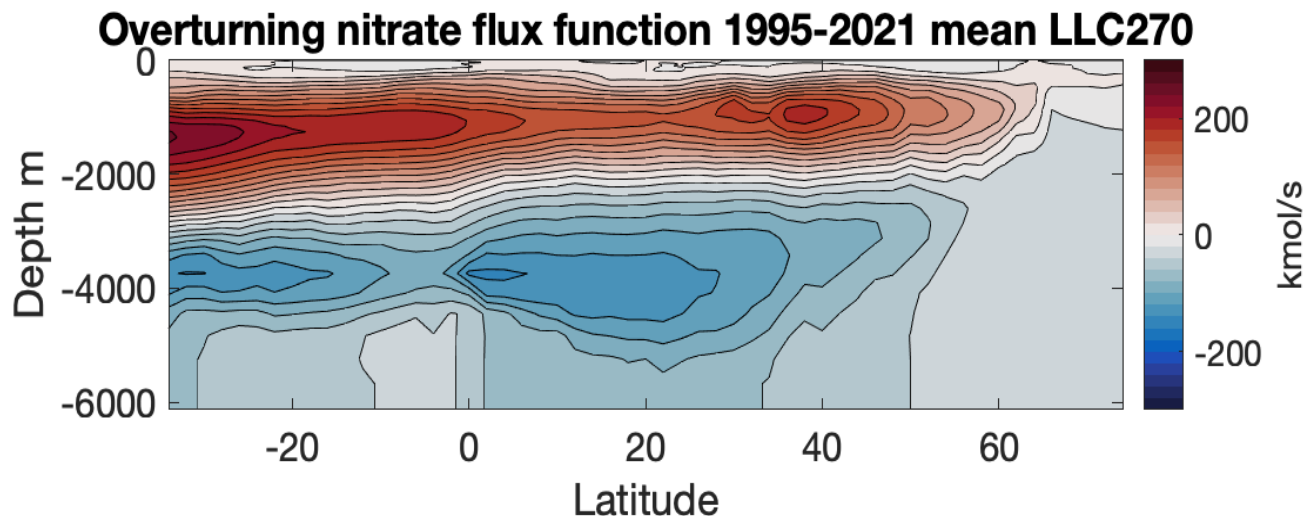
# Separating Physical Contributions to New Production in the Subarctic Atlantic Profile



# AMOC vertically integrated meridional fluxes

Overturning 50% stronger in  
V4r5 vs LLC270 and penetrates  
deeper in the N. Atl.

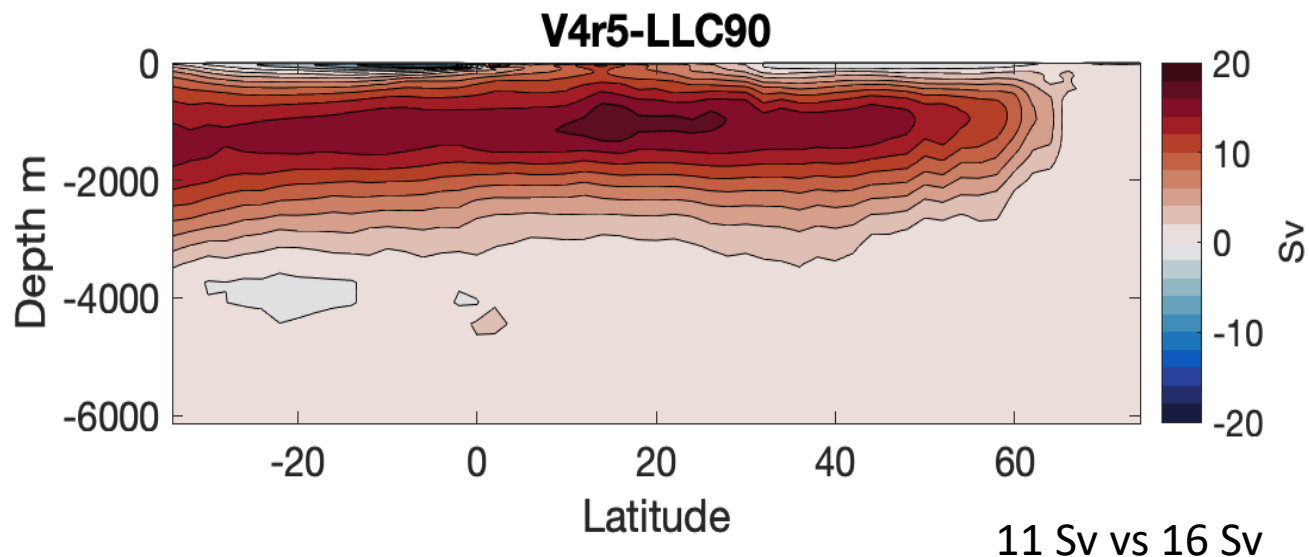
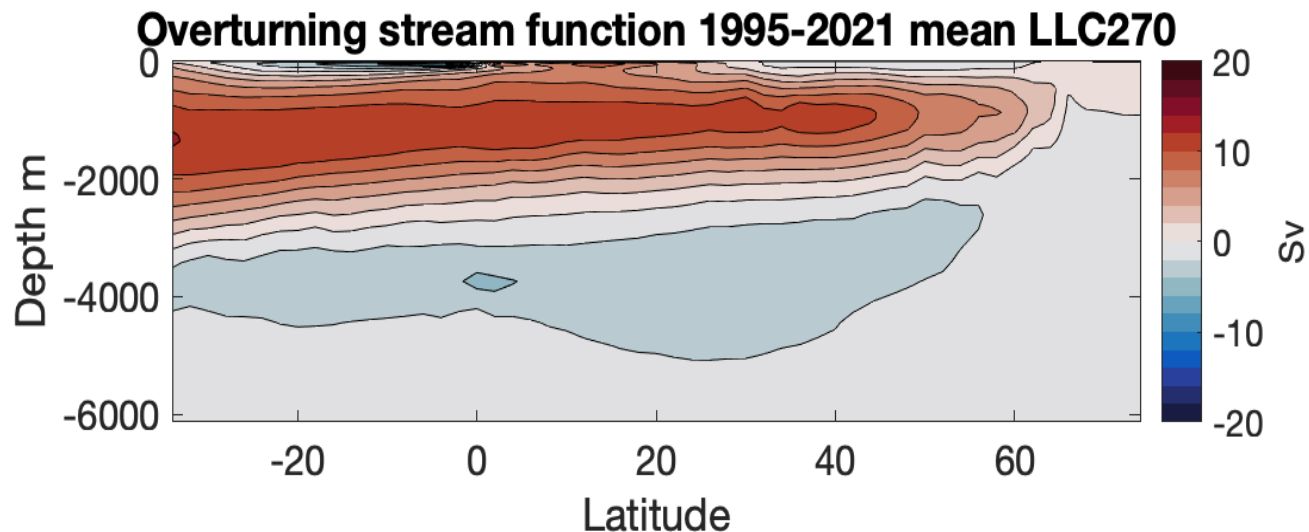
Overturning is stronger at all  
latitudes in V4r5



190 kmol/s vs 290 kmol/s

# AMOC vertically integrated meridional fluxes

Virtually all of the difference  
between the nitrate transports  
between V4r5 and LLC270 is due  
to difference in volume transport



Overturning, vertical mixing, and biology/export interact to control the nutrient dynamics of the Subarctic North Atlantic

It remains challenging to simulate and thus quantify the nutrient dynamics of the Subarctic Atlantic and the role of MOC therein

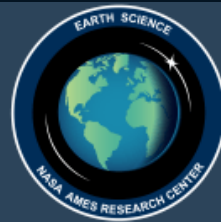
Slower MOC likely explains low and declining Subarctic Atlantic nitrate in LLC270 and presumably impacts other biogeochemical tracers too

# Thanks

Dan Whitt

[Daniel.b.whitt@nasa.gov](mailto:Daniel.b.whitt@nasa.gov)

[danielwhitt.github.io](https://danielwhitt.github.io)





Dan Whitt

Ocean circulation and biogeochemistry

Earth Science Division, Ames Research Center

National Aeronautics and Space Administration

[daniel.b.whitt@nasa.gov](mailto:daniel.b.whitt@nasa.gov)

[danielwhitt.github.io](https://github.com/danielwhitt)

