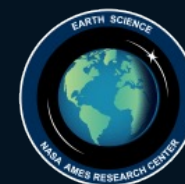


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Elucidating the role of ocean circulation in changing North Atlantic nutrients and biological productivity

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

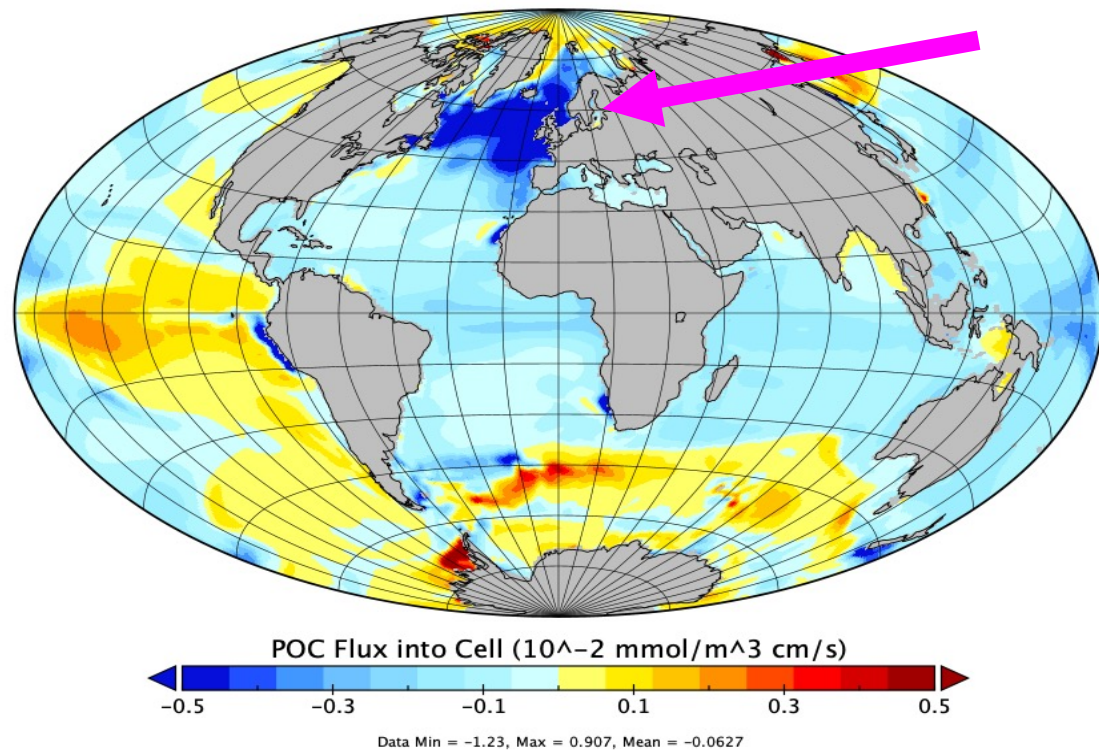
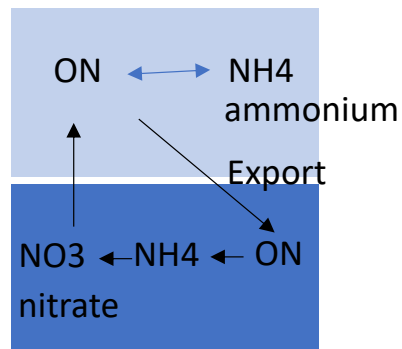


MOTIVATION

Earth system models indicate that the Subarctic Atlantic biological productivity is particularly sensitive to global warming

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

Schematic part of
the N cycle



PRIOR CONTRIBUTIONS

Four papers...

2019

4

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

David B. Whitt

ABSTRACT

The Gulf Stream transports macronutrients aboard 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 subpolar North Atlantic on interannual timescales. Simulations of the RCP4.5 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 15% declines in the associated nitrate transport between 2000 and 2080. The declining Gulf Stream transport largely explains contemporaneous 40% declines in zonally-integrated volume and nitrate transport in 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 subpolar 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 0.44 kmol/s per year. A review of various small-scale ocean physical 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 subpolar origins converge and both the volume and nutrient transport increases in a great junction of the global ocean circulation.

National Center for Atmospheric Research, Boulder, CO, USA

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2020

Slower nutrient stream suppresses Subarctic Atlantic ocean biological productivity in global warming

David B. Whitt^{1,2} and Malte F. Jansen³

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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 (ESMs) 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 ocean. The theory also informs generalizing lessons in a set of ESM simulations as well as the physical underpinnings of those 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, 2) which contributes to a major regional sink of anthropogenic CO_2 (3) and sustain valuable fisheries along its margins (4). However, Earth system models (ESMs) project that biological 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), but future declines may be far more dramatic (5, 6).

Studies have attributed these rapid regional declines in Subarctic Atlantic Ocean productivity to particularly substantial reductions in the depth of surface mixed layer and a slower chemical nutrient turnover in the AMOC, which led to a vertical decoupling of the surface productivity from the chemical nutrient at depth (5, 8). Based on evidence that the inorganic nutrient entering the mixed layer is transformed directly to dense North Atlantic Deep Water and nutrient transport in the AMOC is important for North Atlantic Ocean productivity (9, 10), some studies recently suggested that the slowing meridional nutrient transport in the North Atlantic Ocean nutrient stream (11–15) which occurs in conjunction with slower AMOC is a stronger physical driver of North Atlantic Ocean productivity declines in 21st-century projections than slowing surface mixing (16, 17). However, the mechanisms that lead to productivity decline in ESMs can be hard to disentangle (5, 16–20), and the relative importance of the physical drivers for the projected 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, 19). We also use the box model to interpret approximately ESM simulations

of marine physical and biogeochemical dynamics in the Subarctic Atlantic Ocean, including the present-day dynamics and 21st-century warming scenarios. We start by considering the upper layer of our model, which represents the surface mixed layer of the Subarctic Atlantic Ocean, with parameters optimized to reflect present-day conditions (Materials and Methods). The annual cycle is the dominant timescale of biogeochemical variability here (21, 22) and therefore an important target for constraining biogeochemical models and improving process understanding. For example, consider the horizontally averaged dynamics of surface nitrate NO_3^- . Although a significant fraction of net primary productivity is reflected recycling, nitrate consumption primarily reflects new productivity associated with physical transport of nutrients that are lost via export of organic material from the surface layer (23). Every winter, after the sun retreats toward the Southern Hemisphere, the Subarctic Atlantic Ocean cools and turbulence mixes water vertically over depths of hundreds of meters (Fig. 1A). As a result, the nitrate concentration is relatively high at the surface and fairly well mixed vertically over the top several hundred meters (Fig. 1A and D). As the sunlight increases, the surface mixed layer depth D_m shoals, and the marine ecosystem consumes the nitrate in the surface mixed layer (Figs. 1C and D and S2) at a rate

$$\frac{dN_s}{dt} = \frac{\text{PROD}}{N_s} - \frac{D_m}{N_s} \quad (1)$$

where N_s is the nitrate concentration in the surface mixed layer and PROD is the rate of consumption of nitrate by the ecosystem, i.e., new productivity. As the nitrate is drawn down to relatively low concentrations during summer, new productivity

reduces in the following winter. This article is a PNAS Direct Submission. Published online April 14, 2020. This article is part of the special issue "Global Biogeochemical Cycles." Data deposition: All data and model outputs are cited in the references and described in SI Appendix and Supplementary Materials, available at <https://doi.org/10.1073/pnas.2008018117>. *To whom correspondence may be addressed. Email: dwhitt@ucar.edu. This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2008018117/-/DCSupplemental>.

Author contributions: D.B.W. and M.F.J. designed research, performed research, contributed new reagents/constructs, tools, analyzed data, and wrote the paper. The authors declare no competing interest.

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*To whom correspondence may be addressed. Email: dwhitt@ucar.edu. This article contains supporting information online at [www.pnas.org/cgi/doi/10.1073/pnas.2008018117](https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2008018117/-/DCSupplemental.</p></div><div data-bbox=)

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Global Biogeochemical Cycles

RESEARCH ARTICLE

10.1073/pnas.2008018117

Key Points:

- In the Perseus Atlantic Plain region, subsurface oceanic nitrate is a major nutrient source for the upper 21st-century ocean.
- Projected changes in oceanic nitrate export from the 21st-century ocean are a result of changes in subsurface oceanic nitrate.
- Including subsurface oceanic nitrate export in the 21st-century ocean model improves the model's ability to simulate the ocean's nitrate cycle.

Supporting Information:

Supporting Information can be found at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2008018117/-/DCSupplemental>.

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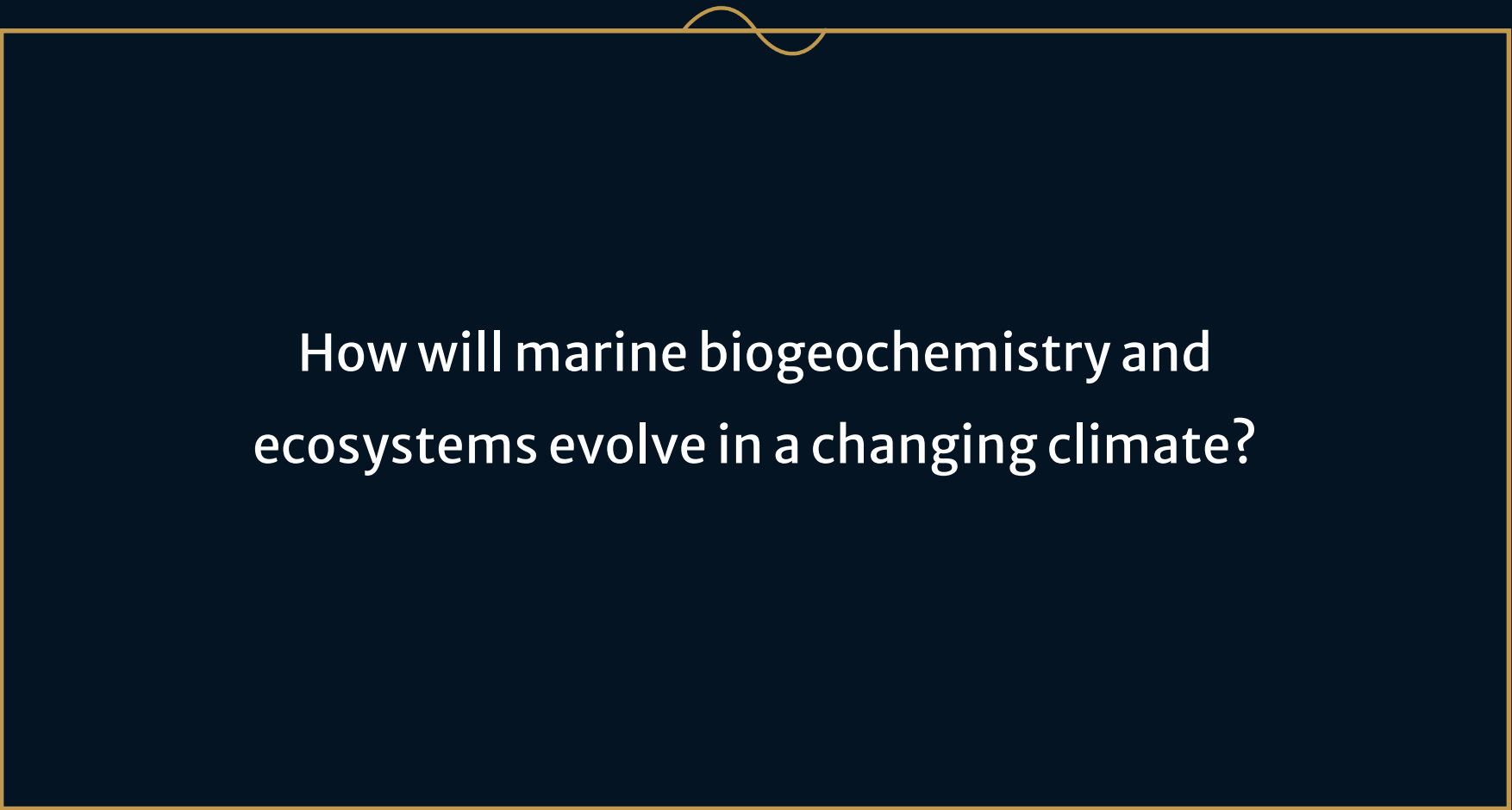
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How will marine biogeochemistry and
ecosystems evolve in a changing climate?



How does the ocean physics influence marine
biogeochemistry and ecosystems?

SUBARCTIC ATLANTIC OCEAN

Seasonal cycle

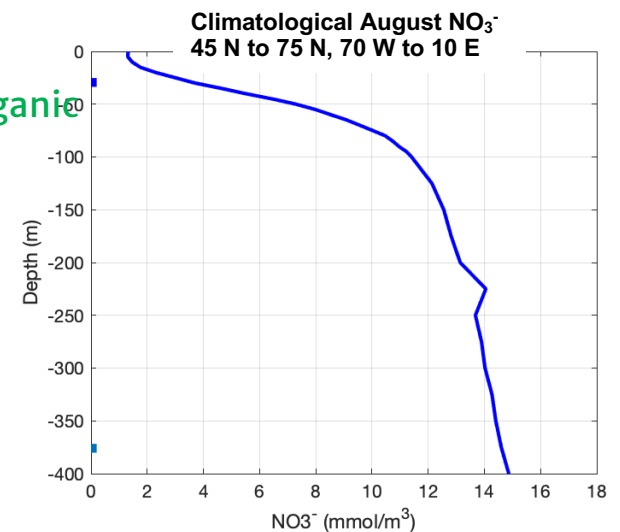
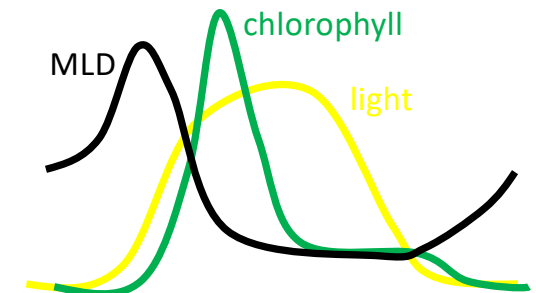
Phytoplankton require light and nutrients such as nitrate (NO_3^-) to grow.

NO_3^- is low at the surface and replete at depth during summer.

Wintertime vertical mixing replenishes NO_3^-

Spring solar radiation shoals the mixing layer, and phytoplankton draw down NO_3^-

Sinking detrital material is remineralized back to NO_3^- in the seasonal thermocline or deeper



Dynamics are essentially local/vertical/1-D

SUBARCTIC ATLANTIC OCEAN

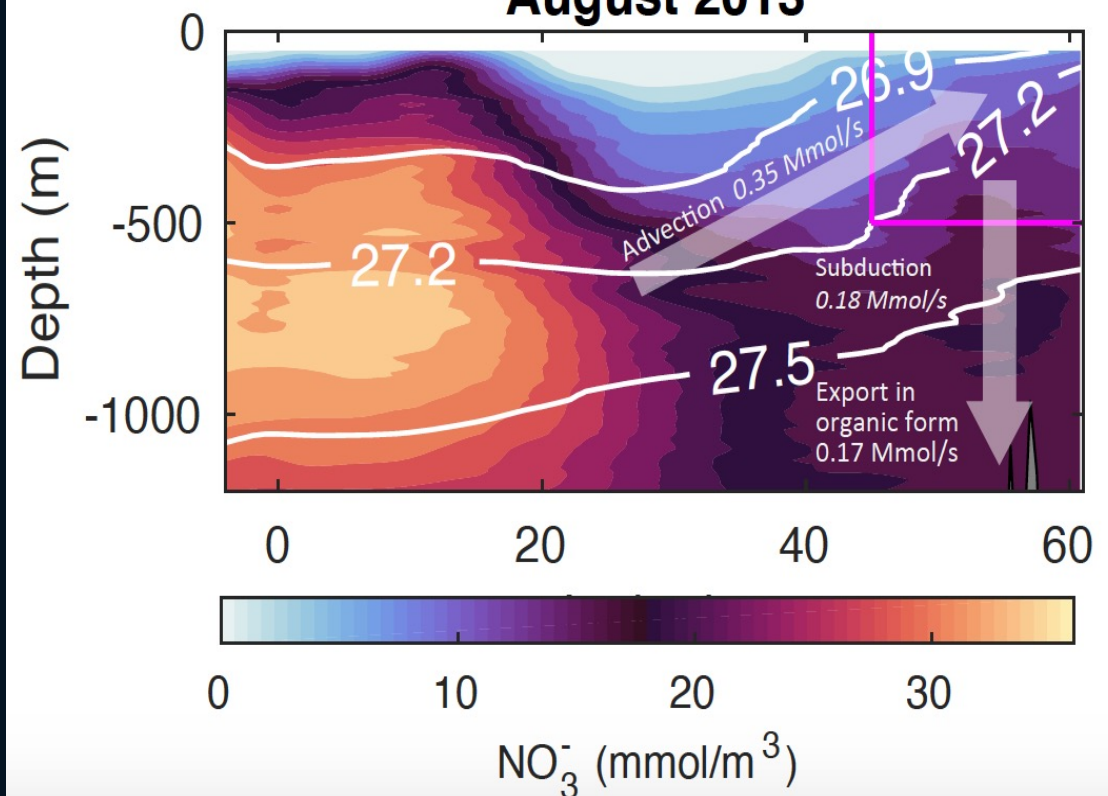
Annual mean

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 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?

We can only understand it after we can model it.

Evaluation of ECCO–Darwin
Zonal–mean Atlantic Nitrate

Annual mean

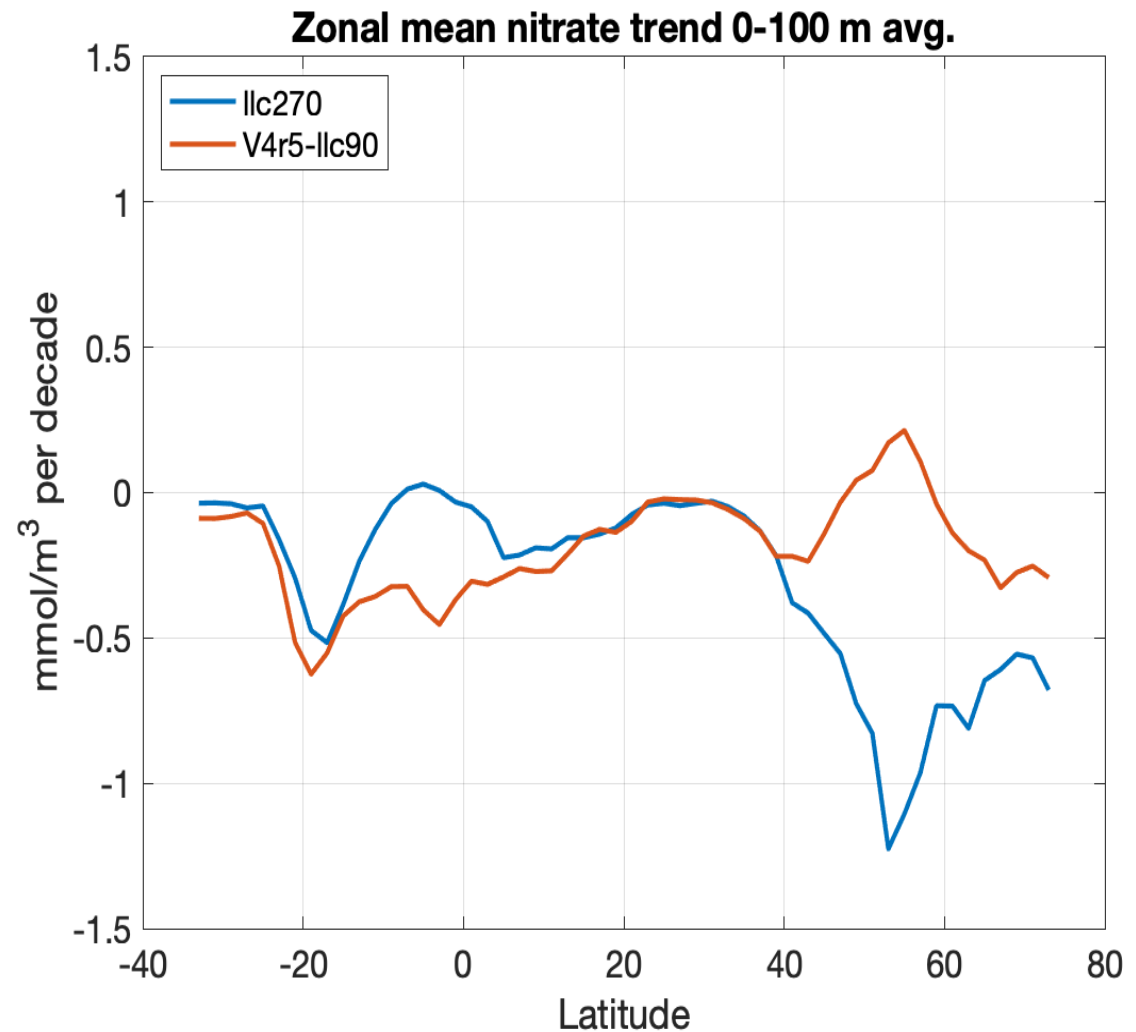
Below 500 m:

Nitrate > 18 mmol/m³

Trends ~0.1-1 mmol/m³/decade

Biases ~1-3 mmol/m³ are small

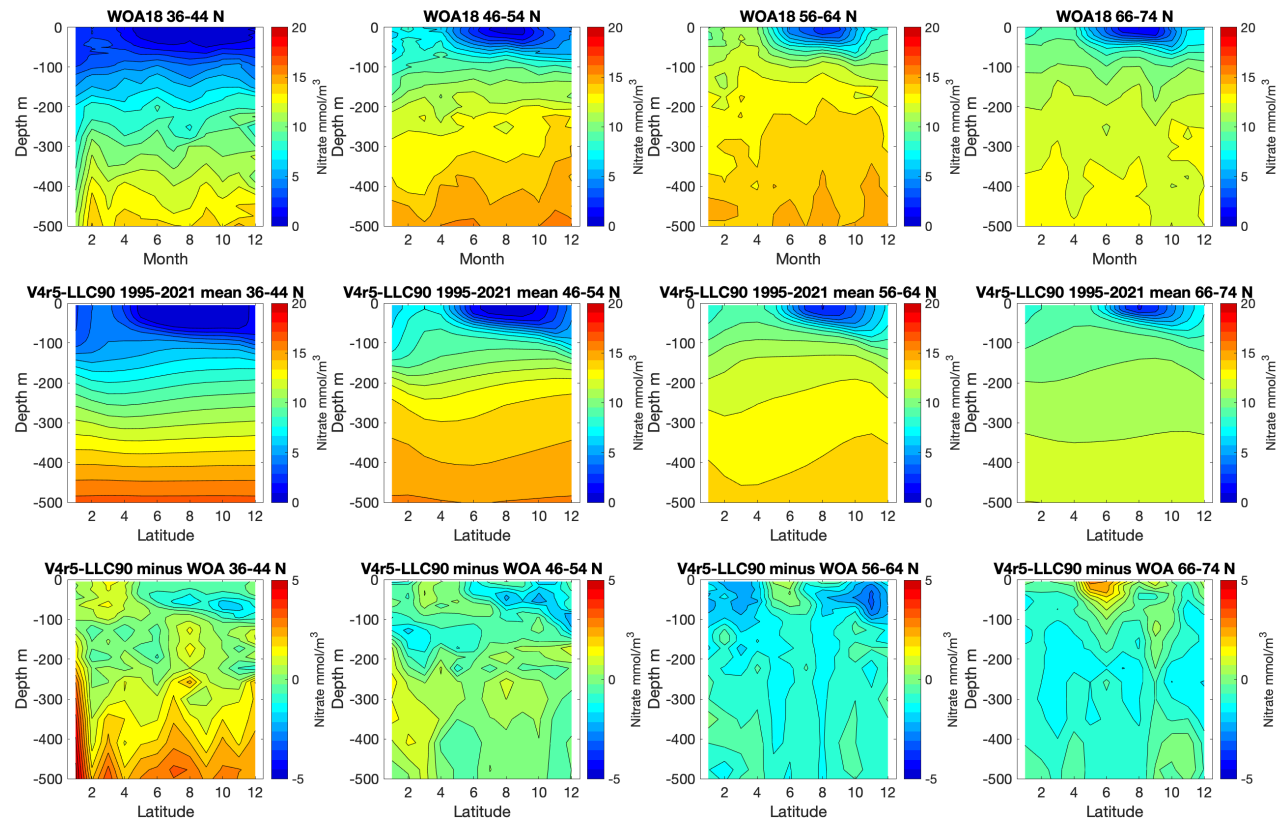
Patterns are qualitatively
reasonable in the upper ocean,
but exhibit large biases and trends
compared to low reference
concentrations.



Seasonal cycle in the Subarctic Atlantic

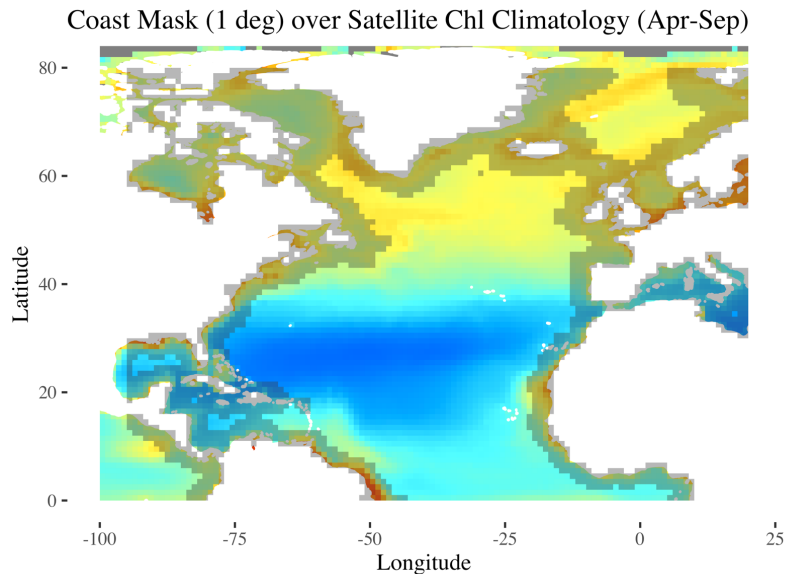
V4r5 is fairly realistic

LLC270 (not shown) has
low-bias that is most
pronounced in winter,
damped seasonal cycle

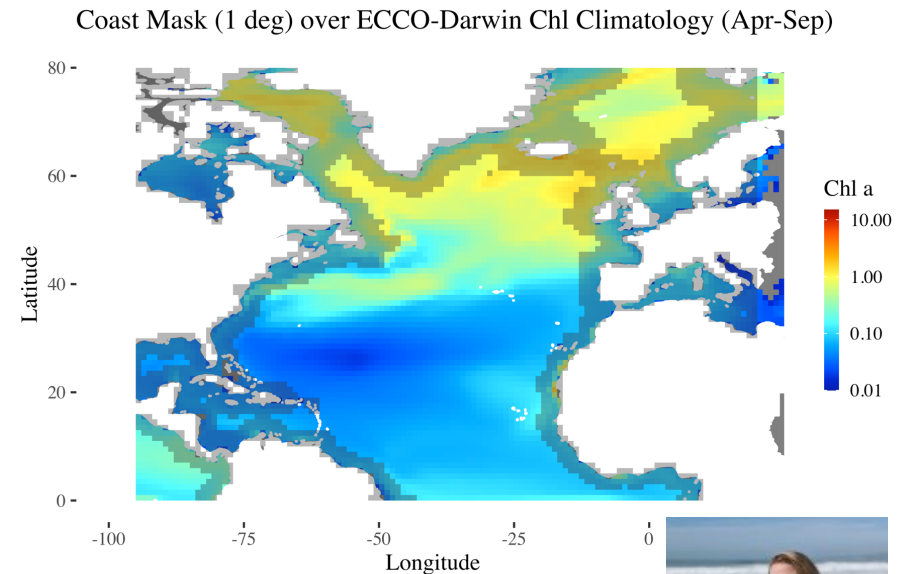


Evaluation of ECCO-Darwin
Zonal-mean Atlantic Nitrate

State estimates qualitatively capture climatological open-ocean chlorophyll



Low modeled growing season chlorophyll in LLC270 vs
satellite qualitatively consistent with low-nutrient biases



Post-doc Casey Schine
Now at Middlebury

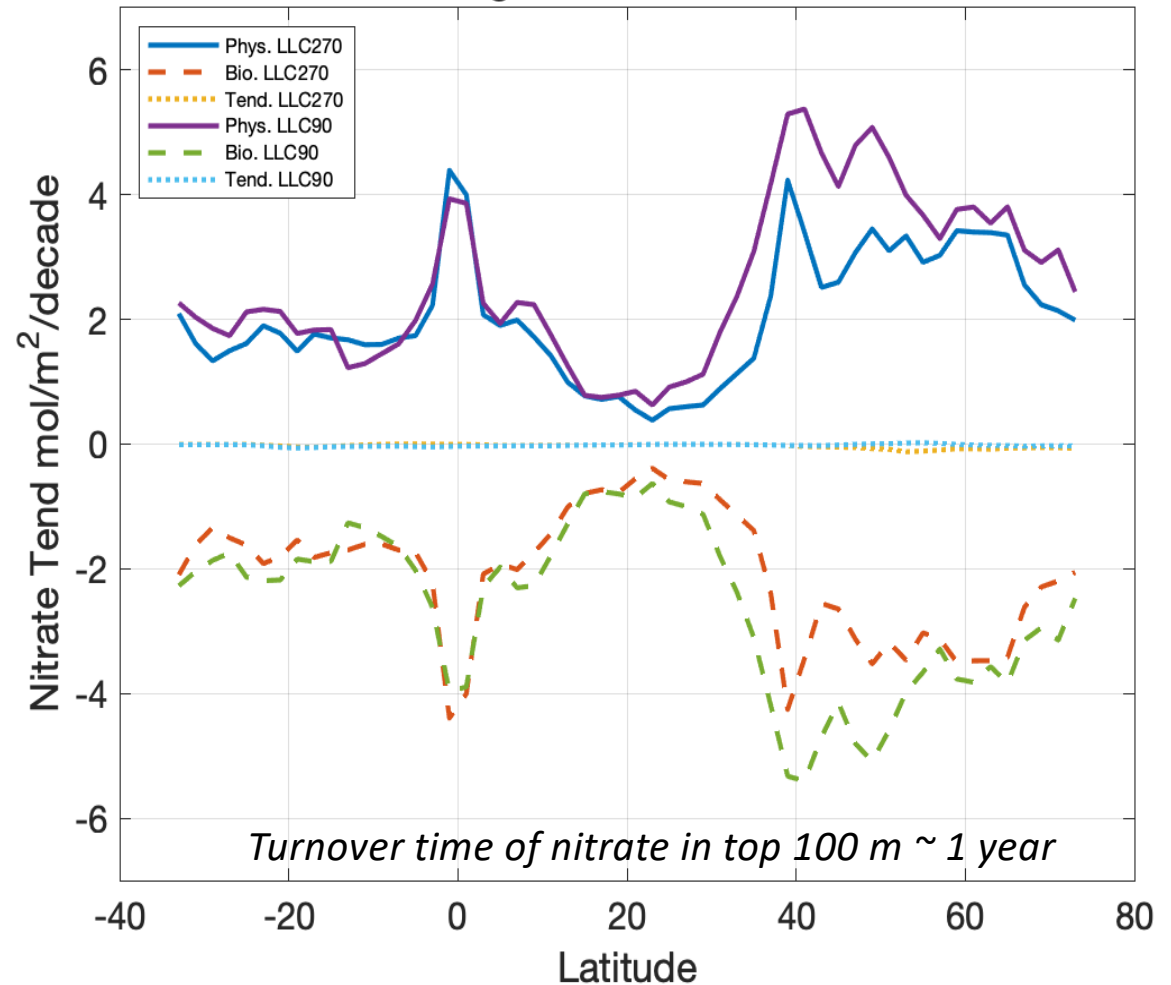


Top 100 m

Physical transport supplies and biology consumes and exports nitrate in the upper 100 m on a timescale ~ 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

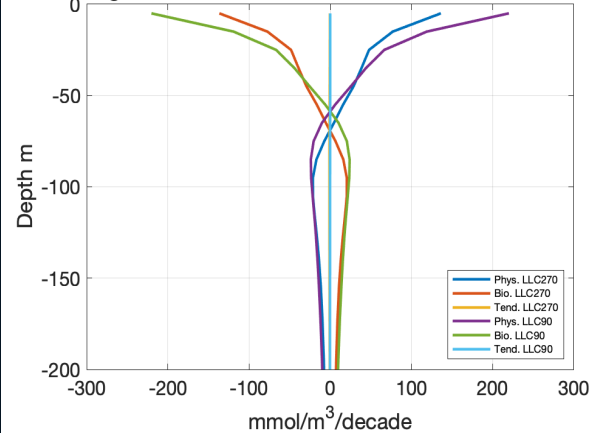


Subarctic Atlantic Profile

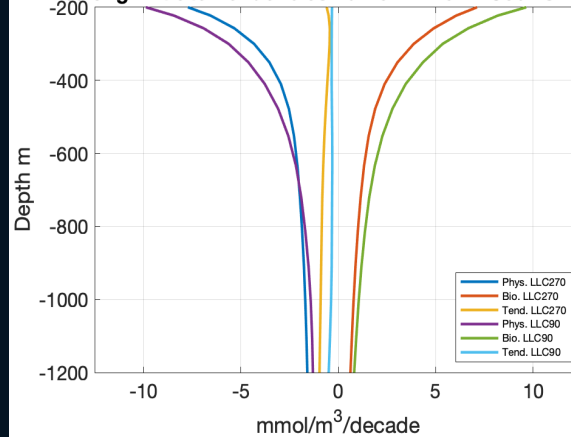
The nitrate tendency due to new productivity in the euphotic zone and remineralization at depth largely mirrors physical transport

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

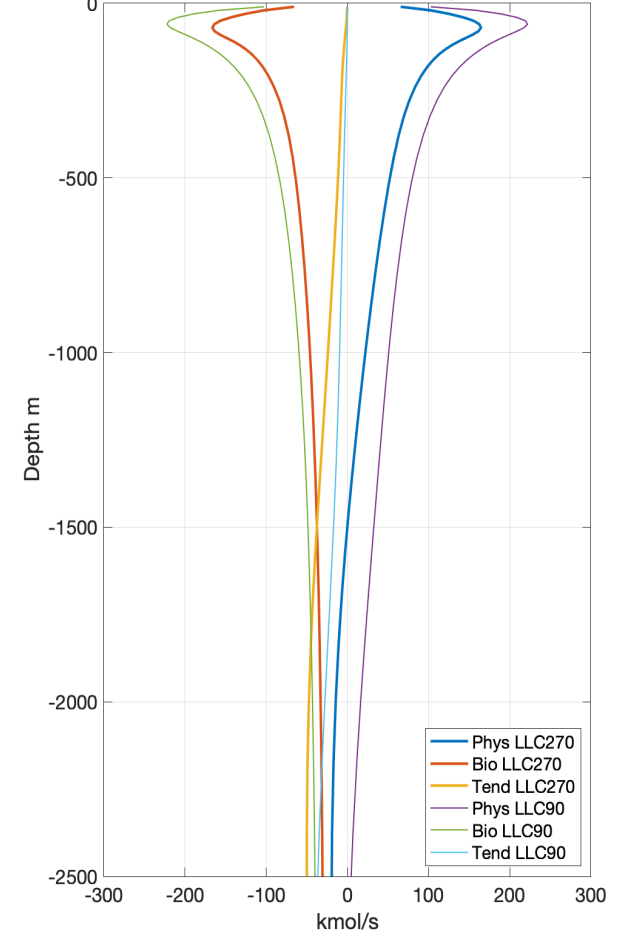
Area avg. Nitrate Tendencies 40-75N V4r5-LLC90 vs LLC270



Area avg. Nitrate Tendencies 40-75N V4r5-LLC90 vs LLC270



Nitrate Tend profiles 40-75N (integrated down)



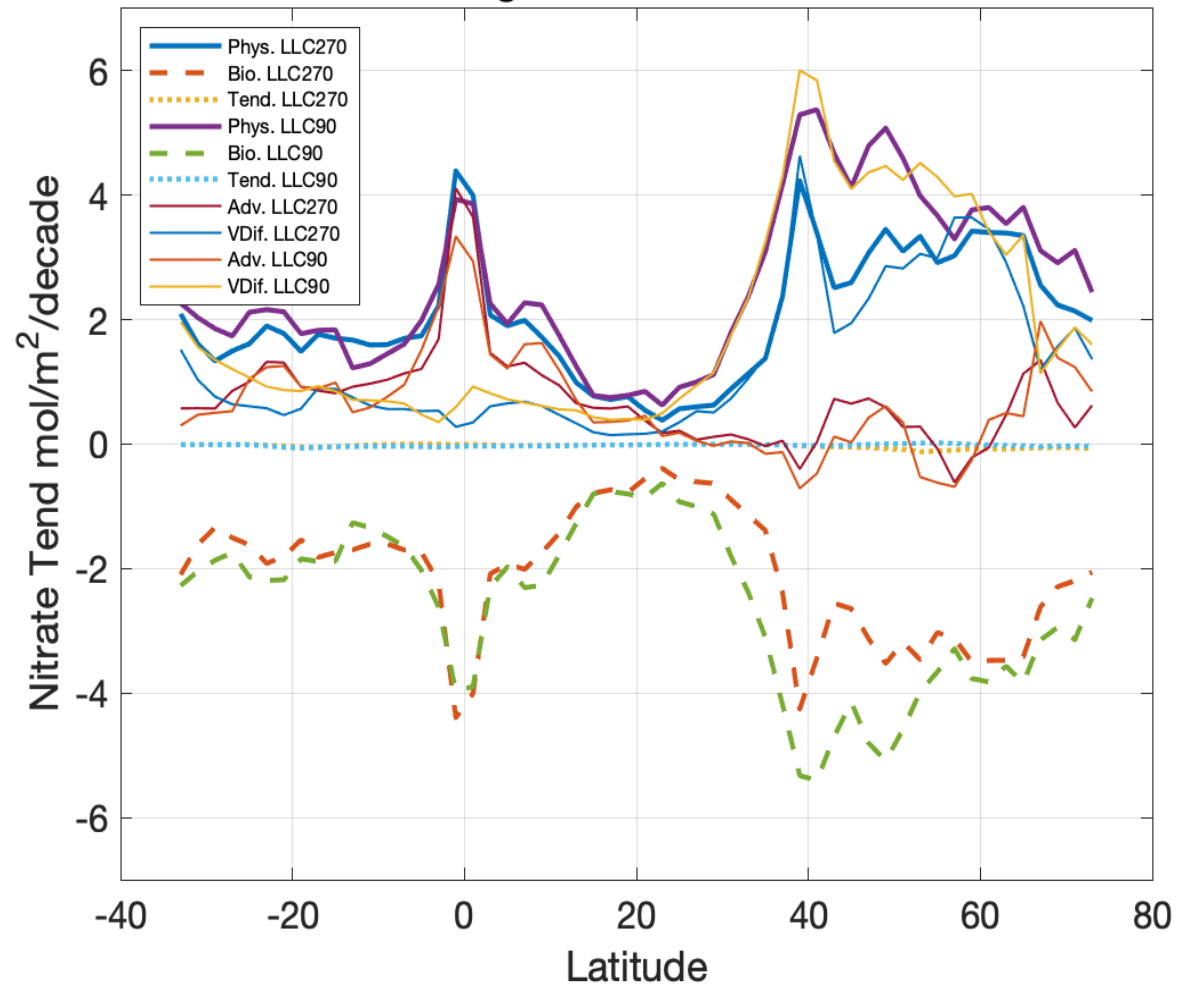
Dynamics of ECCO–Darwin
Zonal–mean Atlantic Nitrate

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



Dynamics of ECCO–Darwin
Zonal–mean Atlantic Nitrate

Separating Physical Contributions to New Production in the Subarctic Atlantic Profile

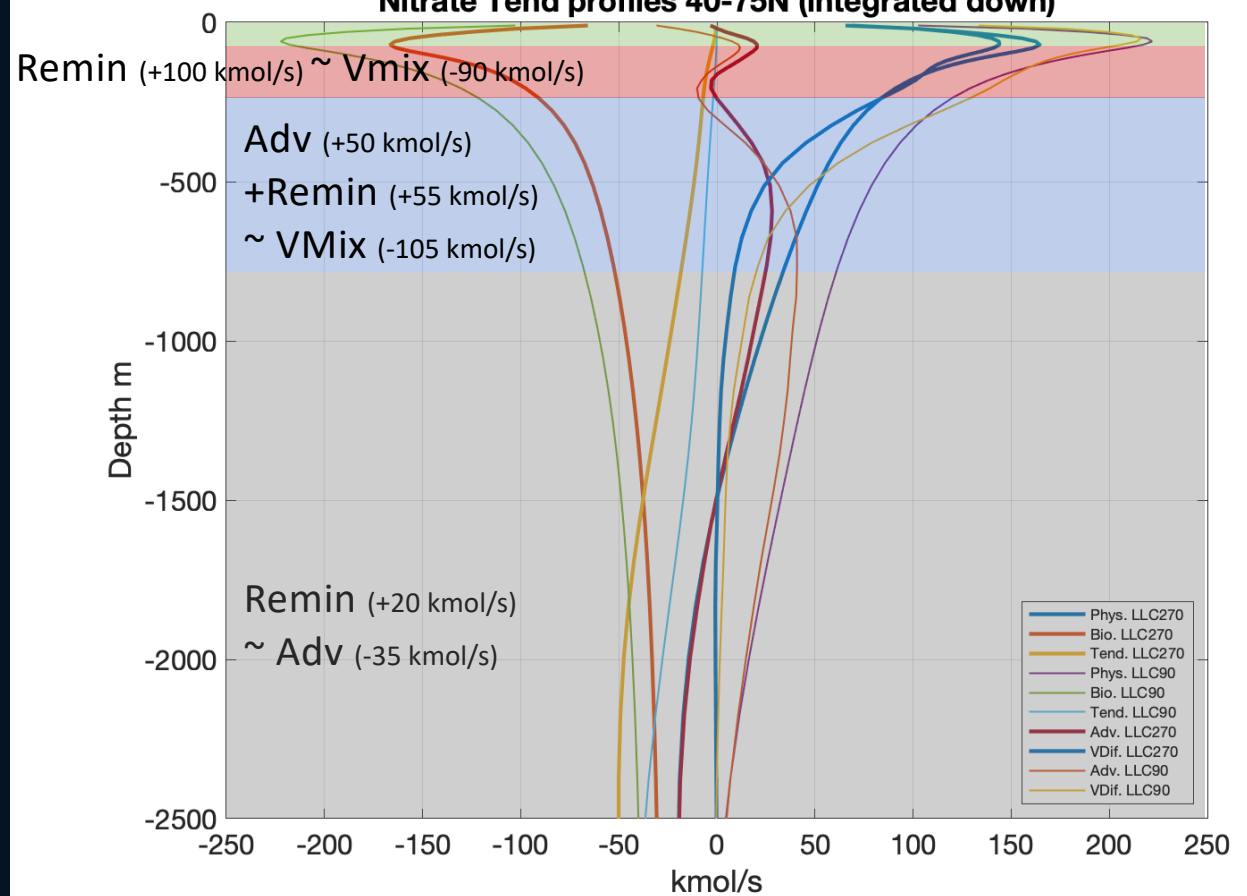
Mixing drives the shallow cycle

Advection drives the deep cycle

Dynamics are qualitatively similar in V4r5 and LLC90

$V_{mix} (+220 \text{ kmol/s}) \sim \text{New Prod.} (-220 \text{ kmol/s})$

Nitrate Tend profiles 40–75N (integrated down)



Thanks

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