The supply of excess phosphate across the Gulf Stream and the maintenance of subtropical nitrogen fixation

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[1] The subtropical North Atlantic is considered a hot spot for biological nitrogen fixation, with estimated rates between 1 and 20 × 10^{11} mol nitrogen fixed annually. However, the region's nutrient reservoir beneath the euphotic zone is so enriched in nitrate relative to phosphate that it is perplexing how fixation might be sustained there. Here, we investigate whether the physical transport of excess phosphate into the subtropical gyre is sufficient to sustain nitrogen fixation in the gyre. Specifically, we assess the Ekman advection and isopycnal mixing of excess phosphate to the subtropical North Atlantic, using detailed hydrographic and nutrient sections occupied across the Gulf Stream combined with satellite wind data. Ekman advection and along-isopycnal mixing provide a source of approximately 2 × 10^{10} mol yr^{-1} of excess phosphate in the northwestern subtropics, a physical mechanism that has the potential to support more than 3 × 10^{11} mol yr^{-1} of biological nitrogen fixation, after accounting for alternative sinks of excess phosphate. This excess phosphate supply across the gyre's northern boundary and high nitrogen fixation there offers a mechanism that can explain both the maintenance of subtropical North Atlantic nitrogen fixation in a phosphate-poor environment and help account for the weak gradients in the proxies of fixation observed along interior circulation pathways of the gyre.

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1. Introduction

[2] Biological nitrogen fixation is thought to add fixed nitrogen to the subtropical North Atlantic at rates of 1–20 × 10^{11} mol N per year [*Gruber and Sarmiento*, 1997; *Capone et al.*, 2005; *Mahaffey et al.*, 2005; *Hansell et al.*, 2007]. However, the nutricline in the region is so enriched in nitrate relative to phosphate, it would appear that non-N_2 fixing phytoplankton should have more than enough nitrate to fully consume all available phosphate [*Wu et al.*, 2000; *Sañudo-Wilhelmy et al.*, 2001]. Under such circumstances, it is believed that the energetically costly process of N_2 fixation is discouraged [*Redfield et al.*, 1963; *Tyrrell*, 1999; *Ganeshram et al.*, 2002; *Deutsch et al.*, 2004], even though other requirements for nitrogen fixation such as low surface nitrate concentrations and relatively high inputs of iron are met. Thus, it is puzzling that N_2 fixation should occur in the North Atlantic subtropical gyre at all, and even more so that it should proceed at the robust rates estimated by various studies (see *Mahaffey et al.* [2005] for a detailed review).

[3] One possible solution to this puzzle is that phosphate in excess of the biological nitrate demanded by non-N_2 fixing phytoplankton is transported across the subtropical gyre's boundaries, which delimit the phosphate-depleted region (Figure 1a). N_2-fixing organisms could then consume this physical supply of excess phosphate without the accumulation of a measurable phosphate pool. If the nitrogen fixation occurred preferentially near the gyre's boundaries, this scenario would also help explain the perplexing results from studies of the isotopic proxy of N_2 fixation (depleted $\partial^{15}N$) [*Knapp et al.*, 2005, 2008]. These studies detect little isotopic transformation, and therefore little indication of biological N_2 fixation, at Bermuda and between Bermuda and Puerto Rico; yet, in these same waters, the isotopic signature suggests that approximately 50% of the nitrate in the subtropical upper thermocline is due to "recent" biological N_2 fixation. *Knapp et al.* [2008] use the term "recently-fixed" nitrogen to mean nitrogen that was biologically fixed in the tropical and/or subtropical North Atlantic, which they distinguish from nitrogen that is imported from outside the basin. Thus, there is an apparent paradox in that high concentrations of recently fixed nitrogen are measured in the gyre interior where local rates of fixation are low. We hypothesize that fluxes of excess phosphate at the gyre's boundaries may sustain nitrogen

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