

Nitrogen isotope simulations show the importance of atmospheric iron deposition for nitrogen fixation across the Pacific Ocean

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[1] Nitrogen (N) fixation by specialized microorganisms (diazotrophs) influences global plankton productivity because it provides the ocean with most of its bio-available N. However, its global rate and large-scale spatial distribution is still regarded with considerable uncertainty. Here we use a global ocean nitrogen isotope model, in comparison with $\delta^{15}\text{NO}_3^-$ observations, to constrain the pattern of N_2 fixation across the Pacific Ocean. N_2 fixation introduces isotopically light atmospheric N_2 from to the ocean ($\delta^{15}\text{N} = 0\text{‰}$) relative to the oceanic average near 5‰, which makes nitrogen isotopes suitable to infer patterns of N_2 fixation. Including atmospheric iron limitation of diazotrophy in the model shifts the pattern of simulated N_2 fixation from the South Pacific to the North Pacific and from the East Pacific westward. These changes considerably improve the agreement with meridional transects of available $\delta^{15}\text{NO}_3^-$ observations, as well as excess P ($\text{PO}_4^{3-} - \text{NO}_3^-/16$), suggesting that atmospheric iron deposition is indeed important for N fixation in the Pacific Ocean. This study highlights the potential for using $\delta^{15}\text{N}$ observations and model simulations to constrain patterns and rates of N fixation in the ocean. **Citation:** Somes, C. J., A. Schmittner, and M. A. Altabet (2010), Nitrogen isotope simulations show the importance of atmospheric iron deposition for nitrogen fixation across the Pacific Ocean, *Geophys. Res. Lett.*, 37, L23605, doi:10.1029/2010GL044537.

1. Introduction

[2] Nitrogen (N) fixation is the dominant source of biologically available nitrogen (fixed-N) into the ocean [Codispoti, 2007], which is performed by specialized prokaryotes (diazotrophs) that can reduce N_2 gas instead of oceanic fixed-N (NO_3^- , NO_2^- , NH_4^+) during photosynthesis. Since diazotrophs are not limited by fixed-N, they can grow in N-depleted surface water provided other required nutrients (e.g., phosphorus (P) and iron (Fe)) are available. Diazotrophs can have an important influence on climate because fixed-N limits primary production and biological sequestration of atmospheric CO_2 . The efficiency, with which diazotrophs can balance the N-loss from denitrification and anammox, the major sinks for fixed-N,

determines if the oceanic fixed-N inventory could fluctuate significantly enough to affect atmospheric CO_2 .

[3] Throughout much of the contemporary ocean, biological productivity is limited by fixed-N suggesting other factors, such as light, temperature, P and Fe availability, and/or NO_3^- inhibition, are preventing diazotrophs from fixing atmospheric N. It has been observed that blooms of *Trichodesmium*, one of the most important and best studied diazotrophs, occur more frequently and are more extensive in warm ($>25^\circ\text{C}$) surface water where fixed-N is depleted and rates of atmospheric Fe deposition are high such as the North Atlantic, Indian, and North Pacific compared to areas of low Fe deposition such as the South Pacific where the abundance of *Trichodesmium* appears to be much lower [Carpenter, 1983; Karl *et al.*, 2002; Carpenter and Capone, 2008]. This pattern of less N_2 fixation in Fe-depleted waters is also consistent in the South Atlantic [Moore *et al.*, 2009]. This suggests that temperature and Fe availability may be the most important factors that determine where N_2 fixation is able to occur. However, other more uncharacterized unicellular diazotrophs have been observed to grow in cooler water near 20°C [Needoba *et al.*, 2007], and it has been suggested that they also may significantly contribute to the global N_2 fixation rate [Zehr *et al.*, 2001; Montoya *et al.*, 2004].

[4] The large spatial and temporal variability of diazotrophs makes it difficult to constrain the global rate of N_2 fixation. Recent estimates range widely between $\sim 100\text{--}200 \text{ Tg N yr}^{-1}$ and predict significantly different spatial patterns [Gruber and Sarmiento, 1997; Karl *et al.*, 2002; Deutsch *et al.*, 2007; Moore and Doney, 2007]. For example, a model that calculates N_2 fixation based on the depletion of xsP ($\text{PO}_4^{3-} - \text{NO}_3^-/16$) observations at the surface within an ocean circulation model estimates that N_2 fixation is tightly coupled with denitrification in the Pacific Ocean [Deutsch *et al.*, 2007]. In contrast, the Biogeochemical Elemental Cycling model [Moore and Doney, 2007], which explicitly includes the effects of Fe availability, predicts that N_2 fixation should be more abundant in the Western North Pacific, where atmospheric Fe deposition is greater, and suggests that the Pacific represents a fixed-N sink because the absence of sufficient Fe prevents N_2 fixation from balancing denitrification throughout much of the South Pacific.

[5] N_2 fixation introduces relatively isotopically light N ($\delta^{15}\text{N} = 0\text{‰}$) into the ocean compared to the global mean $\delta^{15}\text{NO}_3^-$ near 5‰. Therefore, the ratio of the two stable nitrogen isotopes, represented in the $\delta^{15}\text{N}$ notation where $\delta^{15}\text{N} = [({}^{15}\text{N}/{}^{14}\text{N})_{\text{sample}} / ({}^{15}\text{N}/{}^{14}\text{N})_{\text{atmosphere}} - 1] \cdot 1000$, may be a powerful tool to trace patterns of N_2 fixation. Here we compare a model of nitrogen isotopes, embedded within the ocean component of a global Earth System Climate Model, with $\delta^{15}\text{NO}_3^-$ measurements across the Pacific Ocean to

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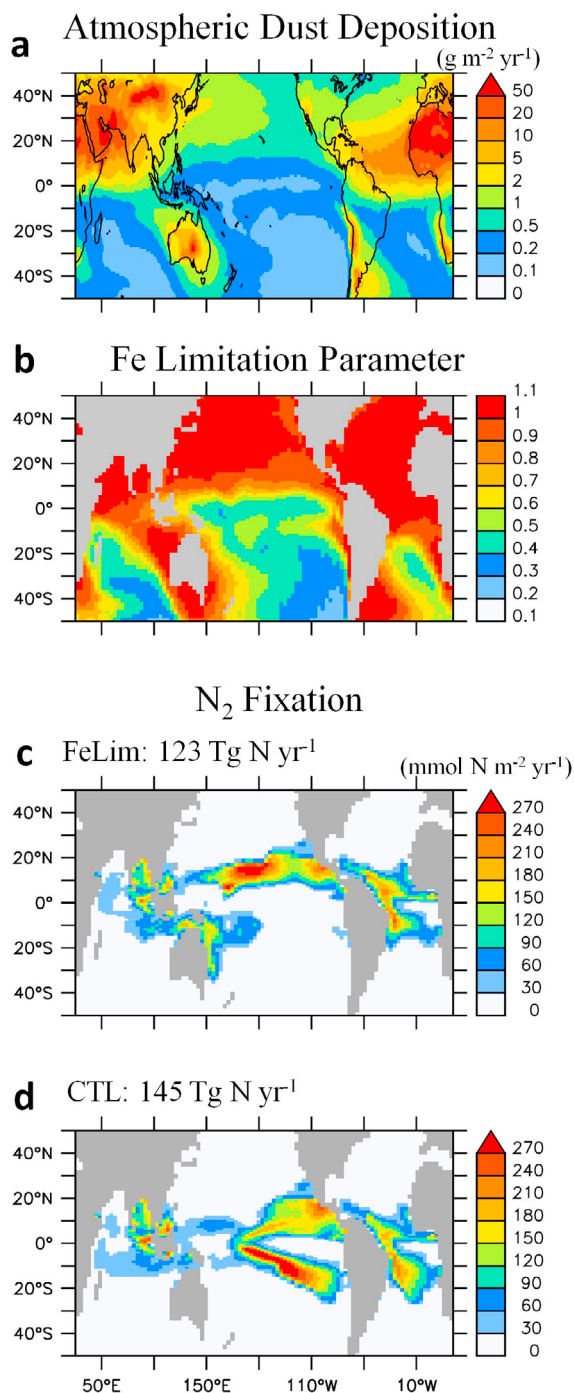


Figure 1. (a–b) Annual rates of dust deposition [Mahowald *et al.*, 2005] and FeLim parameter used to decrease the growth rate of diazotrophs. (c–d) Vertically integrated N₂ fixation in FeLim and CTL.

constrain N₂ fixation focusing on the effect of atmospheric Fe limitation of diazotrophy.

2. Marine Ecosystem/Biogeochemical Model Description

[6] The marine ecosystem/biogeochemical model including N isotopes is a 2N2PZD (2 Nutrients, 2 Phytoplankton, Zooplankton, Detritus) model that includes N₂ fixation, water

column denitrification, and benthic denitrification in a coarse resolution (1.8°→0.9°(in tropics) × 3.6°, 19 vertical levels) ocean general circulation model. It has run for over 1500 years as it approaches equilibrium. We provide a brief description of N₂ fixation and N isotopes below and refer to *Somes et al.* [2010] for a complete model description.

[7] Diazotrophs grow according to the same principles as the “general” phytoplankton class in the model, but we also account for some of their different characteristics. Since fixing dissolved N₂ is energetically more costly than assimilating fixed-N, the growth rate of diazotrophs is lower than that of general phytoplankton in the model. It is zero in waters cooler than 15°C and increases 50% slower with temperature than the growth rate of general phytoplankton (note this value is increased from 40% in *Somes et al.* [2010], which results in an additional ~20 Tg N yr⁻¹ of N₂ fixation). Diazotrophs are not limited by NO₃⁻ and can out-compete general phytoplankton in surface waters that are depleted in fixed-N, but still contain sufficient P (i.e., high xsP water due to denitrification). However, diazotrophs will consume NO₃⁻ if it is available, consistent with culture experiments [Mulholland *et al.*, 2001; Holl and Montoya, 2005], which is another factor that inhibits N₂ fixation in the model. Denitrification, and the propagation of N-deficient waters into the shallow thermocline by physical transport processes, creates an ecological niche for diazotrophs stimulating N₂ fixation [Tyrrell, 1999]. Fe is currently not included as a prognostic tracer in the model. However, we include a simple parameterization of atmospheric Fe limitation of diazotrophy as described in Section 3.

[8] The nitrogen isotope model simulates the distribution of the two stable nitrogen isotopes, ¹⁴N and ¹⁵N, in all N species included in the marine ecosystem model. The processes in the model that fractionate nitrogen isotopes are algal NO₃⁻ assimilation ($\epsilon_{\text{ASSIM}} = 5\text{‰}$), zooplankton excretion ($\epsilon_{\text{EXCR}} = 6\text{‰}$), water column denitrification ($\epsilon_{\text{WCD}} = 25\text{‰}$), and N₂ fixation ($\epsilon_{\text{NFIX}} = 1.5\text{‰}$). Fractionation results in the isotopic enrichment of the more reactive, thermodynamically preferred, light ¹⁴N into the product of each reaction by a process-specific fractionation factor [Mariotti *et al.*, 1981]. Although little fractionation occurs during N₂ fixation in the model, it has an important effect on $\delta^{15}\text{N}$ by introducing isotopically light atmospheric N₂ ($\delta^{15}\text{N} = 0\text{‰}$) into the oceanic fixed-N pool. Benthic denitrification has been observed to have little effect on the oceanic isotopic N pool because denitrifiers consume nearly all NO₃⁻ diffusing into the reactive zones within the sediments, leaving the oceanic N pool mostly unaltered [Brandes and Devol, 2002; Lehmann *et al.*, 2007]. Therefore, in the model, there is no fractionation during benthic denitrification ($\epsilon_{\text{BD}} = 0\text{‰}$), although this is a simplification of observations [Lehmann *et al.*, 2007].

3. Atmospheric Fe Limitation of Diazotrophy

[9] The nitrogenase enzyme, which fixes N₂ in diazotrophs, has a large structural iron (Fe) requirement [Raven, 1988; Sanudo-Wilhelmy *et al.*, 2001]. Diazotrophs may depend on Fe from atmospheric deposition in oligotrophic waters, where a deep pycnocline inhibits upward mixing of subsurface Fe-replete waters into the euphotic zone. Therefore, we include an atmospheric Fe limitation of diazotrophy experiment (Figure 1, FeLim), where diazotrophs’ growth rate is further reduced by the Fe limitation parameter (FeL), which

Table 1. Global Measures of $\delta^{15}\text{NO}_3^-$ and Excess P Model Performance^a

Model	$\delta^{15}\text{NO}_3^-$			Excess P		
	<i>r</i>	STD	RMS	<i>r</i>	STD	RMS
CTL	0.668	1.76	1.33	0.520	1.30	1.27
FeLim	0.680	1.33	0.982	0.530	0.898	1.01

^aCorrelation coefficient (*r*), standard deviation (STD), and root mean squared (RMS) error. STD and RMS have been normalized by the standard deviation from the observations.

scales an estimate of monthly climatological atmospheric dust deposition [Mahowald *et al.*, 2005] between 0 and 1 (Figure 1) by multiplying atmospheric dust deposition rate by a constant factor, and setting the maximum value to 1 (i.e., maximum growth rate = $\mu_D \cdot \text{Fe}L$). This parameterization does not account for any Fe that reaches the surface through vertical mixing or upwelling. Since this source of Fe will be accompanied by large concentrations of subsurface NO_3^- and PO_4^{3-} , we assume that the faster-growing general phytoplankton class will consume all of this Fe along with the

macronutrients. The model does not include Fe input from rivers or shelf sediments.

4. Results

[10] The control (CTL) simulation does not include Fe limitation of diazotrophs (i.e., maximum growth rate = μ_D) and results in large N₂ fixation rates in the Central and Eastern Tropical South Pacific (Figure 1). The only factor that prevents N₂ fixation from occurring in the Eastern Tropical Pacific of CTL is the presence of high surface NO_3^- in the core of the High Nutrient Low Chlorophyll region, where diazotrophs consume NO_3^- instead of fixing dissolved N₂ to meet their N requirement for growth. This tight coupling of N₂ fixation and denitrification in the Eastern Tropical South Pacific is similar with the model of Deutsch *et al.* [2007], which can only indirectly account for Fe limitation and NO_3^- inhibition through xsP observations. Deficiencies in their coarse resolution model (e.g., overestimated nutrient fluxes to the surface with low xsP in the upwelling zone of the Eastern Tropical South Pacific [Gnanadesikan *et al.*, 2002;

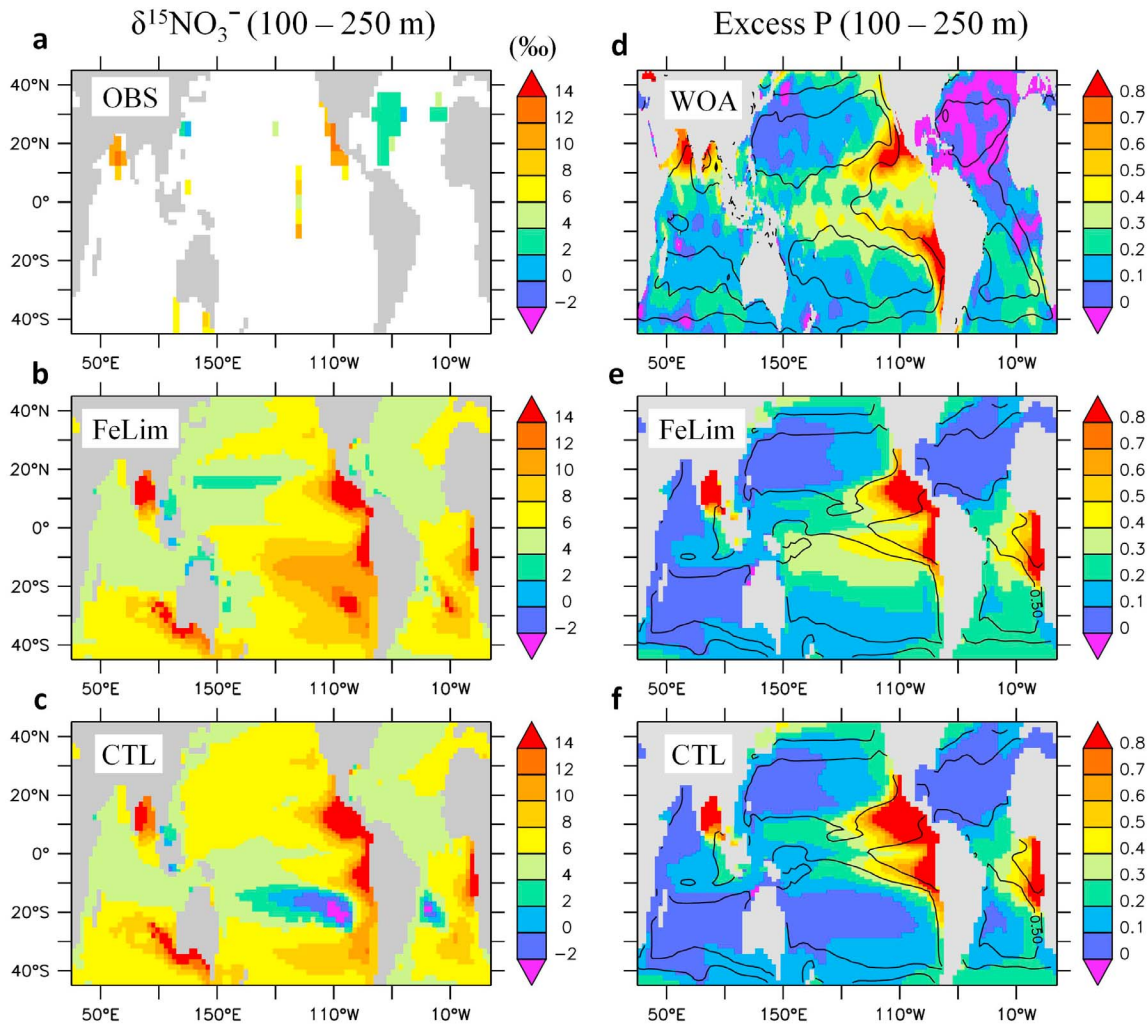


Figure 2. Comparison of (a–c) FeLim and CTL with $\delta^{15}\text{NO}_3^-$ observations [Somes *et al.*, 2010] and (d–f) World Ocean Atlas 2005: xsP and near-surface (0–100m) NO_3^- contours of 5.0 and 0.5 μM . Note that due to the too low N:P for diazotrophs in the model (N:P = 16:1) compared to observations (N:P = \sim 50:1) [Letelier and Karl, 1998; Krauk *et al.*, 2006; White *et al.*, 2006], a slight overestimation of xsP is to be expected where N₂ fixation occurs.

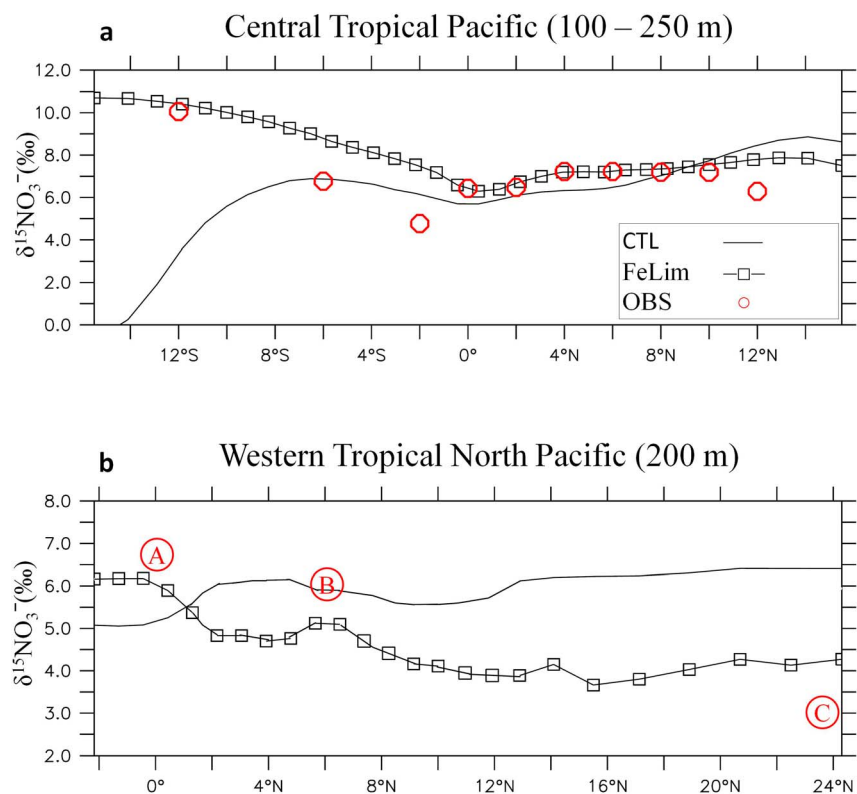


Figure 3. Comparison of FeLim and CTL $\delta^{15}\text{NO}_3^-$ with observations in the (a) Central Equatorial Pacific (140°W) (100–250 m) [Altabet, 2001] (reanalysis), and (b) Western North Pacific (100–250 m) (model transect connects through latitude/longitude of each data point): Location A, $\sim 6.75\text{‰}$ at 0°N/S, 140°E [Yoshikawa *et al.*, 2006]; location B, $\sim 6.0\text{‰}$ at 6°N, 125°E [Kienast *et al.*, 2008]; location C, $\sim 3.0\text{‰}$ at 25°N, 123°E [Liu *et al.*, 1996].

Doney *et al.*, 2004) could lead to an overestimation of N₂ fixation there [Moore and Doney, 2007].

[11] Global patterns of N₂ fixation in FeLim—such as high values in the tropical/subtropical North Pacific, the western tropical/subtropical South Pacific, the western tropical/subtropical South Atlantic, the tropical/subtropical North Atlantic and the Indian Ocean—are more consistent with direct observations [e.g., Karl *et al.*, 2002; Carpenter and Capone, 2008] and with results from a more complex ecosystem/biogeochemical model [Moore and Doney, 2007]. Nevertheless, N₂ fixation in our model does not extend northward of $\sim 30^\circ\text{N}$ in the North Pacific, whereas some observations show N₂ fixation as far north as 35–40°N [Needoba *et al.*, 2007; Kitajima *et al.*, 2009]. We hypothesize this discrepancy occurs due to the oversimplified fast-recycling microbial loop parameterization, which recycles organic matter to inorganic nutrients at N:P=16. It has been suggested that dissolved organic P recycles more efficiently relative to dissolved organic N and may also be directly consumed [Wu *et al.*, 2000], which is a mechanism that could help relieve diazotrophs of their P limitation throughout the tropical/subtropical oligotrophic ocean and stimulate additional N₂ fixation.

[12] Global measures of $\delta^{15}\text{NO}_3^-$ and xsP improve in FeLim compared to CTL (Table 1). Generally lower $\delta^{15}\text{NO}_3^-$ and xsP in the Northern Hemisphere relative to the Southern Hemisphere in FeLim, due to more N₂ fixation occurring in the Northern Hemisphere where more atmospheric Fe deposition exists, result in a better match with observations than in CTL

(Figure 2). The Central and Western Tropical Pacific represent regions where N₂ fixation may occur as high xsP flows westward “downstream” from the suboxic zones. Measured $\delta^{15}\text{NO}_3^-$ shows a decreasing trend northwards in the two transects across the Pacific (Figure 3), with a minimum near the equator in the Central Pacific. This equatorial minimum is reproduced in the model due to the low degree of surface NO₃⁻ utilization as a result of extensive NO₃⁻ supply to the surface from equatorial upwelling. The northward decreasing $\delta^{15}\text{NO}_3^-$ trend in FeLim in both transects is due to more N₂ fixation occurring north of the equator, where sufficient atmospheric Fe deposition exists (Figure 1). When atmospheric Fe limitation of diazotrophy is not included in the model (CTL), the opposite $\delta^{15}\text{NO}_3^-$ trend is simulated because more N₂ fixation occurs south of the equator, in contrast to the observations.

[13] Global rates of N₂ fixation, water column denitrification, and benthic denitrification are smaller in FeLim (123, 89.4, 35.3 Tg N yr⁻¹, respectively) compared to CTL (145, 119, 34.6 Tg N yr⁻¹, respectively) because a tighter coupling of N₂ fixation and denitrification exists in CTL in the Eastern Pacific. More N₂ fixation occurring in and around denitrification zones leads to increased export production and remineralization of organic matter at depth, lower oxygen concentrations, and more denitrification. Since denitrification creates an ecological niche for diazotrophs, its increase will stimulate additional N₂ fixation, creating a positive feedback effect. This results in a bigger suboxic zone and more denitrification in the Eastern Tropical South Pacific in CTL compared to FeLim. The amount of this high xsP water that

reaches the Southern Ocean and escapes the Pacific Ocean through the Antarctic Circumpolar Current determines the degree to which the Pacific Ocean will be a fixed-N sink. In CTL, the Pacific Ocean is a fixed-N sink of 10 Tg N yr⁻¹ because high xsP water communicates with the Southern Ocean through the subsurface where N₂ fixation cannot occur. Since there is less denitrification, and thus less xsP in the Eastern Tropical Pacific subsurface that can mix into the Southern Ocean, the Pacific Ocean is a fixed-N sink of only 4 Tg N yr⁻¹, even though Fe limits N₂ fixation at the surface throughout much of the South Pacific. Note that both model versions underestimate xsP off of Peru and Chile because the coarse-resolution model cannot capture suboxia there. In the real ocean, a part of this water may sustain high xsP until it reaches a region with sufficient Fe (e.g., North Atlantic or North Indian Ocean), which could take hundreds of years, and result in a significant decoupling of N₂ fixation from denitrification that occurs in the Fe-depleted Southern Hemisphere [see also Falkowski, 1997].

5. Conclusion

[14] Model simulations that include Fe limitation of diazotrophy show a much better agreement with $\delta^{15}\text{NO}_3^-$ and xsP observations compared to a model that neglects this effect (Table 1 and Figures 2 and 3). Nitrate isotope observations show a decreasing northward trend across two transects in the Central and Western Pacific (Figure 3). Comparisons with model results reveal that these trends can be best explained by the input of isotopically light N by N₂ fixation, where higher rates of atmospheric Fe deposition exist. This highlights the potential of $\delta^{15}\text{NO}_3^-$ as a tool to infer the spatial pattern of N₂ fixation. If no N₂ fixation was occurring, the $\delta^{15}\text{NO}_3^-$ value would be expected to be very high ($\delta^{15}\text{NO}_3^- > 10\text{‰}$) due to the nearly complete utilization of surface NO₃⁻ in the oligotrophic ocean [Altabet and Francois, 1994; Somes et al., 2010], which is a drastically different $\delta^{15}\text{N}$ signature than what would be expected if N₂ fixation was significantly contributing to the local N pool ($\delta^{15}\text{N}_2 = 0\text{‰}$). Our results suggest that $\delta^{15}\text{N}$ observations, in combination with models, can be used to constrain N₂ fixation patterns in present and past oceans.

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