

Response to Reviewers

We thank the reviewers for their constructive feedback. Based on their suggestions, the following changes have been made:

We have included a figure illustrating the location of the field work (Fig. 1a), as well as included additional data to provide more context for the results. The additional data include a section plot showing the $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ at additional stations across the transect (Fig. 1b), as well as the fluorescence trace on the figure of the $\delta^{15}\text{N}$ budgets to indicate the range in depth and magnitude of productivity within the euphotic zone (Fig. 1c).

Additional changes in response to specific comments are described below in italics.

Review #1:

The manuscript by Angela Knapp and colleagues describes rates of nitrogen fixation via the analysis of nitrogen isotopes. This is a topic that Angela knows very well and has published multiple times on previous occasions. It is therefore not surprising that the manuscript is well-written with a good knowledge of the relevant literature. I recommend the manuscript for publication with just a few minor comments.

Specific comments

1. This work seems to suggest there is an offset of N isotope analysis from to in situ ^{15}N incubations which might be resolved or understood with time, rather than just analytical differences leading to variable results. Is this the case or am I just optimistic?

*The reviewer is correct that recent work shows an offset between N_2 fixation rates estimated by $^{15}\text{N}_2$ bottle uptake experiments and $\delta^{15}\text{N}$ budgets. A discussion of potential causes for this offset can be found in Knapp et al., 2016, PNAS. Some factors specific to the OUTPACE study that potentially contributed to the lower N_2 fixation rates estimated by $\delta^{15}\text{N}$ budgets than those estimated by $^{15}\text{N}_2$ bottle uptake experiments are addressed in the text briefly, and include potential decoupling during a large *Trichodesmium* spp. bloom at LD B, as well as the fate of that newly fixed N, which is further discussed in de Verniel et al., 2018, as well as Caffin et al., 2018, both this issue.*

2. Some of the geochemical description on Page 5 Lines 13-28 and Page 6 Lines 1-12 could go into the Methods section which could use the extra length

The text has been modified as suggested, and this text is now section 2.4 in the Methods.

3. Some broader context for the sediment traps might be helpful - where was the 150 m depth horizon with regards to the 1% light level or the DCM or the nutricline?

We appreciate the Reviewer's interest in a more complete representation of the biogeochemistry of the sediment trap stations. We have included the fluorescence trace in Fig. 1c, which can be compared with the $\text{NO}_3^- + \text{NO}_2^-$ concentration and $\delta^{15}\text{N}$ profiles, and have included more information in Figure 1 as described above.

4. I realize OUTPACE has multiple publications, but a map showing station locations would be useful to quickly orientate the reader without having to look it up.

We appreciate the feedback and have now included a map of the station locations (Fig. 1a).

Review #2

The manuscript by Knapp and colleagues estimates the input of N via N₂ fixation using a biogeochemical approach in the western south Pacific Ocean. The manuscript is well-written, and explains the conclusions well, addressing the relevant references. However, this reviewer considers that a few minor changes need to be addressed before publication.

Specific comments.

I do agree with Reviewer 1 in two points. First, though it is clear that this manuscript is related to many other publications coming from OUTPACE probably showing a map of station, having the map here will be useful for readers beginning from this work, instead of having to look for the geographical context on their own. Second, it will be useful to extend a bit the context of the sediment traps, maybe adding an additional line in Fig 1 showing either the mixed layer depth or the The units of Average PN_{sink} flux in Table 1 and in the Results section are not the same. The text is in $\mu\text{mol N}$, and the table in mmol N . I recommend units in agreement in both parts.

As suggested by both reviewers, we have included a map in Fig. 1, as well as additional data, please see the above description. We also thank the Reviewer for their careful attention to detail – the units for the mass flux in Table 1 have been changed so that they are consistent with the units in the text, as well as with the units for N₂ fixation, which improves the readability of the manuscript.

Some parts of section 3.2 could be moved to the Methods section, while others seem to fit better in the Discussion, as a first subsection 4.1. My suggestion is that P7 L25 to P8 L14 and P9 L4 to P11 L7 move to the Discussion, while P8 L15 to L23 up to “of the source NO₃” move to the Methods. This way the Results subsection is reduced to the description of the results themselves (P8 L23 to P9 L3). P3 L26.

We appreciate the Reviewer’s suggestion, and have moved the last two paragraphs of the original Results section to the beginning of the Discussion section as suggested.

However, we felt that the paragraph describing NO₃⁻+NO₂⁻ $\delta^{15}\text{N}$ gradients with depth (in the original manuscript P8 L15 to L23), that the Reviewer suggested be moved to Methods, was better suited to the Results section because it felt out of sequence to move a description of the NO₃⁻+NO₂⁻ $\delta^{15}\text{N}$ gradients with depth to methods before those values were described. Additionally, since we were not interpreting these gradients, just describing the measurements, we felt this text best fit in the Results section. Similarly, we felt that the first paragraph of the Results section was better suited there than in the Discussion, since it describes what the quantitatively relevant terms are in the regional $\delta^{15}\text{N}$ budgets.

Just curiosity, but is there a reason for using the term Oxygen Deficient Zones instead of the mosth widely used Oxygen Minimum Zones (OMZs)?

Oxygen deficient zones (ODZs) has become the preferred term to identify water columns “where the water column oxygen concentration is so low (low nanomolar range) that oxygen respiration is precluded and denitrification and other low-oxygen (suboxic) metabolisms predominate” (Devol, 2015, Annual Reviews of Marine Science)”, and is used to differentiate from other water columns which have higher oxygen concentrations, but all of which have a minimum in oxygen concentrations at some depth that typically coincides with the depth of peak rates of oxic respiration (i.e., remineralization).

P5-P6. The description of the geochemical tools could be moved to the Methods section. And it could be more intuitive to begin the name of the variables by δ_{15N} -xx. It is a bit confusing reading $NO_3+NO_2 \delta_{15N}$, for instance.

The text has been moved as suggested.

P7 L16. What do the authors mean with “thermocline NO_3+NO_2 ”? Do they refer to subsurface NO_3+NO_2 as in section 3.2, or NO_x produced in the thermocline?

Here we refer to $NO_3^-+NO_2^-$ in the thermocline, i.e., between roughly 100 and 800 m, which is plotted in Fig. 1c. This depth range records the isotopic signature of NO_3^- reduction processes that occurred in the ODZs of the eastern tropical South Pacific. However, in section 3.2 when we use the term “subsurface”, it is to refer to the upper portion of the thermocline, i.e., below the euphotic zone, and specifically the depth range over which the majority of the $NO_3^-+NO_2^-$ that fuels phytoplankton growth in the euphotic zone is sourced.

Distribution and rates of nitrogen fixation in the western tropical South Pacific Ocean constrained by nitrogen isotope budgets

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15 **Abstract.** Constraining the rates and spatial distribution of di-nitrogen (N₂) fixation fluxes to the ocean informs our understanding of the environmental sensitivities of N₂ fixation as well as the timescale over which the fluxes of nitrogen (N) to and from the ocean may respond to each other. Here we quantify rates of N₂ fixation as well as its contribution to export production along a zonal transect in the Western Tropical South Pacific (WTSP) Ocean using N isotope (“δ¹⁵N”) budgets. Comparing measurements of
20 water column nitrate+nitrite δ¹⁵N with the δ¹⁵N of sinking particulate N at a western, central, and eastern station, these δ¹⁵N budgets indicate high, modest, and low rates of N₂ fixation at the respective stations. The results also imply that N₂ fixation supports exceptionally high, i.e., ≥50%, of export production at the western and central stations, which are also proximal to the largest iron sources. These geochemically-based rates of N₂ fixation are equal to or greater than those previously reported in the
25 tropical North Atlantic, indicating that the WTSP Ocean has the capacity to support globally significant rates of N₂ fixation, which may compensate for N removal in the oxygen deficient zones of the eastern tropical Pacific.

Key Points:

- Higher N₂ fixation rates are observed at the western vs. eastern end of a zonal transect in the
30 western tropical South Pacific

- Nitrogen isotope budgets indicate that $\geq 50\%$ of export production was supported by N_2 fixation at stations with significant dissolved iron
- N_2 fixation in the western tropical southwest Pacific may compensate for N loss in the eastern tropical Pacific

1 Introduction

The primary source of nitrogen (N) to the ocean is the biologically-mediated reduction of di-nitrogen (N_2) gas to ammonia, which is then assimilated into the biomass of the organisms carrying out this process, known as diazotrophs (Gruber, 2004). While the distribution and rates of this process in the ocean play a central role in regulating the fertility and community structure of marine ecosystems, these first-order properties of marine N_2 fixation remain poorly constrained. Historically, the highest rates of N_2 fixation in the global ocean have been associated with the tropical North Atlantic (Mahaffey et al., 2005; Sohm et al., 2011). The high $^{15}N_2$ incubation-based N_2 fixation rates observed in the tropical Atlantic (Luo et al., 2012) are consistent with both the preference of diazotrophs for warm waters (Breitbarth et al., 2007; Stal, 2009) as well as the high atmospheric dust flux to the region (Mahowald et al., 2009; Prospero, 1996) that helps fulfil the high iron requirement of the enzyme, nitrogenase, carrying out N_2 fixation (Berman-Frank et al., 2001; Kustka et al., 2003). Additionally, the elevated ratio of nitrate (NO_3^-) to phosphate (PO_4^{3-}) concentrations (Gruber and Sarmiento, 1997) and low $\delta^{15}N-NO_3^-$ (Knapp et al., 2008) in the upper thermocline of the North Atlantic are attributed to high regional N_2 fixation rates, and have supported the hypothesis that iron availability plays a key role in regulating the spatial distribution of N_2 fixation in the ocean (Moore et al., 2009; Moore and Doney, 2007) (“ $\delta^{15}N$ ”, where $\delta^{15}N = \{[(^{15}N/^{14}N)_{\text{sample}}/(^{15}N/^{14}N)_{\text{reference}}] - 1\} * 1000$, with atmospheric N_2 as the reference).

While the highest inputs of N to the ocean have traditionally been associated with the North Atlantic, it has also been argued that this association results from the significant sampling bias in favor of the tropical Atlantic (Sohm et al., 2011), with large regions of the South Pacific and Indian Ocean under-sampled with respect to direct N_2 fixation rate measurements (Luo et al., 2012). More recently, the Eastern Tropical South Pacific (ETSP) has seen increased sampling due to nutrient distribution-based modelling predictions that the highest global N_2 fixation rates would be found in surface waters above and adjacent to oxygen deficient zones (ODZs), where significant phosphorus (P) would be available to support N_2 fixation (Deutsch et al., 2007). However, field campaigns have found exceedingly low rates of N_2 fixation in the ETSP gyre (Knapp et al., 2016a; Raimbault and Garcia, 2008) (Moutin et al.,

2008), which have been attributed to limited iron availability (Dekaezemacker et al., 2013). Consequently, existing measurements indicate that the dominant sinks for N in the ocean, benthic and water column denitrification and anaerobic ammonium oxidation, focused in the ODZs of the eastern tropical Pacific and Arabian Sea (Gruber and Galloway, 2008), are spatially segregated from the dominant N₂ fixation inputs in the tropical Atlantic. This spatial decoupling of N inputs and outputs necessarily corresponds to a temporal decoupling, requiring the time scale of ocean circulation for N₂ fixation to respond to changes in rates of denitrification, and vice versa. In spite of the apparent spatial decoupling in the modern ocean, paleoceanographic evidence indicates that N fluxes to and from the ocean have been closely balanced over ≥ 20 kya, requiring feedbacks in the N cycle to operate on time scales shorter than ocean circulation, and thus implying a tighter spatial coupling of N sources and sinks (Brandes and Devol, 2002; Deutsch et al., 2004). While N loss in the ocean is constrained to suboxic sediments and water column ODZs, similar constraints on the location of the largest N₂ fixation fluxes to the ocean are lacking, and thus the degree to which marine N sources and sinks have been coupled through time remains uncertain.

While prior modelling analyses emphasized the importance of iron *or* phosphorus in supporting N₂ fixation, the most recent modelling studies reflect the importance of elevated surface temperatures, adequate iron, *and* the potential for low surface ocean NO₃⁻:PO₄³⁻ concentration ratios to support a unique ecological niche for diazotrophs (Dutkiewicz et al., 2012; Monteiro et al., 2011; Weber and Deutsch, 2014). Attention has consequently shifted to the relatively undersampled Western Tropical South Pacific (WTSP) Ocean, where atmospheric dust fluxes to warm surface waters are higher than in the central and eastern tropical South Pacific (Mahowald et al., 2009), and where surface ocean NO₃⁻ and PO₄³⁻ concentrations and ratios are relatively advantageous for diazotrophs (Moutin et al., 2005; Van Den Broeck et al., 2004). While seasonally some regions nearer to islands experience PO₄³⁻ drawdown to lower levels (e.g., (Van Den Broeck et al., 2004), Moutin, this issue), in parts of the WTSP gyre surface ocean NO₃⁻ concentrations are ≤ 0.1 μ M and PO₄³⁻ concentrations are ~ 0.05 to 0.2 μ M (Garcia et al., 2014), with corresponding positive P* values (where $P^* = [\text{PO}_4^{3-}] - [\text{NO}_3^-]/16$) (Deutsch et al., 2007). Additionally, early remote sensing work detected significant and persistent

blooms of *Trichodesmium* spp. in the WTSP (Dupouy et al., 2000), consistent with more recent direct observations of elevated *Trichodesmium* spp. abundance and N₂ fixation rates observed near Melanesian islands (i.e., New Caledonia, Vanuatu, and Fiji) (Moisander et al., 2010; Shiozaki et al., 2014; Stenegren et al., 2018; Yoshikawa et al., 2015) and in the Solomon Sea (Bonnet et al., 2009; 2015; Berthelot et al., 2017). These high *Trichodesmium* spp. abundances and N₂ fixation rates have been attributed to sea surface temperatures >25 °C and continuous nutrient inputs of terrigenous and volcanic origin (Labatut et al., 2014; Radic et al., 2011). Prior molecular work has also shown higher rates of N₂ fixation in the WTSP at locations where surface ocean dissolved iron (DFe) concentrations were higher and where *Trichodesmium* spp. were less stressed for iron (Chappell et al., 2012). Together, these observations and modelling-based predictions highlight the potential for significant N₂ fixation rates in regions of the WTSP where diazotrophs can meet their iron and phosphorus requirements.

Here we use geochemical tools to quantify rates of N₂ fixation along a zonal transect in the WTSP where surface waters are ≥25 °C, have favourable macronutrient concentrations and ratios, and where DFe concentrations are an order of magnitude higher than in the South Pacific Gyre, and are mainly attributable to shallow hydrothermal input (Guieu et al., under review). We then compare these geochemical estimates of N₂ fixation rates with other metrics of N₂ fixation evaluated on this cruise, as well as with the global distribution of marine N₂ fixation rates.

2 Methods

2.1 Sample collection

Sampling for the Oligotrophic to UItTra-oligotrophic PACific Experiment (“OUTPACE”) cruise was conducted on the R/V L’Atalante, which left Noumea, New Caledonia on 18 February 2015 and arrived in Papeete, Tahiti, on 2 April 2015. This cruise followed a roughly zonal transect along 18 to 19 °S between 159 °E and 160 °W. Details of the cruise and experimental design are described comprehensively in (Moutin et al., 2017), but briefly, sediment traps were deployed at three “Long Duration” (LD) stations A, B, and C (Table 1) (Fig. 1a). Water column samples were collected from

Niskin bottles deployed on a CTD-rosette at both LD as well as “short duration” (SD) stations (Fig. 1a), and water was stored at -20 °C in HDPE bottles for analysis on land.

2.2 $\text{NO}_3^- + \text{NO}_2^-$ concentration and $\delta^{15}\text{N}$ measurements

The concentrations of $\text{NO}_3^- + \text{NO}_2^-$ in water column samples collected on the OUTPACE cruise were measured by colorimetric methods (Aminot and Kerouel, 2007). The $\delta^{15}\text{N}$ of $\text{NO}_3^- + \text{NO}_2^-$ in samples collected on the OUTPACE cruise was measured using the denitrifier method (Casciotti et al., 2002; Sigman et al., 2001), with modifications (McIlvin and Casciotti, 2011) (Fig. 1b). Typical standard deviation of the $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ analyses was $\leq 0.2\text{‰}$, with error bars for individual analyses shown in Fig 1c.

2.3 Sinking particulate N flux and $\delta^{15}\text{N}$ measurements

Surface-tethered floating particle-interceptor traps (PPS5) were deployed on the OUTPACE cruise at 150, 330 and 520 m for ~5 days at Stations LD_A and LD_B, and at 150 and 330 m at LD_C (Moutin et al., 2017). The mass flux (“ PN_{sink} flux”) and $\delta^{15}\text{N}$ of the PN_{sink} flux was determined by combustion-GC interfaced to an isotope ratio mass spectrometer at the Mediterranean Institution of Oceanography with a lower detection limit of 2.2 $\mu\text{g N}$ and precision of $\pm 0.3\text{‰}$ for 80 μg samples, with a precision of $\pm 1.0\text{‰}$ for 10 to 20 μg samples typical of what was collected in the sediment traps at the LD stations.

2.4 $\delta^{15}\text{N}$ budget calculations

Here we compare the $\delta^{15}\text{N}$ of the two dominant sources of “new” N to surface waters, subsurface NO_3^- and N_2 fixation, with the $\delta^{15}\text{N}$ of the sinking particulate N (PN_{sink}) flux to estimate the relative importance of both NO_3^- and N_2 fixation as a source of new N to surface waters. This approach relies on subsurface NO_3^- and N_2 fixation having distinct isotopic compositions. N_2 fixation introduces new N to the ocean with a $\delta^{15}\text{N}$ of $\sim -1\text{‰}$ (Carpenter et al., 1997; Hoering and Ford, 1960; Minagawa and Wada, 1986). In contrast, in the Pacific, NO_3^- mixed up from the subsurface is impacted by water column denitrification and can have a NO_3^- $\delta^{15}\text{N} > 20\text{‰}$ (e.g., (Brandes et al., 1998; Casciotti et al., 2013; Rafter and Sigman, 2016)), although as upper thermocline waters move westward in the Pacific, the very high NO_3^- $\delta^{15}\text{N}$ signal is diluted and typical values are between 5 and 10‰ (Lehmann et al., 2018; Rafter et al., 2013). The relative importance of each source for supporting export production can be determined

using the two end-member mixing model described in Eqn. 1 (“ $\delta^{15}\text{N}$ budget”) where the fractional importance of N_2 fixation for supporting export production (x) is defined as:

$$\text{PN}_{\text{sink}} \delta^{15}\text{N} = x(-1\text{‰}) + (1 - x)(\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}) \quad \text{Eq. 1}$$

Rearranging and solving for x yields:

$$x = (\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N} - \text{PN}_{\text{sink}} \delta^{15}\text{N}) / (1 + \text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}) \quad \text{Eq. 2}$$

10 Multiplying the fraction of export production supported by N_2 fixation (x) by the PN_{sink} mass flux provides a time-integrated N_2 fixation rate that can be compared with $^{15}\text{N}_2$ incubation-based N_2 fixation rate measurements (Knapp et al., 2016a). Here it is hypothesized that both rates of N_2 fixation and its importance for fuelling export production will be higher at stations in the western vs. central and eastern regions of the WTSP because of their closer proximity to iron sources (Guieu et al., under review).

3 Results

3.1 $\text{NO}_3^- + \text{NO}_2^-$ concentration and $\delta^{15}\text{N}$, and $\text{PN}_{\text{sink}} \delta^{15}\text{N}$

Samples collected in the upper 70 m at the LD stations had $\leq 0.1 \mu\text{M}$ $\text{NO}_3^- + \text{NO}_2^-$ (Caffin et al., 2017) and increased with depth, consistent with prior regional observations (Garcia et al., 2014) (Fig. 1c). All nutrient concentration data are available at: <http://www.obs-vlfr.fr/proof/php/outpace/outpace.php>.

Water column profiles of thermocline $\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}$ are available at: <https://www.bco-dmo.org/dataset/733237/data> and show similar trends at the LD stations, with 650 m $\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}$ $\sim 7\text{‰}$, increasing to $\sim 8.5\text{‰}$ at 400 m (Fig. 1b, 1c) (Knapp et al., 2018), which fall within the range of previous regional measurements (Yoshikawa et al., 2015). The elevation of thermocline $\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}$ relative to the mean ocean $\text{NO}_3^- + \text{NO}_2^- \delta^{15}\text{N}$ of 5‰ is attributed to denitrification and/or anammox occurring in the ODZs of the ETSP, where thermocline $\text{NO}_3^- \delta^{15}\text{N}$ can exceed 20‰ (e.g., (Altabet et al., 2012; Casciotti et al., 2013)). The average, mass-weighted $\delta^{15}\text{N}$ of the PN_{sink} flux collected in the 150 m

trap increased from the western to eastern stations, from $0.6 \pm 1.0\text{‰}$ at LD_A, to $3.1 \pm 1.0\text{‰}$ at LD_B, and to $7.7 \pm 1.0\text{‰}$ at LD_C (Table 1) (Fig. 1c).

3.2 Results of the $\delta^{15}\text{N}$ budget: N_2 fixation rates and their contribution to export production

Estimates of N_2 fixation rates and their contribution to export production determined using $\delta^{15}\text{N}$ budgets include the quantitatively dominant fluxes of N into and out of the surface ocean. Here, the dominant fluxes of N into the surface ocean include subsurface NO_3^- and newly fixed N introduced from diazotrophs, and the dominant loss term is represented by the PN_{sink} flux (Eq. 1). In the event that total dissolved N (TDN) concentrations vary in space/time, they may be included as well, however, surface ocean TDN concentrations from the OUTPACE cruise show little to no zonal gradient, and were typically between 5 and 7 μM in the upper 100 m (Moutin et al., This issue), and so are not included in $\delta^{15}\text{N}$ budget calculations. Additionally, the importance of N in atmospheric deposition has recently received significant attention, especially in the northwest Pacific (e.g., (Kim et al., 2014)), raising the possibility that atmospheric N deposition might also be an important source of N in the WTSP. However, the atmospheric N deposition flux measured on the OUTPACE cruise, $0.2 \mu\text{mol N m}^{-2} \text{d}^{-1}$ (Caffin et al., 2017), is several orders of magnitude lower than the mass flux captured in the 150 m sediment traps, 30 to 300 $\mu\text{mol N m}^{-2} \text{d}^{-1}$ (Table 1), indicating that atmospheric N deposition is an insignificant source of new N to regional surface waters, and so is neglected in our $\delta^{15}\text{N}$ budget calculations.

While gradients with depth in subsurface $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ at the OUTPACE LD stations are modest compared to those in the ETSP, due to the relatively low sampling resolution in the upper thermocline where NO_3^- is likely sourced, we calculate $\delta^{15}\text{N}$ budgets using a range of $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ end-member values, which are represented by the shaded regions in Fig. 1c. At each LD station, the $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ lower bound is represented by the 650 m sample and the upper bound is represented by the 400 m sample. Samples collected shallower than this (i.e., ≤ 200 m) are either within this range or show elevation in $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ as the $\text{NO}_3^- + \text{NO}_2^-$ concentration decreases, and reflects the effect of NO_3^- assimilation, as is commonly observed below the euphotic zone in other oligotrophic regions (Knapp et al., 2016a; Knapp et al., 2008), and thus do not represent the $\delta^{15}\text{N}$ of the source NO_3^- . Using the PN_{sink}

$\delta^{15}\text{N}$ ($\pm 1\text{‰}$ 1 S.D.) and the range in subsurface $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ end-member values in Eq. 2 corresponds to 80 to $83 \pm 13\%$, 50 to 56 $\pm 12\%$, and 0 to $8 \pm 11\%$ of export production supported by N_2 fixation at stations LD_A, LD_B, and LD_C, respectively (Table 1). Multiplying the fractional importance of N_2 fixation by the PN_{sink} mass flux yields a range of estimated N_2 fixation rates of 219 to 290, 11 to 20, and 0 to 9 $\mu\text{mol N m}^{-2} \text{d}^{-1}$ at stations LD_A, LD_B, and LD_C, respectively (Table 1), where the range includes uncertainty in both the PN_{sink} $\delta^{15}\text{N}$ measurement as well as the $\text{NO}_3^- + \text{NO}_2^-$ $\delta^{15}\text{N}$ end-member.

4 Discussion

4.1 Comparison of $\delta^{15}\text{N}$ budget results with other N_2 fixation metrics from the OUTPACE cruise

The N_2 fixation rates derived from the $\delta^{15}\text{N}$ budgets described above are lower than those measured by *in situ* $^{15}\text{N}_2$ incubations at the same OUTPACE stations, with depth-integrated average N_2 fixation rates of 593 ± 51 , 706 ± 302 , and 59 ± 16 $\mu\text{mol N m}^{-2} \text{d}^{-1}$ at LD A, LD B, and LD C, respectively (Caffin et al., 2017). Previous work has also found lower $\delta^{15}\text{N}$ budget-derived N_2 fixation rates relative to $^{15}\text{N}_2$ incubation-based N_2 fixation rates (Knapp et al., 2016a). To the extent that sediment traps under collect the export flux, the two different metrics of N_2 fixation may be reconciled by multiplying “x” from Eq. 2, the fractional importance of N_2 fixation for export production, by other metrics of new or export production such as O_2/Ar ratios, ^{234}Th deficits, or ^{14}C uptake rates (Knapp et al., 2016a). This explanation may reconcile the $\delta^{15}\text{N}$ budget and $^{15}\text{N}_2$ incubation-based N_2 fixation rate estimates at LD A, which differ by a factor of ~ 2.5 , and potentially the rates at LD C as well, which, while they differ by a factor >6 , both correspond to relatively low N_2 fixation rates. However, the $\delta^{15}\text{N}$ budget and $^{15}\text{N}_2$ incubation-based N_2 fixation rates observed at LD B, 11 to 21 and 706 $\mu\text{mol N m}^{-2} \text{d}^{-1}$, respectively, are more difficult to reconcile based on sediment trap under-collection alone, and may be partially attributable to variability encountered while sampling at the end of a phytoplankton bloom as well as the fate of newly fixed N at that station (Caffin et al., 2018; de Verneil et al., 2017). We note that the zonal trend in increasing PN_{sink} $\delta^{15}\text{N}$ to the east is similar to a zonal gradient in suspended particulate N (PN_{susp}) $\delta^{15}\text{N}$ (Bonnet et al., This Issue), suggesting that the $\delta^{15}\text{N}$ of the PN_{sink} observed at LD B is consistent with other regional geochemical data. Additionally, the $^{15}\text{N}_2$ incubation-based N_2 fixation

rate at LD B has relatively large error bars, resulting from observations of decreasing *in situ* N_2 fixation rates over the course of several daily observations at LD B (Caffin et al., 2017), which may also contribute to the offset between the $^{15}N_2$ incubation and $\delta^{15}N$ budget-based N_2 fixation rate estimates. Further, the PN_{sink} flux collected in the 150 m trap at LD B, $0.030 \text{ mmol N m}^{-2} \text{ d}^{-1}$, was somewhat lower than the PN_{sink} flux collected in the 330 and 520 m traps at the same station, 0.034 and $0.036 \text{ mmol N m}^{-2} \text{ d}^{-1}$, respectively, which is unexpected given the more typical mass flux attenuation with depth observed at LD A and LD C, as well as elsewhere in the ocean (Martin et al., 1987). This unusual trend in mass flux with depth suggests either non-steady state sinking flux (Caffin et al., 2018) conditions and/or a problem with the sediment trap sample collection at LD B. Regardless, using the ^{14}C -uptake based estimate of net community production at LD B, $1.91 \text{ mmol N m}^{-2} \text{ d}^{-1}$, instead of the PN_{sink} mass flux to multiply “x” from Eq. 2 by yields an N_2 fixation rate of $2300 \text{ } \mu\text{mol N m}^{-2} \text{ d}^{-1}$. These significant disparities in productivity metrics and resulting N_2 fixation rates at LD B suggests the potential for temporal decoupling of production and export and/or the underestimation of the export flux by the sediment trap, and indicate that N_2 fixation rates are probably higher than those resulting from $\delta^{15}N$ budget calculations based on the mass flux to the 150 m trap at LD B. Regardless, we take the zonal trend in $PN_{sink} \delta^{15}N$ to indicate a decreasing contribution from N_2 fixation to export from the west to the east to be robust as it is consistent with both the $PN_{susp} \delta^{15}N$ measurements as well as the broad trends in $^{15}N_2$ incubation-based N_2 fixation rate estimates that decrease from the west to east.

Comparing the absolute magnitude of the $\delta^{15}N$ budget-based N_2 fixation rates with previous measurements, we find that the 219 to $290 \text{ } \mu\text{mol N m}^{-2} \text{ d}^{-1}$ rate estimated for LD A represents a significant N_2 fixation rate relative to prior global measurements (Luo et al., 2012), in particular if it should be revised upwards to account for the under-collection of the export flux by the sediment trap. In contrast, the estimated rate range at LD B, 11 to $21 \text{ } \mu\text{mol N m}^{-2} \text{ d}^{-1}$, is quite low, as is the range of 0 to $9 \text{ } \mu\text{mol N m}^{-2} \text{ d}^{-1}$ at LD C, and both of these rates are broadly similar to the rates previously measured in the ETSP (Knapp et al., 2016a; Moutin et al., 2008; Raimbault and Garcia, 2008). Similarly, the $\delta^{15}N$ -budget based estimate of the contribution of N_2 fixation to export production at LD C is low and similar to previous $\delta^{15}N$ -budget measurements in the North Pacific (Casciotti et al., 2008) and North Atlantic

(Altabet, 1988; Knapp et al., 2005). However, the fractional contribution of N_2 fixation to export production at LD A, 80 to 83%, is higher than all previous $\delta^{15}N$ budget results. The contribution of N_2 fixation to export production at LD B, 50 to 57%, is also notably high. While the previous $\delta^{15}N$ budgets of (Karl et al., 1997) and (Dore et al., 2002) found evidence for ~50% of export production supported by N_2 fixation near Hawaii, newer methods capable of measuring the $NO_3^- + NO_2^-$ $\delta^{15}N$ at the lower $NO_3^- + NO_2^-$ concentrations found in the upper thermocline that represent a more realistic estimate of the end-member NO_3^- source suggest that N_2 fixation may support closer to 25% of export during the summer in the North Pacific gyre (Bottjer et al., 2017; Casciotti et al., 2008). Consequently, the findings of 50 to 57% and 80 to 83% of export production being supported by N_2 fixation at stations LD B and LD A, respectively, indicates that N_2 fixation plays a significant role supporting carbon fixation and export production in this region of the WTSP, consistent with the high e-ratios (up to 9.7) reported by (Caffin et al., 2017). Direct export of diazotrophs has been reported by (Caffin et al., 2017), but most export is likely indirect, i.e., after the transfer of diazotroph-derived N to non-diazotrophic plankton, that is subsequently exported (Caffin et al., 2018), as has been observed elsewhere in the WTSP (Bonnet et al., 2016; Knapp et al., 2016b).

4.2 Environmental sensitivities of N_2 fixation and the basin-scale coupling of N sources and sinks

The zonal gradient in both N_2 fixation rates as well as their contribution to export production in the OUTPACE study supports emerging hypotheses regarding the controls on the distribution of marine N_2 fixation fluxes in the global ocean. Specifically, the low rates of N_2 fixation documented in this study at LD C and in the ETSP (Knapp et al., 2016a) indicate that low $NO_3^-:PO_4^{3-}$ concentration ratios in the absence of adequate iron (Blain et al., 2008; Fitzsimmons et al., 2014) are insufficient to support significant fluxes of new N to the ocean. Instead, the results presented here are consistent with recent modelling work that has included *both* the high iron requirements of diazotrophs as well as the potential for low $NO_3^-:PO_4^{3-}$ concentration ratios to support elevated diazotroph abundance and N_2 fixation inputs to the ocean (Dutkiewicz et al., 2012; Monteiro et al., 2011; Weber and Deutsch, 2014). Indeed, these new modelling efforts have identified the WTSP as a unique region where PO_4^{3-} concentrations are relatively high, NO_3^- concentrations are low, and atmospheric dust fluxes provide a moderate source of

iron to warm surface waters, conditions seemingly favourable for significant N₂ fixation fluxes. While regions within the WTSP nearer to islands experience significant PO₄³⁻ drawdown, with seasonal PO₄³⁻ turnover times comparable to those observed in the Sargasso Sea (Van Den Broeck et al., 2004; Van Mooy et al., 2009), these modelling predictions are supported by recent reports of high regional ¹⁵N₂ incubation-based N₂ fixation rates (Bonnet et al., 2017).

However, prior to the OUTPACE cruise, our knowledge of DFe concentrations and their sources in the WTSP was limited, especially in the western and central sectors. During OUTPACE, Guieu et al. (Under review) reported high DFe concentrations in the western sector of the WTSP (from 160 °E to 165 °W, average 1.7 nM within the photic layer), i.e., significantly ($p < 0.05$) higher than those reported in the eastern sector (165 °W to 160 °W, average 0.3 nM within the photic layer). The high DFe concentrations measured in the west were previously undocumented, and reveal several maxima (> 50 nM), suggesting significant iron inputs to this region. (Guieu et al., Under review) found that atmospheric deposition in this region was too low to explain the observed DFe concentrations in the water column, and that the iron in the euphotic layer may instead derive from shallow (~500 m) hydrothermal sources associated with the Tonga-Kermadec subduction zone.

Recent studies performed in the western end of the WTSP in the Solomon, Bismarck (Berthelot et al., 2017; Bonnet et al., 2009; Bonnet et al., 2015) and Arafura (Messer et al., 2015; Montoya et al., 2004) Seas also reveal extremely high N₂ fixation rates ($> 600 \mu\text{mol N m}^{-2} \text{ d}^{-1}$), indicating that high N₂ fixation rates have been found over a significant region of the WTSP, extending west to east from Australia to Tonga and north to south from the equator to 25 to 30 °S, or $\sim 13 \times 10^6 \text{ km}^2$ (i.e. ~ 20 % of the South Pacific Ocean area). These significant N inputs may offset the N loss occurring in the ODZs of the eastern tropical Pacific. The ability for marine N inputs and outputs to compensate for each other within the same ocean basin corresponds to a spatial and thus temporal coupling on the scale of years to decades, consistent with the paleoceanographic record (Brandes and Devol, 2002; Deutsch et al., 2004; Weber and Deutsch, 2014), and represents an intermediate view of the distribution of global marine N₂ fixation fluxes consistent with that proposed by (Weber and Deutsch, 2014) where iron availability

controls local N₂ fixation rates but phosphorus availability regulates basin-scale N₂ fixation rates (Moutin et al., 2008 and this issue).

5 Conclusions

The goal of this study was to address the question: do regions other than the tropical Atlantic contribute significantly to global N₂ fixation fluxes? While our results should be taken as a “snapshot” view that cannot necessarily be scaled up to annual fluxes, at stations proximal to iron sources, geochemically-derived N₂ fixation rates of 219 to 290 $\mu\text{mol N m}^{-2} \text{ d}^{-1}$ were observed, and could potentially represent a lower bound of N₂ fixation rates due to the potential under-collection of the PN_{sink} flux by sediment traps. Moreover, at stations LD_A and LD_B, separated by $\sim 27^\circ$ longitude, N₂ fixation was found to support >50% of export production, a finding that has not been replicated elsewhere with sensitive NO₃⁻+NO₂⁻ $\delta^{15}\text{N}$ methods to our knowledge. Together with similar findings from ¹⁵N₂ uptake experiments, these results suggests that N₂ fixation can support a significant fraction of export production over a large region of the WTSP. At the eastern station most distant from iron sources, both rates and the contribution of N₂ fixation to export production were low, ~ 0 to 9 $\mu\text{mol N m}^{-2} \text{ d}^{-1}$ and 0 to 8%, respectively, similar to previous measurements in the ETSP where diazotrophs may also be challenged by iron availability (Dekaezemacker et al., 2013; Knapp et al., 2016a; Moutin et al., 2008). Significant N₂ fixation fluxes in the WTSP may provide a means of balancing N loss occurring in the ODZs of the eastern tropical Pacific, and thus may help reconcile the paleoceanographic record requiring N inputs and losses to balance each other on time scales shorter than ocean circulation (Dutkiewicz et al., 2012; Monteiro et al., 2011; Weber and Deutsch, 2014).

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References

- Altabet, M. A.: Variations in Nitrogen Isotopic Composition between Sinking and Suspended Particles - Implications for Nitrogen Cycling and Particle Transformation in the Open Ocean, Deep-Sea Research Part a- Oceanographic Research Papers, 35, 535-554, 1988.
- Altabet, M. A., Ryabenko, E., Stramma, L., Wallace, D. W. R., Frank, M., Grasse, P., and Lavik, G.: An eddy-stimulated hotspot for fixed nitrogen-loss from the Peru oxygen minimum zone, Biogeosciences, 9, 4897-4908, 2012.
- Aminot, A. and Kerouel, R.: Dosage automatique des nutriments dans les eaux marines: méthodes en flux continu. Ifremer, Plouzanne, France, 2007.
- Berman-Frank, I., Cullen, J. T., Shaked, Y., Sherrell, R. M., and Falkowski, P. G.: Iron availability, cellular iron quotas, and nitrogen fixation in Trichodesmium, Limnology and Oceanography, 46, 1249-1260, 2001.
- Berthelot, H., Benavides, M., Moisander, P. H., Grosso, O., and Bonnet, S.: High nitrogen fixation rates in the particulate and dissolved pools in the Western Tropical Pacific (Solomon and Bismarck Seas), Geophysical Research Letters, 2017. 2017.
- Blain, S., Bonnet, S., and Guieu, C.: Dissolved iron distribution in the tropical and sub tropical South Eastern Pacific, Biogeosciences, 5, 269-280, 2008.
- Bonnet, S., Berthelot, H., Turk-Kubo, K., Fawcett, S., Rahav, E., L'Helguen, S., and Berman-Frank, I.: Dynamics of N₂ fixation and fate of diazotroph-derived nitrogen during the VAHINE mesocosm experiment, Biogeosciences, 13, 2653-2673, 2016.
- Bonnet, S., Biegala, I. C., Dutrieux, P., Slemons, L. O., and Capone, D. G.: Nitrogen fixation in the western equatorial Pacific: Rates, diazotrophic cyanobacterial size class distribution, and biogeochemical significance, Global Biogeochemical Cycles, 23, 1-13, 2009.

- Bonnet, S., Caffin, M., Berthelot, H., Grosso, O., Guieu, C., and Moutin, T.: Contribution of dissolved and particulate fractions to the Hot Spot of N₂ fixation in the Western Tropical South Pacific Ocean (OUTPACE cruise), *Biogeosciences*, This Issue. This Issue.
- 5 Bonnet, S., Caffin, M., Berthelot, H., and Moutin, T.: Hot spot of N₂ fixation in the western tropical South Pacific pleads for a spatial decoupling between N₂ fixation and denitrification, *Proceedings of the National Academy of Sciences*, 114, E2800-E2801, 2017.
- 10 Bonnet, S., Rodier, M., Turk, K., K., Germineaud, C., Menkes, C., Ganachaud, A., Cravatte, S., Raimbault, P., Campbell, E., Qu  rou  , F., Sarthou, G., Desnues, A., Maes, C., and Eldin, G.: Contrasted geographical distribution of N₂ fixation rates and nifH phylotypes in the Coral and Solomon Seas (South-Western Pacific) during austral winter conditions, *Global Biogeochemical Cycles*, 29, 2015.
- Bottjer, D., Dore, J. E., Karl, D. M., Letelier, R. M., Mahaffey, C., Wilson, S. T., Zehr, J., and Church, M. J.: Temporal variability of nitrogen fixation and particulate nitrogen export at Station ALOHA, *Limnology and Oceanography*, 62, 200-216, 2017.
- 15 Brandes, J. A. and Devol, A. H.: A global marine-fixed nitrogen isotopic budget: Implications for Holocene nitrogen cycling, *Global Biogeochemical Cycles*, 16, 2002.
- Brandes, J. A., Devol, A. H., Yoshinari, T., Jayakumar, D. A., and Naqvi, S. W. A.: Isotopic composition of nitrate in the central Arabian Sea and eastern tropical North Pacific: A tracer for mixing and nitrogen cycles, *Limnology and Oceanography*, 43, 1680-1689, 1998.
- 20 Breitbarth, E., Oschlies, A., and LaRoche, J.: Physiological constraints on the global distribution of *Trichodesmium* - effect of temperature on diazotrophy, *Biogeosciences*, 4, 53-61, 2007.
- Caffin, M., Foster, R., Berthelot, H., Stenegren, M., Caputo, A., Berntzo, L., and Bonnet, S.: Fate of N₂ fixation in the Western Tropical South Pacific Ocean: Transfert of diazotroph-derived nitrogen to non-diazotrophic communities and export of diazotrophs, *Biogeosciences Discuss.*, doi: 10.5194/bg-2017-572, 2018. 2018.
- 25 Caffin, M., Moutin, T., Foster, R. A., Bouruet-Aubertot, P., Doglioli, A. M., Berthelot, H., Grosso, O., Helias-Nunige, S., Leblond, N., Gimenez, A., Petrenko, A. A., de Verneil, A., and Bonnet, S.: Nitrogen budgets following a Lagrangian strategy in the Western Tropical South Pacific Ocean: the prominent role of N₂ fixation (OUTPACE cruise), *Biogeosciences Discuss.*, 2017, 1-34, 2017.
- 30 Carpenter, E. J., Harvey, H. R., Fry, B., and Capone, D. G.: Biogeochemical tracers of the marine cyanobacterium *Trichodesmium*, *Deep-Sea Research Part I-Oceanographic Research Papers*, 44, 27-38, 1997.
- Casciotti, K. L., Buchwald, C., and McIlvin, M.: Implications of nitrate and nitrite isotopic measurements for the mechanisms of nitrogen cycling in the Peru oxygen deficient zone, *Deep Sea Research Part I: Oceanographic Research Papers*, 80, 78-93, 2013.

- Casciotti, K. L., Sigman, D. M., Hastings, M. G., Bohlke, J. K., and Hilkert, A.: Measurement of the oxygen isotopic composition of nitrate in seawater and freshwater using the denitrifier method, *Analytical Chemistry*, 74, 4905-4912, 2002.
- Casciotti, K. L., Trull, T. W., Glover, D. M., and Davies, D.: Constraints on nitrogen cycling at the subtropical North Pacific Station ALOHA from isotopic measurements of nitrate and particulate nitrogen, *Deep-Sea Research Part I: Topical Studies in Oceanography*, 55, 1661-1672, 2008.
- Chappell, P. D., Moffett, J. W., Hynes, A. M., and Webb, E. A.: Molecular evidence of iron limitation and availability in the global diazotroph *Trichodesmium*, *Isme Journal*, 6, 1728-1739, 2012.
- de Verneil, A., Rousselet, L., Doglioli, A. M., Petrenko, A. A., and Moutin, T.: The fate of a southwest Pacific bloom: gauging the impact of submesoscale vs. mesoscale circulation on biological gradients in the subtropics, *Biogeosciences*, 14, 3471-3486, 2017.
- Dekazemacker, J., Bonnet, S., Grosso, O., Moutin, T., Bressac, M., and Capone, D. G.: Evidence of active dinitrogen fixation in surface waters of the eastern tropical South Pacific during El Niño and La Niña events and evaluation of its potential nutrient controls, *Global Biogeochemical Cycles*, 27, 768-779, 2013.
- Deutsch, C., Sarmiento, J. L., Sigman, D. M., Gruber, N., and Dunne, J. P.: Spatial coupling of nitrogen inputs and losses in the ocean, *Nature*, 445, 163-167, 2007.
- Deutsch, C., Sigman, D. M., Thunell, R. C., Meckler, A. N., and Haug, G. H.: Isotopic constraints on glacial/interglacial changes in the oceanic nitrogen budget, *Global Biogeochemical Cycles*, 18, 2004.
- Dore, J. E., Brum, J. R., Tupas, L. M., and Karl, D. M.: Seasonal and interannual variability in sources of nitrogen supporting export in the oligotrophic subtropical North Pacific Ocean, *Limnology and Oceanography*, 47, 1595-1607, 2002.
- Dupouy, C., Neveux, J., Subramaniam, A., Mulholland, M. R., Montoya, J. P., Campbell, L., Carpenter, E. J., and Capone, D. G.: Satellite captures trichodesmium blooms in the southwestern tropical Pacific, *EOS*, 81, 13-16, 2000.
- Dutkiewicz, S., Ward, B. A., Monteiro, F., and Follows, M. J.: Interconnection of nitrogen fixers and iron in the Pacific Ocean: Theory and numerical simulations, *Global Biogeochemical Cycles*, 26, 2012.
- Fitzsimmons, J. N., Boyle, E. A., and Jenkins, W. J.: Distal transport of dissolved hydrothermal iron in the deep South Pacific Ocean, *Proceedings of the National Academy of Sciences*, 111, 16654-16661, 2014.
- Garcia, H. E., Locarnini, R. A., Boyer, T. P., Antonov, J. I., Baranova, O. K., Zweng, M. M., Reagan, J. R., and Johnson, D. R.: *World Ocean Atlas 2013, Volume 4: Dissolved Inorganic Nutrients (phosphate, nitrate, silicate)*. NOAA, Silver Spring, MD, 2014.
- Gruber, N.: The dynamics of the marine nitrogen cycle and its influence on atmospheric CO₂ variations. In: *The Ocean Carbon Cycle and Climate*, Follows, M. and Oguz, T. (Eds.), Kluwer Academic, Dordrecht, 2004.

Gruber, N. and Galloway, J. N.: An Earth-system perspective of the global nitrogen cycle, *Nature*, 451, 293-296, 2008.

Gruber, N. and Sarmiento, J. L.: Global patterns of marine nitrogen fixation and denitrification, *Global Biogeochemical Cycles*, 11, 235-266, 1997.

- 5 Guieu, C., Bonnet, S., Petrenko, A., Menkes, C., Chavaganc, V., Desboeufs, K., and Moutin, T.: Iron from a submarine source impacts the productive layer of the Western Tropical South Pacific Scientific Reports, Under review. Under review.

Hoering, T. C. and Ford, H. T.: The Isotope Effect in the Fixation of Nitrogen by *Azotobacter*, *Journal of the American Chemical Society*, 82, 376-378, 1960.

- 10 Karl, D., Letelier, R., Tupas, L., Dore, J., Christian, J., and Hebel, D.: The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean, *Nature*, 388, 533-538, 1997.

Kim, I.-N., Lee, K., Gruber, N., Karl, D. M., Bullister, J. L., Yang, S., and Kim, T.-W.: Increasing anthropogenic nitrogen in the North Pacific Ocean, *Science*, 346, 1102-1106, 2014.

- 15 Knapp, A., McCabe, K., Grosso, O., Leblond, N., Moutin, T., and Bonnet, S.: Water column nitrate+nitrite d15N measurements from R/V L'Atalante in the southwest Pacific Ocean between New Caledonia and Tahiti from February to March 2015. Biological and Chemical Oceanography Data Management Office (BCO-DMO), 2018.

Knapp, A. N., Casciotti, K. L., Berelson, W. M., Prokopenko, M. G., and Capone, D. G.: Low rates of nitrogen fixation in eastern tropical South Pacific surface waters, *Proceedings of the National Academy of Sciences of the United States of America*, 113, 4398-4403, 2016a.

- 20 Knapp, A. N., DiFiore, P. J., Deutsch, C., Sigman, D. M., and Lipschultz, F.: Nitrate isotopic composition between Bermuda and Puerto Rico: Implications for N(2) fixation in the Atlantic Ocean, *Global Biogeochemical Cycles*, 22, 2008.

- 25 Knapp, A. N., Fawcett, S. E., Martínez-García, A., Leblond, N., Moutin, T., and Bonnet, S.: Nitrogen isotopic evidence for a shift from nitrate- to diazotroph-fueled export production in the VAHINE mesocosm experiments, *Biogeochemistry*, 13, 4645-4657, 2016b.

Knapp, A. N., Sigman, D. M., and Lipschultz, F.: N isotopic composition of dissolved organic nitrogen and nitrate at the Bermuda Atlantic time-series study site, *Global Biogeochemical Cycles*, 19, 2005.

- 30 Kustka, A. B., Sanudo-Wilhelmy, S. A., Carpenter, E. J., Capone, D., Burns, J., and Sunda, W. G.: Iron requirements for dinitrogen- and ammonium-supported growth in cultures of *Trichodesmium* (IMS 101): Comparison with nitrogen fixation rates and iron: carbon ratios of field populations, *Limnology and Oceanography*, 48, 1869-1884, 2003.

Labatut, M., Lacan, F., Pradoux, C., Chmieleff, J., Radic, A., Murray, J. W., Poitrasson, F., Johansen, A. M., and Thil, F.: Iron sources and dissolved-particulate interactions in the seawater of the Western Equatorial Pacific, iron isotope perspectives, *Global Biogeochemical Cycles*, doi: doi:10.1002/2014GB004928, 2014. 2014.

- Lehmann, N., Granger, J., Kienast, M., Brown, K. S., Rafter, R. A., Martínez-Méndez, G., and Mohtadi, M.: Isotopic Evidence for the Evolution of Subsurface Nitrate in the Western Equatorial Pacific, *Journal of Geophysical Research: Oceans*, 0, 2018.
- 5 Luo, Y. W., Doney, S. C., Anderson, L. A., Benavides, M., Berman-Frank, I., Bode, A., Bonnet, S., Boström, K. H., Böttjer, D., Capone, D. G., Carpenter, E. J., Chen, Y. L., Church, M. J., Dore, J. E., Falcón, L. I., Fernández, A., Foster, R. A., Furuya, K., Gómez, F., Gundersen, K., Hynes, A. M., Karl, D. M., Kitajima, S., Langlois, R. J., LaRoche, J., Letelier, R. M., Marañón, E., McGillicuddy Jr, D. J., Moisander, P. H., Moore, C. M., Mourinho-Carballido, B., Mulholland, M. R., Needoba, J. A., Orcutt, K. M., Poulton, A. J., Rahav, E., Raimbault, P., Rees, A. P., Riemann, L., Shiozaki, T., Subramaniam, A., Tyrrell, T., Turk-Kubo, K. A., Varela, M., Villareal, T. A.,
- 10 Webb, E. A., White, A. E., Wu, J., and Zehr, J. P.: Database of diazotrophs in global ocean: abundance, biomass and nitrogen fixation rates, *Earth Syst. Sci. Data*, 4, 47-73, 2012.
- Mahaffey, C., Michaels, A. F., and Capone, D. G.: The conundrum of marine N(2) fixation, *American Journal of Science*, 305, 546-595, 2005.
- 15 Mahowald, N. M., Engelstaedter, S., Luo, C., Sealy, A., Artaxo, P., Benitez-Nelson, C., Bonnet, S., Chen, Y., Chuang, P. Y., Cohen, D. D., Dulac, F., Herut, B., Johansen, A. M., Kubilay, N., Losno, R., Maenhaut, W., Paytan, A., Prospero, J. A., Shank, L. M., and Siefert, R. L.: Atmospheric Iron Deposition: Global Distribution, Variability, and Human Perturbations. In: *Annual Review of Marine Science*, *Annual Review of Marine Science*, 2009.
- 20 Martin, J. H., Knauer, G. A., Karl, D. M., and Broenkow, W. W.: Vertex - Carbon Cycling in the Northeast Pacific, *Deep-Sea Research Part a-Oceanographic Research Papers*, 34, 267-285, 1987.
- McIlvin, M. R. and Casciotti, K. L.: Technical Updates to the Bacterial Method for Nitrate Isotopic Analyses, *Analytical Chemistry*, 83, 1850-1856, 2011.
- 25 Messer, L. F., Mahaffey, C., M Robinson, C., Jeffries, T. C., Baker, K. G., Bibiloni Isaksson, J., Ostrowski, M., Doblin, M. A., Brown, M. V., and Seymour, J. R.: High levels of heterogeneity in diazotroph diversity and activity within a putative hotspot for marine nitrogen fixation, *The ISME journal*, doi: 10.1038/ismej.2015.205, 2015. 2015.
- Minagawa, M. and Wada, E.: Nitrogen Isotope Ratios of Red Tide Organisms in the East-China-Sea - a Characterization of Biological Nitrogen-Fixation, *Marine Chemistry*, 19, 245-259, 1986.
- 30 Moisander, P. H., Beinart, R. A., Hewson, I., White, A. E., Johnson, K. S., Carlson, C. A., Montoya, J. P., and Zehr, J. P.: Unicellular Cyanobacterial Distributions Broaden the Oceanic N(2) Fixation Domain, *Science*, 327, 1512-1514, 2010.
- Monteiro, F. M., Dutkiewicz, S., and Follows, M. J.: Biogeographical controls on the marine nitrogen fixers, *Global Biogeochemical Cycles*, 25, 2011.
- 35 Montoya, J. P., Holl, C. M., Zehr, J. P., Hansen, A., Villareal, T. A., and Capone, D. G.: High rates of N₂ fixation by unicellular diazotrophs in the oligotrophic Pacific Ocean, *Nature*, 430, 1027-1031, 2004.

- Moore, C. M., Mills, M. M., Achterberg, E. P., Geider, R. J., LaRoche, J., Lucas, M. I., McDonagh, E. L., Pan, X., Poulton, A. J., Rijkenberg, M. J. A., Suggett, D. J., Ussher, S. J., and Woodward, E. M. S.: Large-scale distribution of Atlantic nitrogen fixation controlled by iron availability, *Nature Geoscience*, 2, 867-871, 2009.
- Moore, J. K. and Doney, S. C.: Iron availability limits the ocean nitrogen inventory stabilizing feedbacks between marine denitrification and nitrogen fixation, *Global Biogeochemical Cycles*, 21, 2007.
- Moutin, T., Doglioli, A. M., de Verneil, A., and Bonnet, S.: Preface: The Oligotrophy to the UTRa-oligotrophy PACific Experiment (OUTPACE cruise, 18 February to 3 April 2015), *Biogeosciences*, 14, 3207-3220, 2017.
- Moutin, T., Karl, D. M., Duhamel, S., Rimmelin, P., Raimbault, P., Van Mooy, B. A. S., and Claustre, H.: Phosphate availability and the ultimate control of new nitrogen input by nitrogen fixation in the tropical Pacific Ocean, *Biogeosciences*, 5, 95-109, 2008.
- Moutin, T., Van Den Broeck, N., Beker, B., Dupouy, C., Rimmelin, P., and Le Bouteiller, A.: Phosphate availability controls *Trichodesmium* spp. biomass in the SW Pacific Ocean, *Marine Ecology Progress Series*, 297, 15-21, 2005.
- Moutin, T., Wagener, T., Fumenia, A., Gimenez, A., Caffin, M., Lefevre, D., Leblanc, K., Bouruet-Aubertot, P., Helias-Nunige, S., Rougier, G., Grosso, O., and de Verneil, A.: Phosphate availability and the ultimate control of the biological carbon pump in the Western Tropical South Pacific Ocean (OUTPACE cruise), *Biogeosciences*, This issue. This issue.
- Prospero, J. M.: Saharan dust transport over the North Atlantic Ocean and Mediterranean: An overview. In: *Impact of Desert Dust across the Mediterranean*, Environmental Science and Technology Library, 1996.
- Radic, A., Lacan, F., and Murray, J. W.: Iron isotopes in the seawater of the equatorial Pacific Ocean: New constraints for the oceanic iron cycle, *Earth and Planetary Science Letters*, 306, 1-10, 2011.
- Rafter, P. A., DiFiore, P. J., and Sigman, D. M.: Coupled nitrate nitrogen and oxygen isotopes and organic matter remineralization in the Southern and Pacific Oceans, *Journal of Geophysical Research-Oceans*, 118, 4781-4794, 2013.
- Rafter, P. A. and Sigman, D. M.: Spatial distribution and temporal variation of nitrate nitrogen and oxygen isotopes in the upper equatorial Pacific Ocean, *Limnology and Oceanography*, 61, 31, 2016.
- Raimbault, P. and Garcia, N.: Evidence for efficient regenerated production and dinitrogen fixation in nitrogen-deficient waters of the South Pacific Ocean: impact on new and export production estimates, *Biogeosciences*, 5, 323-338, 2008.
- Shiozaki, T., Kodama, T., and Furuya, K.: Large-scale impact of the island mass effect through nitrogen fixation in the western South Pacific Ocean, *Geophysical Research Letters*, 41, 2907-2913, 2014.
- Sigman, D. M., Casciotti, K. L., Andreani, M., Barford, C., Galanter, M., and Bohlke, J. K.: A bacterial method for the nitrogen isotopic analysis of nitrate in seawater and freshwater, *Analytical Chemistry*, 73, 4145-4153, 2001.

Sohm, J. A., Webb, E. A., and Capone, D. G.: Emerging patterns of marine nitrogen fixation, *Nature Reviews Microbiology*, 9, 499-508, 2011.

Stal, L. J.: Is the distribution of nitrogen-fixing cyanobacteria in the oceans related to temperature?, *Environmental Microbiology*, 11, 1632-1645, 2009.

- 5 Stenegren, M., Caputo, A., Berg, C., Bonnet, S., and Foster, R. A.: Distribution and drivers of symbiotic and free-living diazotrophic cyanobacteria in the western tropical South Pacific, *Biogeosciences*, 15, 1559-1578, 2018.

Van Den Broeck, N., Moutin, T., Rodier, M., and Le Bouteiller, A.: Seasonal variations of phosphate availability in the SW Pacific Ocean near New Caledonia, *Marine Ecology Progress Series*, 268, 1-12, 2004.

- 10 Van Mooy, B. A. S., Fredricks, H. F., Pedler, B. E., Dyhrman, S. T., Karl, D. M., Koblizek, M., Lomas, M. W., Mincer, T. J., Moore, L. R., Moutin, T., Rappe, M. S., and Webb, E. A.: Phytoplankton in the ocean use non-phosphorus lipids in response to phosphorus scarcity, *Nature*, 458, 69-72, 2009.

Weber, T. and Deutsch, C.: Local versus basin-scale limitation of marine nitrogen fixation, *Proceedings of the National Academy of Sciences*, 111, 8741-8746, 2014.

- 15 Yoshikawa, C., Makabe, A., Shiozaki, T., Toyoda, S., Yoshida, O., Furuya, K., and Yoshida, N.: Nitrogen isotope ratios of nitrate and N^* anomalies in the subtropical South Pacific, *Geochemistry, Geophysics, Geosystems*, 16, 1439-1448, 2015.

Table 1. Location, subsurface $NO_3^-+NO_2^-$ $\delta^{15}N$, PN_{sink} $\delta^{15}N$, and N_2 fixation rate and contribution to export at the OUTPACE long duration stations.

- 20 **Figure 1.** Map of the OUTPACE cruise with “long duration” (LD) stations A, B, and C noted (a), water column $NO_3^-+NO_2^-$ $\delta^{15}N$ measurements from the OUTPACE cruise (b), and CTD fluorescence (green line), $NO_3^-+NO_2^-$ concentration (filled circles), $NO_3^-+NO_2^-$ $\delta^{15}N$ (open circles), and PN_{sink} $\delta^{15}N$ (filled inverted triangles) from OUTPACE stations LD A (c), LD B (d), and LD C (e). Error bars represent 1 standard deviation, and are smaller than the symbol size for $NO_3^-+NO_2^-$ concentration and most $NO_3^-+NO_2^-$ $\delta^{15}N$ analyses. The range of $NO_3^-+NO_2^-$ $\delta^{15}N$ end-member values used for $\delta^{15}N$ budget calculations are represented by the shaded regions. The N_2 fixation end-member $\delta^{15}N$ value, -1‰, is represented by the arrows on the upper x-axis.
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