

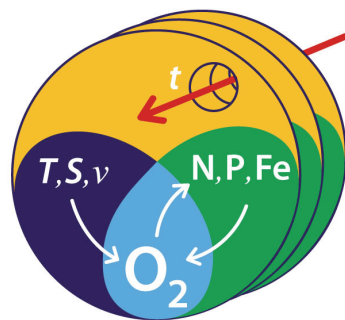


Helmholtz-Zentrum für Ozeanforschung Kiel

Nitrous Oxide Time Series Measurements off Peru

– A Collaboration between SFB 754 and IMARPE –

Annual Report 2011



SFB 754



Berichte aus dem Helmholtz-Zentrum für Ozeanforschung Kiel (GEOMAR)

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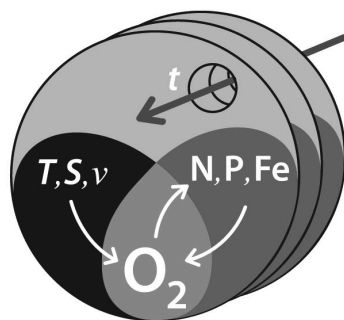


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Nitrous Oxide Time Series Measurements off Peru

– A Collaboration between SFB 754 and IMARPE

Annual Report 2011

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Introduction

Scientific Background

Because of its characteristics as a highly potent greenhouse gas and a key factor in stratospheric ozone destruction, nitrous oxide (N₂O) is steadily moving into focus of scientific activities during the last decades (Codispoti, 2010). The ocean is a major source for N₂O in the atmosphere, with oceanic N₂O emissions contributing about 30 % to the overall emissions of N₂O to the atmosphere (IPCC, 2007). Moreover, eutrophication, global warming and ocean acidification may result in a substantial enhancement of marine N₂O production (Codispoti, 2010).

The magnitude of oceanic N₂O production is depending on the concentration of dissolved oxygen (O₂). Under oxic conditions N₂O is produced as a byproduct of nitrification. In hypoxic waters (here defined after Codispoti, 2010 as waters containing less than ~60 μmol O₂/kg,¹), the N₂O yield during nitrification is strongly enhanced (Codispoti et al., 1992; Goreau et al., 1980; Löscher et al., 2012). Under suboxic conditions (below ~10 μmol O₂/kg, Stramma et al., 2008; Hofmann et al., 2011) N₂O is produced as an intermediate during denitrification. During this process N₂O can also be consumed through further reduction to N₂, which occurs especially when O₂ concentrations are approaching anoxic conditions (0 μmol/kg) (Codispoti et al., 1992). The net N₂O production under suboxic conditions is therefore depending on the interplay of N₂O production and -consumption by denitrification.

Due to the enhanced N₂O production under hypoxic and suboxic conditions, oxygen minimum zones (OMZs) are key areas of N₂O production. In spite of covering merely 1.0 % of the global ocean volume, they are accounting for 25 – 50 % of oceanic N₂O production (Suntharalingam et al., 2000).

¹ Codispoti 2010 defined hypoxia using the unit % O₂ saturation. For conversion of values from % O₂ saturation to μmol/kg see Hofmann et al., 2011, Table 1)

Recent observations and models suggest that OMZs are expanding and intensifying globally, leading to more hypoxic and suboxic areas in the future ocean (Stramma et al., 2008; Oschlies et al., 2008). Studies about N₂O in the ocean began only about 30 years ago (Codispoti, 2010), and therefore future changes in oceanic N₂O production due to these changing O₂ regimes are hard to predict. To get better estimates on these and the resulting impact on global warming and ozone depletion, it has been suggested to put more focus on potential N₂O production hotspots such as OMZs (Codispoti, 2010).

The Callao Time Series Transect

The Callao Time Series Transect (Callao TST), an onshore/offshore transect off Callao/Lima (Peru, 12°S) is located in such a hotspot of N₂O production (Figure 1). Since 1992 the Instituto del Mar del Perú (IMARPE) is conducting time series measurements for several biogeochemical parameters (CTD, pH, O₂, nutrients) along this transect. It consists of 7 stations which are sampled regularly on an annual or monthly basis. Being situated on the central Peruvian continental shelf within the upper 200 m of the water column, it is directly located within the intense OMZ off central Peru (overall mean depth of the OMZ at Station 2 (10 nm off the Peruvian coast): 52.3 m (± 33.2 m) (Gutierrez et al., 2008)).

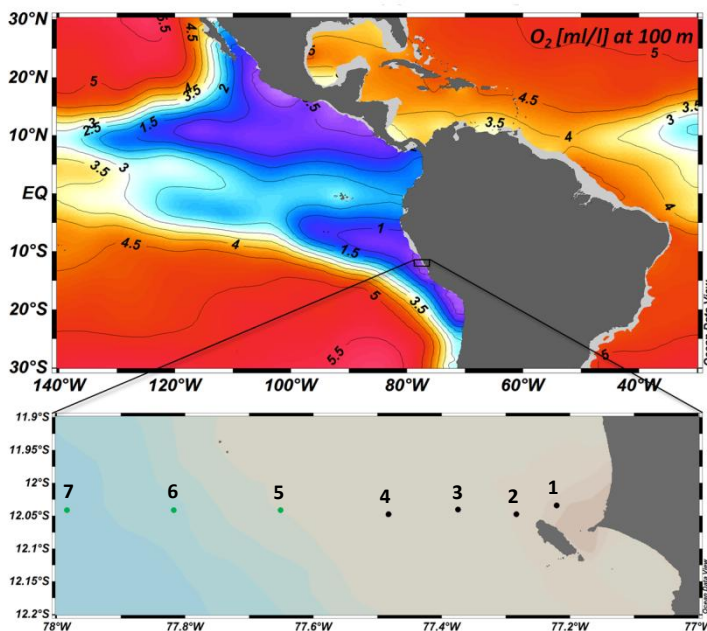


Figure 1: Location of the Callao Time Series Transect, sampled by the Instituto del Mar del Perú. Upper panel: Location of the transect within the intense OMZ off central Peru. Underlying colors show the O₂ concentration in ml/L at 100 m depth. Data are taken from the Ocean Data View version of the global oxygen climatology given in the World Ocean Atlas 2009 (WOA09: Garcia et al., 2010). **Lower panel:** Location of the 7 stations which are sampled regularly. Stations 1-4 (black dots) are sampled on a monthly, Stations 5-7 (green dots) on an annual basis. Maximum sampling depth along the transect is 200 m.

Over longer time scales (several years) the O₂ regime along the transect is highly variable (Figure 2), which is due to the interplay between periods of intense O₂ depletion and remotely-forced oxygenation episodes which occur on the central Peruvian continental Shelf (Gutierrez et al., 2008).

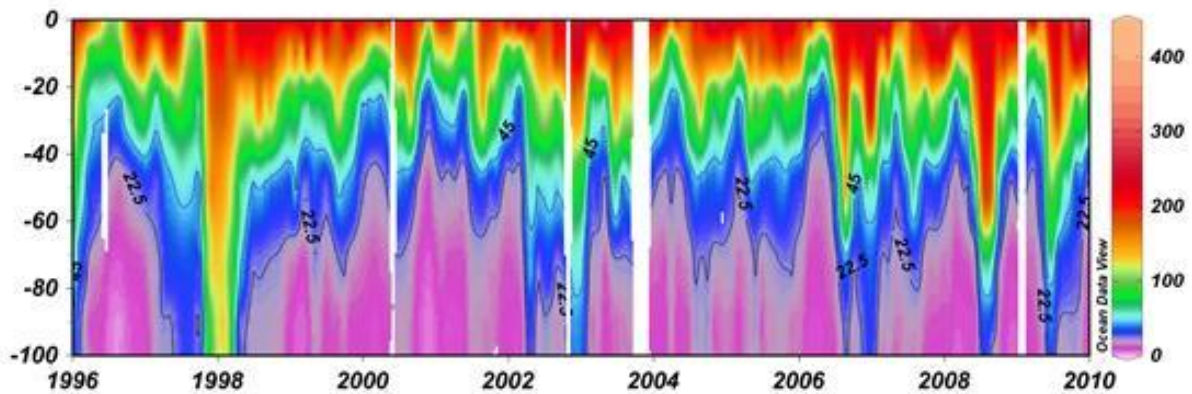


Figure 2: Time Series of dissolved O₂ (µmol/L) at Station 4 (12.04°S/77.5°W) located 20 nm off the Peruvian coast. The figure shows the significant temporal variability of dissolved O₂ concentrations along the Callao TST, caused by the interplay between intense O₂ depletion over the continental shelf on one hand and oxygenation periods forced by Equatorial Kelvin Waves on the other hand (Gutierrez et al., 2008). The figure was kindly provided by Michelle Graco, IMARPE.

Project Aim

General Project Aim

It is still an open question in which magnitude marine N₂O production will change due to the predicted changing O₂ regime towards larger low-oxygen areas in the future ocean (see “Introduction”). Therefore this project has the objective to make a step towards answering this question. This is to be achieved by conducting simultaneous time series measurements of O₂ and N₂O to investigate the distribution of N₂O in dependence of short term (seasonal) and long term (inter annual) changes of dissolved O₂ concentrations in the ocean.

Because of their crucial role in marine N₂O production, OMZs offer a suitable oceanic area to conduct these measurements. Due to its location within the intense OMZ off Peru and the influence of remotely forced oxygenation periods, the Callao TST provides an ideal basis to investigate the response of N₂O production to changes in dissolved O₂ concentrations.

This project therefore aims at including dissolved N₂O as well as dissolved hydroxylamine (NH₂OH) and hydrazine (N₂H₄) into the compounds being measured along the Callao TST. The two last named compounds can be used as specific indicators for key processes of the nitrogen cycle and therefore give more information about which microbiological nitrogen process (nitrification or denitrification) is producing N₂O along the transect. Since so far there are no possibilities of analyzing the three compounds named above on site, one of the major goals of this project is to establish N₂O analysis at IMARPE. With this, not only laborious and expensive shipping of N₂O samples would be avoided. Also

the sampling of NH_2OH and N_2H_4 , which cannot be conserved well enough for shipping, would be made possible.

Project Aim for 2011

The goal of this project for 2011 was to establish the collaboration between the Chemical Oceanography department of the IMARPE and the TP B4 of the SFB 754 and to initialize N_2O sampling along the Callao TST. Since the IMARPE staff had no experience with N_2O analysis before the establishment of the collaboration, the first goal was to introduce the IMARPE staff to the theoretical background around marine N_2O production and the method of trace gas sampling. After this, sampling of N_2O along the Callao TST was to be initialized in a first Callao TST cruise with staff from IMARPE as well as the SFB 754.

To make a first step towards the projects long term goal of establishing N_2O analysis at IMARPE, a further goal in 2011 was to introduce staff from IMARPE to N_2O analysis using the static equilibration method and a gas chromatography-electron capture detector (GC-ECD) system (Walter et al., 2006).

Project Progress

Sampling of N_2O along the Callao TST was initialized during a visit of Tina Baustian (member of SFB 754 in 2011) to the Chemical Oceanography group of IMARPE, in May 2011. At first a small workshop was organized in which the IMARPE staff was introduced to some theoretical background about N_2O in the ocean as well as to the N_2O sampling technique applied in the laboratories of Dr. Hermann Bange, PI of SFB 754 TP B4 (Figure 3).



Figure 3: Some impressions of the N_2O workshop held at IMARPE in May 2011. Upper row: practicing air bubble free sampling; Lower row: checking sample for air bubbles.

The first Callao TST cruise including N₂O sampling was then conducted together with staff of IMARPE as well as SFB 754 at the end of May 2011 (Figure 4). A second Callao TST cruise in 2011 was conducted at the end of October, where N₂O was sampled by IMARPE staff only. During both cruises Stations 1 to 4 of the Callao TST were sampled (Figure 1). Five (Station 1) to eight (Station 4) depths were taken at the individual stations, covering the entire water column from surface to bottom. Samples for dissolved O₂ concentration were analyzed directly after sampling according to the Winkler method (Carrit and Carpenter, 1966). Triplicate samples of N₂O were taken for each depth. All samples were conserved with a saturated HgCl₂ solution directly after sampling (final HgCl₂ concentration in sample 0.185 mg/ml). Samples were analyzed at IFM-GEOMAR using the static equilibration method and a GC-ECD system.

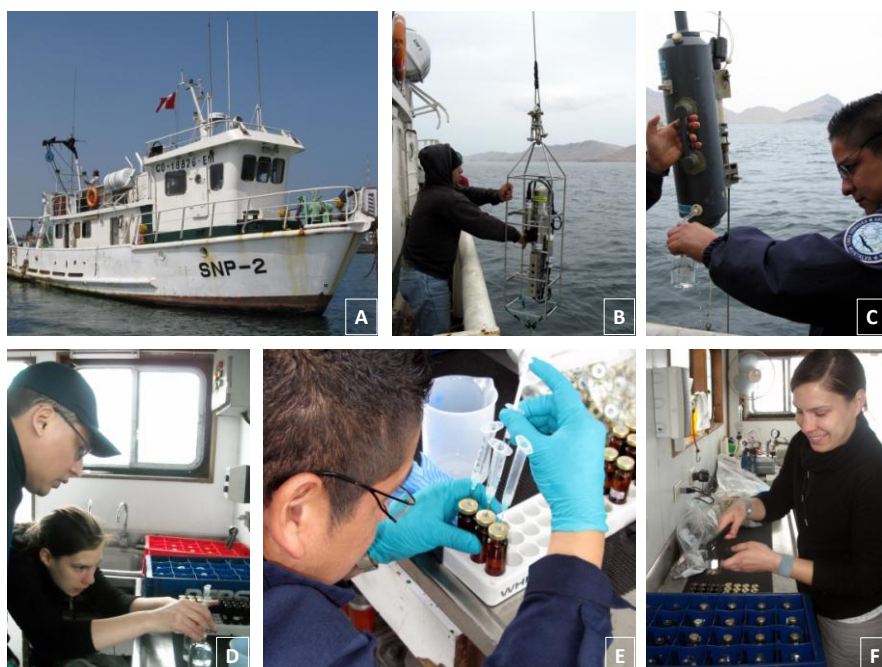


Figure 4: Impressions of the first Callao TST cruise including N₂O sampling. The cruise was conducted at the end of May 2011. **A:** Samples were taken with R/V SNP-2 **B:** CTD cast **C:** taking sample for O₂ analysis according to the Winkler method **D-F:** conserving N₂O samples during cruise.

Furthermore, during the first week of November 2011 two colleagues from the IMARPE (Dr. Michelle Graco, Georgina Flores) visited the IFM-GEOMAR. During their visit they could further practice the N₂O sampling technique during a one day cruise on the Kiel Fjord with R/B Polarfuchs. Additionally they were introduced to the analysis of N₂O samples using the static equilibration method and a GC-ECD system.

Beyond that the visit was used for extensive discussions about the currently collected data as well as future plans concerning the collaboration during SFB 754 Phase II, yielding a plan about future cruises and experiments concerning the collaboration as well as a detailed work plan for 2012.

Preliminary Results

The two Callao TST cruises including N_2O sampling during 2011 covered two different seasons: austral autumn (sampling May) and austral spring (sampling October).

Oxygen concentrations along the transect were steadily decreasing with depth in both seasons respectively (from 221.4 $\mu\text{mol/kg}$ to 16.9 $\mu\text{mol/kg}$ in May and 274.0 $\mu\text{mol/kg}$ to 8.2 $\mu\text{mol/kg}$ in October), yielding a clearly distinguishable OMZ (Figure 5). During October the OMZ was much more pronounced. Here the upper border of the hypoxic zone was found at depths of ~ 5 m to ~ 30 m, while in May hypoxic conditions began at depths of ~ 50 m to ~ 80 m. Additionally in October suboxic conditions were found above the bottom of Stations 1-3, while during May lowest O_2 values (down to 16.9 $\mu\text{mol/kg}$) still exceeded suboxic conditions.

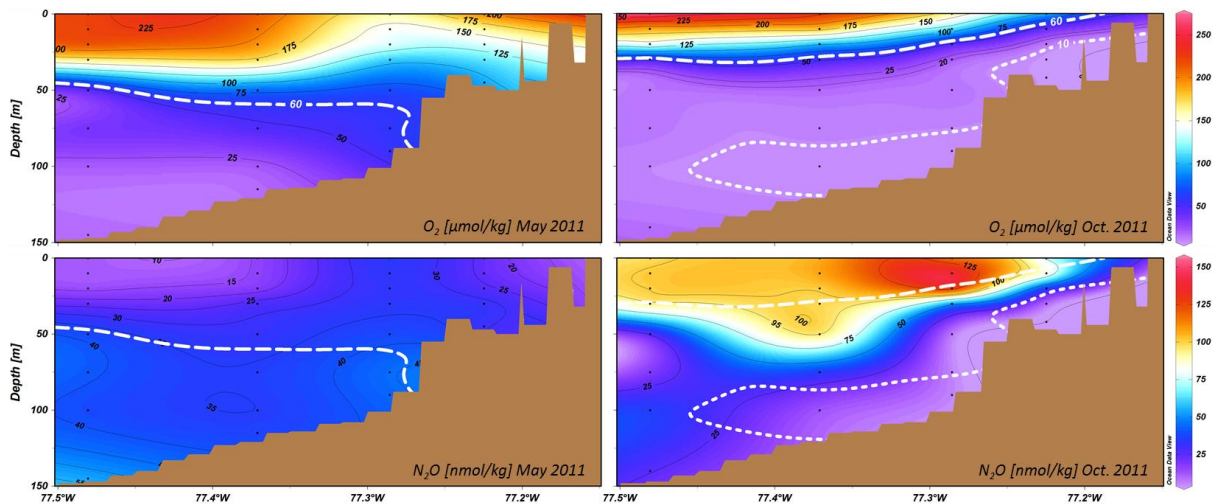


Figure 5: Comparison of results for dissolved O_2 and N_2O during Callao TST cruises in 2011. Left column: Results from cruise in May 2011, **Right column:** Results from cruise in October 2011. **Upper panels:** O_2 ($\mu\text{mol/kg}$), **lower panels:** N_2O (nmol/kg); Notice that for O_2 and N_2O respectively, the color bar for both samplings is fitted to the same scale. **Dashed white line:** Upper border of the hypoxic water mass (O_2 concentration of 60 $\mu\text{mol/kg}$). **Dotted white line:** upper border of the suboxic water mass (O_2 concentration of 10 $\mu\text{mol/kg}$).

During both cruises most of the water column along the transect was supersaturated with N_2O (see Appendix), indicating N_2O production. Observed N_2O concentrations reached values up to 17 times higher than the corresponding equilibrium concentration.

In October, where the OMZ was much more intense compared to May (see above), also much higher N_2O concentrations were found (Figure 5). The maximum N_2O concentration in October (155.6 nmol/kg) was about 3 times as high as the one in May (53.2 nmol/kg). For both samplings maximum N_2O concentrations found were within the range of maximum N_2O concentrations in other oceanic regions (Figure 6).

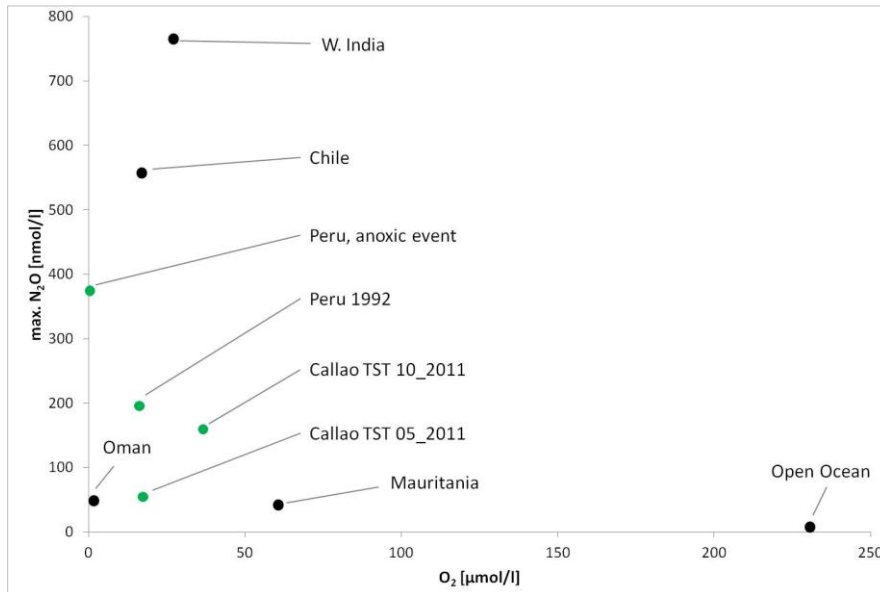


Figure 6: Maximum N₂O concentrations vs. associated O₂ concentrations in coastal upwelling regions. Green dots mark samples taken off Peru. For comparison a typical N₂O surface concentration in the tropical open ocean is shown as well. (Fig.: Bange and Baustian, unpublished).

During May, where only hypoxic conditions were found, the water column was supersaturated with N₂O throughout the transect (see Appendix). In contrast, during October the two Stations closest to the shore (Stations 1 and 2) contained water undersaturated with N₂O within the last 20 m to 50 m above the bottom (see Appendix). Here the water was suboxic. This indicates N₂O consumption to N₂ by the process of denitrification, which occurs in suboxic water masses (see “Scientific Background”). Further assumptions about which process was producing N₂O along the transect during May and October, could be made by plotting the N₂O concentrations against their corresponding O₂ concentration for both cruises, respectively (Figure 7). The samples taken in May show a clear inverse linear relationship between O₂ and N₂O concentrations ($R^2 = 0.8$). This suggests that nitrification was the main N₂O producing process in May 2011. During nitrification ammonium (NH₄⁺) is oxidized to nitrate (NO₃⁻). NH₄⁺ is produced as an end product of organic matter respiration, an O₂ consuming process. Therefore, the more respiration is taking place (i.e. the more O₂ is used up) the more NH₄⁺ is produced, enabling more nitrification, which leads to the observed inverse linear relationship between N₂O and O₂ concentrations.

In contrast, for the samples taken during October 2011, no linear relationship between N₂O and O₂ concentrations was found. Therefore, N₂O is most likely not mainly produced by nitrification, but by denitrification. This assumption is supported by the fact that during October suboxic conditions were found along some areas of the transect and that in these areas the water was undersaturated with N₂O, indication N₂O consumption by denitrification.

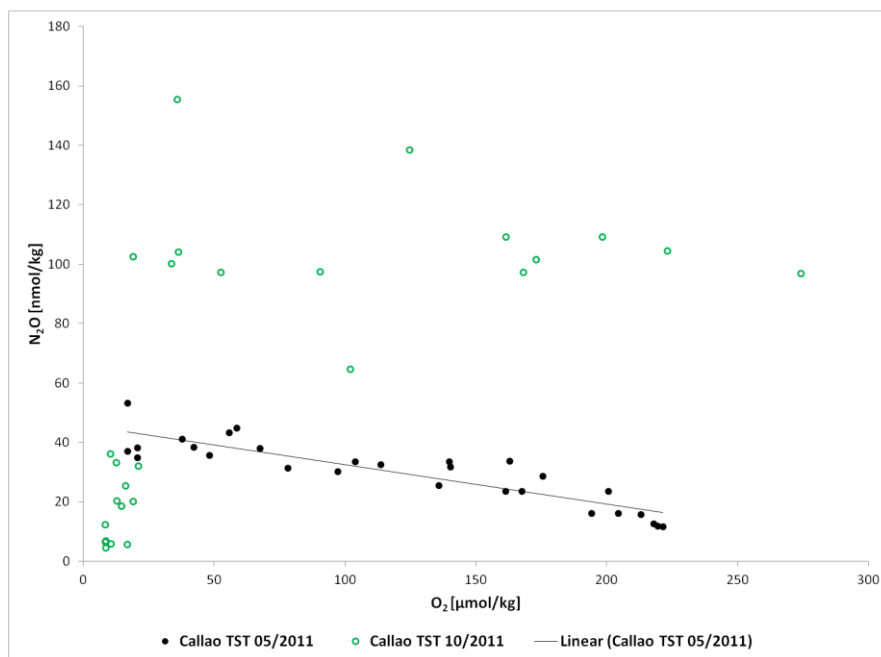


Figure 7: N_2O concentrations vs. associated O_2 concentrations for both samplings at Callao TST conducted during 2011. See key for explanation of symbols

Not only the magnitudes of N_2O concentrations and assumingly the processes producing N_2O differed between seasons, but also the vertical distribution of N_2O along the transect. During May, highest N_2O concentrations could be found within the hypoxic water mass (below 50 m) while during October highest concentrations were found at the upper 50 m of the water column, above and around the upper border of the hypoxic water mass (Figure 5).

Conclusions and Outlook

The two Callao TST cruises conducted during 2011 yielded some interesting first insights into the N_2O distribution along the Callao TST in dependence of its O_2 concentration. It was shown that in austral spring, where the OMZ is more intense than in austral summer also N_2O concentrations were much higher, and that also the vertical distribution of N_2O in the water column differed between seasons. Additionally the processes producing N_2O off Peru seem to differ between seasons. While in autumn, where hypoxic conditions prevail, nitrification was assumingly the main N_2O producing process, denitrification additionally seemed to play an important role in N_2O production during spring where also suboxic conditions were found.

The help of the IMARPE staff provided by taking N_2O samples along the Callao TST and providing their data of other biogeochemical parameters collected along the transect (see above) is an important support for the SFB 754 TP B4. Additionally, also the IMARPE profits from the collaboration by receiving training in trace gas analysis and therefore broadening their methodological skills, as well

as receiving additional data for broadening their understanding about the processes occurring at the Callao TST.

The close partnership established between the SFB 754 and the IMARPE during 2011 sets the basis for a quick start of the work planned by project B4 during SFB 754 Phase II (2012 - 2015). In 2012 the annual variability as well as diurnal variations of the O₂ and N₂O distribution along the Callao TST will be studied. For this three more Callao TST cruises are planned (May, July, October), covering three seasons (autumn, winter, spring). During the cruise in May a 24h time series experiment will be conducted additionally. Staff from IMARPE as well as the SFB 754 will participate in this cruise.

Furthermore it is planned for staff from the IMARPE and the SFB 754 to participate together in three R/V Meteor cruises to the OMZ of the southeast Pacific (M90-SFB754, Nov. 2012 (Stramma/Frank)), and to the upwelling off Peru (M91-SOPRAN, Dec. 2012 (Bange) and M93-SFB754, Feb. 2013 (Lavik/Kanzow)), to assess the distribution of N₂O, NH₂OH and N₂H₄ in this area. Because of the laborious work on board the support of IMARPE staff will be an invaluable help for the SFB 754.

During the above named cruises N₂O, NH₂OH and N₂H₄ will be analyzed on board. Therefore, the introduction into N₂O analysis for Dr. Michelle Graco and Georgina Flores Gonzales during their visit in November 2011 (see above) will be beneficial for these cruises. Additionally, it was also a first step towards the collaboration's long term goal of establishing N₂O analysis at IMARPE (see "Project Aims"). With the above named activities the collaboration between SFB 754 and the IMARPE established during 2011 will strongly support answering the questions that the SFB 754 TP B4 is dealing with during Phase II. Furthermore, it sets the basis for other collaboration projects between Peru and Germany for example the mesocosm experiments planned off Peru in 2015.

Acknowledgements

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Nitrous Oxide Time Series Measurements off Peru

Appendix: Data collected during Callao TST cruises in 2011

Cruise	Station	Date	Local Time Peru (GMT -5h)	Latitude [°N]	Longitude [°E]	Bottom- depth [m]	Depth [m]	Temperature [°C]	Salinity [PSU]	Density [kg/l]	O ₂ concentration [μmol/kg]	O ₂ saturation [%]	N ₂ O equilibrium concentration [nmol/kg]	N ₂ O concentration Mean [nmol/kg]	N ₂ O concentration SD [nmol/kg]	N ₂ O saturation [%]
Callao_TST_05_2011	1	27/05/2011	12:20	-12.0389	-77.2248	48	0	18.55	34.79	1.0249	200.49	86	7.66	23.54	0.31	307
Callao_TST_05_2011	1	27/05/2011	12:20	-12.0389	-77.2248	48	10	18.15	34.97	1.0253	161.31	69	7.74	23.50	0.99	303
Callao_TST_05_2011	1	27/05/2011	12:20	-12.0389	-77.2248	48	20	17.94	34.98	1.0254	135.81	58	7.80	25.39	0.54	326
Callao_TST_05_2011	1	27/05/2011	12:20	-12.0389	-77.2248	48	30	17.64	34.97	1.0255	113.71	48	7.87	32.51	0.18	413
Callao_TST_05_2011	1	27/05/2011	12:20	-12.0389	-77.2248	48	45	17.45	34.98	1.0256	97.08	41	7.92	30.24	0.50	382
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	0	18.04	34.81	1.0251	162.87	70	7.78	33.66	0.52	433
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	10	18.03	34.94	1.0253	139.80	60	7.78	33.44	1.01	430
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	20	18.01	34.95	1.0253	140.13	60	7.78	31.78	0.29	408
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	30	17.95	34.96	1.0254	103.74	44	7.79	33.53	1.45	430
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	50	16.97	34.97	1.0257	67.53	28	8.04	37.99	0.80	473
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	75	16.92	34.97	1.0258	58.55	24	8.05	44.77	2.18	556
Callao_TST_05_2011	2	26/05/2011	16:55	-12.0481	-77.2857	94	90	No Data	No Data	No Data	55.61	No Data	No Data	43.28	0.78	No Data
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	0	19.89	34.9	1.0247	213.06	94	7.34	15.80	0.15	215
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	10	19.87	35.02	1.0249	204.41	90	7.34	16.18	0.54	221
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	20	19.26	35.01	1.0251	194.08	85	7.48	16.05	0.46	215
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	30	17.84	34.97	1.0254	175.56	75	7.82	28.58	1.30	365
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	50	17.15	34.95	1.0257	78.08	33	7.99	31.25	2.61	391
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	75	16.54	34.96	1.0259	48.09	20	8.15	35.64	1.85	437
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	100	No Data	No Data	No Data	20.59	No Data	No Data	34.86	1.54	No Data
Callao_TST_05_2011	3	26/05/2011	14:01	-12.0384	-77.3711	119	115	No Data	No Data	No Data	16.88	No Data	No Data	37.00	0.46	No Data
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	0	20.51	34.95	1.0246	221.44	99	7.20	11.60	0.39	161
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	10	20.51	35.07	1.0247	219.50	98	7.19	11.89	0.27	165
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	20	19.99	35	1.0248	217.84	97	7.31	12.62	1.40	173

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Nitrous Oxide Time Series Measurements off Peru

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Cruise	Station	Date	Local Time	Latitude	Longitude	Bottom- depth	Depth	Temperature	Salinity	Density	O ₂	O ₂	N ₂ O	N ₂ O	N ₂ O	N ₂ O
			Peru								concentration	saturation	equilibrium concentration	concentration mean	concentration SD	saturation
			(GMT -5h)	[°N]	[°E]	[m]	[m]	[°C]	[PSU]	[kg/l]	[μmol/kg]	[%]	[nmol/kg]	[nmol/kg]	[nmol/kg]	[%]
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	30	18.9	35.02	1.0252	167.61	73	7.56	23.62	0.79	312
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	50	16.49	34.98	1.0258	42.20	18	8.16	38.33	2.90	469
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	75	16.17	34.98	1.0260	37.63	16	8.25	41.03	2.18	497
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	100	15.9	34.99	1.0262	20.59	8	8.32	38.26	1.69	460
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	132	14.44	34.99	1.0267	No Data	No Data	8.73	No Data	No Data	No Data
Callao_TST_05_2011	4	26/05/2011	10:35	-12.0399	-77.4805	145	145	No Data	No Data	No Data	16.87	7	No Data	53.18	1.20	No Data
Callao_TST_10_2011	1	19/10/2011	12:20	-12.0389	-77.2248	48	0	14.16	34.94	1.0261	101.92	40	8.82	64.68	0.36	734
Callao_TST_10_2011	1	19/10/2011	12:20	-12.0389	-77.2248	48	10	13.53	34.95	1.0263	36.09	14	9.00	104.09	0.46	1156
Callao_TST_10_2011	1	19/10/2011	12:20	-12.0389	-77.2248	48	20	13.41	34.94	1.0264	12.59	5	9.04	20.36	0.48	225
Callao_TST_10_2011	1	19/10/2011	12:20	-12.0389	-77.2248	48	30	13.41	34.94	1.0264	8.38	3	9.04	6.89	0.18	76
Callao_TST_10_2011	1	19/10/2011	12:20	-12.0389	-77.2248	48	42	13.39	34.94	1.0265	8.36	3	9.04	4.66	0.69	52
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	0	14.96	34.90	1.0259	161.41	65	8.59	109.28	0.76	1272
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	10	13.97	34.92	1.0262	124.39	49	8.87	138.45	1.12	1560
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	20	13.59	34.93	1.0263	35.67	14	8.99	155.62	1.08	1732
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	30	13.41	34.94	1.0264	20.95	8	9.04	32.13	1.10	355
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	50	13.22	34.93	1.0265	16.72	6	9.10	5.70	0.13	63
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	75	13.22	34.93	1.0266	10.36	4	9.10	6.05	0.12	66
Callao_TST_10_2011	2	19/10/2011	16:55	-12.0481	-77.2857	94	90	13.22	34.93	1.0267	8.23	3	9.10	6.55	0.54	72
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	0	15.22	34.94	1.0259	223.01	90	8.51	104.62	0.68	1229
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	10	14.09	34.92	1.0262	198.19	78	8.84	109.22	0.45	1236
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	20	13.68	34.94	1.0263	90.23	35	8.96	97.53	0.51	1089
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	30	13.49	34.94	1.0264	52.38	20	9.02	97.37	1.29	1080
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	50	13.36	34.94	1.0265	18.81	7	9.05	102.66	0.78	1134
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	75	13.2	34.94	1.0266	12.43	5	9.10	33.22	0.58	365
Callao_TST_10_2011	3	18/10/2011	14:01	-12.0384	-77.3711	119	100	13.13	34.93	1.0267	8.23	3	9.12	12.32	0.09	135

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Nitrous Oxide Time Series Measurements off Peru

Table continued from previous page

Cruise	Station	Date	Local Time	Latitude	Longitude	Bottom- depth	Depth	Temperature	Salinity	Density	O ₂	O ₂	N ₂ O	N ₂ O	N ₂ O	N ₂ O
			Peru								concentration	saturation	equilibrium	concentration	concentration	saturation
			(GMT -5h)	[°N]	[°E]	[m]	[m]	[°C]	[PSU]	[kg/l]	[μmol/kg]	[%]	[nmol/kg]	[nmol/kg]	[nmol/kg]	[%]
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	0	15.75	34.94	1.0258	274.01	112	8.37	96.93	1.51	1159
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	10	15.26	34.92	1.0259	172.93	70	8.50	101.67	No Data	1196
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	20	14.66	34.95	1.0261	167.91	67	8.67	97.28	0.18	1122
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	30	14.55	34.92	1.0261	33.53	13	8.70	100.35	0.39	1153
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	50	13.79	34.92	1.0264	18.81	7	8.93	20.15	0.42	226
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	75	13.34	34.94	1.0266	14.51	6	9.06	18.70	0.31	206
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	100	13.13	34.93	1.0268	10.29	4	9.12	36.32	0.21	398
Callao_TST_10_2011	4	18/10/2011	10:35	-12.0399	-77.4805	145	140	12.33	34.89	1.0271	15.97	6	9.37	25.40	0.32	271

The data is archived in MEMENTO (The Marine Methane and Nitrous Oxide database: <https://memento.geomar.de/>)

Parameter information:

- O₂ concentration: measured with a modified Winkler method (Carrit and Carpenter, 1966).
- O₂ saturation calculated as: $\% O_2 = \frac{\text{measured } O_2 \text{ concentration}}{O_2 \text{ equilibrium concentration}} \times 100$
- N₂O equilibrium concentration: calculated according to Weiss and Price (1980) with an atm. N₂O dry mole fraction of 321 ppb (see AGAGE monitoring network <http://agage.eas.gatech.edu/>) and an atmospheric pressure of 1 atm.
- N₂O concentration mean: calculated according to Walter et al. (2006). The mean is the arithmetic mean of three replicates.
- N₂O concentration standard deviation (SD): calculated according to Walter et al. (2006).
- N₂O saturation: calculated as: $\% N_2O = \frac{\text{measured } N_2O \text{ concentration}}{N_2O \text{ equilibrium concentration}} \times 100$

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