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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1131834
Project Title:	Reconstructing Glacial Nitrogen and Carbon Cycling Using Isotopes
PD/PI Name:	Andreas Schmittner-Boesch, Principal Investigator Alan C Mix, Co-Principal Investigator
Recipient Organization:	Oregon State University
Project/Grant Period:	09/01/2011 - 08/31/2015
Reporting Period:	09/01/2014 - 08/31/2015
Submitting Official (if other than PD\PI):	Andreas Schmittner-Boesch Principal Investigator
Submission Date:	11/24/2015
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Andreas Schmittner-Boesch

Accomplishments

*** What are the major goals of the project?**

Here we propose to use a three-dimensional model of both
nitrogen and carbon isotopes (δ15N, δ13C and Δ14C), incorporated in a global circulation and biogeochemical model, in order to better understand the glacial nitrogen cycle and its impact on
atmospheric CO2. The cycling of oxygen, nitrogen and carbon depends strongly on the largescale
ocean circulation. Reproducing the glacial circulation pattern will therefore be an important aspect of the project. Carbon isotopes will provide constraints on ocean circulation and the biological pump.

We will test three specific null-hypotheses:
H1: The bio-available nitrogen inventory of the ocean during the Last Glacial Maximum
(LGM) was not larger than during the Late Holocene (LH).
H2: Changes in iron supply did not increase the efficiency of nitrate consumption by
phytoplankton in polar oceans during glacial periods.
H3: Changes in the nitrogen cycle (H1 & H2) did not contribute significantly to glacial-interglacial
variations of atmospheric CO2 concentrations.

Specific goals were:

yr 1) Model improvement (Including the iron cycle), calibration; building LH databases of δ15N, δ13C and Δ14C measurements.

yr 2) LGM simulations and databases

yr 3) Analysis, hypotheses tests

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

1. Model development activities have focused on the iron model. Juan Muglia has included geothermal iron sources in the global Model of Ocean Biogeochemistry and Isotopes (MOBI). He has calibrated the model with modern observations. Muglia has also analyzed dust and iron flux data to examine the uncertainty and spatial variability of aeolian iron fluxes to the ocean. He has run long pre-industrial simulations and planned long LGM simulations.
2. We have performed idealized LGM simulations with MOBI (Schmittner and Somes, submitted manuscript), and more realistic simulations (Somes and Schmittner, in preparation).
3. We have revised and resubmitted a manuscript on wind stress effects to Geophysical Research Letters (Muglia and Schmittner, 2015).
4. We have revised and resubmited a manuscript on LGM tidal mixing to Geophysical Research Letters (Schmittner and Green, 2015).
5. Organization of inaugural joint workshop of OC3/iPODS (Sep. 30-Oct. 3, 2014, Bern Switzerland). Schmittner leads Ocean Circulation and Carbon Cycling (OC3), which is a PAGES working group.
6. Assembled published sedimentary (benthic foraminiferal) d13C data from different databases,
7. Organization of a teacher workshop on climate change (Aug. 11, 2015).

Specific Objectives: The specific objectives for the above activities were

1. to improve iron cycling in MOBI, and to assess uncertainties in aeolian iron fluxes on modern and LGM simulations,
2. to exploring constraints of nitrogen and carbon isotopes on the biological

pump and to reconstruct quantitatively the glacial ocean's nitrogen budget,
3. to explore effects of wind stress on the LGM Atlantic Meridional Overturning Circulation (AMOC),
4. to explore effects of changes in tidal mixing on the LGM MOC,
5. to initiate new collaborative and international projects to synthesize paleoceanographic data,
6. to create the prototype OC3 database,
7. to improve public climate literacy.

Significant Results:

1. (a) Including geothermal iron fluxes improves model agreement with observations, and (b) a relationship between dust and soluble iron fluxes to the ocean such that their ratio (dust/iron) is reduced at low dust fluxes consistent with the idea that iron solubility increases during atmospheric transport.
2. Carbon and nitrogen isotopes provide complementary constraints on the efficiency of the biological pump,
3. Enhanced wind stress over the North Atlantic due to the presence of the Laurentide ice sheet increases the AMOC.
4. Enhanced tidal mixing increases the LGM MOC.
5. Interest by the international paleoceanographic community to collaborate.
6. Tentative results indicate that d13C changes during the early deglaciation (LGM-Heinrich Stadial 1) were restricted to intermediate depths, whereas the deep ocean changed during the late phases of the deglaciation (Bolling/Allerod-Younger Dryas-Holocene).
7. Teachers appreciate learning about climate science.

Key outcomes or Other achievements:

1. We have achieved the first, to our knowledge, global model simulations with interactive carbon and nitrogen isotopes and compared the model results to sediment reconstructions (Schmittner and Somes, submitted manuscript).
2. These simulations, which are consistent with first order changes in the sediment reconstructions of whole ocean radiocarbon, as well as spatial distributions of d13C, d15N and oxygen, indicate an increased efficiency of the biological pump during the LGM due to faster phytoplankton growth rates (by ~15-30%). This falsifies H2 and H3. However, these simulations show a smaller ocean carbon inventory, indicating the importance of sediment interactions in creating whole ocean alkalinity changes. This requires further investigation with an interactive sediment model.
3. The results of Schmittner and Somes (submitted manuscript) illustrate interesting interactions between the carbon and nitrogen cycles, such that an increase in the biological pump may lead to enhanced water column denitrification (WCD) and nitrogen fixation (NF), and a lower global fixed nitrogen inventory thus countering physical effects such as cooling, which tends to decrease WCD and NF. However, the nitrogen isotope models that fit the reconstructions best all have a higher nitrogen inventory thus suggesting that the physical effects dominate the biology. Even though the changes in the nitrogen inventory are relatively small O(10%), these results indicate that H1 may be false.
4. We have created the first global model with both carbon and nitrogen isotopes and an interactive iron cycle. Ongoing and future simulations with this model have the potential to lead to new insights and better constraints on the glacial ocean circulation and its coupled iron-carbon-nitrogen cycle.

5. We have layed the groundwork for new international collaboration.
6. We have created the the initial OC3 database.
7. We have contributed to improved public climate literacy.

*** What opportunities for training and professional development has the project provided?**

Graduate student Juan Muglia has been trained in climate physics, biogeochemistry, modeling, data analysis, presentation of results in meetings, and writing papers. He has published his first paper in the peer-reviewed literature.

The project has provided an internship for two undergraduates, Emma Gleeman and Aaron Rachels, through Oregon State University's College of Earth, Ocean, and Atmospheric Sciences Research Experience for Undergraduates (REU) program.

The project has provided an opportunity for training in climate science and professional development for 17 oregon educators, as well as for interactions between teachers and scientists. http://people.oregonstate.edu /~schmita2/Outreach/TeacherWS_2015

*** How have the results been disseminated to communities of interest?**

We have presented the results at scientific meetings and conferences and published them in peer-reviewed journals (see products).

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Buizert, C. and Schmittner, A. (2015). Southern Ocean Control of Glacial AMOC Stability and Dansgaard-Oeschger interstadial Duration. *Paleoceanography*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2015PA002795

Galbraith, E. D., Kienast, M., Albuquerque, A. L., Altabet, M., Batista, F., Bianchi, D., Calvert, S. E., Contreras Quintana, S., Crosta, X., De Pol Holz, R., Dubois, N., Etourneau, J., Francois, R., Hsu, T.-C., Ivanochko, T., Jaccard, S. L., Kao, S.-J., Kiefer, T., Kienast, S., Lehmann, M. F., Martinez, P., McCarthy, M., Meckler, A. N., Mix, A. C., Mobius, J., Pedersen, T. F., Quan, T. M., Robinson, R. S., Ryabenko, E., Schmittner, A., Schneider, R., Schneider-Mor, A., Shigemitsu, M., Sinclair, D., Somes, C., Studer, A. S., Tesdal, J.-E., Thunell, R., and Yang, J.-Y. T. (2013). The acceleration of oceanic denitrification during deglacial warming. *Nature Geoscience*. 6 579. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1038/ngeo1832

Lund, D. C., Tessin, A. C., Hoffman, J. L., and Schmittner, A. (2015). Southwest Atlantic watermass evolution during the last deglaciation. *Paleoceanography*. 30 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2014PA002657

Muglia, J. Schmittner, A. (2015). Glacial Atlantic overturning increased by wind stress in climate models. *Geophysical Research Letters*. 42 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2015GL064583

Robinson, R. S., Kienast, M., Albuquerque, A. L., Altabet, M., Contreras Quintana, S., De Pol Holz, R., Dubois, N., Francois, R., Galbraith, E., Hsu, T.-C., Ivanochko, T., Jaccard, S., Kao, S.-J., Kiefer, T., Kienast, S., Lehmann, M., Martinez, P., McCarthy, M., Mobius, J., Pedersen, T., Quan, T. M., Ryabenko, E., Schmittner, A., Schneider, R., Schneider-Mor, A., Shigemitsu, M., Sinclair, D., Somes, C., Studer, A., Thunell, R., and Yang, J.-Y. (2012). A review of nitrogen isotopic alteration in marine sediments. *Paleoceanography*. 24 PA4203. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1029/2012PA002321

Schmittner, A. Jaccard, S. L. Mix, A., C. Sikes, E. L. (2015). Deglacial Ocean Circulation and Carbon Cycling. *PAGES Magazine*. 23 (1), 30. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = No

Schmittner, A. Lund, D. C. (2015). Early deglacial Atlantic overturning decline and its role in atmospheric CO2 rise inferred from carbon isotopes (δ13C). *Climate of the Past*. 11 135. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/cp-11-135-2015

Schmittner, A., and C. J. Somes (2015). Complementary Constraints from Carbon (13C) and Nitrogen (15N) Isotopes on the Efficiency of the Glacial Ocean's Biological Pump. *Paleoceanography*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Schmittner, A., Gruber, N., Mix, A. C., Key, R. M., Tagliabue, A., and Westberry, T. K. (2013). Biology and air-sea gas exchange controls on the distribution of carbon isotope ratios (δ13C) in the ocean. *Biogeosciences*. 10 5793. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/bgd-10-5793-2013

Somes, C. J. Schmittner, A. Oschlies, A. (2015). Isotope Constraints on the Oceanic Nitrogen Cycle during the Last Glacial Maximum. *Nature Geoscience*. . Status = OTHER; Acknowledgment of Federal Support = No ; Peer Reviewed = No

Somes, C. J., Oschlies, A., and Schmittner, A. (2013). Isotopic constraints on the pre-industrial oceanic nitrogen budget. *Biogeosciences*. 10 5889. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/bgd-10-5889-2013

Licenses

Other Conference Presentations / Papers

Schmittner, A. Lund, D. (2014). *Carbon isotopes support Atlantic Meridional Overturning Circulation decline as a trigger for early deglacial CO2 rise*. American Geophysical Union Fall Meeting. San Francisco. Status = OTHER; Acknowledgement of Federal Support = Yes

Schmittner, A. (2015). *Developments at OSU: MOBI & OSUVic*. UVic Model Symposium. Victoria, BC, Canada. Status = OTHER; Acknowledgement of Federal Support = Yes

Schmittner, A. Lund, D. (2014). *Early Deglacial AMOC Decline and its role for atmospheric CO2 Rise Inferred from Carbon Isotopes*. Deglacial Deep Ocean Circulation and Biogeochemical Cycling. Bern, Switzerland. Status = OTHER; Acknowledgement of Federal Support = Yes

Somes, C. Schmittner, A. Oschlies, A. (2015). *Estimating the Size of the Fixed Nitrogen Inventory during the Last Glacial Maximum (using d15N)*. ASLO Aquatic Sciences Meeting. Granada. Status = OTHER; Acknowledgement of Federal Support = No

Somes, C., J. Schmittner, A. Oschlies, A. (2014). *Estimating the Size of the Marine Nitrogen Inventory during the Last Glacial Maximum: Sensitivity to Atmospheric Iron Deposition*. American Geophysical Union Fall Meeting. San Francisco. Status = OTHER; Acknowledgement of Federal Support = Yes

Schmittner, A. (2014). *Modeling Biogeochemical Consequences of Ocean Circulation Changes*. Gordon Conference on Ocean Global Change Biology. Waterville Valley NH. Status = OTHER; Acknowledgement of Federal Support = Yes

Schmittner, A. Mix, A. (2014). *OC3 Core-Top Calibration*. Deglacial Deep Ocean Circulation and Biogeochemical Cycling. Bern, Switzerland. Status = OTHER; Acknowledgement of Federal Support = No

Schmittner, A. Lund, D. (2015). *Using Carbon Isotopes (δ13C) to Reconstruct AMOC Changes During the Last Deglaciation*. RAPID - US AMOC International Science Meeting. Bristol, UK. Status = OTHER; Acknowledgement of Federal Support = Yes

Schmittner, A. Lund, D. (2015). *Was the Early Deglacial CO2 Rise Caused by a Reduction of the Atlantic Meridional Overturning Circulation (AMOC) ?*. Leopoldina Symposium. Halle, Germany. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Other Publications

Patents

Technologies or Techniques

Model of Ocean Biogeochemistry and Isotopes source code.

http://people.oregonstate.edu/~schmita2/Models/MOBI/MOBI1.6/

Thesis/Dissertations

Websites

Climate Change: A Workshop for Oregon Educators
http://people.oregonstate.edu/~schmita2/Outreach/TeacherWS_2015/index.html

Teacher Workshop website

Ocean Circulation and Carbon Cycling (OC3)
http://people.oregonstate.edu/~schmita2/Projects/OC3/index.html

OC3 website

Reconstructing Glacial Nitrogen and Carbon Cycling Using Isotopes
http://people.oregonstate.edu/~schmita2/Projects/LGM/

Project website.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
draftAGU.pdf	Schmittner and Somes (submitted manuscript)	Andreas Schmittner-Boesch	11/24/2015

Filename	Description	Uploaded By	Uploaded On
Supporting-Information.pdf	Schmittner and Somes (supplementary information)	Andreas Schmittner-Boesch	11/24/2015

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Schmittner-Boesch, Andreas	PD/PI	3
Mix, Alan	Co PD/PI	1
Somes, Christopher	Postdoctoral (scholar, fellow or other postdoctoral position)	3
Muglia, Juan	Graduate Student (research assistant)	12
Gleeman, Emma	Research Experience for Undergraduates (REU) Participant	3
Rachels, Aaron	Research Experience for Undergraduates (REU) Participant	3

Full details of individuals who have worked on the project:

Andreas Schmittner-Boesch
Email: aschmittner@coas.oregonstate.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 3

Contribution to the Project: Project lead and coordination. Model development, set-up, and analysis of results. Writing papers.

Funding Support: NA

International Collaboration: No
International Travel: Yes, United Kingdom - 0 years, 0 months, 4 days; Canada - 0 years, 0 months, 2 days

Alan C Mix
Email: mix@coas.oregonstate.edu
Most Senior Project Role: Co PD/PI

Nearest Person Month Worked: 1

Contribution to the Project: Sediment data compilation and analysis.

Funding Support: NA

International Collaboration: No
International Travel: No

Christopher Somes
Email: csomes@geomar.de
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 3

Contribution to the Project: Model development, set-up, and analysis of results. Writing papers.

Funding Support: German Science Foundation.

International Collaboration: Yes, Germany
International Travel: No

Juan Muglia
Email: jmuglia@coas.oregonstate.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Model development (iron), set-up, analysis of results, writing papers.

Funding Support: This project.

International Collaboration: No
International Travel: Yes, Switzerland - 0 years, 0 months, 5 days

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Emma Gleeman
Email: emma_gleeman@brown.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 3

Contribution to the Project: Compilation of d13C database.

Funding Support: College REU program.

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: Brown University
Government fiscal year(s) was this REU participant supported: 2015

Aaron Rachels
Email: aaron_rachels@brown.edu
Most Senior Project Role: Research Experience for Undergraduates (REU) Participant
Nearest Person Month Worked: 3

Contribution to the Project: Compilation of d13C database.

Funding Support: This project.

International Collaboration: No
International Travel: No
Year of schooling completed: Sophomore
Home Institution: Brown University
Government fiscal year(s) was this REU participant supported: 2015

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
McGill University	Academic Institution	Montreal, Canada
University of Kiel	Academic Institution	Kiel, Germany

Full details of organizations that have been involved as partners:

McGill University

Organization Type: Academic Institution
Organization Location: Montreal, Canada

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Eric Galbraith is a collaborator on the nitrogen cycle model.

University of Kiel

Organization Type: Academic Institution
Organization Location: Kiel, Germany

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Chris Somes continued to work on the nitrogen isotope model. Levin Nickelson works on including the iron cycle. Andreas Oschlies supervises both.

What other collaborators or contacts have been involved?
Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Findings from this project have impacted the field of paleoceanography by improving our understanding of the ice age ocean, both its physical drivers and its biogeochemical cycles.

The improved model will likely be useful for future studies of paleoceanographic problems.

What is the impact on other disciplines?

The finding of inconsistencies between state-of-the-science climate model simulations if the ice age ocean and reconstructions from sediments casts doubt on future projections of ocean circulation changes with these models. This will likely impact the climate modeling community by triggering investigation into the reasons for this discrepancy, which may improve climate models that are used for future projections.

What is the impact on the development of human resources?

This project has provided opportunities for research in paleoceanography for graduate student Juan Muglia, and two undergraduate students, Emma Gleeman and Aaron Rachels. The project provided exposure to climate science for teachers and other educators from Oregon. The project provided opportunities to present results, learn, participate in discussions, network, initiate new collaborations for early career scientists and scientists from developed countries by facilitating their participation in the OC3/iPODS workshop “Deglacial Deep Ocean Circulation and Biogeochemical Cycling” held in Bern, Switzerland 09-30-2015 to 10-03-2015.

What is the impact on physical resources that form infrastructure?

A new storage devise (RAID array) with a capacity of 32 TB has been added to an existing local compute cluster.

What is the impact on institutional resources that form infrastructure?

This project has led to the creation of two new international, collaborative projects focused on paleoceanographic data synthesis.

OC3 – Ocean Circulation and Carbon Cycling, led by Schmittner, aims to synthesize benthic foraminiferal carbon isotope data. As a Past Global Changes (PAGES) working group this project contributes to paleoceanographic activities within PAGES as well as to promotion of PAGES within the wider paleoceanographic community. http://www.pages-igbp.org/ini/wg/oc3/intro

iPODS – Investigating Past Ocean Dynamics, led by Luke Skinner, aims to synthesize radiocarbon and other circulation proxy (e.g. eNd, Pa/Th) data. As an international focus group of the International Quaternary Association (INQUA) this group brings the paleoceanographic community together with the traditionally more terrestrial INQUA community. http://wserv4.esc.cam.ac.uk/pastclimate/?page_id=14

What is the impact on information resources that form infrastructure?

The global Model of Ocean Biogeochemistry and Isotopes (MOBI) has been improved significantly by merging carbon and nitrogen isotope compoments and by adding an interactive iron cycle. The model is publicly available (see products) and part of the widely used University of Victoria Earth System Climate Model (UVic ESCM).

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?

This project facilitated various outreach activities of the project members such as the teacher workshops mentioned above, public presentations, letters to the editor, and participation in the Climate Change National Forum blog (http://climatechangenationalforum.org/) and Climate Feedback (http://climatefeedback.org/) all of which are intended to advance climate literacy of the general public.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.