



HAL
open science

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta, Fabien Roquet, S. Falahat, Q. Zhang, Gurban Madec

► **To cite this version:**

M. Ballarotta, Fabien Roquet, S. Falahat, Q. Zhang, Gurban Madec. Impact of the oceanic geothermal heat flux on a glacial ocean state. *Climate of the Past Discussions*, 2015, 11, pp.3597-3624. 10.5194/cpd-11-3597-2015 . hal-04115512

HAL Id: hal-04115512

<https://hal.science/hal-04115512>

Submitted on 6 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Abstract

The oceanic geothermal heating (OGH) has a significant impact on the present-day ocean state, but its role during glacial periods, when the ocean circulation and stratification were different from those of today, remains poorly known. In the present study, we analyzed the response of the glacial ocean to OGH, by comparing ocean simulations of the Last Glacial Maximum (LGM, ~ 21 ka ago) including or not geothermal heating. We found that applying the OGH warmed the Antarctic Bottom Waters (AABW) by ~ 0.4 °C and increased the abyssal circulation by 15 to 30 % north of 30° S in the deep Pacific and Atlantic basins. The geothermally heated deep waters were then advected toward the Southern Ocean where they upwelled to the surface due to the Ekman transport. The extra heat transport towards Antarctica acted to reduce the amount of sea ice contributing to the freshening of the whole AABW overturning cell. The global amount of salt being conserved, this bottom freshening induced a salinification of the North Atlantic and North Pacific surface and intermediate waters, contributing to the deepening of the North Atlantic Deep Water. This indirect mechanism is responsible for the largest observed warming, found in the North Atlantic deep western boundary current between 2000 and 3000 m (up to 2 °C). The characteristic time scale of the ocean response to the OGH corresponds to an advective time scale (associated with the overturning of the AABW cell) rather than a diffusive time scale. The OGH might facilitate the transition from a glacial to an inter-glacial state but its effect on the deep stratification seems insufficient to drive alone an abrupt climate change.

1 Introduction

The oceanic geothermal heating (OGH) is the heat flux through the sea floor which is generated by the internal heat content of the lithosphere. This flux is maximum near the oceanic ridges or underwater volcanic regions and is minimum ($\sim 50 \text{ mW m}^{-2}$) in

CPD

11, 3597–3624, 2015

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The impact of the OGH on the zonal mean temperature and salinity patterns is shown in Fig. 2e–h. The temperature differences are significant at all depth except in the upper 200 m where the temperature variability is strong and mainly controlled by the atmospheric state. The North Atlantic cooling found in Fig. 1 is mainly associated with colder surface water in the Nordic Seas (up to 0.7 °C colder) and with the intrusion of colder Antarctic Intermediate Water (AAIW) in the South Atlantic basin (up to 1.3 °C colder). The deep temperatures in the Atlantic Ocean are up to 1.3 °C warmer, particularly between 1500 and 3000 m in the deep western boundary current (Fig. 3), and between 30 and 45° N. In the Indo-Pacific basin, the layer below 1500 m is up to 0.4 °C warmer and the surface layer is slightly colder (0.1 °C colder) in the North Pacific basin and ~ 0.3 °C warmer in the South Pacific. The salinity differences are significant at all depth and the patterns are relatively similar between the Atlantic and the Indo-Pacific basins: the Antarctic Bottom Water (AABW) is ~ 0.1 PSU fresher in GH than in REF whereas the upper layer is between 0.1 and 0.3 PSU saltier.

These differences in the temperature and salinity patterns modify the sea-water density (Fig. 4). The AABW becomes less dense (the density decreases by ~ 0.2 kg m⁻³ in the Indo-Pacific, 0.3 kg m⁻³ in the Atlantic) due to warming and freshening, whereas the density increases up to 0.3 kg m⁻³ in the thermocline due to colder and more saline waters. The stratification is hence increased by ~ 3 % near 2250 m and is reduced by ~ 3 % near 3250 m (not shown).

3.2 Impact of the geothermal heat flux on the thermohaline circulation

Most paleo-climate studies investigate the thermohaline circulation in the latitude-depth coordinates. A better description of the circulation is however found in latitude-density coordinates (Döös, 1994; Döös and Webb, 1994; Ballarotta et al., 2013b). Ballarotta et al. (2014) have also shown that the strength of the glacial overturning strongly depends on the choice of coordinate system. Therefore, we present hereafter the meridional overturning circulation (MOC) in latitude-density coordinates, more precisely σ_4 (i.e., referenced to 4000 m), in order to better capture and compare the abyssal circu-

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



to the variation of the AMOC on climate time scale, such as the 75 % reduction with respect to LGM period during Heinrich stadial 1 (~ 15–18.5 ka ago), the 45 % reduction during the Younger Dryas stadial (~ 12 ka ago) (Ritz et al., 2013), or the values found in fresh water hosing experiments under LGM conditions (> 20 % reduction in Kageyama et al., 2013). In these experiments, the AMOC changes are linked with surface processes, such as the freshwater discharge (Heinrich, 1988; Hemming, 2004) which have a stronger and faster impact on the thermohaline circulation than the processes induced by the OGH.

Similar to Adcroft et al. (2001) and Emile-Geay and Madec (2009), we found that the impact of the OGH on the northward heat transport is weak (~ 10 %) but non-negligible, particularly in the Atlantic Ocean and in the polar regions as a result of the large scale advection of the abyssal heat content. We found that the alteration of the ocean heat transport induced by the OGH in the North Atlantic (~ 0.1 PW) is ~ 3 time larger than the total energy input provided by OGH (0.03 PW). It seems that the Southern Ocean Ekman transport prevents the accumulation of OGH in the abyssal ocean. For a salinity gradient of ~ 1 PSU, a temperature gradient of ~ 3 °C would be required to destabilise the water column (see Appendix B). In the present study, the OGH warms by ~ 0.4 °C. Therefore the OGH alone is not sufficient to destabilise the water column. It seems that OGH facilitates the transition from a glacial to an inter-glacial state by reducing the volume of saline abyssal waters by ~ 15 % and reinvigorating the North Atlantic overturning by ~ 10 %, but it is unlikely that the OGH is the only cause to abrupt climate changes.

5 Conclusions

In the present study, we investigated the response of the ocean to the geothermal heat flux during a glacial period, such as the LGM, when the ocean circulation and stratification were different from today. We found that the heat flux at the sea floor is a significant forcing of the deep ocean and the global thermohaline circulation. The

Acknowledgements. The authors acknowledge the National Supercomputer Centre at Linköping University (Sweden) for providing the computational resources to run the model. The simulations have been run on the Triolith super-computer (<https://www.nsc.liu.se/systems/triolith/>). Many thanks to Laurent Brodeau for installing the NEMO model on the Triolith platform.

References

- Adcroft, A., Scott, J. R., and Marotzke, J.: Impact of geothermal heating on the global ocean circulation, *Geophys. Res. Lett.*, 28, 1735–1738, doi:10.1029/2000GL012182, 2001. 3599, 3606, 3607
- Adkins, J. F.: The role of deep ocean circulation in setting glacial climates, *Paleoceanography*, 28, 539–561, doi:10.1002/palo.20046, 2013. 3608
- Adkins, J. F. and Schrag, D. P.: Reconstructing Last Glacial Maximum bottom water salinities from deep-sea sediment pore fluid profiles, *Earth Planet. Sc. Lett.*, 216, 109–123, doi:10.1016/S0012-821X(03)00502-8, 2003. 3600, 3602
- Adkins, J. F., McIntyre, K., and Schrag, D. P.: The salinity, temperature, and $\delta_{18}\text{O}$ of the glacial deep ocean, *Science*, 298, 1769–1773, doi:10.1126/science.1076252, 2002. 3600, 3602
- Adkins, J. F., Ingersoll, A., and Pasquero, C.: Rapid climate change and conditional instability of the glacial deep ocean from the thermobaric effect and geothermal heating, *Quaternary Sci. Rev.*, 24, 581–594, doi:10.1016/j.quascirev.2004.11.005, 2005. 3599
- Ahn, J. and Brook, E. J.: Atmospheric CO_2 and climate on millennial time scales during the last glacial period, *Science*, 322, 83–85, doi:10.1126/science.1160832, 2008.
- Anderson, R. F., Ali, S., Bradtmiller, L. I., Nielsen, S. H. H., Fleisher, M. Q., Anderson, B. E., and Burckle, L. H.: Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2 , *Science*, 323, 1443–1448, doi:10.1126/science.1167441, 2009.
- Ashkenazy, Y., Gildor, H., Losch, M., Macdonald, F. A., Schrag, D. P., and Tziperman, E.: Dynamics of a snowball Earth ocean, *Nature*, 495, 90–93, doi:10.1038/nature11894, 2013. 3600
- Ashkenazy, Y., Gildor, H., Losch, M., and Tziperman, E.: Ocean circulation under globally glaciated snowball Earth conditions: steady-state solutions, *J. Phys. Oceanogr.*, 44, 24–43, doi:10.1175/JPO-D-13-086.1, 2014. 3600

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Ballarotta, M., Brodeau, L., Brandefelt, J., Lundberg, P., and Döös, K.: Last Glacial Maximum world ocean simulations at eddy-permitting and coarse resolutions: do eddies contribute to a better consistency between models and palaeoproxies?, *Clim. Past*, 9, 2669–2686, doi:10.5194/cp-9-2669-2013, 2013a. 3600, 3601

5 Ballarotta, M., Drijfhout, S., Kuhlbrodt, T., and Döös, K.: The residual circulation of the Southern Ocean: which spatio-temporal scales are needed?, *Ocean Model.*, 64, 46–55, doi:10.1016/j.ocemod.2013.01.005, 2013b. 3603, 3609

Ballarotta, M., Falahat, S., Brodeau, L., and Döös, K.: On the glacial and interglacial thermohaline circulation and the associated transports of heat and freshwater, *Ocean Sci.*, 10, 907–921, doi:10.5194/os-10-907-2014, 2014. 3603

10 Björk, G. and Winsor, P.: The deep waters of the Eurasian Basin, Arctic Ocean: geothermal heat flow, mixing and renewal, *Deep-Sea Res. Pt. I*, 53, 1253–1271, doi:10.1016/j.dsr.2006.05.006, 2006. 3599

Blanke, B. and Delecluse, P.: Low frequency variability of the tropical atlantic ocean simulated by a general circulation model with mixed layer physics, *J. Phys. Oceanogr.*, 23, 1363–1388, 1993. 3601

Brandefelt, J. and Otto-Bliesner, B. L.: Equilibration and variability in a Last Glacial Maximum climate simulation with CCSM3, *Geophys. Res. Lett.*, 36, 1–5, doi:10.1029/2009GL040364, 2009. 3601, 3602

20 Brodeau, L., Barnier, B., Treguier, A.-M., Penduff, T., and Gulev, S.: An ERA40-based atmospheric forcing for global ocean circulation models, *Ocean Model.*, 31, 88–104, doi:10.1016/j.ocemod.2009.10.005, 2010. 3609

Curry, W. B.: Glacial water mass geometry and the distribution of $\delta^{13}\text{C}$ of ΣCO_2 in the western Atlantic Ocean, *Paleoceanography*, 20, 1–13, doi:10.1029/2004PA001021, 2005. 3600, 3608

25 Davies, J. H. and Davies, D. R.: Earth's surface heat flux, *Solid Earth*, 1, 5–24, doi:10.5194/se-1-5-2010, 2010. 3599

de Lavergne, C., Madec, G., Le Sommer, J., George Nurser, A. J., and Naveira Garabato, A. C.: On the consumption of Antarctic Bottom Water in the abyssal ocean, *J. Phys. Oceanogr.*, in revision, 2015. 3599

30 Detrick, R., Williams, D., Mudie, J., and Sclater, J.: The Galapagos spreading centre: bottom-water temperatures and the significance of geothermal heating, *Geophys. J. Int.*, 38, 627–637, doi:10.1111/j.1365-246X.1974.tb05433.x, 1974. 3599

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Döös, K.: Semianalytical simulation of the meridional cells in the Southern Ocean, *J. Phys. Oceanogr.*, 24, 1281–1293, 1994. 3603, 3609
- Döös, K. and Webb, D.: The deacon cell and the other meridional cells of the Southern Ocean, *J. Phys. Oceanogr.*, 24, 429–442, 1994. 3603, 3609
- 5 Duplessy, J. C., Shackleton, N. J., Fairbanks, R. G., Labeyrie, L., Oppo, D., and Kallel, N.: Deepwater source variations during the last climatic cycle and their impact on the global deepwater circulation, *Paleoceanography*, 3, 343–360, 1988. 3600
- Emile-Geay, J. and Madec, G.: Geothermal heating, diapycnal mixing and the abyssal circulation, *Ocean Sci.*, 5, 203–217, doi:10.5194/os-5-203-2009, 2009. 3599, 3600, 3601, 3606, 3607, 3609
- 10 Evans, H. K. and Hall, I. R.: Deepwater circulation on Blake Outer Ridge (western North Atlantic) during the Holocene, Younger Dryas, and Last Glacial Maximum, *Geochem. Geophys. Geosy.*, 9, Q03023, doi:10.1029/2007GC001771, 2008. 3608
- Ferrari, R., Jansen, M., Adkins, J., Burke, A., Stewart, A., and Thompson, A.: Antarctic sea ice control on ocean circulation in present and glacial climates, *P. Natl. Acad. Sci. USA*, 111, 8753–8758, doi:10.1073/pnas.1323922111, 2014.
- 15 Fichetef, T. and Maqueda, M. A. M.: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, *J. Geophys. Res.*, 102, 12609–12646, doi:10.1029/97JC00480, 1997. 3601
- 20 Gaspar, P., Grégoris, Y., and Lefevre, J.-M.: A simple eddy kinetic energy model for simulations of the oceanic vertical mixing: Tests at station papa and long-term upper ocean study site, *J. Geophys. Res.*, 95, 16179–16193, doi:10.1029/JC095iC09p16179, 1990. 3601
- Gent, P. and McWilliams, J.: Isopycnal mixing in Ocean Circulation models, *J. Phys. Oceanogr.*, 20, 150–155, doi:10.1175/1520-0485(1990)020<0150:IMIOCM>2.0.CO;2, 1990. 3601
- 25 Gherardi, J. M., Labeyrie, L., Nave, S., Francois, R., McManus, J. F., and Cortijo, E.: Glacial-interglacial circulation changes inferred from 231 Pa/230 Th sedimentary record in the North Atlantic region, *Paleoceanography*, 24, 1–14, doi:10.1029/2008PA001696, 2009. 3608
- Goutorbe, B., Poort, J., Lucazeau, F., and Raillard, S.: Global heat flow trends resolved from multiple geological and geophysical proxies, *Geophys. J. Int.*, 187, 1405–1419, doi:10.1111/j.1365-246X.2011.05228.x, 2011. 3599
- 30 Hautala, S. L., Johnson, H. P., and Bjorklund, T.: Geothermal heating and the properties of bottom water in Cascadia Basin, *Geophys. Res. Lett.*, 32, L06608, doi:10.1029/2004GL022342, 2005. 3599

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Heinrich, H.: Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years, *Quaternary Res.*, 29, 142–152, doi:10.1016/0033-5894(88)90057-9, 1988. 3607

Hemming, S. R.: Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint, *Rev. Geophys.*, 42, RG1005, doi:10.1029/2003RG000128, 2004. 3607

Hieronymus, M. and Nycander, J.: The budgets of heat and salinity in NEMO, *Ocean Model.*, 67, 28–38, doi:10.1016/j.ocemod.2013.03.006, 2012. 3599

Hofmann, M. and Maqueda, M.: Geothermal heat flux and its influence on the oceanic abyssal circulation and radiocarbon distribution, *Geophys. Res. Lett.*, 36, L03603, doi:10.1029/2008GL036078, 2009. 3599, 3606

Joyce, T. M., Warren, B. A., and Talley, L. D.: The geothermal heating of the abyssal subarctic Pacific Ocean, *Deep-Sea Res.*, 33, 1003–1015, doi:10.1016/0198-0149(86)90026-9, 1986. 3599

Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., Ohgaito, R., Roche, D. M., Singarayer, J., Swingedouw, D., and X Zhang: Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study, *Clim. Past*, 9, 935–953, doi:10.5194/cp-9-935-2013, 2013. 3607

Large, W. G. and Yeager, S. S.: Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. NCAR Technical Note, NCAR/TN-460+STR, Boulder, Colorado, CGD Division of the National Center for Atmospheric Research, 2004. 3601

Lecointre, A.: Variabilité interannuelle à décennale en atlantique nord et mers nordiques: études conjointe d'observations, simulations numériques et réanalyses, PhD thesis, Université Joseph Fourier, Grenoble 1, 2009. 3609

Lippold, J., Luo, Y., Francois, R., Allen, S. E., Gherardi, J., Pichat, S., Hickey, B., and Schulz, H.: Strength and geometry of the glacial Atlantic Meridional Overturning Circulation, *Nat. Geosci.*, 5, 813–816, doi:10.1038/ngeo1608, 2012. 3608

Lynch-Stieglitz, J., Adkins, J. F., Curry, W. B., Dokken, T., Hall, I., Herguera, J. C., Hirschi, J., Ivanova, E., Kissel, C., Marchal, O., Marchitto, T. M., McCave, I. N., McManus, J. F., Mulitza, S., Ninnemann, U., Peeters, F., Yu, E. F., and Zahn, R.: Atlantic meridional overturning circulation during the Last Glacial Maximum, *Science*, 316, 66–69, doi:10.1126/science.1137127, 2007. 3600, 3608

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Madec, G.: NEMO ocean engine, Note du Pôle de modélisation de l'Institut Pierre-Simon Laplace No. 27, Institut Pierre-Simon Laplace, Paris, France, 2008. 3600, 3601
- Marchitto, T. M. and Broecker, W. S.: Deep water mass geometry in the glacial Atlantic Ocean: a review of constraints from the paleonutrient proxy Cd/Ca, *Geochem. Geophys. Geosys.*, 7, Q12003, doi:10.1029/2006GC001323, 2006. 3608
- Mashayek, A., Ferrari, R., Vettoretti, G., and Peltier, W. R.: The role of the geothermal heat flux in driving the abyssal ocean circulation, *Geophys. Res. Lett.*, 40, 3144–3149, doi:10.1002/grl.50640, 2013. 3599
- McDougall, T. J.: Neutral density surface in the ocean: implications for modelling, *Geophys. Res. Lett.*, 14, 797–800, doi:10.1029/GL014i008p00797, 1987. 3609
- Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z.-C.: Global climate projections, in: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007. 3606
- Monnin, E., Indermühle, A., Daellenbach, A., Flueckiger, J., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J.-M.: Atmospheric CO₂ concentrations over the Last Glacial Termination, *Science*, 291, 112–114, doi:10.1126/science.291.5501.112, 2001. 3600
- Otto-Bliesner, B. L., Hewitt, C. D., Marchitto, T. M., Brady, E. C., Abe-Ouchi, A., Crucifix, M., Murakami, S., and Weber, S. L.: Last Glacial Maximum ocean thermohaline circulation: PMIP2 model intercomparisons and data constraints, *Geophys. Res. Lett.*, 34, 1–6, doi:10.1029/2007GL029475, 2007. 3600
- Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, 399, 429–436, 1999.
- Ritz, S. P., Stocker, T. F., Grimalt, J. O., Menviel, L., and Timmermann, A.: Estimated strength of the Atlantic overturning circulation during the last deglaciation, *Nat. Geosci.*, 6, 208–212, 2013. 3607

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Roquet, F., Madec, G., McDougall, T. J., and Barker, P. M.: Accurate polynomial expressions for the density and specific volume of seawater using the TEOS-10 standard, *Ocean Model.*, 90, 29–43, 2015. 3601

Sarnthein, M., Winn, K., Jung, S. J. A., Duplessy, J. C., Labeyrie, L., Erlenkeuser, H., and Ganssen, G.: Changes in east Atlantic deep-water circulation over the last 30,000 years – 8 time slice reconstructions, *Paleoceanography*, 9, 209–267, 1994. 3600

Scott, J., Marotzke, J., and Adcroft, A.: Geothermal heating and its influence on the meridional overturning circulation, *J. Geophys. Res.*, 106, 31141–31154, doi:10.1029/2000JC000532, 2001. 3599

Siegenthaler, U., Stocker, T. F., Monnin, E., Lüthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V., and Jouzel, J.: Stable carbon cycle-climate relationship during the last Pleistocene, *Science*, 310, 1313–1317, doi:10.1126/science.1120130, 2005.

Skinner, L. C., Fallon, S., Waelbroeck, C., Michel, E., and Barker, S.: Ventilation of the deep Southern Ocean and deglacial CO₂ rise, *Science*, 328, 1147, doi:10.1126/science.1183627, 2010.

Stein, C. and Stein, S.: A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature*, 359, 123–129, doi:10.1038/359123a0, 1992. 3599

Tagliabue, A., Bopp, L., Roche, D. M., Bouttes, N., Dutay, J.-C., Alkama, R., Kageyama, M., Michel, E., and Paillard, D.: Quantifying the roles of ocean circulation and biogeochemistry in governing ocean carbon-13 and atmospheric carbon dioxide at the last glacial maximum, *Clim. Past*, 5, 695–706, doi:10.5194/cp-5-695-2009, 2009. 3608

Timmermann, R., Goosse, H., Madec, G., Fichet, T., Etche, C., and Dulière, V.: On the representation of high latitude processes in the ORCA-LIM global coupled sea ice-ocean model, *Ocean Model.*, 8, 175–201, doi:10.1016/j.ocemod.2003.12.009, 2005. 3601

Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric CO₂, and climate change during the ice ages, *Paleoceanography*, 21, PA2005, doi:10.1029/2005PA001154, 2006.

Urakawa, L. and Hasumi, H.: A remote effect of geothermal heat on the global thermohaline circulation, *J. Geophys. Res.*, 114, C07016, doi:10.1029/2008JC005192, 2009. 3599

Watson, A. J. and Garabato, A. C. N.: The role of Southern Ocean mixing and upwelling in glacial–interglacial atmospheric CO₂ change, *Tellus B*, 58, 73–87, doi:10.1111/j.1600-0889.2005.00167.x, 2006.

Worthington, L.: Genesis and evolution of water masses, Meteor. Mon., 8, 63–67, 1968.

Zhang, X., Lohmann, G., Knorr, G., and Xu, X.: Different ocean states and transient characteristics in Last Glacial Maximum simulations and implications for deglaciation, Clim. Past, 9, 2319–2333, doi:10.5194/cp-9-2319-2013, 2013. 3601

- 5 Zhou, S., Qu, L., Zhao, X., and Wan, W.: Laboratory simulation of the influence of geothermal heating on the interior ocean, Acta Oceanol. Sin., 33, 25–31, doi:10.1007/s13131-014-0512-8, 2014. 3599

CPD

11, 3597–3624, 2015

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

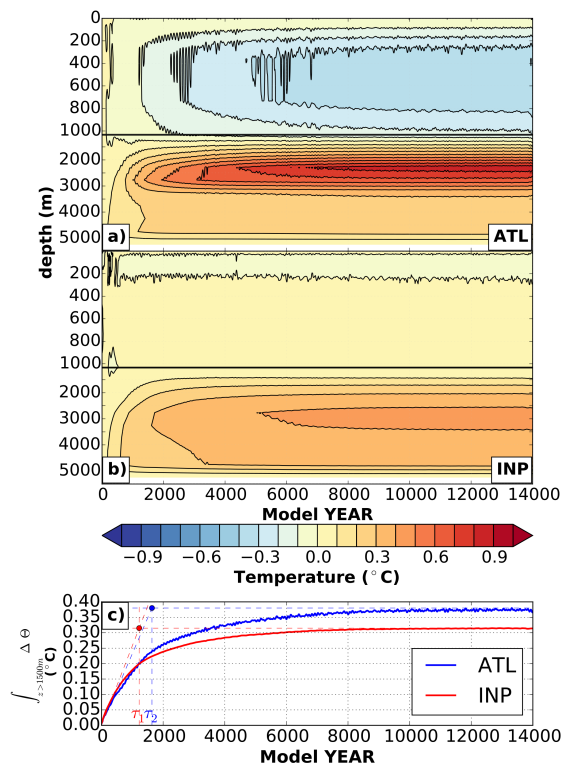


Figure 1. Annual mean potential temperature drift (in °C) induced by the geothermal heat forcing as a function of depth averaged in (a) the Atlantic basin and (b) the Indo-Pacific basin. Contour intervals are every 0.1 °C. Note the vertical scale is increased in the upper 1000 m. (c) Time-series of the mean temperature accumulation (in °C) due to the geothermal heat below 1500 m in the Atlantic and Indo-Pacific basins. $\tau_1 \sim 1200$ years and $\tau_2 \sim 1600$ years denote the characteristic time scale, i.e. the amount of time required for the response to reach $(1 - 1/e) \approx 63\%$ of the maximum heat accumulation, in the Indo-Pacific and the Atlantic basins.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

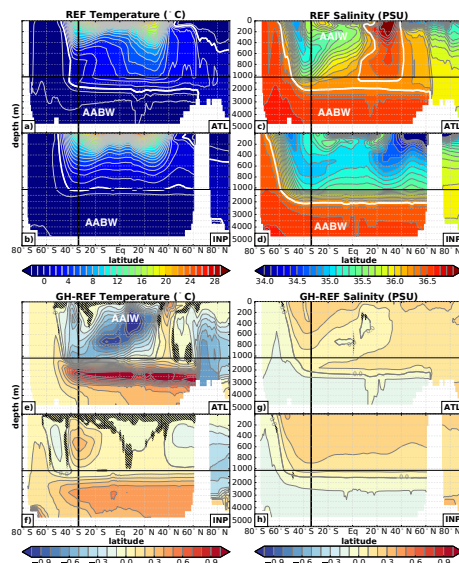


Figure 2. Annual zonal mean potential temperature patterns (in °C) in the reference experiment (REF) for **(a)** the Atlantic basin, **(b)** the Indo-Pacific basin (Contour interval every 1 °C, thick white contour is 0 °C); salinity patterns (in °C) in the reference experiment (REF) for **(c)** the Atlantic basin, **(d)** the Indo-Pacific basin (Contour interval every 0.1 PSU, thick white contour is 36.3 PSU); the temperature difference between REF and GH for **(e)** the Atlantic basin, and **(f)** the Indo-Pacific basin (Contour interval every 0.1 °C, thick grey contour is 0 °C); and salinity difference between REF and GH for **(g)** the Atlantic basin, and **(h)** the Indo-Pacific basin (Contour interval every 0.1 PSU, thick white contour is 0 PSU). The thick vertical black line shows the location of the South Atlantic entrance at 34° S. Note the vertical scale is increased in the upper 1000 m. The patterns in each Southern Ocean sector are shown in each panel between 80 and 34° S. The dashed contours represent the region where the difference is insignificant at a 95 % confidence level (based on a *t* test). AABW: Antarctic Bottom Water, AAIW: Antarctic Intermediate Water.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



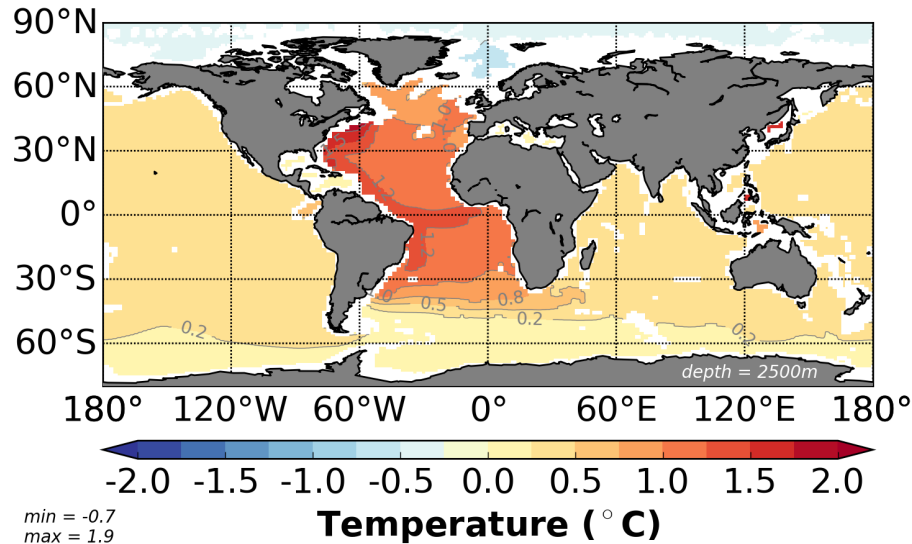


Figure 3. Map of the annual mean temperature difference (in °C) between GH and REF at 2500 m. Maximum and minimum values are denoted in the lower left corner. The largest warming is in the Atlantic deep western boundary current.

**Impact of the oceanic
geothermal heat flux
on a glacial ocean
state**

M. Ballarotta et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



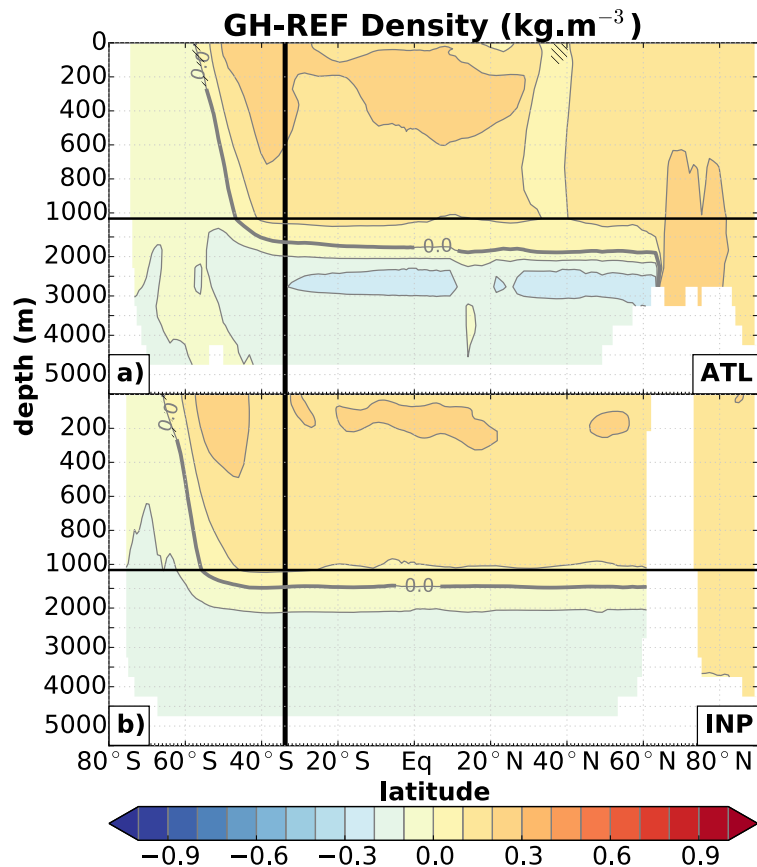


Figure 4. Difference in the annual mean and zonal mean potential density patterns (σ_4 in $\text{kg}\cdot\text{m}^{-3}$) between REF and GH for **(a)** the Atlantic basin, and **(b)** the Indo-Pacific basin. Contour and scale same as in Fig. 2

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

[Title Page](#)

[Abstract](#) [Introduction](#)

[Conclusions](#) [References](#)

[Tables](#) [Figures](#)

[◀](#) [▶](#)

[◀](#) [▶](#)

[Back](#) [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

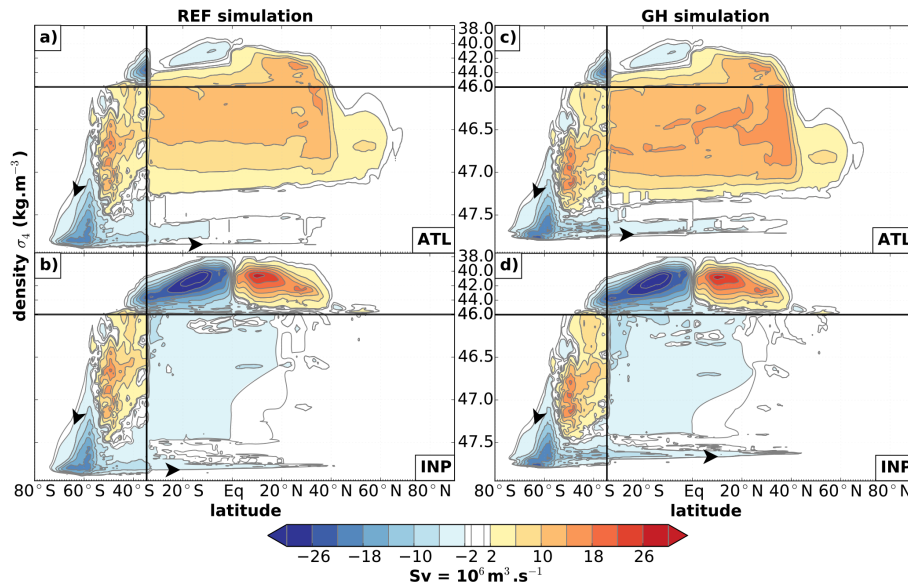


Figure 5. Annual mean density-binned effective (Eulerian + eddy-induced velocities) meridional overturning circulation (in Sv) in the experiment *without* geothermal heating (REF) for (a) the Atlantic basin, and (b) the Indo-Pacific basin; and in the experiment *with* geothermal heating (GH) for (c) the Atlantic basin, and (d) the Indo-Pacific basin. The thick black line shows the location of the South Atlantic entrance at 34°S. The annual mean meridional overturning circulation in the Southern Ocean is shown in each panel between 80 and 34°S. Positive (negative) contours represent clockwise (anti-clockwise) circulations. Contour interval is every 4 Sv, and -1 and +1 Sv contours are added. Density bins intervals every 0.01 $\text{kg} \cdot \text{m}^{-3}$. Note the vertical scale is increased for $\sigma_4 > 46 \text{ kg} \cdot \text{m}^{-3}$.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

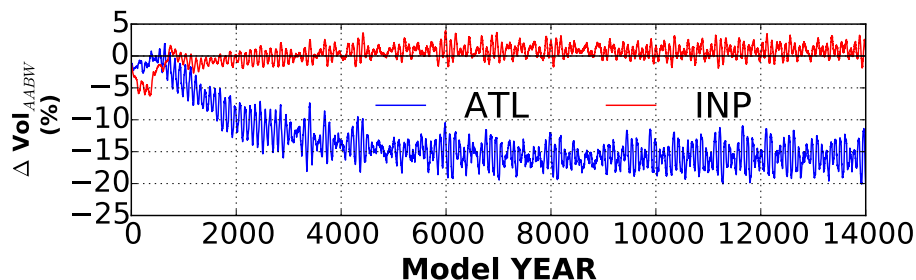


Figure 6. Time-series of the AABW volume variation (in %) in the Atlantic and Indo-Pacific basins. The AABW volume is computed as the volume of water below 2000 m where the annual mean effective overturning circulation in latitude-depth coordinates is negative (Fig. 8a, b).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

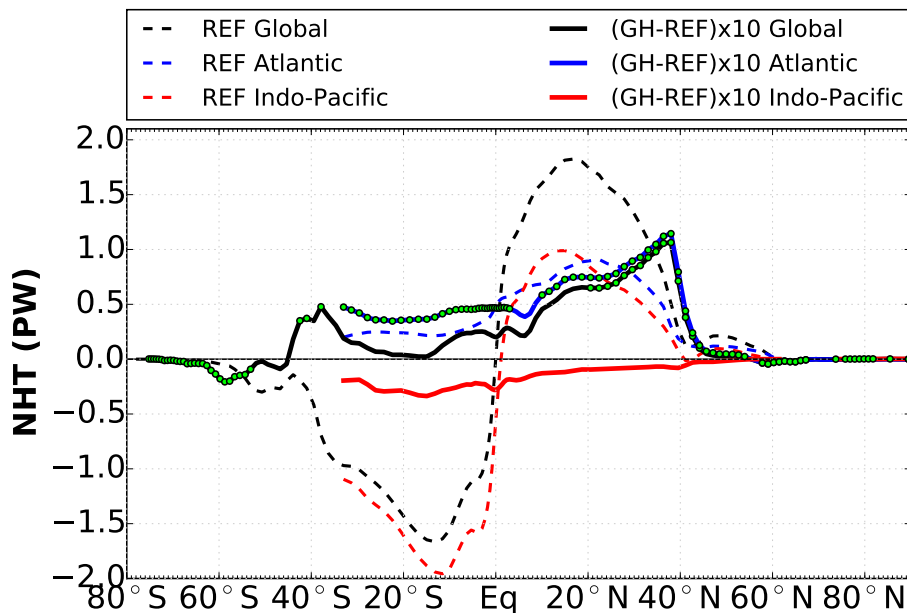


Figure 7. Annual mean effective (Eulerian mean + eddy-induced velocities) northward heat transport (in $\text{PW} = 10^{15} \text{ W}$) in the Global Ocean, the Atlantic and the Indo-Pacific basins in the reference experiment (dashed line); and the difference between REF and GH in the annual mean northward heat transport (thick line). Note that the difference is magnified by a factor 10. The green dots show where the difference is significant at a 95% confidence level (based on a t test).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of the oceanic geothermal heat flux on a glacial ocean state

M. Ballarotta et al.

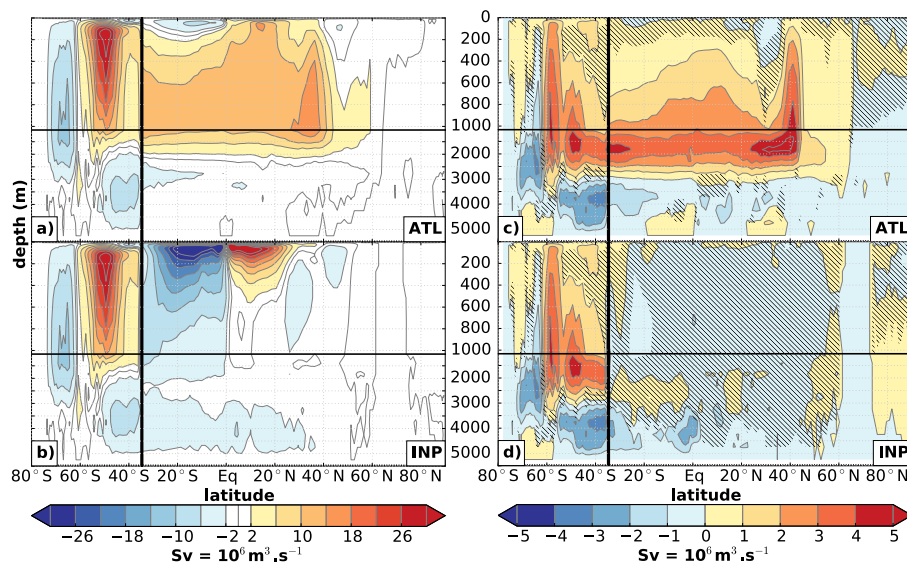


Figure 8. Annual mean effective (Eulerian mean + eddy-induced velocities) meridional overturning circulation in latitude-depth coordinates (in $\text{Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) in the reference experiment (REF) for **(a)** the Atlantic basin, and **(b)** the Indo-Pacific basin. Contour interval is every 4 Sv, and the 0 Sv contours is added. Positive (negative) values represent clockwise (counterclockwise) circulation. Difference in the effective meridional overturning circulation between REF and GH for **(c)** the Atlantic basin, and **(d)** the Indo-Pacific basin. Contour interval is every 1 Sv. The annual mean meridional overturning circulation and the difference in the meridional overturning circulation in the Southern Ocean between GH and REF is shown 80 and 34° S. Note the vertical scale is increased in the upper 1000 m. The dashed contours represent the region where the difference is insignificant at a 95 % confidence level (based on a t test).