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TIPPING POINTS IN THE EARTH SYSTEM

D2.1 Modelling protocol for DO events for CMIP-PMIP

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Summary for publication

Dansgaard-Oeschger (DO) events are abrupt, large climate swings that punctuated the last glacial period. There is uncertainty whether current IPCC-relevant models can effectively represent the processes that cause DO events. Current Earth system models (ESMs) seem overly stable against external perturbations and incapable of reproducing most abrupt climate changes of the past (Valdes, 2011). If this holds true, this could noticeably influence their capability to predict future abrupt transitions, with significant consequences for their use in the identification of Tipping Elements (TEs), and more in general, for the delivery of precise climate change projections. In this task, the objectives of this study are twofold: (1) to compile and analyse model output for any spontaneously oscillating simulations, and (2) to formulate possible pathways to a DO PMIP (Paleoclimate Modelling Intercomparison Project) protocol that could help investigate cold-period instabilities through a range of insolation-, freshwater-, GHG-, and NH ice sheet-related forcings, as well as evaluating the possibility of spontaneous internal oscillations. Such a model protocol is crucial since (1), there is currently no PMIP common guidance to investigate DO events, (2) it could help carry out simulations in ESM and Earth system models of intermediate complexity (EMIC) under a common framework, and (3) it will be essential in guiding a more methodical search for DO events in current models.

MIS3 was a period of noticeable millennial-scale climate variability, characterised by the most regular incidence of DO events (Schulz et al., 1999). Although most abrupt DO events happened during MIS3, only few studies investigate AMOC stability in coupled general circulation models under MIS 3 conditions (e.g., Kawamura et al., 2017; Zhang and Prange, 2020). Here, we therefore suggest that more specific sensitivity experiments performed under MIS 3 boundary conditions are needed in order to better understand the mechanisms behind millennial-scale climate variability; this may help clarify the preferred incidence of DO events during MIS 3.

Thus, we focus on the MIS3 period and propose a MIS3 baseline experiment as the Tier 1 experiment (hereafter termed MIS3-cnt experiment) of the DO PMIP protocol. For this MIS3-cnt experiment we suggest using boundary conditions for an specific time slice between 30 and 40 thousand of years BP (hereafter ka) which is a period characterised by a rather regular sequence of DO events. The MIS3-cnt experiment can help answer the question, "are models too stable?".

We suggest a range of MIS3 sensitivity experiments as the Tier 2 experiments of the DO PMIP protocol. These experiments can be very useful to (1) explore AMOC variability under intermediate glacial conditions, (2) better understand the mechanisms behind millennial-scale climate variability, (3) look for spontaneous DO-type oscillations, and (4) disentangle the effect of variations in individual boundary conditions, and therefore help with the interpretation of the MIS3-cnt experiment. The recommended experiments are:

- MIS3-co2 experiments, in which all forcings are set to MIS3 values except for the CO2 concentration, which is the same as in the PI control simulations and/or PMIP4 Tier 1 LGM experiment (190 ppm – Kageyama et al. (2017)).
- MIS3-ice experiments, in which all forcings are set to MIS 3 values except for the ice sheet distribution, which is the same as in the PI control simulation and/or PMIP4 Tier 1 LGM experiment (Kageyama et al., 2017).
- MIS3-orb experiments, in which all forcings are set to MIS3 values except for the orbital parameters, which are the same as in the PI control simulations and/or PMIP4 Tier 1 LGM experiment (Kageyama et al., 2017).

- MIS3-fw experiments, in which all forcings are set to MIS3 values except for additional freshwater fluxes injected into the North Atlantic. We suggest perturbations ranging from very small (±0.005 Sv) to very large (±1 Sv) freshwater fluxes (Sime et al., 2019; Zhang and Prange, 2020).

Work carried out

Details on the work carried out

The main objective of this study is to put together DO-event modelling protocol that could help investigate cold-period instabilities through a range of insolation-, freshwater-, GHG-, and NH ice sheet-related forcings, as well as evaluating the possibility of spontaneous internal oscillations. In this task, we have been reviewing/collating the literature on modelling DO events and writing preliminary material for a 'possible pathways to a PMIP DO protocol manuscript'. We have also included in this manuscript all the feedback we have so far received from the PMIP-community during two first discussions. An important part of our work has been in organizing these discussion meetings with all who expressed interest at the PMIP 2020 conference. These meeting were held in October 2020 and December 2020. Now we have this preliminary manuscript in hand, we would like ask again the whole PMIP community about this initiative and incorporate all ideas in a way that works as-best-as-can-be-managed for the whole community.

Additionally, we are gathering model output for any spontaneously oscillating simulations. We will cross compare existing simulations (published or unpublished) with any spontaneous DO-type oscillation. We will analyse how the atmosphere, ocean and sea ice may interact to lead to DO events. This is also a good step towards the DO-event modelling protocol. It will probably be a standalone model intercomparison project. A successful example of the latter is the LongRunMIP project (http://www.longrunmip.org/), which has compiled a large number of coupled model simulations of any stabilizing scenario simulating more than 1000 years.

In addition, we are exploring HadCM3 (UK Met Office coupled atmosphere-ocean general circulation model) simulations performed at 30 ka and 21 ka that show spontaneous DO-type oscillations. We have derived a scaled overturning streamfunction using twice vertically-integrated meridional density gradients (Butler et al., 2015; Sime et al, 2006). Meridional overturning can be influenced by meridional pressure gradients, as variations in the meridional pressure profile will result in variations in the zonal flow, affecting zonal pressure profiles, and therefore leading to variations in meridional flow. We are also using spectral analysis (continuous wavelet transform) over the AMOC time series of these simulations to detect early warning signals prior to the DO Tipping event.

Moreover, we are running additional sensitivity simulations to explore the parameter space in which HadCM3 tends to oscillate under 30 ka conditions. A number of 30ka sensitivity simulations (based on the 30ka control run) are running modifying the following parameters (one at a time):

- the CO_2 concentration, implementing a range of different CO_2 concentrations between 180 and 270 ppm,
- the orbital forcing, implementing different orbital parameters for e.g. 21ka and 56ka and,
- the height of the NH ice sheets, scaling up and down the height of the Laurentide ice sheet (this is work in progress).

These sensitivity simulations are very useful to (1) help define the parameter space where HadCM3 tends to oscillate, and (2) examine the effect of the different parameters (CO_2, orbital forcing and NH ice sheet height) on the occurrence of the DO-type oscillations, and on the periodicity of the DO oscillations.

Which partner contributed to which tasks

The work/tasks mentioned above has been mainly carried out by Irene Malmierca-Vallet (UKRI BAS), supported by Louise Sime (UKRI BAS) and Paul Valdes (UNIVBRIS).

Explain the reasons for deviations/delays

There has been a delay in the deliverable which is to put together DO-event modelling protocol. We have encountered a number of difficulties.

First of all, the COVID-19 outbreak has caused a delay of around six months for recruiting and the working time of staff members involved in the project has been considerably reduced (e.g. for care time and home schooling).

In addition, huddling and reaching consensus in a big community like PMIP, where individual research groups all have their own ideas and objectives can be very challenging. There are normally disagreements as people bring different perspectives, information and ideas to the table.

Another difficulty we have identified is linked to the 30 ka sensitivity simulations that we are running with HadCM3. These are very expensive and very long runs (each takes about 2-months run time), and disc storage is the biggest problem. Each run generates more than 1Tb and so it quickly fills up our disc space. This substantially limits the number of simulations we can run at the same time.

Main results achieved

(1) We have writing preliminary material for a 'possible pathways to a PMIP DO protocol manuscript'. This manuscript (1) proposes several possible pathways to a DO PMIP protocol, (2) establishes PMIP common guidance to investigate DO events, and (3) defines a more methodical search for DO events in current models.

(2) An important part of our work has been in organizing discussion meetings with all who expressed interest in the DO-event modelling protocol. Although challenging, we have been able to organize the discussion meetings considering all the different options, wants and needs of the different individual research groups. This in turn has enabled the big PMIP group to come together in finding common ground in the area of abrupt climate change, particular on DO events.

(3) We have successfully set up a number of 30 ka sensitivity simulations with HadCM3. These experiments will help define the parameter space where HadCM3 tends to oscillate, and (2) examine the effect of the different parameters (CO_2, orbital forcing and NH ice sheet height) on the occurrence of the DO-type oscillations, and on the periodicity of the DO oscillations.

Progress beyond the state of the art

Abrupt warming episodes punctuate Greenland ice core records throughout the last glacial period and are generally referred to as DO events. Broecker and Peteet (1985) pointed to changes in the Atlantic Meridional Overturning Circulation (AMOC) as a primary cause behind DO events. Since then, a variety of additional and alternative hypotheses have been proposed. These include sea ice variability (Gildor and Tziperman, 2003; Kaspi et al., 2004; Li et al., 2005, 2010; Sime et al., 2019), solar variability (Braun et al., 2008), sea ice fluctuations linked to ice-shelf growth and decay (Alley et al., 2001; Petersen et al., 2013; Boers et al., 2018), shifts in wind patterns in the Southern and Northern Hemisphere (Seager and Battisti, 2007; Banderas Carreño et al., 2012; Banderas et al., 2015), and reorganization of the tropics (Clement et al., 2001; Seager and Battisti, 2007). There is currently no consensus regarding the various processes that might have caused the DO events and on how to properly model theses abrupt climate transitions. Numerous modelling approaches have been used, including changes in GHG and orbital parameters, variability of sea ice coverage, changes in the NH ice sheet configuration, melt water release and changes in ocean missing values. There is currently no DO-event modelling protocol and therefore a lack of consensus within the wider PMIP community on how to run/analysis or cross compare DO-event simulations. Until recently, we thought that climate models were too stable and did not have the ability to oscillate spontaneously.

Given the current state of the art, the main objective of this project of putting together a DO-event modelling protocol is a very ambitious one because (1) consensus needs to be reached among the wider PMIP community which is formed by many international research groups with very different interests and objectives, and (2) running DO-type simulations during glacial states (30-40 ka) for a very long time – many 1000s of years can be very computationally expensive.

As part of this project, we have been able to organize several discussion meetings with all who expressed interest in the DO-event modelling protocol. This in turn has enabled the big PMIP group to come together in finding common ground in the area of abrupt climate change, particular on DO event. We have now writing preliminary material for a 'possible pathways to a PMIP DO protocol manuscript'. This is a unique outcome in that it could help (1) carry out simulations in CMIP-class models under a common framework, and (2) guide a more methodical search for DO events in current models.

Impact

How has this work contributed to the expected impacts of TiPES?

Our work has contributed to the following expected impacts of TiPES:

Expected impact	TiPES outcome/results	Contribution to expected impact
"Supporting major international scientific assessments such as the IPCC"	TiPES will put forward guidelines for improving the accuracy and reliability of climate models, model selection, and computation of TPs across the model hierarchy. Shortcomings in the present generation of earth system models will be investigated. New EMIC and ice sheet model parameterizations will be generated; the boundary conditions for TEs will be better defined for all models; and new ESM (isotope) code will be written to enable more appropriate model-data evaluations. (WP2-5/O1).	The DO events of the last ice age represent one of the best studied abrupt climate transitions, yet we still lack a comprehensive explanation for them. Moreover, there is uncertainty whether current IPCC-relevant models can effectively represent the processes that cause DO events. Current Earth system models (ESMs) seem overly stable against external perturbations and incapable of reproducing most abrupt climate changes of the past (Valdes, 2011). If this holds true, this could noticeably influence their capability to predict future abrupt transitions, with significant consequences for their use in the identification of Tipping Elements (TEs), and more in general, for the delivery of precise climate change projections. In this sense, our work on putting together a DO-event modelling protocol (1) improves computation of TPs (in particular of DO events) across the model hierarchy, (2) helps improve the accuracy and reliability of climate models by investigating why EMSs are apparently too stable against external perturbations, and (3) stablishes common guidelines/boundary conditions to perform DO events simulations and therefore permits a more methodical search for DO events in current models.
	The combinations of ESMs and paleoclimatic observations of abrupt transitions in the past will identify relevant TEs and possible TPs for the future (WP1-WP2/O1).	We are using spectral analysis (continuous wavelet transform) over AMOC time series to detect early warning signals prior to the DO Tipping event. This could help test/provide early warming metrics for the identification and validation of early warning signals.
"increase confidence in climate	TiPES will assess and improve the parameterisations of comprehensive ESMs (in particular EC-Earth, HadGEM3/UKESM, and CESM) of the CMIP-6 class to improve the	If the models are to be employed for the prediction of future events of abrupt change, their capability to simulate abrupt changes like DO events needs to be firmly established. The

change projections”	representation of TEs in a collaborative effort of WPs 1-3 (O1).	DO PMIP protocol helps improve the ability of current models to simulate abrupt climate change transitions (in particular DO events) and therefore increases the confidence in climate change projections.
“sustaining Europe's leadership in climate science”	TiPES is a collaborative effort across diverse disciplines, such as Earth system modelling, time series analysis, paleoclimatology, applied mathematics and statistics, theoretical physics, formal risk assessment and decision theory. The groups taking part in TiPES are leading in their respective fields and are spread across eleven European countries.	This project provides strong interdisciplinary collaborations across Europe and international community. Synergies have been created with other projects such as PMIP and several PAGES working groups.
	The TiPES research endeavours are ambitious and far reaching: we will aim at attracting the best international talents to join our team, and take advantage of our extensive international research networks to solicit and educate excellent candidates.	This project helps training future leaders and ensures the best young scientists in the future, interdisciplinary scientists who are able to work on a vast range of problems related to critical transitions in the climate system, and able to radically improve our understanding of abrupt transitions in the Earth system. Ours is an interdisciplinary project, which enables young scientists to dialogue/collaborate with a wide range of international researchers from very different backgrounds (e.g. ice sheets modellers, statisticians, oceanographers ...).
	TiPES is strongly embedded in the climate science community, with PIs, Co-PIs and Steering Committee Members of projects such as PAGES, Past Earth Network, RISE actions, CMIPs and PMIPs (including the deep-time versions PlioMIP and DeepMIP), Copernicus Climate Services, CliMathNet, MCRN, SIAM MPE, CLIMCOR, EU-PolarNet, Blue Action, CRESCENDO, East-GRIP, Oldest Ice, ITNs, ERC and other prestigious national and international grants. Among the TiPES team members there is a Lead Author of IPCC’s AR3 and coordinating Lead Author of AR4, as well as two Lead Authors of IPCC’s AR5, and five EGU medallists.	We are putting together a DO-event modelling protocol that will ensure excellence and scientific impact upon the European climate science community, as well as the international community way beyond the funding period of TiPES.

Table 4: Modified version of TiPES Grant Agreement Table 4: expected impacts

Lessons learned and Links built

Lessons learned

Reaching consensus within the different international research groups that constitute the wider PMIP community has been a big challenge. An important lesson learned is that the different opinions, wants and needs of the different research groups need to be considered. This in turn has enabled the group to come together in finding common ground.

Engaging the different members/research groups in the project ideas and the timeline for the project progress has been another big challenge. We have learnt how important it is to ensure that the project remains of interest to the members by tracking progress and keeping members informed, mainly through emails and the online latex editor "overleaf".

A positive lesson learnt from the experiences of our work is that working with an interdisciplinary group of people like the PMIP community can promote new ideas and effectively redefine the project structure. In particular, the idea of gathering and cross comparing model output for any spontaneously oscillating simulations was brought/defined during one of our meetings with members of the PMIP community. It will probably be a standalone model intercomparison project.

Links built

Synergies have been created with two different PAGES working groups: SISAL (Speleothem Isotopes Synthesis and AnaLysis) and QUIGS (PAGES-PMIP working group on quaternary interglacials). We are working in close collaboration with the research groups of Sandy Harrison (University of Reading) and Kira Rehfeld (University of Heidelberg) who are mainly putting together a synthesis of DO data. This DO events data will be used to provide the most direct evaluation of the models.

We are also working closely together with the international PMIP community to put together a common protocol for model simulations of DO events.

Links built with other deliverables and WPs

Moreover, synergies have been created with other deliverables and WPs such as Tipping Points in Antarctica Climate Components (TIPACCs), Southern Ocean Carbon and Heat Impact on Climate (SO-CHIC) and Deep icE corE Proxies to Infer past antarctiC climatE dynamics (DEEPICE).

In addition, we have organised a workshop on Dansgaard–Oeschger focussed simulations on Friday 19th February 2021. Annex 1 shows the agenda for the meeting.

Contribution to the top level objectives of TiPES

Our project of putting together a PMIP DO protocol contributes directly to O1 (identifying tipping elements and their interaction in model and data) and O3 (Characterise climate response in the presence of Tipping Points). In this task, our project defines possible pathways to a DO-event modelling protocol which will be very useful to investigate abrupt transitions during cold climates in TiPES models via a range of freshwater-, insolation-, and ice sheet-related forcings, assessing as well the possibility of internal oscillations. Such a protocol is necessary since current CMIP-PMIP guidance does not yet include protocols to guide the investigation of DO events, thus we have no standard international approach yet that can permit assessment of whether our models are indeed too stable.

In addition, as part of this deliverable we are gathering model output for any spontaneously oscillating simulations (published or unpublished). This multi model-data synthesis project contributes directly to O1 (identifying tipping elements and their interaction in model and data) and O3 (Characterise climate response in the presence of Tipping Points). In this task, this multi model-data synthesis project investigates the properties of these particular models that have led to this apparently unique success in reproducing spontaneous DO-type oscillations. The plan is to cross compare existing simulations using a common set of diagnostics so we can compare the mechanisms and the characteristics of the oscillations. This project will help define metrics for characterizing unforced DO-type variability in a quantitative way. A number of research groups have already showed interest in this model intercomparison project initiative.

Furthermore, as part of this deliverable, we are analysing a set of MIS3 simulations performed with the HadCM3 climate model that shows spontaneous DO-type oscillations. We explain the AMOC asymmetric response with a mechanistic explanation. In particular, we analyse the role of temperature and salinity by reconstructing the AMOC behaviour from meridional density gradients. We are also analysing AMOC time series with spectral analysis (continuous wavelet transform) with the objective to test early warning metrics. Thus this part of the project contributes directly to O2 (Provide approaches for the identification and validation of Early Warning Signals).

References (Bibliography)

Alley, R., Anandakrishnan, S., and Jung, a. P.: Stochastic resonance in the North Atlantic, Paleoceanography, 16, 190–198, 2001.

Armstrong, E., Hopcroft, P. O., and Valdes, P. J.: A simulated Northern Hemisphere terrestrial climate dataset for the past 60,000 years, Scientific data, 6, 1–16, 2019.

Banderas, R., Alvarez-Solas, J., Robinson, A., and Montoya, M.: An interhemispheric mechanism for glacial abrupt climate change, Climate Dynamics, 44, 2897–2908, 2015.

Banderas Carreño, R., Álvarez Solas, J., and Montoya, M.: Role of CO2 and Southern Ocean winds in glacial abrupt climate change, Climate of the Past, 8, 1011–1021, 2012.

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and Chappellaz, J.: Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present, Geophysical Research Letters, 42, 542–549, 2015.

Berger, A.: Long-term variations of daily insolation and Quaternary climatic changes, Journal of the atmospheric sciences, 35, 2362–2367, 1978.

Boers, N., Ghil, M., and Rousseau, D.-D.: Ocean circulation, ice shelf, and sea ice interactions explain Dansgaard–Oeschger cycles, PNAS, 115, E11 005–E11 014, 2018.

Braun, H., Ditlevsen, P., and Chialvo, D.: Solar forced Dansgaard-Oeschger events and their phase relation with solar proxies, Geophys. Res. Lett., 35, 2008.

Broecker, W. and Peteet, D.: Does the ocean-atmosphere system have more than one stable mode of operation?, Nature, 315, 21–26, https://doi.org/10.1038/315021a0, 1985.

Brown, N. and Galbraith, E. D.: Hosed vs. unhosed: interruptions of the Atlantic Meridional Overturning Circulation in a global coupled model, with and without freshwater forcing., Climate of the Past, 12, 2016.

Butler, E.D. and Oliver, K.I.C and Hirschi, J.J.M and Mecking, J.V.: Reconstructing global overturning from meridional density gradients. Climate Dynamics, 46, 2593–2610, 2016.

Clark, P. U., Pisias, N. G., Stocker, T. F., and Weaver, A. J.: The role of the thermohaline circulation in abrupt climate change, Nature, 415, 863–869, 2002.

Clement, A. C., Cane, M. A., and Seager, R.: An orbitally driven tropical source for abrupt climate change, Journal of Climate, 14, 2369– 2375, 2001.

Davies-Barnard, T., Ridgwell, A., Singarayer, J., and Valdes, P.: Quantifying the influence of the terrestrial biosphere on glacial–interglacial climate dynamics, Climate of the Past, 13, 1381–1401, 2017.

Dokken, T. M., Nisancioglu, K. H., Li, C., Battisti, D. S., and Kissel, C.: Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to the Nordic seas, Paleoceanography, 28, 491–502, 2013.

Drijfhout, S., Gleeson, E., Dijkstra, H. A., and Livina, V.: Spontaneous abrupt climate change due to an atmospheric blocking–sea-ice–ocean feedback in an unforced climate model simulation, Proceedings of the National Academy of Sciences, 110, 19 713–19 718, 2013.

Ganopolski, A. and Rahmstorf, S.: Rapid changes of glacial climate simulated in a coupled climate model, Nature, 409, 153–158, 2001.

Gildor, H. and Tziperman, E.: Sea-ice switches and abrupt climate change, Philos. Trans. R. Soc. London, Ser. A, 361, 1935–1942, https://doi.org/10.1098/rsta.2003.1244, 2003.

Hu, A., Otto-Bliesner, B. L., Meehl, G. A., Han, W., Morrill, C., Brady, E. C., and Briegleb, B.: Response of thermohaline circulation to freshwater forcing under present-day and LGM conditions, Journal of Climate, 21, 2239–2258, 2008.

Jackson, L. and Vellinga, M.: Multidecadal to centennial variability of the AMOC: HadCM3 and a perturbed physics ensemble, Journal of climate, 26, 2390–2407, 2013.

Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G., Roche, D., Singarayer, J., Swingedouw, D., and Zhang, X.: Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study., Climate of the Past Discussions, 8, 2012.

Kageyama, M., Albani, S., Braconnot, P., Harrison, S. P., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Marti, O., Peltier,W. R., Peterschmitt, J. Y., et al.: The PMIP4 contribution to CMIP6-Part 4: Scientific objectives and experimental design of the PMIP4-CMIP6 Last Glacial Maximum experiments and PMIP4 sensitivity experiments, Geoscientific Model Development, 10, 4035–4055, 2017.

Kaspi, Y., Sayag, R., and Tziperman, E.: A "triple sea-ice state" mechanism for the abrupt warming and synchronous ice sheet collapses during Heinrich events, Paleoceanography, 19, https://doi.org/10.1029/2004PA001009, 2004.

Kawamura, K., Abe-Ouchi, A., Motoyama, H., Ageta, Y., Aoki, S., Azuma, N., Fujii, Y., Fujita, K., Fujita, S., Fukui, K., et al.: State dependence of climatic instability over the past 720,000 years from Antarctic ice cores and climate modeling, Science advances, 3, 1600 446, 2017.

Kleppin, H., Jochum, M., Otto-Bliesner, B., Shields, C. A., and Yeager, S.: Stochastic atmospheric forcing as a cause of Greenland climate transitions, Journal of Climate, 28, 7741–7763, 2015.

Klockmann, M., Mikolajewicz, U., and Marotzke, J.: Two AMOC states in response to decreasing greenhouse gas concentrations in the coupled climate model MPI-ESM, Journal of Climate, 31, 7969–7984, 2018.

Li, C. and Born, A.: Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events, Quaternary Science Reviews, 203, 1–20, 2019.

Li, C., Battisti, D., Schrag, D., and Tziperman, E.: Abrupt climate shifts in greeland due to displacements of the sea ice edge, Geophys. Res. Lett., 32, https://doi.org/10.1029/2005BL023492, 2005.

Li, C., Battisti, D., and Bitz, C.: Can North Atlantic sea ice anomalies account for Dansgaard-Oeschger climate signals?, J. Clim., 23, 5457–5475, https://doi.org/10.1175/2010JCLI3409.1, 2010.

Liu, Z., Otto-Bliesner, B., He, F., Brady, E., Tomas, R., Clark, P., A.E., C., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., and Cheng, J.: Transient simulation of last deglaciation with a new mechanism for Bolling-Allerod warming, Science, 325, 310–314, https://doi.org/10.1126/science.1171041, 2009.

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.-M., Raynaud, D., Stocker, T. F., and Chappellaz, J.: Orbital and millennial-scale features of atmospheric CH 4 over the past 800,000 years, Nature, 453, 383–386, 2008.

Manabe, S. and Stouffer, R.: Two stable equilibria of a coupled ocean-atmosphere model, Journal of Climate, 1, 841–866, 1988.

Martin, T., Park, W., and Latif, M.: Southern Ocean forcing of the North Atlantic at multi-centennial time scales in the Kiel Climate Model, Deep Sea Research Part II: Topical Studies in Oceanography, 114, 39–48, 2015.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C., and Shackleton, N. J.: Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy 1, Quaternary research, 27, 1–29, 1987.

Menviel, L., Timmermann, A., Friedrich, T., and England, M.: Hindcasting the continuum of Dansgaard-Oeschger variability: mechanisms, patterns and timing, Climate of the Past, 10, 63–77, https://doi.org/10.5194/cp-10-63-2014, 2014.

Peltier, W. R.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE, Annu. Rev. Earth Planet. Sci., 32, 111–149, 2004.

Peltier, W. R. and Vettoretti, G.: Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: A “kicked” salt oscillator in the Atlantic, Geophysical Research Letters, 41, 7306–7313, 2014.

Petersen, S. V., Schrag, D. P., and Clark, P. U.: A new mechanism for Dansgaard-Oeschger cycles, Paleoceanography, 28, 24–30, 2013.

Rahmstorf, S.: Ocean circulation and climate during the past 120,000 years, Nature, 419, 207–214, https://doi.org/10.1038/nature01090, 2002.

Rasmussen, T. L. and Thomsen, E.: The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations, Palaeogeography, Palaeoclimatology, Palaeoecology, 210, 101–116, 2004.

Roberts, W. H., Valdes, P. J., and Payne, A. J.: Topography's crucial role in Heinrich Events, Proceedings of the National Academy of Sciences, 111, 16 688–16 693, 2014.

Roche, D. M., Wiersma, A. P., and Renssen, H.: A systematic study of the impact of freshwater pulses with respect to different geographical locations, Climate Dynamics, 34, 997–1013, 2010.

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

Schilt, A., Baumgartner, M., Schwander, J., Buiron, D., Capron, E., Chappellaz, J., Loulergue, L., Schüpbach, S., Spahni, R., Fischer, H., et al.: Atmospheric nitrous oxide during the last 140,000 years, Earth and Planetary Science Letters, 300, 33–43, 2010.

Schulz, M., Berger, W. H., Sarnthein, M., and Grootes, P. M.: Amplitude variations of 1470-year climate oscillations during the last 100,000 years linked to fluctuations of continental ice mass, Geophysical Research Letters, 26, 3385–3388, 1999.

Seager, R. and Battisti, D. S.: Challenges to our understanding of the general circulation: Abrupt climate change, Global Circulation of the Atmosphere, pp. 331–371, 2007.

Shaffer, G., Olsen, S. M., and Bjerrum, C. J.: Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events, Geophysical Research Letters, 31, 2004.

Sidorenko, D., Rackow, T., Jung, T., Semmler, T., Barbi, D., Danilov, S., Dethloff, K., Dorn, W., Fieg, K., Gößling, H. F., et al.: Towards multi-resolution global climate modeling with ECHAM6–FESOM. Part I: model formulation and mean climate, Climate Dynamics, 44, 757–780, 2015.

Sime, L.C., and Stevens, D.P., and Heywood, K.J. and Oliver, K.I.C: A decomposition of the Atlantic Overturning Circulation. Journal of Physical Oceanography, 36, 2253–2270, 2006.

Sime, L. C., Hopcroft, P. O., and Rhodes, R. H.: Impact of abrupt sea ice loss on Greenland water isotopes during the last glacial period, PNAS, 116, 4099–4104, https://doi.org/10.1073/pnas.1807261116, https://www.pnas.org/content/116/10/4099, 2019.

Singarayer, J. S. and Valdes, P. J.: High-latitude climate sensitivity to ice-sheet forcing over the last 120 kyr, Quaternary Science Reviews, 29, 43–55, 2010.

Singh, H. A., Battisti, D. S., and Bitz, C. M.: A heuristic model of Dansgaard–Oeschger cycles. Part I: Description, results, and sensitivity studies, Journal of climate, 27, 4337–4358, 2014.

Stommel, H.: Thermohaline convection with two stable regimes of flow, Tellus, 13, 224–230, 1961.

Stouffer, R. J., Yin, J., Gregory, J., Dixon, K., Spelman, M., Hurlin, W., Weaver, A., Eby, M., Flato, G., Hasumi, H., et al.: Investigating the causes of the response of the thermohaline circulation to past and future climate changes, Journal of Climate, 19, 1365–1387, 2006.

Timmermann, A., Gildor, H., Schulz, M., and Tziperman, E.: Coherent resonant millennial-scale climate oscillations triggered by massive meltwater pulses, Journal of Climate, 16, 2569–2585, 2003.

Valdes, P.: Built for stability, Nature Geoscience, 4, 414–416, 2011.

Vettoretti, G. and Peltier, W. R.: Thermohaline instability and the formation of glacial North Atlantic super polynyas at the onset of Dansgaard-Oeschger warming events, Geophysical Research Letters, 43, 5336–5344, 2016.

Zhang, X. and Prange, M.: Stability of the Atlantic overturning circulation under intermediate (MIS3) and full glacial (LGM) conditions and its relationship with Dansgaard-Oeschger climate variability, Quaternary Science Reviews, 242, 106 443, 2020.

Zhang, X., Lohmann, G., Knorr, G., and Purcell, C.: Abrupt glacial climate shifts controlled by ice sheet changes, Nature, 512, 290–294, 2014.

Zhang, X., Knorr, G., Lohmann, G., and Barker, S.: Abrupt North Atlantic circulation changes in response to gradual CO2 forcing in a glacial climate state, Nature Geoscience, 10, 518–523, 2017.

Dissemination and exploitation of TiPES results

Dissemination activities

Type of dissemination activity	Name of the scientist (institution), title of the presentation, event	Place and date of the event	Estimated budget	Type of Audience	Estimated number of persons reached	Link to Zenodo upload
Participation to a conference	**Irene Malmierca-Vallet (UKRI-BAS), Title: PMIP 2020 conference**	**Virtual meeting, 26-30 October 2020**	**Free**	Scientific Community (higher education, Research)	**100**	
Participation to a conference	**Louise C. Sime (UKRI-BAS) Title: PMIP 2020 conference**	**Virtual meeting, 26-30 October 2020**	**Free**	Scientific Community (higher education, Research)	**100**	
Participation to a workshop	**Irene Malmierca-Vallet (UKRI-BAS), Title: PALSEA (PALeo constraints on SEA level rise) meeting**	**Virtual meeting, 15-16 September 2020**	**Free**	Scientific Community (higher education, Research)	**40**	
Participation to a conference	**Irene Malmierca-Vallet (UKRI-BAS) and Louise C. Sime (UKRI-BAS) Title: QUIGS-IFG meeting on**	**Virtual meeting, 10-12 November 2020**	**Free**	Scientific Community (higher education, Research)	**60**	

	glacial terminations					
Participation to a workshop	**Irene Malmierca-Valelt (UKRI-BAS) Title: TiPES Workshop “Abrupt climate and ecosystem transitions in paleoclimate**	**Virtual meeting, 8-9 October 2020**	**Free**	Scientific Community (higher education, Research)	**100**	
Participation to a workshop	**Louise C. Sime (UKRI-BAS) Title: TiPES Workshop “Abrupt climate and ecosystem transitions in paleoclimate**	**Virtual meeting, 8-9 October 2020**	**Free**	Scientific Community (higher education, Research)	**100**	
Organisation and hosting a meeting	**Irene Malmierca-Valelt (UKRI-BAS) Title: towards a PMIP4/5 DO protocol**	**Online meeting, 9 October 2020**	**Free**	Scientific Community (higher education, Research)	**20**	
Organisation and hosting a meeting	**Irene Malmierca-Valelt (UKRI-BAS) Title: towards a PMIP4/5 DO protocol**	**Online meeting, 15 December 2020**	**Free**	Scientific Community (higher education, Research)	**20**	
Organisation and hosting	**Irene Malmierca-**	**Virtual Workshop, 19th**	**Free**	Scientific Community (higher	**50**	

of a workshop	**Valelt (UKRI-BAS) Title: TiPES Workshop "Dansgaard–Oeschger focussed simulations"**	**February 2021**		education, Research)		

Peer reviewed articles

Title	Authors	Publication	DOI	Is TiPES correctly acknowledged?	How much did you pay for the publication?	Status?	Open Access granted	Comments on embargo time imposed by the publisher	If in Green OA, provide the link where this publication can be found
Sea ice feedbacks influence the isotopic signature of Greenland ice sheet elevation changes: last interglacial HadCM3 simulations	I. Malmierca-Vallet, L.C. Sime, P.J. Valdes and J.C. Tindall.	Climate of the past	https://doi.org/10.5194/cp-16-2485-2020	YES	€1,848.00	Published	Yes	none	

Uptake by the targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is*:*

Y	The general public (PU) is and is made available to the world via CORDIS.
	The project partners, including the Commission services (PP)
	A group specified by the consortium, including the Commission services (RE)
	This reports is confidential, only for members of the consortium, including the Commission services (CO)

ANNEX A – Agenda online meeting, 19th February 2021

Dansgaard-Oeschger events in CMIP6 models (EU-TiPES)

1. **EU TiPES Objectives**
    - **Objective 1-Identify tipping elements (TEs) and their interactions in models and data**
      Multi-model protocol – draft PMIP community manuscript
      Multi-model data synthesis
    - **Objective 2-Provide approaches for the identification and validation of Early Warning Signals**
      Multi-model protocol – draft PMIP community manuscript
    - **Objective 3-Characterise climate response in the presence of Tipping Points (TPs)**
      Multi-model data synthesis

2. **Multi-model data synthesis**
    - Why?
    - Request for details - google spreadsheet:
      https://docs.google.com/spreadsheets/d/1IvHpvIWh7oj5kY-266tJmRaJAf85agejzdHmlwG2yao/edit?usp=sharing
    - How we plan to deal with the data.
    - Discussion.

3. **Multi-model protocol – draft PMIP community manuscript**
    - Why? And why now?
    - Overview of draft on Overleaf and request to contribute:
      https://www.overleaf.com/6167331833cxbzknbdmwpz
    - Summary from those already contributing (Lev Tarasov, Alex Robinson, Sandy Harrison, Kevin Oliver, Guido Vettoretti)
    - Discussion.