SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Modelling Interglacial Climate
Computer Project Account:	Spdklang
Start Year - End Year :	2014 – 2015
Principal Investigator(s)	Peter L. Langen Rasmus A. Pedersen
Affiliation/Address:	Danish Meteorological Institute Lyngbyvej 100 2100 Copenhagen Denmark
Other Researchers (Name/Affiliation):	

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project is a part of the Ph.D. project by Rasmus Anker Pedersen, which aims to investigate the last interglacial climate state using GCM simulations with EC-Earth. The original version of the model has been expanded with a module that allows for orbital changes, and the model can now be used for paleoclimate simulations. The main experiment is a simulation of the last interglacial climate (the Eemian, 125,000 years ago), and a pre-industrial climate simulation (year 1850) is used as control climate. These have been the basis for a suite of experiments with an atmosphere-only setup of the model aiming to separate the direct impact of the insolation change from the secondary impact of changed sea surface conditions (i.e. the sea surface temperature and the sea ice anomalies).

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

In the initial stage, implementation of the orbital changes into EC-Earth ver 2 proved more difficult than first anticipated, which delayed the progress of the project. The HPC change and our related change of model version required some time and offered some technical challenges, which were solved in collaboration with colleagues from Stockholm. After successful setup of the new model version on CCA, the simulations proved to be more computationally expensive than running the old model version on C2A. Thus, we (successfully) applied for additional resources in February 2015.

The new version of the model was suffering from occasional numerical problems in the ocean component. We found an acceptable solution to this, but it required some effort and computational time to test potential ways to overcome these issues. The same problem is occurring on other systems too and is not related to our setup or CCA specifically.

The model consists of three components: atmosphere, ocean, and coupler – the latter requiring very few resources compared to the others. Running on few nodes on CCA results in several idle CPUs, as the coupler occupies a full node while only few CPUs are needed. An alternative setup that allows one node to be shared across executables would thus reduce the computational cost of running climate models like EC-Earth.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application procedure was smooth and easy.

The aim of the progress reports could be communicated more clearly – e.g. regarding the relative weight of scientific and technical details in the report.

The support during the project period has been excellent, both in relation to application for additional resources and in terms of actual technical support.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

The following summary consists of excerpts from the Ph.D. thesis by Rasmus A. Pedersen which is based on the papers listed below. The two papers describe the simulated last interglacial climate: The first paper presents the global changes and the key mechanisms, while the second focuses on the Greenland ice sheet and comparison to ice core reconstructions.

Experimental design

The model used for this study is the EC-Earth global climate model in the most recent version 3.1. EC-Earth consists of the IFS atmospheric model (cycle 36r4, ECMWF) and the NEMO ocean model (version 3.3.1) including the LIM3 sea ice model. The atmospheric model has a T159 spectral resolution (roughly 1.125° × 1.125° horizontal resolution) with 62 layers in the vertical. The NEMO ocean model is running on a tripolar ORCA grid with a horizontal resolution of approximately 1 degree and has 46 levels.

In order to allow paleoclimate simulation, the model has been expanded with an option to modify the insolation according to any given orbital configuration. The insolation is internally calculated following Berger (1978) using the same code modification as Muschitiello et al. (2015).

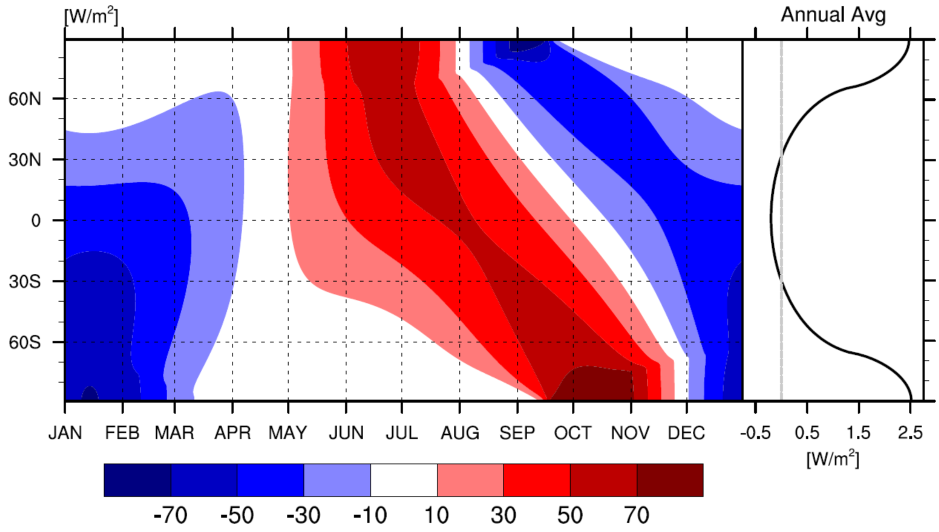

Figure 1 *Insolation anomalies [W m^{-2}] in LIG compared to PI. Left panel displays zonal anomalies through the year, right panel the zonal annual mean. Time labels on the left panel mark the beginning of each month.*

The main experiment is a snapshot simulation of the last interglacial period at 125 ka (LIG). We focus on 125 ka, when high northern latitude temperatures are near peak LIG warming (NEEM community members, 2013; Bakker et al., 2013) and the sea level stabilizing (Masson-Delmotte et al., 2013; Kopp et al., 2013) indicating that ice sheet retreat and related freshwater flux into the ocean is diminishing. The simulation is only forced by insolation changes and changes in the atmospheric gas composition, while the ice sheets and vegetation are kept unchanged. The last interglacial climate is compared to a pre-industrial control simulation (PI), forced by insolation and atmospheric components from 1850. The insolation anomaly is shown in Figure 1.

Table 1 Boundary conditions for AGCM experiments.

Experiment	Insolation and GHGs	SSTs and sea ice
iP+oP	Pre-industrial	Pre-industrial
iL+oL	Last interglacial	Last interglacial
iL+oP	Last interglacial	Pre-industrial
iP+oL	Pre-industrial	Last interglacial

To further investigate the dynamics behind the last interglacial warming, we have designed a series of simulations in an atmosphere-only version of the model (AGCM) based on the two coupled model experiments. We aim to disentangle and compare the direct impact of the insolation changes and the secondary impact arising from changed sea surface temperature and sea ice conditions. Accordingly, two hybrid experiments have been designed based on the results from the coupled simulations. The first ("iL+oP") is forced by LIG insolation (and GHGs) and PI SST and sea ice conditions, while the other ("iP+oL") conversely is forced by PI insolation and LIG SST and sea ice conditions. These simulations allow for an assessment of the impact of the insolation change without the contribution from the oceanic changes, and vice versa. The experiments are described in Table 1.

Results

The coupled simulation yields an annual mean global warming of approximately 0.5°C compared to pre-industrial conditions. The Arctic region shows a warming of more than 2°C in all seasons. The seasonal mean near-surface air temperature anomalies are presented in Figure 2 alongside the zonal mean insolation changes. Comparison of the insolation forcing and the temperature response reveals that the overall response over the continents follows the annual cycle of the insolation anomalies. Nevertheless, some regions stand out with temperature response that cannot be attributed to a direct warming (cooling) from increased (decreased) insolation: High northern latitudes exhibit warming, and the African and Indian monsoon regions exhibit cooling throughout the year.

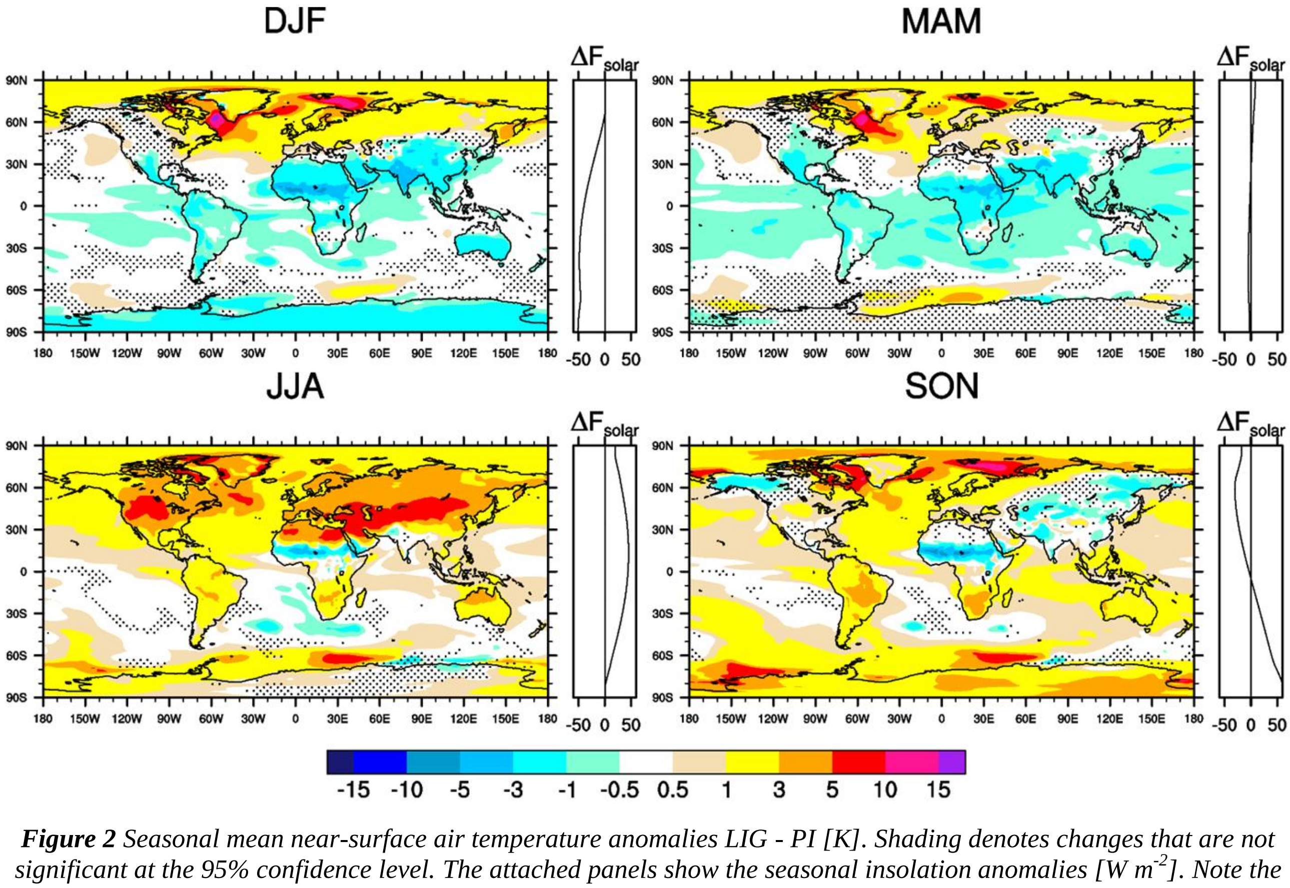

Figure 2 *Seasonal mean near-surface air temperature anomalies LIG - PI [K]. Shading denotes changes that are not significant at the 95% confidence level. The attached panels show the seasonal insolation anomalies [W m^{-2}]. Note the irregular spacing of the color bar.*

The series of AGCM simulations is designed to investigate the mechanisms behind the simulated changes, and compare the direct and indirect effects of the insolation anomalies. Figure 3 displays the seasonal mean near-surface air temperature anomalies relative to iP+oP (PI conditions) in the three simulations: iL+oL (LIG conditions), iL+oP (LIG insolation, PI SST and sea ice), and iP+oL

(PI insolation, LIG SST and sea ice). The response in iL+oP is obviously limited to the continents (and sea ice covered areas), as the near-surface air temperature over the ocean is largely determined by the prescribed SSTs. Conversely, the iP+oL experiment reveals that the changed oceanic conditions have impacts across all continents even with unchanged insolation. Hence, the oceanic changes dominate the response at high northern latitudes, including the North Atlantic region and Europe, while the direct insolation impact is more dominant in the tropics.

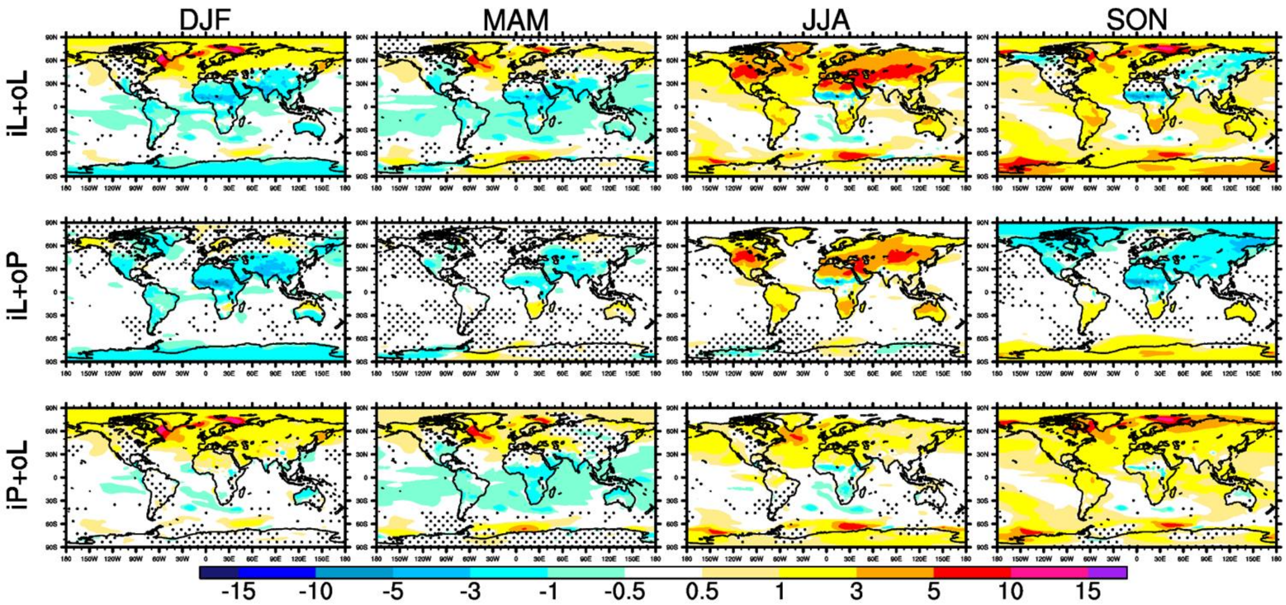

Figure 3 *Seasonal mean warming [K] in the AGCM experiments: iL+oL (LIG conditions; top row), iL+oP (LIG insolation, PI SSTs; middle row), and iP+oL (PI insolation, LIG SSTs; bottom row). All anomalies are relative to iP+oP (PI insolation, PI SSTs). Black shading marks anomalies that are not statistically significant at the 95% confidence level. Note the irregular spacing of the color bar*

As evident from Figure 3, the continental warming during the insolation maximum in Northern Hemisphere summer (JJA) is dominated by the direct impact of the insolation (the iL+oP experiment). The oceanic changes (iP+oL) do, however, contribute to temperature increase over high northern latitudes and over Europe. The oceanic conditions appear to dominate the response over the same regions during fall and winter, where widespread warming occurs despite the lower insolation. Part of this all-year warming in the high northern latitudes, especially in the North Atlantic region including Greenland and Europe, can be ascribed to an AMOC increase and a seasonal memory of sea ice retreat. In these regions, the oceanic changes more than outweigh the direct impact of the fall (SON) insolation decrease.

Figure 4 focuses on Greenland, and shows warming in all seasons in the full Eemian experiment, iL+oL. The peak warming is generally found in the coastal regions, but the central, high altitude Summit region warms more than 2 K in both summer (JJA) and winter (DJF).

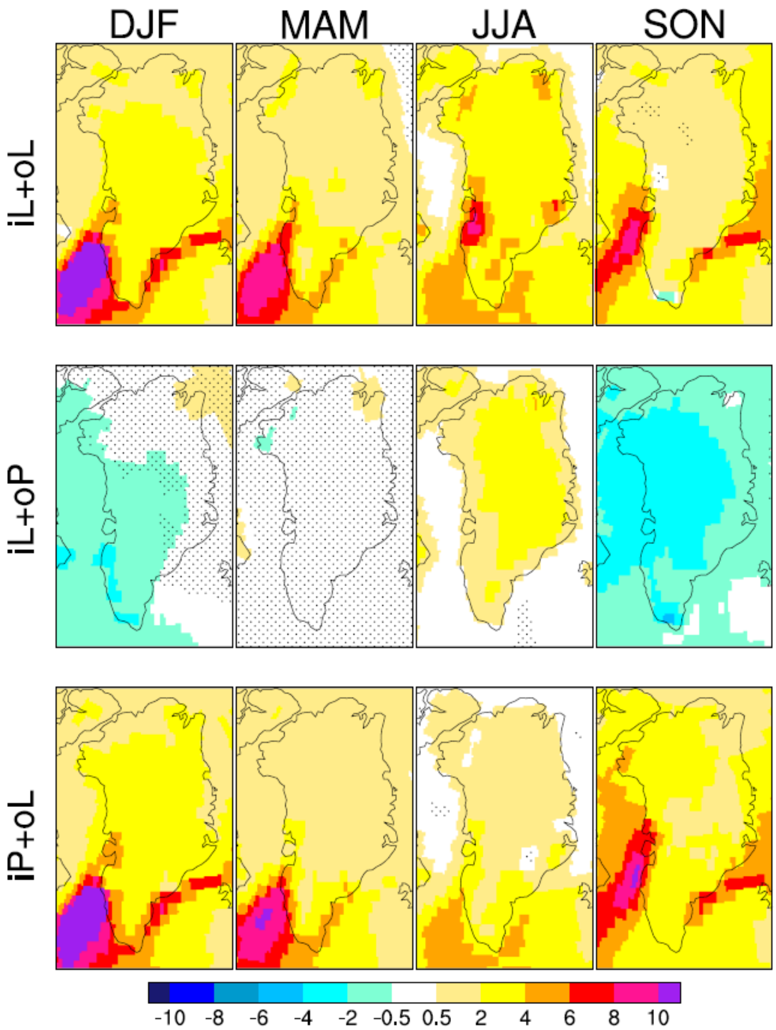

Figure 4 *Seasonal mean near-surface temperature anomalies [K] compared to iP+oP in the three experiments: iL+oL (top), iL+oP (middle), and iP+oL (bottom). Black dotted shading marks anomalies that are not statistically significant at the 95 % level.*

The hybrid simulations, iP+oL and iL+oP, exhibit very different annual cycles of warming. Following the insolation changes, iL+oP only shows warming during summer covering the entire Greenland, whereas fall (SON) and winter exhibit cooling; the winter cooling is limited to the southwestern part of Greenland. A small area in northwestern Greenland is warming through winter and spring (MAM).

The oceanic changes in iP+oL cause warming over entire Greenland, peaking in the colder seasons fall and winter. Warming due to sea ice loss peaks during winter, following increased turbulent heat flux from the ocean surface where the insulating sea ice layer is lost [in agreement with previous studies of sea ice loss (Pedersen et al., 2016a; Vihma, 2014)]. Additional SST increase from ocean circulation changes and increased summertime shortwave absorption expands the regions with positive turbulent heat flux anomalies beyond the areas of sea ice loss. The total impact of the oceanic changes thus counters the direct impact of the insolation during fall and winter, resulting in the all-year warming observed in iL+oL, which closely resembles the sum of the iP+oL and iL+oP.

Conclusions

The simulated LIG climate revealed an annual mean temperature response resembling the multi-model mean from Lunt et al. (2013). While the spatial pattern is similar, the annual mean warming of 0.5 K is high compared to the multi-model ensemble. A prominent feature of the annual mean temperature pattern is a cooling over the tropical monsoon regions in India and northern Africa. The cooling is related to an intensified monsoon leading to increased precipitation and cloud cover. The most pronounced warming is simulated in the North Atlantic region in response to an increased AMOC and a northward retreat of the sea ice edge. The simulated North Atlantic warming shows fair agreement with proxy records, but does not capture the regional cooling suggested by the temperature reconstructions. Correlation and regression estimates suggest that the AMOC increase alone cannot explain the model-data discrepancy.

A series of AGCM simulations was used to separate the direct impact of the insolation and the indirect impact of changed sea surface conditions. These experiments revealed that the monsoon response was driven by the insolation, while the oceanic changes were important for the mid- to high northern latitude warming – especially in the Arctic, where the sea ice loss and SST increase prolongs the impact of the summertime forcing resulting in an all-year warming.

The simulated last interglacial climate underestimates the warming on Greenland compared to reconstructions from the NEEM ice core (NEEM community members 2013). The hybrid AGCM experiments reveals that the largest contribution to GrIS warming is related to the changed SST and sea ice conditions. Estimates of the precipitation-weighted temperature, which accounts for changes in precipitation-seasonality, show that the direct impact of insolation and the indirect impact of oceanic changes would have comparable impacts on the warming signal in the NEEM ice core record.

References

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Muschitiello, F., Q. Zhang, H. S. Sundqvist, F. J. Davies, and H. Renssen, Arctic climate response to the termination of the African Humid Period, Quaternary Science Reviews, 125, 91–97, doi:10.1016/j.quascirev.2015.08.012, 2015.

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Pedersen, R. A., I. Cvijanovic, P. L. Langen, and B. M. Vinther, The Impact of Regional Arctic Sea Ice Loss on Atmospheric Circulation and the NAO, Journal of Climate, 29 (2), 889–902, doi:10.1175/JCLI-D-15-0315.1, 2016.

Vihma, T., Effects of Arctic Sea Ice Decline onWeather and Climate: A Review, Surveys in Geophysics, 35 (5), 1175–1214, doi:10.1007/s10712-014-9284-0, 2014.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The results from this project will be further used to assess the Greenland ice sheet response to the simulated Eemian climate.

List of publications/reports from the project with complete references

Pedersen, R. A., Modelling Interglacial Climate – investigating the mechanisms of a warming climate, Ph.D. thesis, University of Copenhagen, May 2016

Pedersen, R. A., P. L. Langen, B. M. Vinther, The last interglacial climate - comparing direct and indirect impacts of insolation changes, Climate Dynamics (in review), 2016

Pedersen, R. A., P. L. Langen, B. M. Vinther, Greenland warming during the last interglacial: the relative importance of insolation and oceanic changes, Climate of the Past Discussions, 2016

Pedersen, R. A., P. L. Langen, B. M. Vinther, The last interglacial climate in EC-Earth – comparing the direct and indirect impacts of the insolation changes, Poster presentation, Geophysical Research Abstracts, Vol. 18, EGU2016-13881, EGU General Assembly 2016

Pedersen, R. A., R. Mottram, P. Thejll, S. Davies, H. Lamb, and H. Roberts, Can an Earth System Model Reproduce the Palaeo-Climate Proxy Record in eastern Africa during the Eemian?, Poster presentation, Geophysical Research Abstracts, Vol. 18, EGU2016-15088, EGU General Assembly 2016