Barcelona Supercomputing Center
Centro Nacional de Supercomputación

RES RED ESPAÑOLA DE SUPERCOMPUTACIÓN

AECT-2017-2-0018 Impact of increased horizontal resolution on processes underlying climate variability and change

1. General Information

Activity Id
AECT-2017-2-0018

Previous Activity Id
AECT-2016-3-0008

a) Activity Title
Impact of increased horizontal resolution on processes underlying climate variability and change

b) Area
Astronomy, Space and Earth Sciences

2. Results of this activity from the previous application periods

a) Description of the results obtained during the previous periods
In the first period of this activity we utilized the state-of-the-art Nucleus for European Modelling of the Ocean model version 3.3 (NEMO3.3, Madec 2008) with the embedded Louvain-la-Neuve sea ice model version 3 (LIM3, Vancoppenolle et al. 2009). This ocean-and-sea-ice general circulation model (OGCM) was forced by the DFS5.2 surface forcing fields (Dussin et al. 2016) following the bulk formulae of Large and Yeager (2004) in ORCA1L75 (nominal 1deg horizontal resolution) and ORCA025L75 (nominal 0.25deg horizontal resolution) configurations (both having 75 vertical levels). Our numerical system was initialized on 1 January 1960 from ensemble-mean of the ECMWF's Ocean Reanalysis System 4 (ORAS4, Balmaseda et al. 2013) and the associate ensemble-mean sea ice reconstruction produced with the same OGCM through the methodology described in Guemas et al. (2014). Preliminary analysis show a number of interesting differences between ORCA1 and ORCA025 resolutions in the North Atlantic circulation and the structure of Arctic sea ice cover. The Atlantic meridional overturning circulation becomes stronger and delivers more ocean heat transport into the Arctic with important impact on the variability and change of sea ice cover there (particularly in boreal winter). The produced surface-forced ocean-and-sea-ice climate simulations are critical for comparison with fully coupled climate simulations that will be produced in the next period of this activity because dynamical coupling with an atmospheric general circulation model enables two-way coupling and feedbacks that are suppressed in surface-forced OGCM simulations. In other words, the

impact of this increase in horizontal resolution will be likely more evident in different climate components and regions of interests around the globe.

b) List of publications, communications in conferences, presentations, patents, etc, resulted in previous periods of this Activity

3. Research Project Description

a) Specific Activity proposed

In the third phase of Coupled Model Intercomparison Project (CMIP3) typical horizontal resolution was 250 km in the atmosphere and 1.5 degree in the ocean, while seven years later in CMIP5 this has only increased to typically 150 km and 1 degree. Higher resolution simulations, with at least 50 km in the atmosphere and 0.25 degree in the ocean, have only been performed at a relatively few research and operational centers. They show a promising improvements in the simulation of aspects of the climate system such as El Niño Southern Oscillation (ENSO) (Shaffery et al., 2009; Masson et al., 2012), the Gulf Stream (Kirtman et al., 2012) and its influence on the atmosphere (Kuwano-Yoshida et al., 2010; Small et al., 2014), the global water cycle (Demory et al., 2014), snow cover (Kapnick and Delworth 2013), and Atlantic ITCZ (Doi et al., 2012).

In the spirit of the High Resolution Model Intercomparison Project (HighResMIP: Haarsma et al. 2016), formulated in the framework of CMIP6, this RES activity will explore the benefit of increased resolution for the fidelity of historical climate variability and change on global and regional spatial scales. More precisely, we examine whether increase of horizontal resolution alone can generate a better simulation of physical processes critical for selected aspects of regional climate with EC-Earth3 coupled climate model and its ocean-sea-ice component that have not been the subject of such targeted investigation so far.

We will perform process-level assessment of elements of the North Atlantic, Arctic and European climate in the produced model outputs. The focus is on the 1960-2015 period with high-quality observations to support study of selected processes aiming to determine reasons for potentially better capturing small-scale and consequently large-scale phenomena with increasing horizontal resolution. The novel process understanding arising from this study will be potentially critical for developing schemes or error correction methods that could possibly compensate for absence of a range of processes not resolved in lower resolution models. This two-period activity will utilize a HPC-intense state-of-the-art ocean-sea-ice GCM (OGCM) and the associated coupled climate GCM (CGCM) having this OGCM coupled to also comprehensive atmosphere-land GCM (AGCM) with two different horizontal resolutions in OGCM and AGCM.

In the first period of this activity we produced two forced OGCM 1960-2015 historical simulations at ORCA1L75 (nominal 1deg horizontal resolution) and ORCA025L75 (nominal 0.25deg horizontal resolution) configurations (both having 75 vertical levels).

In the next (2nd) period of proposed activity we will use the EC-Earth CGCM (Hazeleger et al., 2010, 2012) version 3.1. It incorporates as the AGCM the European Centre for Medium-Range Weather Forecasts' Integrated Forecasting System (IFS) with the standard T255 and high T511 horizontal resolutions (both having 91 vertical layers). The H-TESSEL land surface component, with 4 active soil layers, is also part of IFS. Our EC-Earth3.1 also includes NEMO3.3-LIM3 OGCM with standard ORCA1L75 and high-resolution ORCA025L75 grids. The IFS-H-TESSEL and NEMO3.3-LIM3 models are globally coupled through the OASIS v3 coupler without flux adjustment. The system will be initialized on 1 January 1960 same as the OGCM in the first part of activity and the atmospheric component will be initialized from ERA-40 reanalysis (Uppala et al. 2005) and forced with the short-wave radiation flux at the top of the atmosphere and observed greenhouse gasses and aerosols.

The produce model outputs will enable us to investigate potential improvements in reconstructions of historical climate variability and change due to an increase of horizontal resolution in ocean and sea ice components as well as due to the coupled climate feedbacks (that are not present in the forced OGCM in the first period). We will perform new process study of scale interactions in the ocean, atmosphere and sea ice also utilizing available high-resolution satellite date for validation. We will analyze how potentially improving representation of mesoscale and synoptic processes reduces model biases. This should be possible because increase in horizontal resolution should lead to better resolved eddy activity in the atmosphere, but even more importantly in the ocean (due to much smaller baroclinic Rossby radius of deformation than in the atmosphere, Chelton et al. 1998).

We will examine the ocean state in the North Atlantic and the Arctic sea ice variability and change that is particularly strong in the high north (Stroeve et al., 2012). The principal component analysis (PCA) and K-means clustering will be applied as tools for reduction of dimensionality of model outputs (Wilks 2011, Fuckar et al. 2016). We will also put the scope on the Arctic Oscillation (AO), the dominant mode of internal variability in the mid- and high-latitude atmosphere in the Northern Hemisphere with strong impact on European climate (Thompson and Wallace, 1999).

NEMO-LIM3 and EC-Earth3 with two different horizontal resolutions will be in position to demonstrate if such increase in horizontal resolution (while keeping as much as possible the same set of subgrid-scale parameterizations) is sufficient to improve representation of physical processes of interest. We will examine if this change will lead to better representation of internal variability of the North Atlantic mixed layer, surface fronts and ocean heat transport, Arctic sea ice cover, and European surface pressure and temperature. The natural variability of these elements of regional climate, and its interaction with the long-term climate change, is typically subdued in coarse-resolution models. Finding how much increased horizontal resolution improves the fidelity of climate processes and large-scale dynamics in EC-Earth family of climate models will contribute to HPC intense effort to advance state-of-the-art climate models. Dynamical forecasting systems with practical regional skill in key variables of interest to users are the ultimate goal of climate model development in research and operational centers around the world.

The numerical climate experiments of this two-period activity and follow-up analysis will enable us to demonstrate the importance, as well as limitations, of specified increase in horizontal resolution in ocean, sea ice and atmosphere important for the development and application of EC-Earth climate model. BSC is a member of the EC-Earth consortium which is a multi-institutional research activity brining together climate and computer scientist from 10 European countries (http://www.ec-earth.org/index.php/community/ec-earth-consortium).

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Doi T, et al.: Biases in the Atlantic ITCZ in seasonal-to-interannual variations for a coarse- and a high-resolution coupled climate model, J. Climate, 25, 50 5494–5511, 2012.
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Haarsma RJ, Roberts M, Vidale PL, Senior CA, Bellucci A, Bao Q, Chang P, Corti S, Fuckar NS, Guemas V., et al.: High Resolution Model Intercomparison Project (HighResMIP), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-66, in review, 2016.
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Shaffrey LC, et al.: U.K. HiGEM: the new U.K. High-Resolution Global Environment Model-model description and basic evaluation, J. Climate, 22, 1861-1896, 2009.
Small RJ, et al.: The Benguela upwelling 20 system: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model, J. Climate, 28, 9409-9432, 2015.
Stroeve JC, et al.: Arctic sea ice decline: Faster than forecast. Clim. Change 110(3–4):1005–1027, 2012.
Thompson DWJ and Wallace JM: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. Geophys Res Lett 25:1297–1300, 1998.
Uppala SM, et al.: The ERA-40 re-analysis. Q.J.R. Meteorol. Soc., 131, 2961-3012, 2005.
Vancoppenolle M, et al.: Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation. Ocean Modell., 27, 33–53, 2009.
Wilks D: Statistical methods in the atmospheric sciences, 3rd ed. Academic Press, London, 2011.

b) Computational algorithms and codes outline

EC-Earth3.1 has three key elements: IFS (with H-TESSEL), NEMO3.3 (with LIM3) and OASIS3. We have to configure and build separate executable for each one of them. IFS and NEMO3 fully support a parallel environment, while OASIS3 coupler supports a pseudo-parallel environment. OASIS3 requires Cray pointers. For IFS there is a possibility to activate an OpenMP switch but in this case the implemented MPI should be thread-safe. IFS generates the output in GRIB format and NEMO3 in NetCDF.

For configuring and building the model executable, GNU make 3.81 or 3.81+, FORTRAN 77/90/95 complaint compiler with preprocessing capabilities and NetCDF4 deployed with HDF5 and SZIP are needed. A newly designed tool for automatic build configuration called "ec-conf" can be used. This useful tool requires Python 2.4.3 or 2.4.3+ (although it does not work yet with Python 3.0+). For NEMO3, the FCM bash and perl mechanism is essential, as it is the I/O GRIB_API 1.9.9 or 1.9.9+ and GRIBEX 370 mechanism are needed for IFS. To test the model with the run scripts, GNU date (64-bit) is also required.

EC-Earth3.1 and NEMO3.3 are available in two configurations. We use the standard configuration of T255-ORCA1L which corresponds to a spatial resolution of 80 km in the atmosphere and 100 km in the ocean, and the high resolution configuration of T511-ORCA025, which corresponds to 40 km in the atmosphere and 30 km in the ocean. We also plan to perform ocean-only NEMO3.3 experiments in the standard configuration of ORCA1 and high-resolution ORCA025. In order to store sources and initial data, the experiments require at least about 100 GB of disk space for each release.

Previously performed benchmarking inthe EC-Earth 3.1 version suggest that, taking into account the average load of the Marenostrum queues, optimum performance is obtained when using 502 cores in the standard resolution configuration, and 1706 cores in the high resolution configuration. For the ocean-only and atmosphere-only configurations in the standard resolution, optimum performance is obtained when using 96 and 384 cores, respectively. With the aforementioned number of cores, these configurations run faster than previous experiments at Marenostrum but still remain scalable. The size of the generated output per month of simulation is 2 and 9 GB for the coupled standard and high-resolution configuration, and 1 GB for the uncoupled configurations.

4. Software and Numerical Libraries

Software components that the project team requires for the activity.

a) Applications + Libraries

BLAS, FFTW, HDF5, LAPACK, NETCDF, R, SCALAPACK, OPENMPI, UDUNITS, NCO

b) Compilers and Development Tools

GCC, TOTALVIEW, INTEL

c) Utilities + Parallel Debuggers and Performance Analysis Tools

CMAKE, PERL, PYTHON, VALGRIND, NCVIEW, NCL, AUTOCONF

d) Other requested software

GRIB_API, CDFTOOLS v2

e) Proprietary software

5. Research Team Description

a) Personal Data

Name of Team Leader Neven Stjepan Fuckar
Institution Barcelona Suprecomputing Center, Earth Sciences Department
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Phone +34-934-13-76-78
Nationality Croatia

b) The employment contract of the activity leader with the research organisation is valid at least 3 months after the end of the allocation period.

Yes

c) Curriculum Vitae of the Team Leader

The scientist leading this proposal, Dr. Neven Stjepan Fuckar, is a Juan de la Cierva Cierva-incorporacion fellow in the Climate Prediction Group within the Earth Sciences Department, directed by ICREA Research Professor Francisco J. Doblas-Reyes, at the Barcelona Supercomputing Center – Centro Nacional de Supercomputacion (BSC-CNS).

He obtained a Ph.D. in Atmospheric and Oceanic Sciences at the Princeton Unversity, Princeton, NJ, USA in 2010, while doing his research with ocean and coupled climate general circulation models at the NOAA Geophysical Fluid Dynamics laboratory in Princeton. After completion of Ph.D. under the supervision of Prof. Geoffrey K. Vallis Dr. Fuckar continued his research in climate dynamics and prediction at the International Pacific Research Center at the University of Hawaii, Honolulu, HI, USA, working with Prof. Shang-Ping Xie. In 2013 Dr. Fuckar moved to Barcelona to work with Dr. Virginie Guemas and Prof. Doblas-Reyes on Arctic and global climate dynamics and prediction with specific interest in historical reconstruction and improvements of climate predictions through development of various initialization, and bias correction and statistical methods.

As early carrer scientist he has published 16 publications that so far garnered 521 citation on Google scholar (https://scholar.google.com/citations?user=RXf04_QAAAAJ&hl=es) and participated in the USA in 4 research projects founded by NOAA, in Spain - PICA-ICE from MINECO, EU FP7 SPECS, H2020 PRIMAVER and H2020 APPLICATE research projects and 9 RES (of which he led 3) projects performed at BSC. Dr Fuckar gave 4 different classes at Princeton University, lectured at UPC, UAB and IS-ENES 2014 and 2016 summer schools at BSC and FMI, presented his research at more than 30 international conferences (e.g., EGU meetings, AGU meeting, Ocean Science meetings, AOFD conference, etc.) and gave talks at many universities, research and operational institutions (e.g., MIT, Yale University, University of Hawaii, Columbia University, MPI-Meteorology, ECMWF, NASA GISS, University of Reading, Stockholm University, ..). He is the convener of EGU 2015, EGU 2016 and EGU 2017 sessions on Polar Climate Predictability and Prediction.

The members of Earth Sciences Department at BSC-CNS participating in this activity have extensive and diverse knowledge and experience with climate modeling, and they have already successfully completed numerous previous activities with the NEMO and EC-Earth coupled climate system on MareNostrum3.

d) Names of other researchers involved in this activity

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e) Relevant publications

e) Relevant publications

Doblas-Reyes, F.J., I. Andreu-Burillo, Y. Chikamoto, J. Garcia-Serrano, V. Guemas, M. Kimoto, T. Mochizuki, L.R.L. Rodrigues and G.J. van Oldenborgh (2013). Initialized near-term regional climate change prediction. Nature Communications, 4, 1715, doi:10.1038/ncomms2704

Frierson, D. M. W., Y.-T. Hwang, N. S. Fuckar, R. Seager, S. M. Kang, A. Donohoe, E. A. Maroon, X. Liu, and D. S. Battisti (2013), Contribution of ocean overturning circulation to tropical rainfall peak in the Northern Hemisphere, Nature Geosciences, 6(10), 1–5.

Fuckar, N. S., Guemas, V., Johnson, N. C., Massonnet, F., and Doblas-Reyes, F. J. (2015) Clusters of interannual sea ice variability in the northern hemisphere (2016), Clim. Dynam., doi: 10.1007/s00382-015-15 2917-2

Guemas, V., Blanchard-Wrigglesworth, E., Chevallier, M., Day, J. J., Deque, M., Doblas-Reyes, F. J., Fuckar, N. S., Germe, A., Hawkins, E., Keeley, S., Koenigk, T., Salas y Melia, D. and Tietsche, S. (2014), A review on Arctic sea-ice predictability and prediction on seasonal to decadal time-scales. Q.J.R. Meteorol. Soc.. doi: 10.1002/qj.2401

RJ Haarsma, M Roberts, PL Vidale, CA Senior, A Bellucci, S Corti, NS Fuckar, V Guemas, J von Hardenberg, W Hazeleger, C Kodama, T Koenigk, LR Leung, J Lu, JJ Luo, J Mao, MS Mizielinski, R Mizuta, P Nobre, M Satoh, E Scoccimarro, T Semmler, J Small, JS von Storch (2016), High Resolution Model Intercomparison Project (HighResMIP), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-66

6. Resources

a) Estimated resources required for the Activity for the current Application Period

Requested machine MareNostrum 4 ((Technical description to be confirmed)
Interprocess communication Null

Typical Job Run				
Number of processors needed for each job		1706.00		
Estimated number of jobs to submit		110.00		
Average job durations (hours) per job		6.00		
Total memory used by the job (GBytes)		64.00		
Largest Job Run				
Number of processors needed for each job		1706.00		
Estimated number of jobs to submit		110.00		
Average job durations (hours) per job		6.00		
Total memory used by the job (GBytes)		64.00		
Total disk space (Gigabytes)	**Minimum**	1500.00	**Desirable**	2500.00
Total scratch space (Gigabytes)	**Minimum**	15000.00	**Desirable**	20000.00
Total tape space (Gigabytes)	**Minimum**	0.00	**Desirable**	0.00

Total Requested time (Thousands of hours) 1200.00

If this activity is asking for more than 2Million CPU hours, you need to justify the amount of resources requested for the activity (max 1000 characters)

INFORMATION: The estimated cost of the requested hours, considering only the electricity cost, is 13716 euros.

The required resources have to be executed in the selected machines, the other architectures do not fit the requirements to execute the proposal.
** this option implies that if no hours in this machine/these machines are available, the acces committee will reject the full application

7. Abstract for publication

A high-resolution climate model offers substantial potential for reconstruction and explaining observed climate variability and change with better fidelity than coarse resolution equivalent. We examine the impact of an increase in horizontal resolution and dynamical coupling between the atmosphere and ocean-sea-ice on representation of selected physical processes in a state-of-the-art ocean-sea-ice model (NEMO-LIM3) and the associated coupled climate model (EC-Earth3). Potential improvements of dynamics at the process level in the North Atlantic, Arctic sea ice cover and the lower troposphere due to stronger eddy activity (i.e. internal variability) should boost our confidence in EC-Earth3. We aim to advance development of seasonal-to-decadal climate predictions and climate projections for the benefit of a wide spectrum of stakeholders.

8. Contact with CURES during last year

Information about the RES Users Committee (CURES).

a) User has contacted the CURES during last year

No

b) If not, indicate why you have not contacted the CURES

Because I contacted other RES representatives (e.g. Access Committee or User Support).