HighResMIP CMIP6 endorsement application

Name of MIP
HighResMIP

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Websites
http://www.wcrp-climate.org/index.php/modelling-wgcm-mip-catalogue/modelling-wgcm-mips/429-wgcm-hiresmip

https://dev.knmi.nl/projects/highresmip/wiki

Goal of HighResMIP
For the first time, we want to assess the robustness of improvements in the representation of important climate processes with "weather-resolving" global model resolutions (~25km or finer), within a simplified framework using the physical climate system with constrained aerosol forcing.
Recent simulations with global high-resolution climate models have demonstrated the added value of enhanced resolution compared to the output from models in the CMIP3 and CMIP5 archive. They showed significant improvement in the simulation of aspects of the large scale circulation such as such as El Niño Southern Oscillation (ENSO) (Shaffrey et al 2009), Tropical Instability Waves (Roberts et al 2009), the Gulf Stream and its influence on the atmosphere (Chassignet and Marshall 2008; Kuwano-Yoshida et al 2010), the global water cycle (Demory et al. 2014), extra-tropical cyclones and storm tracks (Hodges et al. 2011) and Euro-Atlantic blocking (Jung et al 2012). In addition, the increased resolution enables more realistic simulation of small scale phenomena with potentially severe impacts such as tropical cyclones (Zhao et al. 2009), tropical-extratropical interactions (Haarsma et al. 2013) and polar lows. Other phenomena that are sensitive to increasing resolution are ocean mixing, sea-ice dynamics and monsoons. The improved simulation of climate also results in better representation of extreme events such as heat waves, droughts and floods.

The requirement for a multitude of multi-centennial simulations, including poorly constrained Earth System processes and feedbacks, has meant that model resolution within CMIP has progressed very slowly. In CMIP3 the typical resolution was 250km in the atmosphere and 1.5° in the ocean, while more than seven years later in CMIP5 this had only increased to 150km and 1° respectively. Until now high-resolution simulations have been performed at only a few research centers without overall coordination. Due to the large computer resources needed for these simulations, synergy will be gained if these runs are done in a coordinated way, which enables the construction of a multi-model ensemble (since ensemble size for each model will be limited) with common integration periods, forcing and boundary conditions. The CMIP3 and CMIP5 data bases provide outstanding examples of the success of this approach. The multi-model mean has proven often to be superior to individual models in seasonal and decadal forecasting. Moreover, significant scientific understanding has been gained from analyzing the inter-model spread and attempting to attribute to model formulation.

HighResMIP will coordinate the efforts in the high-resolution modeling community. Joint analysis, based on process-based assessment and seeking to attribute model performance to emerging physical climate processes (without the complications of Earth System feedbacks) and sensitivity of model physics to model resolution, will further highlight the impact of enhanced resolution on the simulated climate. As a result of the widespread impact of resolution on the simulation of the climate, HighResMIP will contribute to all of the five grand challenges of the WCRP, and hence such analysis may begin to reveal at what resolution particular processes can be robustly represented.

The European institutes in Table I are participating in the European H2020 project PRIMAVERA that coordinates the simulation and analyses of high-resolution runs. If HighResMIP is endorsed they will follow that protocol. Presently the following modelling centres have expressed their interest in participating in HighResMIP

- EC-Earth consortium, (KNMI, IC3, SMHI)
- Met. Office, UK
- NCAR, USA
- CMCC, Italy
- GFDL, USA
- CNRM, France
- MRI, Japan
- MPI, Germany
- CPTEC, Brazil
- IAP, China
- CAMS, China
- INM, Russia
- JAMSTEC, Japan
- NICAM, Japan
- BCC, China
- CESS, China
- PNNL, USA

In addition institutes that are not able to undertake the HighResMIP simulations currently due to limited computer resources, such as the ARC Centre of Excellence for Climate System Science (Australia) have expressed their strong interest in analyzing the HighResMIP simulations.

Institution	MO/NCAS/ NOCS	KNMI/SMHI/ IC3/CNR	CERFACS	MPI	CMCC	ECMWF	AWI
Model names	UM / NEMO	ECEarth / NEMO	Arpege / NEMO	ECHAM / MPIOM	CCESM / NEMO	IFS / NEMO	ECHAM/ FESOM
Atmospheric resolution	60-25	T239-T799	T359	T255	25km	T239-T799	T255
Oceanic resolution	¼-1/12^{o}	¼^{o}-1/12^{o}	¼-1/12^{o}	¼-1/10^{o}	¼	¼	¼ - 1/12 spatially variable

Table I: European institutes, together with the models and the resolutions that are committed to HighResMIP (note that the eddy resolving 1/10-1/12˚ ocean may be used for a small subset of simulations).

Proposed Experiments

The main experiments will be divided between Tier 1 and Tier 2, with further optional ideas in Tier 3 .

The Tier 1 experiments will be AMIP runs. A few institutes have already performed high resolution AMIP runs and published their results. These runs will not impose such prohibitively large technical difficulties and it is feasible for a considerable number of institutes to deliver a coordinated and coherent set of experiments.

For the coupled experiments the situation is somewhat different. Although a few institutes already have carried out high resolution coupled simulations, there still remain issues with for instance biases and spin-up. Due to these issues and the large amount of computer resources needed, only a limited number of institutes will be able to afford these coupled simulations, and hence they will be done in Tier 2.

Standard CMIP6 resolution experiments
To evaluate the impact of increased resolution the experiments in Tier 1 and Tier 2 will be repeated with the standard CMIP6 resolution. The experimental set-up and design of the standard resolution experiments will be exactly the same as for the high-resolution runs. This enables the use of HighResMIP simulations for sensitivity studies investigating the impact of resolution.

- **Tier 1**

AMIP runs

Resolution: *minimum 25-50 km at mid-latitudes for high resolution + a standard resolution configuration.*
This resolution is significantly higher than used in CMIP5. Century integrations for this resolution are now feasible.

Periods of integration: *Mid term 1950-2050*
The mid term period is relevant for decision makers, whereas prominent changes in climate and variability will only become more visible at the end of the 21st century. The start year of the integrations is 1950 to cover significant historical changes, and to allow a longer period of assessment than is found in standard AMIP-type simulations (typically 1979-2008).

Forcing: *CMIP6 scenario's*
CMIP6 scenarios that span the range from middle to high end scenarios. For the historical period all forcings natural and anthropogenic will be included.
For optimal comparison between the models aerosol concentrations should be used and not emissions – we plan coordination with HistMIP/RFMIP in order to secure historical aerosol concentrations (or else enough information to allow us to calculate concentrations from aerosol optical properties and number concentrations).

The full details of the forcing datasets and strategy proposed can be found from the WCRP website (http://www.wcrp-climate.org/index.php/modelling-wgcm-mip-catalogue/429-wgcm-hiresmip). In summary, SST and sea-ice from 1950-present will likely be much the same as for standard AMIPII integrations (based on HadISST since this is the only dataset that is long enough), while the future period will use methodologies such as Mizuta et al (2008) but adapted to make a continuous timeseries.

Minimum number of integrations: *1*
Any manageable number is too low for a rigorous estimate of the internal variability. However, because the aim of the high-res protocol is to perform simulations at the highest possible resolution, the ensemble size has to be kept low. By using a strictly common protocol that is followed by many institutes, the effective multi-model ensemble will be much larger, enabling a much wider sampling than previously of the multi-model robustness of resolution impacts. In addition, if models can be proven to be portable, the ensemble size could be increased if other computer resources are available (discussions are already underway with the European PRACE supercomputing infrastructure). Some centers may be able to produce much larger ensembles, enabling a more robust estimate of internal variability.

- **Tier 2**

Coupled runs

The coupled runs will consist of pairs of both scenario (historic for the past) runs and, for comparison, control runs using fixed 1950s forcings. This will allow an evaluation of the model drift in addition to the climate change signal. It may be possible to use the ocean initial condition from pre-existing or already planned spin-up from historic or similar integrations.

Resolution: *Atmosphere same as AMIP-runs. Ocean ~0.25 degree.*
This enables the ocean to have some variability (compared to non-eddy permitting models), particularly in the tropics, and has been shown to change the strength of atmosphere-ocean interactions (Kirtman et al, 2012).

Period of integration:
- *Scenario runs: Same as for AMIP runs*
- *Control runs: Minimal length as AMIP runs.*

Forcing: *Same as for AMIP runs*

Minimum number of integrations: *1 for each of control and historic forcings*
Ideally the ensemble number would be of order 3 simulations for each forcing, to help in evaluating model drift and enabling an improved sampling of internal variability, but this will quickly become very onerous on computing.

Coupling: *Minimal daily coupling between ocean and atmosphere. Preferably more frequent, 3hr or 1hr.*
Ocean-atmosphere interaction occurs on all time scales. With 3hr or 1hr the diurnal time scale can be resolved.

Initial state: Due to limited computer resources an equilibrated initial ocean state is not feasible. Possible solutions to circumvent this are bias correction or the interpolation of an initial state of the low resolution DECK runs. For the latter a prerequisite is that the dynamics of the low- and high resolution ocean model are sufficient similar.

- **Tier 3**

Optional additional simulations to be discussed by interested parties
These could include

1. Extension of the AMIP simulations to 2100 with agreed forcings, to give a stronger signal to noise ratio
2. Additional ensemble members for both AMIP and coupled simulations. Even if these are primarily at the standard resolution, it would enable a better understanding of internal variability, and hence be able to say if the high resolution differs significantly from that distribution.
3. Aqua planet simulations. These idealized simulations facilitate a more straight forward interpretation of the impact of resolution on model physics and dynamical behavior.
4. Switch-on 4xCO2 in coupled models. This will enable assessment of possible changes in climate extremes and in climate sensitivity due to improved resolution which cannot be well simulated by the DECK-counterpart.

Connection with DECK
The DECK simulations will serve as an entry card for the CMIP6-Endorsed MIPS. The DECK experiments are

- AMIP simulations
- Pre-industrial control simulations
- 1%/yr increase in CO2 concentration
- Switch-on 4XCO2

The AMIP DECK simulation with the standard CMIP6 resolution will serve as the entry card for the Tier 1 HighResMIP simulations. For Tier 2 the other three coupled simulations of DECK with the standard CMIP6 simulations will serve as an entry card. This applies also to the CMIP6 Historical simulation which consists of a historical simulation from 1850-2014 using specific forcings consistent with CMIP6.
For the high-resolution simulations the DECK is too expensive in computer resources, but the comparison between the standard resolution simulations within HighResMIP and the DECK simulations will be informative in themselves.

Connection with other MIPS

GMMIP for global monsoons.
There is known sensitivity to monsoon flow and rainfall with model resolution in the West African monsoon, Indian monsoon (particularly via monsoon depressions) and possibly East Asian monsoon. As stated in GMMIP the monsoon rainbands are usually at a maximum width of 200 km. Climate models with low or moderate resolutions are generally unable to realistically reproduce the mean state

and variability of monsoon precipitation for the right reasons. This is partly due to the model resolution. The Tier 1 AMIP runs of HighResMIP will be used in Task-4 of GMMIP to examine the performance of high-resolution models in reproducing both the mean state and year-to-year variability of global monsoons.

SensMIP for parameter sensitivity
It is unclear how much the experimental design in SensMIP and HighResMIP overlap or complement each other. The multi-model high resolution ensemble could give one axis of uncertainty/variability from models, while a corresponding parameter sensitivity study would explore a different axis, but the limited number of parameters proposed to change in SensMIP may limit its use here.

CORDEX and **GGDEX** for downscaling
Collaboration with these will be sought. HighResMIP can provide boundary conditions for downscaling and provide the stimulus to cloud resolving simulations.

OMIP for ocean analysis and initial state
It will be investigated if OMIP can provide the equilibrated ocean initial conditions for the coupled runs and exchange diagnostic/analysis techniques to understand ocean circulation changes at different resolutions.

Grand Challenges
HighResMIP will address the grand challenges of the WCRP in the following way

Clouds, Circulation and Climate Sensitivity (Rank 1)
HighResMIP will address this Grand Challenge in many different ways. The sensitivity of increasing resolution on water vapour loading, cloud formation, circulation characteristics and climate sensitivity will be investigated.

To improve the robustness of our understanding, the multi-model ensemble at different resolutions, together with the longer period AMIP integrations, will allow us to:

(i) link tropospheric circulation to changing patterns of SSTs, land-surface properties, and understanding the role of cloud processes in natural variability
(ii) examine the extent and limits of our understanding of patterns of precipitation
(iii) examine changes in model biases (such as humidity) with resolution, since there are some indications that these may be linked to climate sensitivity

Increasing resolution affects in particular small scale process such as the formation of clouds. Although the formation of clouds has still to be parameterized in the resolution of HighResMIP the dynamical constraints for the formation of clouds, such as the location and magnitude of upwards and downwards motion, as well as moisture availability, are sensitive to resolution. This also applies to the response of the circulation to cloud formation.

Cryosphere in a Changing Climate (Rank 5)
Because in the Tier 1 experiments the sea-ice distribution is prescribed the contribution to this grand challenge is limited. Its main impact will be on the distribution of snow fall and subsequent accumulation and melting of snowpack that affect land surface hydrology. For instance the occurrence of intense polar systems, such as deep polar-lows that are accompanied by abundant snowfall will be better represented with increasing resolution.

In the Tier 2 coupled simulations the historic simulation will affect the growth of sea-ice and the air-sea heat flux, processes that are strongly affected by small scale processes. Here we can study the effect of model resolution on Arctic sea-ice variability, and possible influences on mid-latitude circulation.

Understanding and Predicting Weather and Climate Extremes (Rank 3)
HighResMIP is strongly related to this grand challenge. Increasing resolution of climate models will bring us closer to the ultimate goal of seamless prediction of weather and climate. Extremes mostly occur and are driven by processes on small temporal and spatial scales that are not well resolved by standard CMIP6 climate models. Dynamical down scaling only partially resolves this due to the non-linear interaction between large and small spatial scales and the importance of representing global teleconnection patterns. We aim to improve our understanding of the interaction between global modes of variability (e.g. ENSO, NAO, PDO) and regional climate inter-decadal variability and extremes.

Regional Climate Information (Rank 4)
Regional climate information focuses on smaller scales and extreme events, which are relevant for stakeholders and adaptation strategies. This requires high resolution modeling to provide reliable information. Recent high resolution modeling studies (Di Luca et al. 2012; Bacmeister et al. 2013) and comparisons of CMIP3 and CMIP5 results (Watterson et al. 2014) have demonstrated the added value of increased resolution for regional climate information. Model outputs from HighResMIP could also be used by the regional climate modeling community for comparison of dynamical downscaling and global high resolution approaches and for further downscaling by cloud resolving regional models.

Sea-Level Rise and Regional Impacts (Rank 6)
For Tier 1 simulations there is no contribution to this grand challenge. For Tier 2 the contribution is limited although there is the potential for large contribution. If for instance the deep water formation and MOC response appears to be highly sensitive to resolution than there is a considerable impact on regional sea level rise. In addition resolving the topographic effect at high-resolution should have profound impacts on regional details about the sea level rise that are relevant for policy making and planning.

Changes in Water Availability (Rank 2)
HighResMIP is very relevant to this grand challenge. Resolution affects the hydrological cycle by modifying the land/sea partitioning of precipitation. Increasing resolution in general increases the moisture convergence over land (Demory et al. 2014) although regionally this can be reversed such for instance in Europe during the winter due to changes in the position of the storm track (Van Haren et al. 2014). In addition simulation of extreme precipitation events are highly sensitive to increasing resolution. How robust are these results across the multi-model ensemble? Can higher resolution models help to give insight into inconsistencies between global precipitation and energy balance datasets?

Biospheric forcings and feedbacks (Rank 7)
There is no direct link to this collaboration theme as the biosphere is not explicitly modelled. Because the response of the biosphere depends critically on the accurate simulation of the physical environment there is potential for spin-off studies, for instance by interpreting diagnostic information about vegetation production. Recycling of water is an important aspect of biospheric forcings and feedbacks, and the way that vegetation responds to drying depends on their role in recycling water - given the

small scales of the involved processes this is strongly affected by model resolution.

GEWEX

HighResMIP fits in the GEWEX research focus of "Develop accurate global model formulation of the energy and water budget and demonstrate predictability of their variability and response to climate forcing". Accurate modeling of the energy and water budget is sensitive to the adequate simulation of the energy conversions and phase transitions as well as the transport that occur on small spatial scales.

Overview of the proposed evaluation and analysis

The analysis will focus on the impact of increasing resolution on the simulation of the climate. The robustness of the impact of increasing resolution on the simulation of these phenomena among the different HighResMIP models will be investigated and their response to global warming assessed. One of the primary strengths of the simple experimental design for HighResMIP is that it enables a wide range of process-based analysis –simulation campaigns which included 1-2 models such as UPSCALE (Mizielinski et al. 2014) and Athena (Kinter et al. 2014) already have an extremely active number of analysis projects associated with them and insightful papers.

The increased resolution will enable a better simulation of regional climates. The analysis will therefore also have a focus on regional climate such as for instance Latin America.

The results of the analysis of HighResMIP will be compared with the CMIP6 DECK experiments. Their experimental design, data format and documentation will follow the DECK experiments as far as possible.

The storage and distribution of the high resolution model data is a challenging issue that requires further discussion within HighResMIP. In PRIMAVERA the JASMIN platform will be used for data exchange and as a common analysis platform. Because the resolution of HighResMIP approaches the scales necessary for realistic simulation of weather, daily and sub-daily data will be stored to allow the investigation of weather phenomena including those related to monsoons and tropical climate.

Proposed timing

Start of the experiments: Beginning of 2016
End of the experiments: No fixed date.

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