Response to anonymous referee #1

"Main comments:
1. My main comment is that the current draft does not make a compelling case as why such a comparison is needed and what are the expected scientific benefits. Many are claimed but the current text does not justify them in a clear way."

We simply do not agree with this assertion. There are a large number of references in the manuscript which describe the impact of model resolution in single model or small-scale comparisons, and which also try to ascribe such changes to simulated processes and their representation. This can be extremely difficult using just one model, since it is not possible to discover if it may be caused by particular aspects of that model. The described protocol will, for the first time, enable a systematic evaluation of the impact of model horizontal resolution. The examples of CMIP3 and CMIP5 have demonstrated the tremendous advantages of a common protocol that enables a clear comparison between the models and improved understanding of the underlying physical processes.

"2. For example a major claim is that such a MIP will help model improvements. But I could not find in practice what will this mean, i.e. how the knowledge obtain will inform model development. Increasing the resolution has always been a natural pathway for modelling groups and it is unclear how having this MIP or not will change the related priorities."

We are slightly unsure what you mean here. The manuscript does not claim to help model improvements (please indicate specifically where if you think so) – it simply sets out a common protocol to provide the framework for understanding model differences due to horizontal resolution, and to ascribe these to process representation where possible. It will help to clarify which processes will benefit from increased horizontal resolution and how this will affect the model's climate, natural variability and the response to global warming. This will help in a better understanding of these processes that will ultimately result in improved representation, including in models of lower resolution.

We agree that increasing resolution is a natural pathway for modelling groups. However, an examination of the change in horizontal resolution of many models over the last few CMIP exercises reveals that it is much less emphasized compared to complexity – our aim is to examine whether that is the correct choice or not. The advantage of a common protocol is that the impact for an individual modelling center of their simulations with increased resolution will strongly increase, because their simulation will be analyzed by many researchers and compared with other high resolution simulations. In addition the standardized output following the HighResMIP/CMIP6 protocol will strongly facilitate the analysis. The fact that already 17 centers have expressed their intention to participate in the HighResMIP simulations indicates the strong appeal of a common protocol for high resolution simulations.

"3. Another example is that only horizontal resolution is included in the protocol. This is a very serious shortcoming as many processes depend on both resolutions (horizontal and vertical) such as atmospheric convection or ocean mixing. As quickly alluded to, solving the diurnal cycle over the ocean requires 1m vertical resolution at the top level of the ocean and 2-3 hours coupling time step. I was surprised that this is not a requirement for this MIP."

We agree that the correct representation of physical processes depend on both resolutions. The scaling between horizontal and vertical resolution must obey N/f, where N is the Brunt-Väisälä frequency and f the coriolis parameter. This implies a factor of 100, between horizontal and vertical resolution. This is well satisfied by the model configurations in the HighResMIP group. We therefore focused on the increase in horizontal resolution, which we consider as the most limiting factor for many processes and makes this comparison tractable. From a practical standpoint, changing vertical resolution can be extremely complex (due to many interactions with parameterisations particularly in the atmosphere) and in our opinion more likely to be dependent on individual model choices, and hence does not lend itself to a clean intercomparison (at least at this time). In addition the combination of increased horizontal and vertical resolution would complicate to assign the contribution of each of those. We have added these arguments in the text (line 4-11 page 4.).

"4. The introduction suggests that modes of interannual variability can be analysed in these short simulations, which is not the case for ENSO for example (several centuries are needed). The details given near the end are careful not to include the modes prone to this sampling issue but the introduction should clarify these limits upfront."

This is a good point. We do not want to overstate this and we agree that this should be clarified already in the introduction. This is now discussed in lines 32-35 page 3.

"5. The forcings are going to be different between the CTRL and the HiRes simulations for some model (e.g. aerosols). This is an issue that will prevent a clean comparison. Along the same lines, when changing the resolution one can never have "exactly the same parameters". This limit also renders the comparison less informative."

We agree that with built-in scale dependence of some parameters, one never can have "exactly the same parameters". We also agree that due to interpolation the forcings at different resolutions will be somewhat different (but as close as is currently possible). However, simply because the comparison is not perfect does not lessen the amount we can learn. As long as we can account for these inherent difficulties, we have the opportunity to find out if the impact of enhanced resolution is robust across models, given a common protocol. This has been clearly shown by the analyzes of the already existing high resolution simulations, discussed in the introduction. In addition these obstacles for a clean comparison will likely deviate between the models.

"6. The use of daily SSTs for the AMIP simulation is an issue I believe. As shown by several studies (Wu and Kirtman 2005, 2007, Cassou 2015), the mid-latitudes ocean is forced by the atmosphere, not the other way around. The classical use of smoothed monthly SSTs somewhat mitigates this problem. The use of daily SST requires a much better justification and an analysis that this will not have a impact on extremes over land (adverse impact was shown by Cassou 2015)."

The temporal resolution of SST in AMIP runs is indeed an issue. In AMIP runs the ocean has an infinite heat capacity. This has a deleterious impact on the phase relationships between SSTs, overlying atmosphere, and surface fluxes (Barsugli and Battisti, 1998). This occurs also on monthly time scales as outlined by Sutton and Mathieu (2002). Indeed there is in the mid-latitudes a strong forcing of the ocean by the atmosphere, however, recent studies (Minobe et al., 2008; Kirtman et al, 2012; Parfitt et al., 2015; Ma et al., 2015; O'Reilly et al., 2015) revealed that there is also a significant forcing of atmosphere by the ocean especially along ocean fronts,

with sharp temperature gradients and energetic mesoscale eddy activities that are collocated in the genesis regions of the storm tracks. A correct simulation of these processes requires that the strong SST gradients and mesoscale eddies are resolved. This implies the use of daily data, because due to the strong meandering of the western boundary currents, time averaging will strongly smooth the SST fields. Because we focus in HighResMIP on the impact of horizontal resolution and how this affects the small scale processes we therefore will use daily, 0.25 degree SSTs.

In conclusion we state that due to the fundamental problems with AMIP runs, there is no general preferred time scale for averaging SSTs although for certain aspects and processes of the climate system the problem will somewhat mitigated by time averaging as explained by you. On the other hand time averaging will mask important processes that we hypothesize to be resolution dependent and therefore a focus of HighResMIP. We have added a discussion on the use of daily SSTs on page 8, lines 7-12.

We will make use of the DECK AMIP simulations, as well as our smoothed SST experiment, to better understand the impact of higher resolution and frequency SSTs. Most modeling groups typically use similar SST datasets (OI-SST, ESA CCI, ERA-Interim) for research purposes, particular as model resolution is enhanced, and hence one expected outcome of HighResMIP is an indication of the strengths and weaknesses of such an approach.

"7. Finally the discussion on the benefits of increased resolution is not balanced, and mostly ignores the studies that don't show any impact of resolution, for example on model biases. The role of physical parameterization is not discussed even though it is central. Improving this balance would strengthen the manuscript which currently mostly appears as a manifesto of like-minded people."

We realize that this manuscript is indeed written by researchers that support the idea of the added value of high resolution runs. This is part of how the new CMIP phase is organized along different specialized MIPs to address the great challenges of the WCRP. We subscribe the hypothesis that high resolution simulations will contribute in resolving those challenges. We are fully aware that other researchers may be more skeptical. Only by doing these experiments will we learn if our hypothesis is justified. At this moment there are sufficient centers and researchers that will participate in these experiments of HighResMIP to produce a much more robust understanding of resolution impacts across a multi-model ensemble, and from this evidence and model output the community will be able to draw its own conclusions.

Although we completely agree with the reviewer about the important role of physical parameterization we will not focus on this in the manuscript. The purpose of this GMD paper is to motivate and outline the high resolution simulations, not to give an overview of the causes of model errors. Other GMD papers in this issue will focus on the role of physical parameterizations (e.g. AerChemMIP, C4MIP and RFMIP) and completely ignore the role of horizontal resolution. We think that is fair and combined this issue will provide an overarching view of the different approaches within the scientific community to address the great challenges of the WCRP. To make this clear we have added in the discussion a section about the importance of parameterization and that it will be the central topic in other MIPs on page 17, line 37-41.

Response to anonymous referee #2.

We thank the reviewer for positive evaluation of HighResMIP and the GMD paper describing the rationale and the protocol. Below we will answer in detail the specific comments.

"Section 2: The 3 Tiers are clearly defined but it is not clear whether there is a ranking behind: are Tier 1 experiments a pre-requisite minimum to participate to HiResMIP ?"

This was indeed not specified in the protocol. It was assumed that all centers participating in HighResMIP would at least do the Tier 1 experiments, because these are considered the least demanding. We have made this now explicit, by requiring that the Tier 1 experiments are a pre-requisite to participate to HighResMIP (page 5, line 15). The Tier 1 experiments are considered the core of HighResMIP that would benefit from an as large as possible ensemble. In addition the value of the Tier 2 coupled experiments would be strongly enhanced if they can could be compared directly with the Tier 1 uncoupled experiments.

"How HighResMIP is linked to CMIP6 (sections 2., 4.1 and 4.2) is ambiguous: since the very high resolution are not run under the DECK conditions (4.1), I guess only the standard resolution is supposed to be in CMIP6 and the very high resolution are complementary to CMIP6 but not really part of CMIP6 (in 2. It is said "linked" but in section 4.2 it says HiResMIP as one of the endorsed MIPs)? Please clarify."

Indeed, due to computational limitations, the DECK simulations will not be performed by the high resolution version. The standard resolution version, will however complete the DECK simulations and be part of CMIP6. The high resolution version is considered as a sensitivity experiment with respect to horizontal resolution. This is the overarching scientific question of HighResMIP "What is impact of enhanced horizontal resolution on the model characteristics?". The standard resolution DECK simulations are considered as the entry card for HighResMIP. Because NWP centers often only can perform SST prescribed simulations, they cannot complete the DECK simulations. We still want to offer them the possibility to participate in HighResMIP. The solution as outlined in the manuscript is that they can still participate in HighResMIP but their simulations will only be visible as HighResMIP and not as CMIP6 runs. We have tried to clarify this more in the revised manuscript and hopefully make it less ambiguous by deleting the expression "linked" in sections 2, 4.1 and 4.2

"Section 2, Page 5, second paragraph on Tier 2: coupled runs are only mentioned as an opportunity to understand the role of natural variability but they are also required to investigate future climate change."

Indeed, although a large part of the focus of HighResMIP is on natural variability, the extension of simulations up to 2050 is motivated by exploring the impact of high resolution on future climate. We have added that in the manuscript (page 5, line 18-19).

"Section 2, Page 5, lines 21 to 26: the lack of tuning will most probably be more critical for coupled runs than for atmospheric alone models which are constrained by a fixed SST. This should be mentioned."

We completely agree and have mentioned that now in the manuscript (page 5, line 36-38).

"Section 2, Pages 5 and 6: For clarity I would recommend to put the sections on common forcing fields (2.1, 2.1.1, 2.1.2, 2.1.3) together with the description 3.1 of the Tier 1. For other Tiers, reference to Tier 1 is then sufficient."

Thank you for your suggestion. We prefer, however, the current structure and keep the common forcing fields in a separate section. They are common across the Tiers. Putting them in Tier 1 does not improve the clarity of the manuscript according to us. In addition it is important for the common protocol that the common forcing fields are well discussed. This warrants a separate section.

"There are some redundancies between section 4.2 on links with other MIPs, section 6 on applications and section 7 on analysis plan. I understand the need for some redundancies but I have the feeling the order of arguments could be optimised. For example, it would be clearer to first describe the analysis plan, emphasizing at the same time the related MIPs (eg CORDEX, CFMIP, GMMIP) and some applications related to analyses, and then the list of other potential applications. For the interactions with other MIPS, they could be spread among the analyses and the description of the additional experiments. A table could summarise all these interactions."

We prefer to keep a separate section on the connection with DECK and the other MIPs. This was also required by the WGNM of the WRCP. They want for the different MIPs explicitly the connection. Incorporating them in the analysis plan would according to us dilute this too much and makes the connections less visible.

We agree with your suggestion of re-ordering the analysis plan and the potential applications and have done this. The analysis plan is now section 6 and the additional potential applications of HighResMIP simulations section 7. In addition we have removed issue 1(Extremes), 5(Scale interactions) and 8(Ocean model biases) and transferred the relevant information to the analysis plan. This reduces, according us, significantly the redundancies. In the analysis plan we have now also made clear the links with the different MIPs for the different specific topics.

We decided not to include an extra table as the topics and connections should now be clear from the text.

"Section 5, page 11, on data: In this part, it is not clear whether the plans for the list of variables to be stored is already fixed or not. Please clarify. "

The data and diagnostic plan will be finalized during the boreal summer of 2016. This is added in the text. (Section 5, line 28)

"It would also be good if an order of magnitude of the storage needed could be given."

The approximate numbers of data storage for the different CMIP6 MIP's, including HighResMIP are provided at http://clipc-services.ceda.ac.uk/dreq/tab01_3_3.html. This is now mentioned in the text. (Section 5, line 32)

"What is meant by the "design of CORDEX will be taken into account"?"

We have removed this phrase. Within HighResMIP protocol we do not describe the forcing to CORDEX. This is left to the individual centers.

"What are priorities 1, 2 and 3 ?"

The HighResMIP data request is based on answering the scientific questions we submitted to the CMIP6 panel: **{** HYPERLINK "http://clipc-services.ceda.ac.uk/dreq/u/HighResMIP.html" **}**
We then needed to find a balance between the data needed to answer as many of these questions as possible, against the ability (and willingness) of as many modeling groups as possible to deliver these high volumes of data. This is how we have prioritized the data request – we consider it should be possible for participating groups to produce all of priority 1 data. We have attempted to organize Priority 2 and 3 data in terms of general usefulness and data volume – priority 2 as lower volume and useful for general questions, priority 3 for more specific questions with very high frequency (and possibly shorter period) output.
This has been clarified now in the manuscript.

"Section 6: lines 24-25: Tier 3 experiments are also limited by using atmosphere only models."

We have added this remark in the text (page 16, line 20-21).

"Page 18, the data availability part should not be in this section but rather with section 5."

To put the data availability at the end of the manuscript is a requirement of Geoscientific Model Development.
(see http://www.geoscientific-model development.net/about/code_and_data_policy.html)
We first put it in section 5 as you suggested, but were requested by GMD to transfer it to the end of the article.

Technical comments ————————-

"Page 4, line 11: results rather than representation ?"

Done

"Page 4, lines 30-32: should be more explicit on which resolution."

Done

"Page 5, lines 10-11: the list of model names do not correspond to the list of models used in the references: models MIROC, GFDL, SINTEX-F2 whereas in the references SINTEX-F2, GFDL, Hadley, CESM"

This has been corrected

"Page 5, line 34, please mention explicitly RCP8.5."

Done

"Section 2, Page 5, lines 41-42: the use of a delta to the climatological forcing is not

clear enough."

This has been now been made more clear.

"Page 6, Figure 1: would be good to add 1, OA and A for Tiers 1, 2 and 3 respectively on the graphs."

Also in response to reviewer 3 we have extended the figure caption. The information of this figure should now be clear.

"Page 7, line 20. It would be good to add here that 3 runs are recommended but not mandatory (rather than page 8 lines 40-43)"

This is a good suggestion. We have changed the text accordingly.

"Page 7, line 36-37: unclear. Is it for detection/attribution ?"

This simply states the properties of the HadISST2 data set and the uses it can potentially be put to – using the multiple ensemble members is not part of the protocol so we could remove the last part of the sentence, but we thought it was useful to be noted.

"Page 8, line 6: what is EN4 ?"

EN4 is version 4 of the Met Office Hadley Centre "EN" series of data sets of global quality controlled ocean temperature and salinity profiles and monthly objective analyses, which covers the period 1900 to present (Good et al., 2013). This is now explained in the manuscript.

"Page 8, lines 34-38: has already been said"

We agree that we have already discussed this before but now in a different context we want to note this again. We have adapted the text to make this more clear.

"Section 3.2.1, Page 9, 3.2.4 is the use of EN4 recommended ? not fully clear"

EN4 is now stated to be the recommended method. This will make the multi-model ensemble consistent, and enable a systematic investigation of model drift from initial conditions which we think would be a valuable new contribution to CMIP.

"Page 12, line 12 the European Copernicus Climate Data Store"

Thank you. Indeed the order of the words was wrong. This has been corrected.

"Page 13, line 22: rather the air quality than the aerosol only effect on health ?"

Agree. We have changed the text accordingly.

"Page 13, line 32: very few models will use eddy-permitting ocean. This is misleading."

We agree that agree that most of the HighResMIP models will use eddy permitting (~1/4 degree) and not fully eddy-resolving ocean models. We have modified the text accordingly.

"Table 1: give a reference to "Historic" boundary conditons."

The Historic simulations are part of the DECK and are outlined in Eyering et al. 2016. The reference has been added.

"Tier 2 future add coupled."

Done

Table 9.1:

" what is the standard resolution of NorESM ?" 2 degrees

"missing information for GFDL" *CM3 standard is 200 km*

Response to anonymous referee #3

We thank the reviewer for his/her critical remarks and the positive attitude towards the manuscript.

"My only concern is the lack of a coupled experiment that is likely to have a large signal to noise ratio. An example might be a quadrupling of CO_2 at some point during the 1950s control. A similar experiment is proposed in CMIP6 (albeit from pre-industrial conditions). The role of high ocean resolution in heat uptake could provide some results that may be difficult to tease out of the tier 2 simulations. The computation costs could be relatively modest. For instance, Kuhlbrodt et al. (2015) showed useful results from a 20-year experiment."

This type of experiment was already proposed and discussed within the HighResMIP community. In our original protocol it was omitted mainly because to limit the number of experiments. In response to your remark we have discussed this option again and we have now explicitly included this experiment as an additional Tier. We agree with you that it has significant added scientific value and that the computational costs are relatively modest. We have added in 3.4 an additional targeted experiment with an abrupt 4xCO2 increase in the coupled climate model.

"Minor comments"

"Abstract: define the acronym MIP"

Done

"Introduction: A few more acronyms to define, e.g. ITCZ, MJO, QBO."

Done.

"Section 2.1: Give a proper reference to the CMIP6 publication in this same special issue."

The reference Eyring et al. 2016, that describes the DECK simulations in this special issue, has been added.

"Figure 1: Provide a more detailed caption."

We have provided a more detailed caption. We hope that the content of the figure is clear now.

"Section 3.1.1: As noted we do not have high resolution data for the entire historical period."

We have added a sentence mentioning this.

"Are there any issues with blending the pre and post satellite era data? Whatever methods are used to produce 1/4 degree SSTs, the raw observations simply are not there. For instance the process outlined for producing future (2015-2050) SSTs relies upon the variability being unchanged in a changing climate. Please comment."

It is true that high resolution observations of SST were not available before the satellite era. The ability to produce 0.25 degree fields of actual SST comes from our use of a satellite-era climatology. The analysis of residuals from that climatology (aka anomalies) which we do on a 5-day timescale is performed on a 1 degree grid. On that spatial and temporal scale, that analysis is perfectly achievable with the data available and is done both for pre-satellite data and satellite-era data alike. Information on covariances between anomalies in different locations gained from the satellite (and in situ) data enables the analysis to be done at the same resolution throughout. The ensemble captures the uncertainty in this process and its spread is wider prior to the satellite era. The Rayner et al manuscript (in prep.) and a technical note for the HadISST (Kennedy, J. et al. in prep.) will describe more in detail the process of generating these data for the past.

For the future, of course you are right that it is a large assumption that the variability will not change. However, we have no other satisfactory way of generating the future forcing, and since the ForcedAtmos future simulations are more useful to contrast different model responses to the same future warming (which is not possible in the coupled models), they are in no way a future projection, so this assumption is not so important.

"Section 4.2, page 10, line 34: insert a space somewhere in andreanalysis."

Done

"Section 6, page 12, last line: No need to define ToE as acronym not used."

Done

"Section 6, Ocean model biases: insert the word "coastal" before upwelling as the equatorial upwelling zone bias is often different to this."

Done

"Section 7.1, page 14, 2nd to last sentence: Is there any evidence that sea ice simulations might improve with increasing resolution. If so give a reference. The project will be moving towards the limit of where the continuum hypothesis is reasonable, which may be an issue."

The reviewer correctly points out that the continuum hypothesis used to model sea ice dynamics may become an issue as we move to high (~1/4°) and very high (~1/12°) resolutions. However, there is to our knowledge no scientific evidence that the viscous-plastic or elastic-viscous-plastic rheologies are not adapted (numerically or in terms of results) to such high resolutions. Preliminary tests conducted at 1/4 and 1/12° with the NEMO-LIM3 ocean-sea ice model indicate not only stable results, but also realistic heterogeneities and intermittency behaviors in the sea ice cover. HighResMIP will be the perfect testbed to assess whether these increases in resolution have to be conducted in conjunction with development in model physics (rheology in this case), or if the two can be done separately.
We have added a remark about this in the manuscript.

"Section 7.1, page 14, last sentence: This doesn't sound quite right. Maybe Differences would be better than Difference."

Done

"Section 7.1, last sentence: replace "such as" with "outlined by" or something similar."

Done

"Section 7.4, page 16, paragraph 2: Too many acronyms reduce the readability of manuscripts. AR seems a bit unnecessary as it replaces just two words and sonly used twice. TC (a bit later on) also seems a bit unnecessary, but as it is used a few more times I could live with it."

The acronym AR for atmospheric rivers has been removed.

Response SC1 by Astrid Kerkweg

According to your suggestions we have changed the title of the manuscript in:

High Resolution Model Intercomparison Project
(HighResMIP v1.0) for CMIP6

Response SC2 by Klaus Wyser

"Table 1 and 2 of the paper suggest that the volcanic forcing is from MACv2-SP. However, MACv2-SP is only providing anthropogenic aerosols. The volcanic forcing in High-ResMIP should be handled in a similar way as in the other MIPs: use prescribed strato-spheric aerosols, see http://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6 for details."

Thank you for pointing out this error. We have corrected this in the revised manuscript.

Response to SC3 by Klaus Wyser:

"There is an inconsistency in the suggested GHG forcing (concentrations) between the historical and future run. For the historical run it is suggested to use the new data for CMIP6 but for the future run it will be the old RCP8.5 scenario from CMIP5 (Table 1and 2)."

We agree that there is an inconsistency between using for the historical run the new data of CMIP6 and for the future the old RCP8.5 scenario. The motivation for that is the European H2020 project PRIMAVERA. The partners in this project will start their simulations in the boreal summer of 2016 and will deliver their Tier 3 simulations up to 2050 by the end of 2016. The Tier 2 simulations will be finished in the boreal spring of 2017. The new CMIP6 scenario's will be ready only by the end of 2016 according to present estimates, thereby causing a mismatch with the time schedule of the PRIMAVERA runs. Delaying the PRIMAVERA runs is not a viable option because first of the obligations to the European commission and second because the dependencies of other parts (analysis of the runs, model improvements, impact studies) of PRIMAVERA on those runs. We argue that the switch from CMIP6 historical forcing to future RCP8.5 is an acceptable compromise for the PRIMAVERA partners. The difference between the high-end scenario for CMIP6 and RCP8.5 will be limited up to 2050.

We realize, however, that for other centers, this is a sub-optimal solution and that they would prefer to use a high-end SSPx scenario when it is available. We have therefore decided to make the SSPx as the standard for Tier 2 and 3, and included the RCP8.5 option as a targeted experiment (3.4.e) for those centers that have to start earlier. In the description of this targeted experiment (9.3.5), it is stated that if in a joint analysis the SSPx and RCP8.5 ensembles appear to be significantly different, than the RCP8.5 centers are recommended to repeat their simulations with SSPx, which, due to the short integration period of 36 years, should not be prohibitive.

Below we will in detail discuss the mentioned inconsistencies between CMIP6 and RCP8.5 and how they can be handled.

"This inconsistency causes two problems:

1) It is more difficult to have a model version that can handle both the old and new foricng datasets at the same time. It would be pretty easy if it would be just a text file that changes when going from CMIP5 to CMIP6 forcing, but this is not the case. For CMIP6 it is recommended that the models use monthly varying zonal distributions or at least separate GHG concentrations in the two hemispheres (see http://www.climate-energy-college.net/search/content/cmip6). For CMIP5 on the other hand only global annual means have been prescribed. Implementing both options for 1-d and 3-d forcing is not impossible yet certainly nothing positive."

This is indeed an issue. For the historical period we recommend the CMIP6 forcing including the monthly varying zonal or hemispheric distributions. For the future period the distribution of the end of the historical period can be used and subsequently rescaled according to the change in the global annual mean as given by CMIP5. This has the advantage that the forcing structure is according to CMIP6 for

historical and future period and that when SSPx is available this will only require a change in the content of the input files.

"2) How consistent are the CMIP5 and CMIP6 forcings? I can imagine that there will be a change in GHG concentrations if the new CMIP6 data are used until 2014, and the old data afterwards. We cannot tell because the future GHG emissions aren't available at this stage, but I am pretty sure that the creators of the dataset will check that historical and future scenarios of the CMIP6 datasets match, but I doubt that they check if historical from CMIP6 and future from CMIP5 data sets fit well together. I would suggest that the GHG forcing is kept consistent across the historical and future simulations (as it is to be done in any other MIP). Either we take the CMIP6 GHG forcing for both phases (preferentially), or the old RCP8.5 from CMIP5, but not a blend of the two."

We agree that there will be no perfect match between the historical CMIP6 and future CMIP5 forcings. We are, however, confident that the mismatch will be small, and can be solved with a smooth interpolation. The advantage is that the historical period, which covers 64 years will then be in agreement with the CMIP6 protocol. The much shorter future period of 36 years will deviate, but can more easily be redone if necessary.

Response SC4 by Malcolm Roberts

In order to be consistent with the naming conventions for CMIP6, need to change:

highres-LAI to highresSST-LAI

highres-p4k to highresSST-p4k

highres-4co2 to highresSST-4co2

We recommend that the initial condition for the atmosphere and land for 1950 (for the

highresSST-present, and perhaps the highres-1950 experiment) come from the ERA-

20C reanalysis from January 1950.

The naming is changed according to the CMIP6 conventions. The recommendation for ERA-20C reanalysis from 1950 is added in the manuscript.

High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6

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Abstract
Robust projections and predictions of climate variability and change, particularly at regional scales, rely on the driving processes being represented with fidelity in model simulations. The role of enhanced horizontal resolution in improved process representation in all components of the climate system is of growing interest, particularly as some recent simulations suggest the possibility for significant changes in both large-scale aspects of circulation, as well as improvements in small-scale processes and extremes. However, such high resolution global simulations at climate time scales, with resolutions of at least 50 km in the atmosphere and 0.25° in the ocean, have been performed at relatively few research centers and generally without overall coordination, primarily due to their computational cost. Assessing the robustness of the response of simulated climate to model resolution requires a large multi-model

ensemble using a coordinated set of experiments. The Coupled Model Intercomparison Project 6 (CMIP6) is the ideal framework within which to conduct such a study, due to the strong link to models being developed for the CMIP DECK experiments and other model intercomparison projects (MIPs). Increases in High Performance Computing (HPC) resources, as well as the revised experimental design for CMIP6, now enables a detailed investigation of the impact of increased resolution up to synoptic weather scales on the simulated mean climate and its variability.

The High Resolution Model Intercomparison Project (HighResMIP) presented in this paper applies, for the first time, a multi-model approach to the systematic investigation of the impact of horizontal resolution. A coordinated set of experiments has been designed to assess both a standard and an enhanced horizontal resolution simulation in the atmosphere and ocean. The set of HighResMIP experiments is divided into three tiers consisting of atmosphere-only and coupled runs and spanning the period 1950-2050, with the possibility to extend to 2100, together with some additional targeted experiments. This paper describes the experimental set-up of HighResMIP, the analysis plan, the connection with the other CMIP6 endorsed MIPs, as well as the DECK and CMIP6 historical simulation. HighResMIP thereby focuses on one of the CMIP6 broad questions: "what are the origins and consequences of systematic model biases?", but we also discuss how it addresses the World Climate Research Program (WCRP) grand challenges.

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1 Introduction
Recent studies with global high resolution climate models have demonstrated the added value of enhanced horizontal atmospheric 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 El Niño Southern Oscillation (ENSO) (Shaffrey et al., 2009; Masson et al., 2012), Tropical Instability Waves (Roberts et al., 2009), the Gulf Stream (Kirtman et al., 2012) and Kuroshio (Ma et al., 2016) and their influence on the atmosphere (Minobe et al., 2008; Chassignet and Marshall, 2008; Kuwano-Yoshida et al., 2010; Small et al., 2014, Ma et al., 2015), the global water cycle (Demory et al., 2014), snow cover (Kapnick and Delworth 2013), Atlantic inter tropical convergence zone (ITCZ) (Doi et al., 2012), jet stream (Lu et al., 2015; Sakaguchi et al., 2015), storm tracks (Hodges et al., 2011) and Euro-Atlantic blocking (Jung et al., 2012). High horizontal resolution in the atmosphere has a positive impact in representing the non-Gaussian probability distribution associated with the climatology of quasi-persistent low frequency variability weather regimes (Dawson et al., 2012). In addition, the increased resolution enables a more realistic simulation of small scale phenomena with potentially severe impacts such as tropical cyclones (Shaevitz et al., 2015; Zhao et al., 2009; Bengtsson et al., 2007; Murakami et al., 2015; Walsh et al., 2012; Ohfuchi et al., 2004; Bell et al., 2013; Strachan et al., 2013, Walsh et al., 2015), tropical-extratropical interactions (Baatsen et al., 2015; Haarsma et al., 2013) and polar lows (Zappa et al., 2014). Other phenomena that are sensitive to increasing resolution are ocean mixing, sea-ice dynamics, diurnal precipitation cycle (Sato et al., 2009; Birch et al., 2014; Vellinga et al., 2016), quasi bienennial oscillation (QBO) (Hertwig et al., 2015), the Madden-Julian oscillation (MJO) representation (Peatman et al., 2015), atmospheric low-level coastal jets and their impact on sea surface temperature (SST) bias along eastern boundary upwelling regions (Patricola and Chang, 2016, Zuidema et al., 2016) and monsoons (Sperber et al., 1994; Lal et al., 1997; Martin, 1999). The improved simulation of climate also results in better representation of extreme events such as heat waves, droughts (Van Haren et al., 2015) and floods. Enhanced horizontal resolution in ocean models can also have beneficial impacts on the simulations. Such impacts include improved simulation of boundary currents, Indonesian Throughflow and water exchange through narrow straits, coastal currents such as the Kuroshio, Leeuwin Current, and Eastern Australian Current, upwelling, oceanic eddies, SST fronts (Sakamoto et al., 2012; Delworth et al.,, 2012; Small et al., 2015), ENSO (Masumoto et al., 2004; Smith et al., 2000; Rackow et al., 2016) and sea ice drift and deformation (Zhang et al., 1999; Gent et al., 2010). Although enhanced resolution in atmosphere and ocean models had a beneficial impact on a wide range of modes of internal variability, the relative short high resolution simulations make it difficult to sort that out in detail due to large decadal fluctuations in interannual variability in for instance ENSO (Sterl et al., 2007).

The requirement for a multitude of multi-centennial simulations, due to the slow adjustment times in the Earth system, and the inclusion of Earth System processes and feedbacks, such as those that involve biogeochemistry, has meant that model resolution within CMIP has progressed relatively slowly. In CMIP3, the horizontal typical resolution was 250 km in the atmosphere and 1.5° in the ocean, while more than seven years later in CMIP5 this had only increased to 150 km and 1° respectively. Higher resolution simulations, with resolutions of at least 50 km in the atmosphere and 0.25° in the ocean, have only been performed at a relatively few research centers until now, and generally these have been individual "simulation campaigns" rather than large multi-model comparisons (e.g. Shaffrey et al., 2009; Navarra et al., 2010; Delworth et al., 2012, Kinter et al., 2013; Mizielinski et al., 2014; Davini et al., 2016).

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Due to the large computer resources needed for these simulations, synergy will be gained if they are carried out in a coordinated way, enabling 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 databases provide outstanding examples of the success of this approach. The multi-model mean has often proven to be superior to individual models in seasonal (Hagedorn et al., 2005) and decadal forecasting (Bellucci et al., 2015) as well as in climate projections (Tebaldi and Knutti, 2007) in response to radiative forcing. Moreover, significant scientific understanding has been gained from analyzing the inter-model spread and attempting to attribute this spread to model formulation (Sanderson et al., 2015).

The primary goal of HighResMIP is to determine the robust benefits of increased horizontal model resolution based on multi-model ensemble simulations – to make this practical vertical resolution will not be considered. The argument for this is that the scaling between horizontal and vertical resolution must obey N/f, where N is the Brunt-Väisälä frequency and f the coriolis parameter. This implies a factor of 100, between horizontal and vertical resolution, which is well satisfied by the model configurations in the HighResMIP group. In addition components such as aerosols will be simplified to improve comparability between models. The top priority CMIP6 broad question for HighResMIP is "what are the origins and consequences of systematic model biases", which will focus on understanding model error (applied to mean state and variability), via process-level assessment, rather than on climate sensitivity. This has motivated our choices in terms of proposed simulations, which emphasize sampling the recent past and the next few decades where internal climate variability is a more important factor than climate sensitivity to changes in greenhouses gases (Hawkins and Sutton, 2011), at least at regional scales.

The use of process-based assessment is crucial to HighResMIP, since we aim to better understand the dynamical and physical reasons for differences in model results induced by resolution change, in order to increase our trust in the fidelity of models. Such process understanding will either contribute to bolster our confidence in results from lower resolution (but with greater complexity) CMIP simulations, or to enable a better understanding of the limitations of such models. There are an increasing number of studies suggesting that, in individual models, important processes are better represented at higher resolution indicating ways to potentially increase our confidence in climate projections (e.g. Vellinga et al., 2016). A wide variety of processes will be assessed, from global and regional drivers of climate variability, down to mesoscale eddies in atmosphere and ocean – in the atmosphere these include tropical cyclones (Zhao et al., 2009; Bell et al. 2013; Rathmann et al., 2014; Roberts et al., 2015; Walsh et al., 2015) and eddy-mean flow interactions (Novak et al., 2015; Schiemann et al., 2016), while for the ocean they are an important mechanism for mesoscale air-sea interactions (Chelton and Xie, 2010; Bryan et al., 2010; Frenger et al., 2013; Ma et al., 2015; 2016), trans-basin heat transport (e.g. Agulhas leakage) (Sein et al., 2016), convection and oceanic fronts.

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 (bio)geochemical Earth System feedbacks) and sensitivity of model physics to model resolution, will further highlight the impact of enhanced horizontal resolution on the simulated climate. As the widespread impact of horizontal resolution, in the range of a few hundred to about ten kilometer, on climate simulation has been demonstrated in the past, it is expected that HighResMIP will contribute to many of the grand challenges of the WCRP, and hence such analysis may begin to reveal at what resolution in this range particular processes can be robustly represented.

The remainder of this manuscript is structured as follows. Section 2 gives an overview of the simulations, while section 3 describes the tiers of simulation in detail. Section 4 makes links between these and the CMIP6 DECK and other CMIP6 MIPs, section 5 describes the data storage and sharing plans, and section 6 and 7 describe the analysis and potential application plans. Conclusions and discussion are contained in Section 8. Several appendices contain more detail of the experimental design and forcing.

2 Outline of HighResMIP simulations

The main experiments will be divided into Tiers 1, 2 and 3. They are illustrated in Fig. 1. We provide an outline of these different tiers, with more detail in section 3. Each set of simulations comprise model resolutions at both a standard and a high resolution, where the standard resolution model is expected to be used in a set of CMIP6 DECK simulations and are considered the entry card for HighResMIP.

The Tier 1 experiments will be historical forced atmosphere (ForcedAtmos) runs for the period 1950-2014. A number of centers have already performed similar high resolution simulations and published their results (CAM5 Bacmeister et al., 2014; HadGEM3 Mizielinski et al., 2014; NICAM Satoh et al., 2014; EC-Earth Haarsma et al., 2013) hence these runs should not present prohibitively large technical difficulties. Restricting the ForcedAtmos runs to the historical period also makes it possible for numerical weather prediction (NWP) centers to contribute to the multi-model ensemble. Nineteen international groups have expressed interest in completing these simulations as shown in Appendix 9.1. All centers participating in HighResMIP are obliged to participate at least in Tier 1.

The coupled experiments in Tier 2 are more challenging, but provide an opportunity to understand the role of natural variability, due to the centennial scale, and to investigate the impact of high resolution on future climate. Although a few centers have previously carried out high resolution coupled simulations such as SINTEX-F2, GFDL, Hadley, MIROC and CESM (Masson et al., 2012; Delworth et al., 2012; Mecking et al., 2016; Sakamoto et al., 2012; Small, 2014), considerable issues including mean-state biases, climate drift and ocean spin-up remain. Due to these issues and the large amount of computer resources needed to complete both a reference and a transient simulation, fewer centers (currently six) are confirmed participants for these experiments. The period of the coupled simulations is 1950-2050.

Future atmosphere-only simulations for the period 2015-2100 will be carried out in in Tier 3. Although the future period covers the entire present century, the simulations can for computational reasons be restricted to mid-century (2050).

For a clean evaluation of the impact of horizontal resolution, additional tuning of the high resolution version of the model should be avoided. 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. If unacceptably large physical biases emerge in the high resolution simulations, all necessary alterations should be thoroughly documented. The requirement of no additional tuning is more relevant for the coupled runs because atmosphere alone models are strongly constrained by the prescribed SSTs.

2.1 Common Forcing fields

To focus on the impact of resolution in the design of the HighResMIP simulations should minimize the difference in forcings and model set-up that would hamper the interpretation of the results.
Most of the forcing fields are the same as those used in the CMIP6 Historical Simulation that are described separately in this Special Issue (Eyring et al., 2016) and are provided via the CMIP6 data portal. For the future time period, GHG and aerosol concentrations from a high-end emission scenario
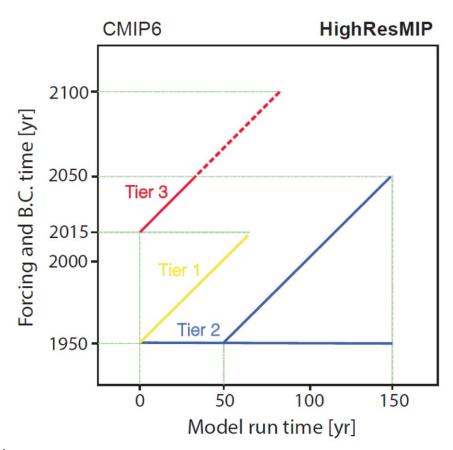
of the Shared Socioeconomic Pathways (SSP) will be prescribed, which in the following will be denoted by SSPx. A summary of the differences in forcing between CMIP6 AMIPII protocol and the Tier 1 and Tier 2 simulations is given in Table I.

2.1.1 Aerosol

A potential large source of uncertainty is the aerosol forcing – for the same aerosol emissions, different models can simulate very different aerosol concentrations, hence producing different radiative forcing. In HighResMIP, each model will use its own aerosol concentration background climatology. To this will added an anthropogenic time-varying, albeit uniform, forcing provided via the MACv2-SP method by Stevens et al. (2015). These will be computed using a new approach to prescribe aerosols in terms of optical properties and fractional change in cloud droplet effective radius to provide a more consistent representation of aerosol forcing. This will provide an aerosol forcing field that minimizes the differences between models as well as reducing the need for model tuning. This method is also the standard method in CMIP6 DECK for models without interactive aerosols.

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Figure 1: Schematic outline of the Tiers 1, 2 and 3. Tier 1 is a 64 year AMIP simulation from 1950-2014 with historical forcings. The first part of Tier 2 (coupled ocean-atmosphere simulations) consists of a 50 year integration starting from 1950 initial state under 1950's conditions. Thereafter this simulation will be continued by two branches of 100 years: one continuing with the 1950's forcing (control run) and the

other using until 2014 historical forcings and for 2015-2050 SSPx (scenario run). Tier 3 is the extension of Tier 1 from to 2014 to2050 (obliged, solid line) and 2051-2100 (optional, dashed line) for SSPx.

2.1.2 Land surface
The land surface properties will also be different from the CMIP6 AMIPII protocol. Given the requirement to make model forcing as simple as possible to aid comparability, the land-surface properties will be climatological seasonally varying conditions of leaf-area index (LAI), with no dynamic vegetation and a constant land-use/land-cover consistent with the present day period, centered around 2000. Consideration was given to attempting to further constrain land surface properties to be more similar between groups, but this was rejected given the complex and different ways in which remotely-sensed values are mapped to model land surface properties. However, an additional targeted experiment has been included to further investigate the sensitivity to land surface representation. This is outlined in section 9.3 "Targeted additional experiments".

2.1.3 Initialization and spin-up of atmosphere-land system
As discussed in Eyring et al. (2016), the initialization of land surface and atmosphere require several years of spin-up to reach quasi-equilibrium before the simulation proper can begin. We recommend this is done using the first few years of the forcing datasets before restarting in 1950. We further recommend that the initial condition for the atmosphere and land for 1950 (for the 0C reanalysis from January 1950. If this is not possible then the exact procedure used should be fully documented by each group.

Detailed description of Tiers

3.1 Tier 1 simulations: ForcedAtmos runs 1950-2014 – *highresSST-present*
The target for high resolution is 25-50 km, which is significantly higher than the typical CMIP5 resolution of 150 km. These ForcedAtmos runs will also be performed with the standard resolution that is used for the DECK and historical simulation.

The 1950-2014 simulation period is longer than the DECK AMIPII that spans 1979-2014. This is motivated primarily by work in many groups interested in climate variability over multi-decadal timescales, focusing on different phases of climate modes of variability such as Atlantic meridional oscillation (AMO) and Pacific decadal oscillation (PDO), as well as improved sampling of ENSO teleconnections (Sterl et al., 2007). The longer period will also improve the robustness of assessing the difference in variability between standard and higher resolution simulations, as well as being important for statistics of teleconnections (e.g. Rowell, 2013). Furthermore, the longer period of integration will enable a much more robust assessment of the ability of models to simulate known modes and their phases of variability, which is a big issue for climate risk assessment and decadal predictions where the combined effect of the global warming signal and natural variability will be considered.

The recommended ensemble size for the high resolution simulations is three, but due to their computational cost many centers will probably be able to simulate only one member. Therefore although an ensemble size of three is recommended it is not a requirement to participate in HighResMIP. The small ensemble size or absence of it will be insufficient for a rigorous estimate of the contribution of the internal variability to the total climate signal. However, by using a strictly common protocol in the various participating centers, the effective multi-model ensemble size will be much larger, enabling a much wider sampling than –pre-HighResMIP 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 auxiliary computer resources should become available at a later stage.

3.1.1 SST and sea-ice forcing

Although there is a significant forcing of the ocean by the atmosphere, in particular in the midlatitudes (Wu et al., 2007), many recent studies have shown that gradients in SST associated with fronts and ocean eddies can have significant influence on the atmosphere via changes in air-sea fluxes (Minobe et al., 2008; Parfitt et al., 2015; Ma et al., 2015; O'Reilly et al., 2015). Similarly, there is evidence that daily variability rather than monthly smoothed forcing can influence model simulations (de Boisseson et al., 2012; Woollings et al., 2010). Since the high resolution simulations will approach 25km, this means there is a requirement for a daily, $\frac{1}{4}$ degree dataset for a period longer than satellite-based datasets (such as Reynolds et al., 2002) are able to provide. Hence, we will use a new dataset based on HadISST2 (Rayner et al., 2016, Kennedy et al., 2016) which has these properties for both SST and sea-ice concentration for the period 1950-2014 – in addition, it provides an ensemble of historic realizations which can potentially be used to produce multiple ensemble members. It should be noted that the use of a daily, 1/4 degree data set will also have adverse effects. This is an inevitable consequence of AMIP runs. In these runs the ocean has an infinite heat capacity, with a detoriative impact on the phase relationships between SSTs, overlying atmosphere and surface fluxes (Barsugli and Battisti, 1998; Sutton and Mathieu, 2003). Although beneficial for the processes discussed above, the daily, 1/4 degree data will be for instance less optimal for the simulation of extremes over land (Cassou, 2015) and MJO's (DeMott et al., 2015).

3.2 Tier 2 simulations: Coupled runs

The coupled simulations are also aimed at addressing questions of model bias in both mean state and variability similar to the ForcedAtmos simulations. There are many examples from previous studies (e.g. Scaife et al., 2011; Bellucci et al., 2010) where these biases become much more evident in the coupled context compared to the forced atmosphere simulations. The systematic comparison between uncoupled (Tier 1) and coupled simulations for the 1950-2050 period, under different horizontal resolutions, will stimulate novel process-oriented studies tackling the origins of well-known biases affecting climate models, such as the double-ITCZ tropical bias.

3.2.1 Control - *control-1950*

These coupled runs will be the HighResMIP equivalent of the pre-industrial control, here being a 1950's control using fixed 1950s forcing. The forcing consists of GHG gases, including O_3 and aerosol loading for a 1950s (~10 year mean) climatology.

This will allow an evaluation of the model drift. The initial ocean conditions are taken from version 4 of the Met Office Hadley Centre "EN" series of data sets of global quality controlled ocean temperature and salinity profiles and monthly objective analyses (EN4 Good et al., 2013) over an average period of 1950-1954. As described below, a short spin-up with these forcings is required (~50 years) to produce initial conditions for both the 100 year simulation within this control, as well as for the historic simulation described in 3.2.2.

3.2.2 Historic – *hist-1950*

These are coupled historic runs for the period 1950-2014 using an initial condition taken from 3.2.1. For this period the external forcings are the same as in Tier 1 (see Table 1).

3.2.3 Future – *highres-future*

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These are the coupled scenario simulations 2015-2050, effectively a continuation of the 3.3.2 historic simulation into the future. For the future period the forcing fields will be based on CMIP6 SSPx. Other forcings are detailed in Table 2.

The atmospheric component of the coupled models will be the same as in the Tier 1 simulations. The minimum resolution for the high resolution ocean model is 0.25°. This enables the ocean to resolve some mesoscale variability (compared to non-eddy permitting models), particularly in the tropics, which has been shown to change the strength of atmosphere-ocean interactions (Kirtman et al., 2012). It also aligns the resolution of the ocean with that of the atmosphere – the ideal atmosphere/ocean resolution ratio remains an open scientific question.

The period of the historic coupled integrations is chosen to be the same as in the Tier 1 simulations. The future end-date is based on a compromise between what is computationally affordable by a sufficient number of centers (~100 years of integration) and what is scientifically relevant.

We again emphasize our interest in model error (bias, fidelity in representation of climate processes and variability) rather than climate sensitivity or transient climate response in configuring these coupled simulations, in particular whether any changes in process representation have an influence on patterns of climate variability and change. As discussed before the number of ensemble members that will be possible, at least initially, in HighResMIP will not be sufficient to fully address internal variability, but it will form an important baseline set of simulations from which already preliminary robust conclusions can be extracted, and should be useful for many of the other CMIP6 MIPs (e.g. DCCP, GMMIP, CORDEX, CFMIP).

The HighResMIP simulations will enable the simulation of weather systems with short time scales that can provoke strong air-sea interactions such as tropical cyclones. Hence, high frequency coupling between ocean and atmosphere is required: a 3hr or 1hr frequency is highly recommended so that the diurnal time scale can be resolved, assuming sufficient vertical model resolution in the upper ocean.

3.2.4 Spin-up
Due to the large computer resources needed, a long spin-up to (near) complete equilibrium is not possible at high resolution (and hence for consistency will not be used at standard resolution). We recommend an alternative approach which will use the EN4 (Good et al., 2013) analyzed ocean state representative of 1950 as the initial condition for temperature and salinity. To reduce the large initial drift a spin-up of ~50 years will be made using constant 1950s forcing. Thereafter, the control run continues for another 100 years with the same forcing and the scenario run for the 1950-2050 period is started (Fig. 1). The difference between control and scenario can then be used to remove the continuing drift from the analysis. Output from the initial 50 years spin-up should be saved to enable analysis of multi-model drift and bias, something that was not possible in previous CMIP exercises, with the potential to better understand the processes causing drift in different models.

3.3 Tier 3 simulations: ForcedAtmos runs 2015-2050 (2100) – *highresSST-future*
The Tier 3 simulations are an extension of the Tier 1 atmosphere-only simulations to 2050, with an option to continue to 2100. To allow comparison with the coupled integrations the same scenario forcing as for Tier 2 (SSPx) will be used. However, since all the HighResMIP models will have the same SST and sea-ice forcing (described below), comparison of the Tier 2 and Tier 3 simulations can help to disentangle the impact of a model bias from forced response. This could be useful for applications such

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as time of emergence (e.g. Hawkins and Sutton, 2012). The forcing fields and scenario are shown in Table 2.

3.3.1 Detailed description of SST and Sea-Ice forcing

The future SST and sea-ice forcing is detailed in Appendix 9.2. It broadly follows the methodology of Mizuta et al. (2008), enabling a smooth, continuous transition from the present day into the future. The rate of future warming is derived from an ensemble mean of CMIP5 RCP8.5 simulations, while the interannual variability is derived from the historic 1950-2014 period. Using SST derived from CMIP5 RCP8.5 in conjunction with a CMIP6 SSPx GHG forcing introduces an inconsistency. However, given the wide range of climate sensitivity among the climate models and the small differences in the model response up to 2050 for different scenario's we argue that this inconsistency is minor.

3.4 Further targeted experiments

In addition to the Tier 1-3 simulations above, discussions with other CMIP6 MIP participants have suggested several targeted experiments that would enable further investigation of specific processes and forcings, as well as potentially informing future CMIP protocols. These are optional experiments, and as such the details of the experimental design will be described in Appendix 9.3. In brief they comprise:

a) Leaf Area Index (LAI) experiment – *highresSST-LAI*
 > Impact of using a common LAI dataset in models, linking with LS3MIP
b) Impact of SST variability on large scale atmospheric circulation – *highresSST-smoothed*
 > Impact of using a smoothed SST and sea-ice forcing dataset, linking with OMIP
c) Idealized forcing experiments with CFMIP – *highresSST-p4K, highresSST-4co2*
 > CFMIP-style experiments to investigate impact of model resolution
d) Abrupt 4xCO2 increase in coupled climate model – *highres-4CO2*
 > CFMIP-style experiment to investigate role of ocean resolution on ocean heat uptake
e) Tier 2 and 3 using RCP8.5 instead of SSPx - *highres-RCP85*
 > For centers that need to start their simulations before the availability of SSPx

4 Connection with DECK and CMIP6 endorsed MIPs

4.1 DECK

For the high resolution models, completing the full set of CMIP6 DECK simulations is too expensive in terms of computer resources. Hence, there is an assumption that groups participating in HighResMIP will complete a set of DECK simulations with the standard resolution model. The HighResMIP simulations will in that case be considered as sensitivity experiments with respect to the standard resolution DECK runs, that are the entry cards for HighResMIP. If groups are not able to do this, because for instance the only available configuration is with prescribed SSTs, which is often the case for NWP centers, they can still participate in HighResMIP but their simulations will only be visible as HighResMIP and not as CMIP6 runs.

the comparisons between the standard resolution simulations within HighResMIP and the DECK simulations will be informative in themselves. The relevance of HighResMIP is that the significant step in horizontal resolution enables us to clarify some of the outstanding climate science questions remaining from CMIP3 and CMIP5 exercises.

For the Tier 1 simulations, there is a strong link with the CMIP6 AMIPII simulations – the latter are likely to provide multiple ensemble members per modeling center, but using slightly different boundary conditions and forcings (SST, sea-ice, aerosols, LAI and land use). Hence this comparison will be informative of the impacts of these changes at the standard resolution common to both AMIPII and HighResMIP. In addition, the multiple ensemble members will provide a measure of internal variability, to assess whether the high resolution simulation lies outside this envelope.

4.2 CMIP6 endorsed MIPs
HighResMIP, as one of the CMIP6 endorsed MIPs, has links with a number of other MIPs. Collaboration with those will enhance the synergy.

GMMIP for global monsoons
There is well-known sensitivity of monsoon flow and rainfall to model resolution in the West African monsoon, Indian monsoon 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 ForcedAtmos 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. As tropical monsoonal rainfall is sensitive to small scale topography, high resolution has potential to improve this. On the other hand, there is strong evidence of the importance of coupled ocean-atmosphere interactions for the summer monsoon dynamics (Robertson and Mechoso, 2000; Robertson et al., 2003; Wang et al., 2005; Nobre et al., 2012). Consideration was given to starting the HighResMIP from 1870 to better compare with GMMIP, but it would not be affordable for many groups. In addition, the quality of observational and reanalysis datasets during the earlier period, to assess the modelled variability and processes, is questionable.

RFMIP
HighResMIP intends to use the MACv2.0-SP simplified aerosol forcing being partly produced and analyzed in RFMIP (Stevens et al., 2015). Additionally, assessment of its impact at different resolutions will contribute to understanding this simplified forcing. The impact of different aerosols on atmospheric circulation and teleconnections in the coupled climate system has been shown before and is likely dependent on model resolution (e.g. Chuwah et al., 2016).

CORDEX
CORDEX regional downscaling experiments provide focused downscaling over particular regions. Comparison between these and global HighResMIP simulations can give insight into the relative importance of global scale teleconnections and interactions, against enhanced local resolution and local processes. HighResMIP can (potentially) provide boundary conditions for downscaling and provide a stimulus to cloud resolving simulations, but data volumes are likely to prohibitive so this will be left to individual groups to coordinate.

OMIP for ocean analysis and initial state
There is potential to jointly examine the spin-up issues in both forced ocean (OMIP) and coupled (HighResMIP) simulations, to improve the understanding of how we might better initialize coupled climate or forced ocean simulations and minimize initialization shock and the required integration time. The targeted experiment 9.3.2 to understand the impact of mesoscale SST variability is another joint

area of research. We will also exchange diagnostic/analysis techniques to understand ocean circulation changes at different resolutions.

LS3MIP
Within the scope of LS3MIP on understanding the land-atmosphere interactions at different horizontal resolutions, HighResMIP can provide useful datasets to evaluate the role of soil moisture on extreme events, as well as the impact of LAI forcing datasets on model variability and mean state at different resolutions via targeted experiment 9.3.1.

DynVAR
Increase of horizontal resolution may also improve the stratospheric basic state through vertical propagation of small-scale gravity waves, which in turn may affect tropospheric circulation. The sensitivity of such troposphere-stratosphere dynamical interactions on horizontal resolution will be analyzed by the DynVAR community, and HighResMIP has actively coordinated with the DynVAR diagnostic request to make this possible.

CFMIP
Targeted experiments in 9.3.3, to look at the clouds and feedback response in different resolution models, can be assessed in conjunction with CFMIP experiments using the standard resolution model.

SIMIP
Coordination of sea ice diagnostic request with SIMIP will enable coordinated assessment of the impact of model resolution on sea ice conditions and processes. Indeed, sea ice drift, deformation and leads (Zhang et al., 1999; Gent et al., 2010) have been shown to be highly sensitive to model resolution in single-model studies. The robustness of these conclusions should be assessed in a coordinated multi-model exercise such as HighResMIP.

5 Data storage and sharing

The storage and distribution of high resolution model data is a challenging issue. Since the resolution of HighResMIP approaches the scales necessary for realistic simulation of synoptic weather phenomena, daily and sub-daily data will be stored to allow the investigation of weather phenomena such as those related to midlatitude storms, blocking, hurricanes and monsoon systems. However, high-frequency output of all 3-dimensional fields will not be affordable to store. Careful considerations are needed to limit the high-frequency output. The considerations should take into account that the information relevant for the end users is concentrated at or near the land surface where people live so that it is desirable to store surface and near-surface variables in high temporal and spatial resolution. Furthermore, in order to evaluate the HighResMIP-ensemble, the high-frequency output should contain variables for which high-frequency observations are available as well.

HighResMIP output data will conform to all the CMIP requirements for standardization. The CMIP6 data and diagnostic plan (Juckes et al., 2016) describes the diagnostic request for all the CMIP6 MIPs. This data request, including that of HighResMIP is available from the CMIP6 website. The data and diagnostic plan will be finalized during the boreal summer of 2016. An estimate of the amount of data that needs to be stored is given at http://clipc-services.ceda.ac.uk/dreq/tab01_3_3.html.

The data storage is divided in three priorities. This is based on a balance between the HighResMIP data request ({ HYPERLINK "http://clipc-services.ceda.ac.uk/dreq/u/HighResMIP.html" }) to answer scientific questions and the large data volumes involved. Priority 1 should be possible for all centers. Priority 2 and 3, involve large data volumes and more specific questions. HighResMIP groups commit to archiving at least the priority 1 data request diagnostics on an Earth System Grid Federation (ESGF) node. The very large data volumes mean that it may be difficult to transfer all of priority 2 and 3 data, and hence a different methodology is needed to cope with this. Discussions with other international data centers are planned to further enable collaborative analysis. In the European Horizon 2020 project PRIMAVERA, the JASMIN platform (STFC/CEDA, UK) will be used for data exchange and as a common analysis platform. In future, it would be a more efficient management of global resources to move analysis tools to data storage centers. The European Copernicus Climate Data Store may also provide useful future avenues for data storage and sharing, which will be explored. Further, the project will explore a close collaboration with the European EUDAT initiative (http://www.eudat.eu), which is developing data storage, preservation, staging and sharing services suitable for extremely large datasets.

One useful approach may be to provide spatially and/or temporally coarsened model output on the ESGF, which would enable initial analysis compared to DECK simulations, and indicate which avenues of analysis may require full model resolution output, with manageable remaining volumes. It would then also be available for any automated assessment tools on the ESGF.

7 Analysis plan

The analysis will focus on the impact of increasing resolution on the simulation of different climate phenomena that are strongly biased in coarse resolution models and that could potentially benefit from higher resolution. The robustness of the impact of increasing resolution on the simulation of weather and climate phenomena such as extreme weather events, atmospheric eddy – jet stream interactions, atmospheric blocking events, typical ocean model biases and ocean model drift among the different HighResMIP models will be investigated and their response to global warming assessed as well as their interannual variabilities.

The increased resolution will permit evaluating whether horizontal resolution alone can generate a better simulation of regional climates. The analysis will therefore also have a focus on regional climate and relative teleconnections. Because HighResMIP will enable a more detailed simulation of small-scale weather systems, the scale interaction between these systems and the large scale circulation will be another focus of the analysis plan. The benefit of atmosphere-ocean coupling at these high resolutions will be addressed as well since we can compare the AMIP-style simulations with fully coupled simulations. Not all modeling centers may be able to afford eddy-resolving ocean simulations; nevertheless, where possible, it will be interesting to investigate scale interactions in the ocean as well.

Five initial foci for analyses have been identified:

6.1 Regional climates

Current climate risks assessments rely on output from ensembles of relatively coarse resolution global climate models or on their downscaled products (e.g. CORDEX) in addition to observations. For Europe, around 15 regional modelling groups downscaled ERA-interim simulations at 50 km and 12.5 km resolution (http://www.euro-cordex.net). Furthermore, historical and future simulations of about 10 different CMIP5 models have been downscaled by a similar number of regional climate models. Also for other regional domains as e.g. Africa (Klutse et al., 2015), North America (Mearns et al., 2013) or the Arctic (Koenigk et al., 2015), multi-model downscaling simulations have been performed. While the

regional models generally fail to improve the large scale atmospheric circulation, probably due to inconsistencies at their lateral boundaries and insufficient vertical resolution, they show added value in the representation of precipitation, in complex terrain and of meso-scale phenomena as e.g. polar lows (Rummukainen, 2015).

A recent study by Jacob et al. (2014) showed that the high-resolution Euro-CORDEX-simulations provide a more realistic representation of precipitation extremes over Europe and a larger increase of extreme precipitation in future simulations compared to the global models. Generally, the regional CORDEX-simulations show a more sensitive response of precipitation to changes in greenhouse gas concentrations compared to their driving global models. However, the bias in the lateral boundary conditions from coarse resolution climate models can strongly affect the simulations in the regional models, such as shown for precipitation trends over Europe by van Haren et al. (2014, 2015).

The HighResMIP simulations will provide the first ensemble of global models with a comparable resolution to the current generation regional models. This will allow for a direct comparison of user-relevant parameters in HighResMIP to the CORDEX results. The comparison will focus on statistics and physics of meteorological events such as intense rainfall, droughts, storms and heat waves. A comparison of the simulation of extreme events in the global models (which are self-contained and include global small-scale to large-scale interactions) and in regional models (forced at the boundary by another model, and typically a one-way downscaling) will be made. Results from various studies (e.g. Scaife et al., 2011; Kirtman et al., 2012), analyzing the benefits of high resolution in the ocean in one single global model, indicate that increased resolution in global models leads to an improved simulation of large scale phenomena such as the North Atlantic Current system and related surface temperature gradients. The impact of such improvements on blocking and storm tracks and the downstream effect on European climate variability and extremes will be analyzed and compared to CORDEX-results. Comparing HighResMIP results, with a globally high resolution, to results from both standard resolution global models and regional CORDEX simulations with a locally high resolution domain (but boundaries based on coarse resolution CMIP5 models) will give us insights into the importance of realistic large scale climate conditions for local climate variations and extremes.

Studying internal variability and long-term change of the Northern Hemisphere sea ice cover in the coupled HighResMIP simulations will enable us to explore the impact of better resolved sea ice dynamics on Arctic and global climate. Preliminary tests conducted at 1/4 and 1/12° with the NEMO-LIM3 ocean-sea ice model indicate not only stable results, but also realistic heterogeneities and intermittency behaviors in the sea ice cover. HighResMIP will be the perfect testbed to assess whether these increases in resolution have to be conducted in conjunction with development in model physics (rheology in this case), or if the two can be done separately. Differences between perennial 1950 and historical simulation will further our understanding of Arctic warming amplification and long-term future of sea ice cover superimposed with pronounced natural variability, using methods outlined by Fučkar et al. (2015).

6.2 Scale interactions
The improved simulation of synoptic scale systems in HighResMIP enables us to analyze multi-scale phenomena such as large-scale circulation, tropical and extratropical cyclones, MJO, tropical wave, convection and cloud in a seamless manner. For example, tropical cyclogenesis has known links to multi-scale phenomena including monsoon, synoptic-scale disturbances, and MJO (e.g. Yoshida and Ishikawa, 2013). Even for the dynamical storm-track, which may be thought satisfactorily resolved by low-resolution climate models, its bias in latitudinal position is related to the cloud amount bias in CMIP5

models (Grise and Polvani, 2014). Existing high-resolution atmosphere simulations suggest that the characteristics of the jet stream (Hodges et al., 2011) and blocking (Jung et al., 2012) will be improved by higher resolution. The MJO, and diurnal precipitation cycle are also of great interest. Such analysis, requiring high frequency data, has implications for the output diagnostics – see Section 5 and Juckes et al. (2016).

In addition, the role of air-sea interactions at the mesoscale, such as analyzed by Chelton and Xie (2010), Bryan et al. (2010) and Ma et al. (2015), can be assessed across models to understand the impact of resolution and the potential feedbacks in the system that may change the mean state.

Regarding the ocean, multi-scale phenomena can be discussed in a similar way. By resolving eddies and having a lower dissipation due to refined resolution, the cold bias in the northwest corner, the pathway of the Gulf stream / North Atlantic current, the Southern Ocean warm bias as well as the Agulhas current have been shown to be substantially improved (Sein et al., 2016). Even at an intermediate ¼° resolution which is not eddy-resolving, improvements have been shown (Marzocchi et al., 2015). This has strong links with OMIP.

6.3 Process studies

Process-level assessment of the simulated climate will give us some insights to improve the physics scheme in the climate models at a range of resolutions. Satellite simulators will be applied to the HighResMIP model output to evaluate cloud and precipitation processes in detail (e.g., Hashino et al., 2013). After the launch of the EarthCare satellite (planned in 2018; Illingworth et al., 2015), a new dataset including vertical distribution of cloud, precipitation, and vertical velocity is expected to be available. The fact that the horizontal resolution of the climate model is approaching that of the satellite observations also motivates us to accelerate synergetic studies between models and observations.

Process studies will aim to pin down the reasons for potentially better capturing small-scale and consequently large-scale phenomena with increasing resolution. Such process understanding will be the basis for developing schemes or error correction methods that could potentially compensate for not capturing a range of processes in standard resolution models.

This topic has links with RFMIP (aerosols), LS3MIP (land surface processes), CFMIP (clouds), SMIP (sea-ice) and DynVar (troposphere-stratosphere processes).

7.4 Extremes and hydrological cycle

Many aspects of climate extremes are associated with the hydrological cycle, together with dynamical drivers such as mid-latitude storm tracks and jets. Analysis following Demory et al. (2014) will assess the multi-model sensitivity of the global hydrological cycle to model resolution, and convergence of moisture over land and ocean. In the tropics, the hydrological extremes due to monsoon systems and interactions between land and atmosphere (Vellinga et al., 2016; Martin and Thorncroft et al., 2015) will be investigated in conjunction with GMMIP. On a regional scale the extremes and hydrological cycle will be analyzed in collaboration with CORDEX. For extremes associated with surface processes there are links with LS3MIP.

In mid-latitudes, the representation of storm tracks and jet streams will be assessed. Novak et al. (2015) investigated the role of meridional eddy heat flux on the tilt of the North Atlantic eddy-driven jet. This

behavior may partly explain the dominant equatorward bias of the jet stream in generations of global climate simulations with model resolutions much coarser than 50km (Kidston and Gerber, 2010; Barnes and Polvani, 2013; Lu et al., 2015). Biases in the jet stream position have been found to correlate with the meridional shift of the jet position in a warmer climate (Kidston and Gerber, 2010).

Atmospheric rivers play a key role in the global and regional water cycle (Zhu and Newell, 1998; Ralph et al., 2006; Leung and Qian, 2009; Neiman et al., 2011; Lavers and Villarini, 2013), and hydrological extremes, and have been shown to be sensitive to model resolution (Hagos et al., 2015). In both North Pacific and North Atlantic, uncertainty in projecting atmospheric river frequency has been linked to uncertainty in projecting the meridional shift of the jet position in the future (Gao et al., 2015; 2016; Hagos et al., 2016), with consequential impacts on robust predictions of regional hydrologic extremes in areas frequented by land falling atmospheric rivers.

With the high resolution simulations resolving more realistic orographic features in western North and South America and western Europe (Wehner et al, 2010), this motivates more detailed analysis of regional precipitation and hydrologic extremes including changes in the amount and phase of extreme precipitation, snowpack, soil moisture, and runoff and rain-on-snow flooding events in a warmer climate than have been attempted previously with the coarser resolution CMIP3 and CMIP5 model outputs.

7.5 Tropical Cyclones

Recent studies (Walsh et al., 2012; 2015; Shaevitz et al., 2014; Scoccimarro et al., 2014; Villarini et al., 2014) have highlighted the benefits of enhanced model resolution on the representation of several aspects of tropical cyclones (TCs), including the formation patterns, genesis potential index, and the relative impact on precipitation. HighResMIP will provide an ideal framework to systematically investigate the influence of model resolution on the representation of tropical cyclones in the next generation of climate models.

It is expected that by improving the representation of the background, large-scale (oceanic and atmospheric) pre-conditioning factors affecting TC dynamics (such as wind shear and ocean stratification) via a refinement of model resolution, the overall representation of TC properties (including structure and statistics) will be affected. The potential remote influence of TCs on high-latitude processes suggested by a few authors - e.g., TC impacts on sea-ice export in the Arctic region (Scoccimarro et al., 2012), extra-tropical transition (Haarsma et al., 2013) and extreme precipitation events over Europe (Krichak et al., 2015) – is another (so far, poorly explored) topic that may benefit from the HighResMIP multi-model effort.

Finally, the 1950-2050 time window targeted in HighResMIP experiments will allow an evaluation of the stationarity of the relationship between TC frequency and intensity, and the underlying, large-scale environmental conditions (Emanuel, 2015).

7. Additional potential applications of HighResMIP simulations
Given the relatively short time period for integration and small ensemble size, and the fact that Tier 3 simulations are also limited by using atmosphere only models, we must give careful consideration to the applications for which the HighResMIP simulations can be used.

Below is a non-exhaustive list of additional issues, not discussed in the analysis plan, that can be addressed by HighResMIP:

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1. **Detection and attribution.** Several studies on detection and attribution of changes of weather and seasonal climate extremes would benefit from having an ensemble up to 2050 and for this shorter-term period the exact emission scenario chosen is not such a significant factor. Although the ensemble size of any single model will be small, it can be complemented over time, and the multi-resolution multi-model ensemble can be a starting point for assessing the occurrence of events within the distribution of the ensemble. Again, the increased resolution will likely result in more plausible and reliable results.

   A better assessment and attribution of the changes in extreme events that are already occurring and of near future changes will provide useful information for regional climate adaptation strategies and other users of climate model output such as infrastructure investments that have a time horizon up to 30 years. The benefit relates to the increased physical plausibility and reliability of simulating the circulation-driven aspects of the weather extremes, which are more biased in coarser resolution climate models. The ensemble could aid in developing scenarios of potential future weather events to which society is vulnerable (Hazeleger et al., 2015) and used for impact studies such as ecosystem studies, meteo-hydrological risks and landslides.

2. **Time of emergence.** The same principle applies to the time of emergence studies: many studies show time of emergence (ToE) now or in the next few decades (depending on the variable and regions of course) – e.g. Hawkins and Sutton (2012). It seems reasonable to assume that having high-resolution simulations could help to achieve this for large scale precipitation-related events.

3. **Decadal fluctuations.** The recent climate record contains several phases in which the global mean surface warming rate is lower in the observed record than predicted by models, and the multi-model multi-resolution ensemble might give insight in this. For instance, to reassess the possible causes for the recent global warming hiatus. In particular, the role of ocean heat uptake simulated by an eddy-permitting OGCM can be examined.

4. **Human health.** The effects of air pollution on human health is becoming a critical issue in some particular regions of complex topography. With the high horizontal resolutions and consequent detailed topographic forcing, the HighResMIP simulations may provide a useful ensemble of meteorological fields to drive either global or regional air quality modules and study the air quality effects on health.

5. **Climate services.** Climate services in different sectors such as agriculture, energy production and consumption could benefit from user-relevant diagnostics computed from high resolution future projections.

Another potential use of these simulations is to give a baseline of the forced response only (using the best estimate of the SST forced response and the SSPx radiative forcing) for near-term decadal predictions. This can then be combined with coupled decadal predictions (or statistical modelling) that also include the ocean variability and its influence. See for instance Hoerling et al. (2011) as a first attempt to do this with low-resolution models.

8 Discussion and conclusions

HighResMIP will for the first time coordinate high resolution simulations and process-based analysis at an international level and perform a robust assessment of the benefits of increased horizontal resolution for climate simulation. As such it is an important step in closing the gap between climate modelling and NWP, by approaching weather resolving scales. A better representation of multiple-scale interactions is essential for a trustworthy simulation of the climate, its variability and its response to time varying forcings and boundary conditions. HighResMIP thereby focuses on one of the three CMIP6 questions "what are the origins and consequences of systematic model biases?". Specifically it will investigate the relation of these model biases with small scale systems in the atmosphere and ocean and how well they are represented in climate models.

Despite the importance of enhancing horizontal resolution, many processes still have to be parameterized. For processes and regions where these parameterizations are crucial, increasing horizontal resolution did not improve the model bias. The role of various parameterizations on model biases will be investigated in other MIPs, for instance in AerChemMIP, CFMIP and RFMIP. Jointly they will address the grand challenges of the WCRP from different angles.

HighResMIP will address the grand challenges of the WCRP in the following way:

Clouds, Circulation and Climate Sensitivity
HighResMIP will address this grand challenge through investigating the sensitivity to increasing resolution of water vapor loading, cloud formation and circulation characteristics, with analysis concentrating on the relevant processes (see 6.3).

To improve the robustness of our understanding, the multi-model ensemble at different resolutions, together with the longer 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 under typical resolution used within HighResMIP, the dynamical constraints for the formation of clouds, such as the location and magnitude of upward and downward motion associated with frontal systems and orography, as well as moisture availability, are sensitive to resolution. This also applies to the response of the circulation to cloud formation.

Changes in Water Availability
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 as 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? How surface water availability (P minus E) changes with warming is of significant societal

relevance. HighResMIP will provide insights on uncertainty in projecting the changes as increasing model resolution alters precipitation (both amount and phase) and evapotranspiration through changes in atmospheric circulation, land surface processes, and land-atmosphere interactions.

Understanding and Predicting Weather and Climate Extremes
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 downscaling only partially resolves this limitation 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, as well as between local topographic features and the triggering of extreme events.

Regional Climate Information
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. Increasing resolution globally allows to better capture, not only local processes that could be captured by regional climate models, but also teleconnections with distant regions which could have a strong impact on the region of interest. 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 dynamical downscaling by cloud resolving regional models and statistical downscaling for impact assessments.

Cryosphere in a Changing Climate
In the Tier 2 coupled simulations, the better representation of sea ice deformation, drift and leads as well as heat storage and release with increased resolution can contribute to better capturing the growth and motion of sea-ice, the air-sea heat flux, and deep-water production in polar regions, processes that are strongly affected by small scale processes. Based on HighResMIP coordinated simulations we can make a robust assessment of the effect of model resolution on Arctic sea-ice variability, including sea ice circulation and export through Fram and Davis straits, and possible influences on mid-latitude circulation. Analysis of the cryosphere in the Tier 1 experiments will, however, be somewhat limited due to the prescribed sea-ice distribution. Its main impact will be on the distribution of snow fall and subsequent accumulation and melting of the snowpack that affect land surface hydrology.

The simulations in HighResMIP will obviously be demanding with respect to High Performance Computing capability, particularly in order to complete them in a reasonable time frame. There are ongoing efforts to acquire supra-national resources in Europe and elsewhere, and also the Tianhe-2 supercomputer, one of the most powerful systems in the world, offers huge computing resources to support HighResMIP in China.

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HighResMIP has evolved from the need to harmonize existing projects of high-resolution climate modelling. The European Horizon2020 project PRIMAVERA, in which major European climate centers are participating, has coordinated the initiatives for a common protocol within the CMIP6 framework. As such, the simulations conducted in PRIMAVERA will be first under the HighResMIP protocol.

It is expected that HighResMIP will be a major step forward in entering the area of weather resolving climate models and thereby opening new avenues of climate research. Fundamental new scientific knowledge is expected on weather extremes, the hydrological cycle, ocean-atmosphere interactions and multiple scale dynamics. As such, it will contribute more trustworthy climate projections and risk assessments.

Data Availability
The model output from the DECK and CMIP6 historical simulations will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. As in CMIP5, the model output will be freely accessible through data portals after registration. In order to document CMIP6's scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centers (see details on the CMIP Panel website at http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip). Further information about the infrastructure supporting CMIP6, the metadata describing the model output, and the terms governing its use are provided by the WGCM Infrastructure Panel (WIP) in their invited contribution to this Special Issue. Along with the data itself, the provenance of the data will be recorded, and DOI's will be assigned to collections of output so that they can be appropriately cited. This information will be made readily available so that published research results can be verified and credit can be given to the modelling groups providing the data. The WIP is coordinating and encouraging the development of the infrastructure needed to archive and deliver this information. In order to run the experiments, datasets for natural and anthropogenic forcings are required. These forcing datasets are described in separate invited contributions to this Special Issue. The forcing datasets will be made available through the ESGF with version control and DOIs assigned.

Input	CMIP6 AMIPII	HighResMIP Tier 1 highresSST-present	Tier 2 coupled hist-1950, control-1950
Period	1979-2014	1950-2014	1950-2014
SST, sea-ice forcing	Monthly 1° PCMDI dataset (merge of HadISST2 and NOAA OI-v2)	Daily ¼° HadISST2-based dataset (Rayner et al., 2016)	N/A
Anthropogenic aerosol forcing	Concentrations or emissions, as used in Historic CMIP6 simulations (Eyring et al., 2016)	Recommended: Specified aerosol optical depth and effective radius deltas from MACv2.0-SP model (Stevens et al., 2015)	Same as Tier 1
Volcanic	As used in Historic	Recommended:As used in Historic	Same as Tier 1
Natural aerosol forcing – dust, DMS	As used in Historic	Same	Same
GHG concentrations	As used in Historic	Same	Same
Ozone forcing	CMIP6 monthly concentrations, 3D field or zonal mean, as in Historic	Same	Same
Solar variability	As in Historic	Same	Same
Imposed boundary conditions – land sea mask, orography, land surface types, soil properties, leaf area index/canopy height, river paths	Based on observations, documented. LAI to evolve consistent with land use change.	Land use fixed in time, LAI repeat (monthly or otherwise) cycle representative of the present day period around 2000	Same as Tier 1
Initial atmosphere state	Unspecified – from prior model simulation, or observations, or other reasonable ways.	ERA-20C reanalysis recommended (ideally same at high and standard resolution)	From spin-up of coupled model in 3.2.1
Initial land surface state	Unspecified – as above. May require several years of spin-up, cycling 1979 or starting in early 1970s	ERA-20C reanalysis recommended, spun-up in some way	From spin-up

Ensemble number	Typically >=3	>= 1	1
Initial ocean/sea-ice state	N/A	N/A	From coupled spin-up

Table 1: Forcings and initialization for the Historic simulations (pre-2015)

Table 2: Forcings for the future climate simulations

Input	High end CMIP6 SSPx Scenario (ScenarioMIP)	HighResMIP Tier 3 highresSST-future	Tier 2 coupled highres-future
Period	2015-2100	2015-2050	2015-2050
SST, sea-ice forcing	N/A	Blend of variability from ¼° HadISST2-based dataset (Rayner et al., 2016) and climate change signal from CMIP5 RCP8.5 models	N/A
Anthropogenic aerosol forcing	Concentrations or emissions (ScenarioMIP)	Specified aerosol optical depth and effective radius deltas from MACv2.0-SP model	Same as Tier 3
Natural aerosol forcing – dust, DMS	ScenarioMIP	Same as Tier 1	Same
Volcanic aerosol	As used in HistoricScenarioMIP	Volcanic climatology	Same as Tier 3
GHG concentrations	ScenarioMIP SSPx	SSPx	Same as Tier 3
Ozone forcing	CMIP6 monthly concentrations, 3D field or zonal mean, 2015-2100, based on SSPx ScenarioMIP	Same	Same
Solar variability	CMIP6 dataset	Same	Same
Imposed boundary conditions – land sea mask, orography, land surface types, soil properties, leaf area index/canopy height, river paths	Based on observations, documented. LAI to evolve consistent with land use change.	Land use fixed in time, LAI repeat (monthly or otherwise) cycle	Same as Tier 1
Initial atmosphere, ocean, sea-ice state	Continuation from Historic simulation	Continuation from Tier 1 simulation	Continuation from Tier 2 historic simulation
Ensemble number	Typically >=3	>= 1	1

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Appendix

9.1 Participating models in HighResMIP

Table 9.1: Model details from groups expressing intention to participate in at least Tier 1 simulations, together with the potential model resolutions (if known/available, blank if not).

Model name	Contact Institute	Atmosphere Resolution (STD/HI) mid-latitude (km)	Ocean Resolution (HI)
AWI-CM	Alfred Wegener Institute	T127 (~100 km) T255 (~50 km)	1-1/4 degree 0.05-1 degree
BCC-CSM2-HR	Beijing Climate Center	T106 (~110 km) T266 (~45 km)	1/3-1 degree
BESM	INPE	T126 (~100 Km) T233 (~60 Km)	0.25 degree
CAM5	Lawrence Berkeley National Laboratory	100 km 25 km	
CAM6	NCAR	100 km 28 km	
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici	100 km 25km	0.25 degree
CNRM-CM6	CERFACS	T127(~100km) T359(~35km)	1 degree 0.25 degree
EC-Earth	SMHI, KNMI, BSC, CNR and 23 other institutes	T255(~80km) T511/T799(~40/25km)	1 degree 0.25 degree
FGOALS	LASG, IAP, CAS	100 km 25 km	0.1-0.25 degree
GFDL	GFDL	200 km -	
INMCM-5H	Institute of Numerical Mathematics	- 0.3 x 0.4 degree	0.25 x 0.5 degree 1/6 x 1/8 degree
IPSL-CM6	IPSL	0.25 degree	
MPAS-CAM	Pacific Northwest National Laboratory	- 30-50km	0.25 degree
MIROC6-CGCM	AORI, Univ. of Tokyo/JAMSTEC/National Institute for	- T213	0.25 degree

	Environmental Studies (NIES)		
NICAM	JAMSTEC/AORI/ The Univ. of Tokyo/RIKEN/AICS	56-28 km 14km (short term)	
MPI-ESM	Max Planck Institute for Meteorology	T127(~100km) T255(~50km)	0.4 degree
MRI-AGCM3	Meteorological Research Institute	TL159(~120km) TL959 (~20km)	
NorESM	Norwegian Climate Service Centre	2 degree 0.25 degree	0.25 degree
HadGEM3-GC3	Met Office Hadley Centre	60km 25km	0.25 degree

9.2 Future SST and sea-ice forcing

Discussion with the HighResMIP participants suggests that the agreed approach is to use the RCP8.5 scenario, and use the CMIP5 models to generate the projected future trend. Numerical code for the following calculations will be made available in Python, as will the final dataset on the ¼ degree daily HadISST2.2.0 grid.

So following Mizuta et al (2008) for the most part, the algorithm is as follows:
For HadISST2.2.0 (Rayner et al., 2016) in the period 1950-2014:

For each year y, month m, and grid point j:
Calculate the time mean, monthly mean $T_{mean}(m, j)$
Calculate the linear monthly trend $T_{trend}(m, j)$ over the period
And then the interannual variability T_{var} as the residual:
$T_{HadISST2}(y, m, j) = T_{mean}(m, j) + T_{trend}(m, j) + T_{var}(y, m, j)$

Then from at least 12 CMIP5 coupled models during the period 1950-2100 (using the Historic and RCP8.5 simulations).
Calculate a monthly mean trend, for each model over this period, as a difference from several years centred at 2014, so that the change in temperature can be smoothly applied to the HadISST2 dataset.
$T_{model\_trend}(y, m, j) = T_{model}(y,m,j) - T_{model}(mean(2004-2024), m, j)$.

Regrid this trend to the HadISST2 1/4 degree grid.
Calculate the multi-model ensemble mean of this monthly trend.
$T_{multi_trend}(y,m,k) = $ ensemble mean(T_{model_trend})

This ensemble mean still contains a large component of both spatial and temporal variability – since the object here is to produce a large-scale, smoothly varying background signal to the HadISST2 variability, this multi-model trend is spatially filtered (using a 20x10 longitude-latitude degree box car filter), and temporally filtered using a Lanczos filter with a 7 year timescale.

Then for the future period, the temperature is:

$T_{future}(y, m, j) = T_{mean}(m, j) + T_{var}(y, m, j) + T_{multi-trend}(y,m,k)$

This will repeat the variability from the past period into the future, but adding the model future trend. The choice of 1950 as a start date for this section is that it has the most similar phase of some of the major modes of variability (AMO, PDO etc) to use for the repeat.

```
HadISST2: 1870-----------------------------1950----------- 2014
Cut out a section                          |----------------------|
Concatenate this section (twice) to the end of HadISST2 at 2014:
HighResMIP_ISST: 1850-------------1950----------2014|----------------|2078|----------|2100
```

Projecting the sea-ice into the future will be based on the following procedure:
1. Using observed SST and sea ice concentration an empirical relationship is constructed (HadISST2 (Rayner et al., 2016) uses the inverse method to derive SST based on sea-ice concentration).
This is done by dividing the SST into bins of 0.1K. The SST of each data point determines in which bin the sea ice concentration of each data point falls. After all data points are handled in this way the mean sea-ice concentration for each bin is computed. The relationship is different for the Arctic and Antarctic and seasonally dependent.
2. Using this empirical relationship between SST and Sea-ice concentration the sea-ice concentrations for the constructed SST are computed.

However, a couple of alternative methods are also being investigated, such as that used in HadISST2 (Titchner and Rayner, 2014), in which the sea-ice edge is located, and then the concentration is filled in from here towards the pole.

9.3 Targeted additional experiments
9.3.1 Leaf Area Index (LAI) experiment – *highresSST-LAI*
The LAI is one of the most common vegetation indices that describe vegetation activity (Chen and Black, 1992). It closely modulates the energy balance, as well as the hydrological and carbon cycles of the coupled land-atmosphere system at different spatiotemporal scales (Mahowald et al., 2015). For atmosphere-ocean GCMs, including those of HighResMIP, the mean seasonal cycle of LAI is commonly prescribed to improve the physical and biophysical simulations of the land-atmosphere system (Taylor et al., 2011). To reduce the potential uncertainties due to inconsistent LAI inputs for different models participating in HighResMIP, we propose to conduct targeted LAI experiments, with a common LAI data set.

Various remote sensing based LAI datasets have been recently developed (Fang et al., 2013; Zhu et al., 2013). Among them, the LAI3g data has been found to be the best, in terms of continuity, quality and extensive applications (Zhu et al., 2013; Mao et al., 2013). For the targeted experiments we will provide a ¼ degree mean LAI3g data set. The other boundary conditions (e.g., greenhouse gases and aerosols, SST and Sea-Ice conditions) will be identical to those in the Tier 1. The new targeted simulations will be directly compared to the Tier 1 results, for which each modeling center has used their preferred LAI. If significant positive impacts are found, then the next CMIP might consider applying LAI3g as a new common high-resolution LAI dataset.

9.3.2 Impact of SST variability on large scale atmospheric circulation – *highresSST-smoothed*

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The impact of mesoscale air-sea coupling on the large-scale circulation (in atmosphere and ocean) is a growing area of research interest. Ma et al. (2015) have shown that mesoscale SST variability in the Kuroshio region can exert an influence on rainfall variability along the U.S. Northern Pacific coast. In order to assess this, we propose parallel simulations of the high resolution ForcedAtmos model using spatially filtered SST forcing.

The modeling approach is to conduct twin-experiments - one with high resolution SST (the reference HighResMIP simulation) and another with spatially low-pass filtered SST. This approach appears to be quite effective in dissecting the effect of mesoscale air-sea coupling. The filter should be the LOESS filter used by Ma et al (2015) and Chelton and Xie (2010). The parallel simulation should start in 1990 from the HighResMIP simulation and be identical apart from the SST forcing.
Period of integration: 10 years. This should be done in an ensemble multi-model approach to ensure statistically significant results.

9.3.3 Idealized forcing experiments with CFMIP – *highresSST-p4K, highresSST-4co2*

CFMIP experiments using +4K and 4xCO2 perturbations are used to evaluate feedbacks, effective radiative forcing and rapid tropospheric adjustments (e.g. to cloud and precipitation). Although the horizontal resolutions used by most groups within HighResMIP do not approach the cloud-system resolving scale (and hence may not be expected to generate a significantly different response), there is potential for differences in response at the regional scale.
Period of integration: 10 years for each +4K and 4xCO2 (in parallel to the 2005-2014 HighResMIP simulation period for best comparison with recent observations).

9.3.4 Abrupt forcing in coupled experiments with CFMIP and OMIP – *highres-4co2*

CFMIP experiments use abrupt 4xCO2 forcing in a piControl experiment to look at ocean heat uptake. We will similarly do abrupt 4xCO2 at the end of the spinup period of the control-1950 simulations for each coupled model resolution, to study the impact of the ocean resolution on heat uptake. This experiment has the added benefit of further investigation of spin-up processes.
Period of integration: 20 years (in parallel with the first 20 years of control-1950, after the initial spin-up period).

9.3.5 Tier 2 and 3 using RCP8.5 instead of SSPx - *highres-RCP85*

This option is included for centers, such as those involved in the European H2020 project PRIMAVERA, that have to start their simulations before the availability of SSPx. It is motivated by the notion that the differences between SSPx and RCP8.5 will be limited up to 2050. If in a joint analysis the SSPx and RCP8.5 ensembles appear to be significantly different, than the RCP8.5 centers are recommended to repeat their simulations with SSPx, which, due to the short integration period of 36 years, should not be prohibitive.

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References

Baatsen, M., Haarsma, R. J., Van Delden, A. J., and De Vries, H. : Severe autumn storms in future western Europe with a warmer Atlantic ocean, Clim. Dynam., 45, 949-964, doi:10.1007/s00382-014-2329-8, 2015.

Bacmeister, J. T., Wehner, M. F., Neale, R. B., Gettelman, A., Hannay, C. E. , Lauritzen, P. H. , Caron, J. M., and Truesdale, J. E.: Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM), J. Climate, 27, 3073–3099, DOI: 10.1175/JCLI-D-13-00387.1., 2014.

Barnes, E. A. and Polvani, L.: Response of the midlatitude jets, and of their variability, to increased greenhosuse gases in the CMIP5 models, J. Climate, 26, 7117-7135, 2013.

Barsugli, J., and Battisti, D. S.:The basic effects of atmosphere-ocean thermal coupling on midlatitude variability, J. Climate, 55, 477-493, 1998.

Bell, R.J., Strachan, J., Vidale, P.L., Hodges, K.I., and Roberts, M.: Response of tropical cyclones to idealized climate change experiments in a global high resolution coupled general circulation model, J. Climate, 26, 7966-7980, 2013.

Bellucci, A. , Gualdi, S., and Navarra, A.: The double-ITCZ syndrome in coupled general circulation models: the role of large-scale vertical circulation regimes, J. Climate, 23, 1127-1145, doi: 10.1175/2009JCLI3002.1, 2010.

Bellucci, A., Haarsma, R., Gualdi, S., Athanasiadis, P., and Co-Workers: An assessment of a multi-model ensemble of decadal climate predictions, Clim. Dynam., 44, 2787-2806, doi:10.1007/s00382-014-2164-y , 2015.

Bengtsson, L., Hodges, K. I., Esch, M., Keenlyside, N., Kornblueh, L., Luo, J.-J., and Yamagata, T.: How may tropical cyclones change in a warmer climate?, Tellus, 59A, 539-561, 2007.

Birch, C. E., Marsham, J. H., Parker, D.J., and Taylor, C. M.: The scale dependence and structure of convergence fields preceding the initiation of deep convection, Geophys. Res. Lett., 41, 4769–4776, doi:10.1002/2014GL060493, 2014.

Bryan, F. O., Tomas, R., Dennis, J. M., Chelton, D. B., Loeb, N. G., McClean, J. L.: Frontal scale air-sea interaction in high-resolution coupled climate models, J. Climate, 23, 6277-6291, doi:10.1175/2010JCLI3665.1, 2010.

Cassou C.: Some critical technical choices for pacemaker experiments, Aspen DCPP Workshop June 2015. (http://www.docfoc.com/aspen-dcpp-workshop-june-2015-some-critical-technical-choices-for-pacemaker).

Chassignet, E. P. and Marshall D. P.: Gulf stream separation in numerical ocean models. In: Hecht, M., Hasumi, H. (eds.), Eddy-Resolving Ocean Modeling, AGU Monog. Ser., 39-62, 2008.

Chelton, D. B. and Xie, S.-P.: Coupled ocean-atmosphere interaction at oceanic mesoscales, Oceanography, 23, 52-69, doi:10.5670/oceanog.2010.05, 2010.

Chen, J. M. and Black, T.: Defining leaf-area index for non-flat leaves, Plant. Cell Environ., 15, 421-429, 1992.

Chuwah, C., van Noije, T., van Vuuren, D. P., Le Sager, P., and Hazeleger, W. : Climate impacts of future aerosol mitigation in an RCP6.0-like scenario, Climatic Change, 134, 1-14, 2016.

de Boisseson, E., Balmaseda, M. A., Vitart, F., and Mogensen, K. :Impact of the sea surface temperature forcing on hindcasts of Madden-Julian Oscillation events using the ECMWF model, Ocean Sci., 8, 1071–1084, doi:10.5194/os-8-1071-201, 2012.

Davini, P., von Hardenberg, J., Corti S., Subramanian, A., Christensen, H.M., Jurike, Watson, P.A.G., S., Weisheimer, A., and Palmer, T.N. : Climate SPHINX: evaluating the impact of resolution and stochastic physics in climate simulations, Geosci. Model Dev., under submission, 2016.

Dawson, A., Palmer, T. N., and Corti, S. :Simulating regime structures in weather and climate prediction models, Geophys. Res. Lett., 39, L21805, doi:10.1029/2012GL053284, 2012.

Delworth, T.L., Rosati, A., Anderson, W., Adcroft, A. J., Balaji, V., Benson, R., Dixon, K., Griffies, S. M., Lee, H.-C., Pacanowski, R. C., Vecchi, G. A., Wittenberg, A. T., Zeng, F., and Zhang, R. : Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model, J. Climate, 25, 2755–2781, doi: 10.1175/JCLI-D-11-00316.1, 2012.

Demory, M.-E., Vidale, P. L., Roberts, M. J., Berrisford, P., Strachan, J., Schiemann, R., and Mizielinski, M. : The role of horizontal resolution in simulating drivers of the global hydrological cycle, Clim. Dynam., 42, 2201-2225, 2014.

DeMott, C. A., Klingaman, N. P. and Woolnough, S. J.:Atmosphere-ocean coupled processes in the Madden-Julian oscillation. Rev. of Geophys, 53, 1099-1154, doi: 10.1002/2014RG000478, 2015.

Di Luca, A., de Elía, R., and Laprise, R. : Potential for added value in precipitation simulated by high-resolution nested Regional Climate Models and observations, Clim. Dynam., 38, 1229–1247, doi: 10.1007/s00382-011-1068-3, 2012.

Doi, T., Vecchi, G. A., Rosati, A. J., and Delworth, T. L.: Biases in the Atlantic ITCZ in seasonal–interannual variations for a coarse- and a high-resolution coupled climate model, J. Climate, 25, 5494–5511, doi: 10.1175/JCLI-D-11-00360.1, 2012.

Emanuel, K.: Effect of upper-ocean evolution on projected trends in tropical cyclone activity, J. Climate, 28, 8165-8170, 2015.

Eyring, V., Bony, S., Meehl, G. A., Senior, C., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organisation, Geosci. Model Dev. Discuss., 8, 10539-10583, doi:10.5194/gmdd-8-10539-2015, 2016.

Fang, H., Jiang, C., Li, W., Wei, S., Baret, F., Chen, J. M., Garcia-Haro, J., Liang, S., Liu, R., Myneni, R. B.,Pinty, B., Xiao, Z., and Zhu, Z. : Characterization and intercomparison of global moderate resolution leaf area index (LAI) products: Analysis of climatologies and theoretical uncertainties, J. Geophys. Res. Biogeosci., 118, 529–548, doi:10.1002/jgrg.20051, 2013.

Frenger, I., Gruber, N., Knutti, R., and Munnich, M.: Imprint of Southern Ocean eddies on winds, clouds and rainfall, Nat. Geosci., 6, 608-612, 2013.

Fučkar, 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, Clim. Dynam., doi: 10.1007/s00382-015-2917-2, 2015.

Gao, Y., Lu, J., Leung, L. R., Yang, Q., Hagos, S., and Qian, Y.: Dynamical and thermodynamical modulations of future changes in landfalling atmospheric rivers over western North America, Geophys. Res. Lett., 42, 7179-7186, doi:10.1002/2015GL065435, 2015.

Gao, Y., Lu, J., Leung, and Leung, L. R.: Uncertainties in projecting future changes in atmospheric rivers and their impacts on heavy precipitation over Europe, J. Clim., in review, 2016.

Gent, P. R., Yeager, S. G. , Neale, R. B., Levis, S., and Bailey, D. A.: Improvements in a half degree atmosphere/land version of the CCSM, Clim. Dynam., 34, 819–833, doi:10.1007/s00382-009-0614-8, 2010.

Good, S. A., Martin, M. J., and Rayner, N. A.: EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates, J. Geophys. Res., 118, 6704–6716, doi: 10.1002/2013JC009067, 2013.

Grise, K. M. and Polvani, L. M.: Southern hemisphere cloud-dynamics biases in CMIP5 models and their implications for climate project ions, J. Climate, 27, 6074-6092, 2014.

Haarsma, R. J., Hazeleger, W., Severijns, C., de Vries, H., Sterl, A., Bintanja, R., van Oldenborgh, G. J., and van den Brink, H. W.: More hurricanes to hit Western Europe due to global warming, Geophys. Res. Lett., doi:10.1002/grl.50360, 2013.

Hagedorn, R., Doblas-Reyes, F. J., and Palmer, T. N.: The rationale behind the success of multi-model ensembles in seasonal forecasting I. Basic concept, Tellus, 57, 219–233, 2005.

Hagos, S., Leung, L. R., Yang, Q., Zhao, C., and Lu, J.: Resolution and dynamical core dependence of atmospheric river frequency in global model simulations, J. Climate, 28, 2764-2776, 2015.

Hagos, S., Leung, L. R., Yoon, J.-H., Lu, J., and Gao, Y.: A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North American from the Large Ensemble CESM simulations, Geophys. Res. Lett., 43, 1357-1363, doi:10.1002/2015GL067392, 2016.

Hashino, T., Satoh, M., Hagihara, Y., Kubota, T., Matsui, T., Nasuno, T., and Okamoto, H.: Evaluating cloud microphysics from NICAM against CloudSat and CALIPSO, J. Geophys. Res., 118, 7273-7292, 2013.

Hawkins, E. and Sutton, R.: The potential to narrow uncertainty in projections of regional precipitation change, Clim. Dynam., 37, 407, doi: 10.1007/s00382-010-0810-6, 2011.

Hawkins, E. and Sutton, R.: Time of emergence of climate signals, Geophys. Res. Lett., 39, L01702, doi:10.1029/2011GL050087, 2012.

Hazeleger, W., van den Hurk, B. J. J. M. van den Hurk, Min, E., van Oldenborgh, G. J., Petersen, A. C., Stainforth, D. A., Vasileiadou, E., and Smith, L. A.: Tales of Future Weather, Nature Climate Change, 5, 107-114, 2015.

Hertwig, E., von Storch, J.-S., Handorf, D., Dethloff, K., Fast, I., and Krismer, T.: Effect of horizontal resolution on ECHAM6-AMIP performance. Clim. Dynam, 45, 185-211, doi:10.1007/s00382-014-2396-x, 2015.

Hoerling, M., Hurrell, J., Kumar, A., Terray, L., Eischeid, J., Pegion, P., Zhang, T., Quan, X. -W., and Xu, T. Y. : On North American Decadal Climate for 2011-2020, J. Climate, 24, 4519-4528, doi:10.1175/2011JCLI4137.1, 2011.

Hodges, K. I., Lee, R. W., and Bengtsson, L.: A comparison of extratropical cyclones in recent re-analyses ERA-Interim, NASA MERRA, NCEP CFSR, JRA-25, J. Climate, 24, 4888-4906, 2011.

Illingworth, A. J., Barker, H. W., Beljaars, A., Ceccaldi, M., Chepfer, H., Cierbaux, N., Cole, J., Delanoë, J., Domenech, C., Donovan, D. P., Fukuda, S., Hirakata, M., Hogan, R. J., Huenerbein, A., Kolias, P., Kubota, T., Nakajima, T. Y., Nishizawa, T., Ohno, Y., Okamoto, H., Oki, R., Sato, K., Satoh, M., Shepherd, M. W., Velazques-Blazquez, A., Wandinger, U., Wehr, T., and vanZadelhoff, G.-J.: The EarthCARE satellite: The next step forward in global measurements of clouds, aerosols, precipitation, and radiation, Bull. Amer. Meteor. Soc., 96, 1311-1332, 2015.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., and Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change, 14, 563–578, doi 10.1007/s10113-013-0499-2, 2014.

Juckes, M., et al: The CMIP6 data request. In prep for GMD, This issue, 2016.

Jung, T., Miller, M. J., Palmer, T. N., Towers, P., Wedi, N., Achuthavarier, D., Adams, J. M., Altshuler, E. L., Cash, B. A., Kinter, J. L., Marx, L., Stan, C., and Hodges, K. I.: High-resolution global climate simulation with the ECMWF model in project Athena: Experimental design, model climate, and seasonal forecast skill, J. Climate, 25, 3155-3172, 2012.

Kapnick, S. B. and Delworth, T. L.: Controls of Global Snow under a Changed Climate, J. Climate, 26, 5537–5562, doi: 10.1175/JCLI-D-12-00528.1, 2013.

Kennedy et al. : Technical Note on HadISST2. In preparation, 2016.

Kidston, J. and Gerber, E. P.: Intermodel variability of the poleward shift of the austral jetstream in the CMIP3 integrations linked to biases in 20th century climatology, Geophys. Res. Lett., 37, L09708, doi: 10.1029/2010GL042873, 2010.

Kinter, III, J. L., Cash, B., Achuthavarier, D., Adams, J., Altshuler, E., Dirmeyer, P., Doty, B., Huang, B., Jin, E. K., Marx, L., Manganello, J., Stan, C., Wakefield, T., Palmer, T., Hamrud, M., Jung, T., Miller, M., Towers, P., Wedi, N., Satoh, M., Tomita, H., Kodama, C., Nasuno, T., Oouchi, K., Yamada, Y., Taniguchi, H., Andrews, P., Baer, T., Ezell, M., Halloy, C., John, D., Loftis, B., Mohr, R., and Wong, K.: Revolutionizing Climate Modeling with Project Athena: A Multi-Institutional, International Collaboration, Bull. Amer. Meteor. Soc., 94, 231–245, doi: 10.1175/BAMS-D-11-00043.1, 2013.

Kirtman, B. P., Bitz, C., Bryan, F., Collins, W., Dennis, J., Hearn, N., Kinter III, J. L., Loft, R., Rousset< C., Siqueira, L., Stan, C., Tomas, R., and Vertenstein, M.: Impact of ocean model resolution on CCSM climate simulations, Clim. Dynam., 39, 1303-1328, doi: 10.1007/s00382-012-1500-3, 2012.

Klutse N. A. B., Sylla, M. B., Diallo, I., Sarr, A., Dosio, A., Diedhiou, A., Kamga, A., Lamptey, B., Ali, A., Gbobaniyi, E. O., Owusu, K., Lennard, C., Hewitson, B., Nikulin, G., Panitz, H.-J., and Büchner, M.: Daily characteristics of West African summer monsoon precipitation in CORDEX simulations, Theor. Appl. Climatol., doi:10.1007/s00704-014-1352-3, 2015.

Koenigk T., Berg, P., and Döscher, R.: Arctic climate change in an ensemble of regional CORDEX simulations, Polar Research, 34, 24603, doi:10.3402/polar.v34.24603, 2015.

Krichak, S. O., Barkan, J., Breitgand, J. S., Gualdi, S., and Feldstein, S. B.: The role of the export of tropical moisture into mid-latitudes for estreme precipitation events in the Mediterranean region, Theor. Appl. Climatol., 121, 499–515, doi:10.1007/s00704-014-1244-6, 2015.

Kuwano-Yoshida, A., Minobe, S., and Xie S-P.: Precipitation response to the Gulf Stream in an Atmospheric GCM, J. Climate, 23, 3676–3698, 2010.

Lal, M., Cubasch, U., Perlwitz, J.P., and Waszkewitz, J.: Simulation of the Indian monsoon climatology in ECHAM3 climate model: Sensitivity to horizontal resolution, Int. J. Climatol., 17, 847-858, 1997.

Lavers, D. A. and Villarini, G.: The nexus between atmospheric rivers and extreme precipitation across Europe, Geophys. Res. Lett., 40, 3259–3264, 2013.

Leung, L. R., and Qian, Y.: Atmospheric rivers induced heavy precipitation and flooding in the western U.S. simulated by the WRF regional climate model, Geophys. Res. Lett., 36, L03820, 2009.

Lu, J., Chen, G., Leung, L. R., Burrows, A., Yang, Q., Sakaguchi, K., and Hagos, S.: Towards the dynamical convergence on the jet stream in aquaplanet AGCMs, J. Climate, 28, 6763-6782, 2015.

Ma, X., Chang, P., Saravanan, R. Montuoro, R., Hsieh, J.-S., Wu, D., Lin, X., Wu, L., and Jing, Z.: Distant Influence of Kuroshio Eddies on North Pacific Weather Patterns?, Scientific Reports, 5, 17785, doi:10.1038/srep17785, 2015.

Ma, X., Jing, Z., Chang, P., Liu, X., Montuoro, R., Small, R. J., Bryan, F. O., Greatbatch, R. J., Brandt, P., Wu, D., Lin, X., and Wu, L.: Western boundary currents regulated by interaction between ocean eddies and the atmosphere, Nature, 2016, in press.

Mahowald, N., Lo, F., Zheng, Y., Harrison, L., and Funk, C.: Leaf Area Index in Earth System Models: evaluation and projections, Earth Syst, Dynam. Discuss., 6, 761–818, 2015.

Mao, J., Shi, X., Thornton, P. E., Hoffman, F. M., Zhu, Z., and Myneni, R. B.: Global latitudinal-asymmetric vegetation growth trends and their driving mechanisms: 1982–2009, Rem. Sens., 5, 1484-1497, 2013.

Martin, G. M.: The simulation of the Asian summer monsoon, and its sensitivity to horizontal resolution, in the UK meteorological office unified model, Q.J.R. Meteorol. Soc., 125, 1499–1525. doi:10.1002/qj.49712555703, 1999.

Martin, E.R. and Thorncroft, C.: Representation of African Easterly Waves in CMIP5 models. J. Climate, 28, 7702-7715, 2015.

Marzocchi, A., Hirschi, J. J.-M., Holliday, N. P., Cunningham, S. A., Blaker, A. T., and Coward, A. C.: The North Atlantic subpolar circulation in an eddy-resolving global ocean model, Journal of Marine Systems, 142, 126-143, 2015.

Masson, S., Terray, P., Madec, G., Luo, J.-J., Yamagata, T., and Takahashi, K.: Impact of intra-daily SST variability on ENSO characteristics in a coupled model, Clim. Dynam., 39, 681-707, 2012.

Masumoto, Y., Sasaki, H., Kagimoto, T., Komori, N., Ishida, A., Sasai, Y., Miyama, T., Motoi, T., Mitsudera, H., Takahashi, K., Sakuma, H., and Yamagata, T.: A fifty-year eddy-resolving simulation of the world ocean—Preliminary outcomes of OFES (OGCM for the Earth Simulator), J. Earth Simulator, 1, 35–56, 2004.

Mearns, L. O., Sain, S., Leung, L. R., Bukovsky, M. S., McGinnis, S., Biner, S., Caya, D., Arritt, R. W., Gutowski, W., Takle, E., Synder, M., Jones, R. G., Nunes, A. M. B., Tucker, S., Herzmann, D., McDaniel, L., and Sloan, L.: Climate change projections of the North American Regional Climate Change Assessment Program (NARCCAP), Clim. Change Lett., 120, 965-975, doi:10.1007/s10584-013-0831-3, 2013.

Mecking, J. V., Drijfhout, S. S., Jackson, L. C., and Graham, T.: Stable AMOC off state in an eddy-permitting coupled climate model, Clim. Dynam., doi: 10.1007/s00382-016-2975-0, 2016.

Minobe, S., Kuwano-Yoshida, A., Komori, N., Xie, S.-P., and Small, R. J.: Influence of the Gulf Stream on the troposphere, Nature, 452, 206-209, doi:10.1038/nature06690, 2008.

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Mizielinski, M. S., Roberts, M. J., Vidale, P. L., Schiemann, R. Demory, M.-E., Strachan, J., Edwards, T., Stephens, A., Lawrence, B. N., Pritchard, M., Chiu, P., Iwi, A., Churchill, J., del Cano Novales, C., Kettleborough, J., Roseblade, W., Selwood, P., Foster, M., Glover, M., and Malcolm, A.: High resolution global climate modelling; the UPSCALE project, a large simulation campaign, Geosci. Model Dev., 7, 563-591, 2014.

Mizuta, R., Adachi, Y., Yukimoto, S., and Kusunoki, S.: Estimation of the future distribution of sea surface temperature and sea ice using the CMIP3 multi-model ensemble mean, Tech. Rep. 56, 28 pp., Meteorol. Res. Inst., Tsukuba, Japan, 2008.

Murakami, H., Vecchi, G. A., Underwood, S., Delworth, T. L., Wittenberg, A. T., Anderson, W. G., Chen, J.-H., Gudgel, R. G., Harris, L. M., Lin, S.-J., and Zeng, F.: Simulation and Prediction of Category 4 and 5 Hurricanes in the High-Resolution GFDL HiFLOR Coupled Climate Model, J. Climate, 28, 9058–9079, doi: 10.1175/JCLI-D-15-0216.1, 2015.

Navarra, A., Kinter, J. L., and Tribbia, J.: Crucial experiments in climate science, Bull. Am. Meteorol. Soc., 91, 343–352, doi:10.1175/2009BAMS2712.1, 2010.

Neiman, P. J., Schick, L. J., Ralph, F. M., Hughes, M., and Wick, G. A.: Flooding in western Washington: The connection to atmospheric rivers, J. Hydrometeor., 12, 1337–1358, 2011.

Nobre, P., De Almeida, R. A., Malagutti, M., and Giarolla, E.: Coupled Ocean–Atmosphere Variations over the South Atlantic Ocean, J. Climate, 25, 6349–6358, doi:10.1175/JCLI-D-11-00444.1., 2012.

Novak, L., Ambaum, M. H. P., and Tailleux, R.: The life cycle of the North Atlantic storm track, J. Atmos. Sci., 72, 821-833, 2015.

O'Reilly, C. H., Minobe, S., and Kuwano-Yoshida, A.: The influence of the Gulf Stream on wintertime European blocking. Clim. Dynam., 1-23, doi: 10.1007/s00382-015-2919-0., 2015.

Ohfuchi, W., Nakamura, H., Yoshioka, M. K., Enomoto, T., Takaya, K. , Peng, X., Yamane, S., Nishimura, T., Kurihara, Y., and Ninomiya, K.: 10-km Mesh Meso-scale Resolving Simulations of the Global Atmosphere on the Earth Simulator – Preliminary Outcomes of AFES (AGCM for the Earth Simulator), J. Earth Sim., 1, 8-34, 2004.

Patricola, C. M., and Chang, P.: The Benguela Low-Level Coastal Jet: Structure, Dynamics, and Biases in Models and Reanalyses, Clim. Dyn., 2016, Submitted.

Parfitt., R., Czaja, A., Minobe, S., and Kuwano-Yoshida, A.: The atmospheric frontal response to SST perturbations in the Gulf Stream region, Geophys. Res. Let., submitted, 2015.

Peatman, S.C., Matthews, A.J., and Stevens, D.P.: Propagation of the Madden-Julian Oscillation and scale interaction with the diurnal cycle in a high-resolution GCM, Clim. Dynam., 45, 2901-2918, doi: 10.1007/s00382-015-2513-5, 2015.

Rackow, T., Goessling, H. F., Jung, T., Sidorenko, D., Semmler, T., Barbi, D., and Handorf, D.: Towards multi-resolution global climate modeling with ECHAM6-FESOM, Part II: climate variability, submitted to Clim. Dynam., 2016.

Ralph, F. M., Neiman, P. J., Wick, G. A., Gutman, S. I., Dettinger, M. D., Cayan, D. R., and White, A. B.: Flooding on California's Russian River: role of atmospheric rivers, Geophys. Res. Lett., 33, L13801, 2006.

Rathmann, N. M., Yang S., and Kaas, E.: Tropical cyclones in enhanced resolution CMIP5 experiments, Clim. Dynam., 42, 665-681, doi:10.1007/s00382-013-1818-5, 2014.

Rayner, N. A., Kennedy, J. J., Smith, R. O., and Titchner, H. A.: The Met Office Hadley Centre Sea Ice and Sea Surface Temperature data set, version 2, part 3: the combined analysis, In prep., 2016.

Reynolds, R., Rayner, N., Smith, T., Stokes, D., and Wang, W.: An improved in situ and satellite SST analysis for climate, J. Climate, 15, 1609-1625, 2002.

Roberts, M. J., Clayton, A., Demory, M.-E., Donners, J., Vidale, P. L., Shaffrey, L., Stevens, D. P., Stevens, I., Wood, R. A., and Slingo, J.: Impact of Resolution on the Tropical Pacific Circulation in a Matrix of Coupled Models, J. Climate, 22, 2541-2556, 2009.

Roberts, M. J., Vidale, P. L., Mizielinski, M., Demory, M.-E., Schiemann, R., Strachan, J., Hodges, K., Camp, J. , and Bell, R.: Tropical cyclones in the UPSCALE ensemble of high resolution global climate models, J. Climate special issue on Hurricanes, 28, 574–596, doi:10.1175/JCLI-D-14-00131.1., 2015.

Robertson, A. W. and Mechoso, C. R.: Interannual and Interdecadal Variability of the South Atlantic Convergence Zone, Mon. Wea. Rev., 128, 2947–2957, 2000.

Robertson, A., Ferrara, J. D., and Mechoso, C. R.: Simulations of the atmospheric response to South Atlantic sea surface temperature anomalies, J. Climate., 16, 2540–2551, 2003.

Rowell, D. P.: Simulating SST Teleconnections to Africa: What is the State of the Art?, J. Climate, 26, 5397–5418, doi: 10.1175/JCLI-D-12-00761.1, 2013.

Rummukainen M.: Added value in regional climate modeling, WIREs Clim. Change 2015, doi: 10.1002/wcc.378, 2015.

Sakaguchi, K., Leung, L. R., Zhao, C., Yang, Q., Lu, J., Hagos, S., Ringler, T. D., Rauscher, S. A., and Dong, L.: Exploring a multi-resolution approach using AMIP simulations, J. Climate, 28, 5549-5574, 2015.

Sakamoto, T. T., Komuro, Y., Nishimura, T., Ishi, M., Tatebe, H., Shiogama, H., Hasegawa, A., Toyoda, T., Mori, M., Suzuki, T., Imada, Y., Nozawa, T., Takata, K., Mochizuki, T., Ogochi, K., Emori, S., Hasumi, H., and Kimoto, M.: MIROC4h - A New High-Resolution Atmosphere-Ocean Coupled General Circulation Model, J. Meteorol. Soc. Japan, 90, 325–359, doi:10.2151/jmsj.2012-301, 2012.

Sanderson B.M., Knutti, R., and Caldwell, P.: Addressing Interdependency in a Multimodel Ensemble by Interpolation of Model Properties, J. Climate, 28, 5150–5170,
doi: 10.1175/JCLI-D-14-00361.1, 2015.

Sato, T., Miura, H., Satoh, M., Takayabu, Y. N., and Wang, Y. Q.: Diurnal cycle of precipitation in the tropics simulated in a global cloud-resolving model, J. Climate, 22, 4809-4826, 2009.

Satoh, M., Tomita, H., Yashiro, H., Miura, H., Kodama, C., Seiki, T., Noda, A. T., Yamada, Y., Goto, D., Sawada, M., Miyoshi, T., Niwa, Y., Hara, M., Ohno, Y., Iga, S., Arakawa, T., Inoue, T., and Kubokawa, H.: The Non-hydrostatic Icosahedral Atmospheric Model: Description and development, Progress in Earth and Planetary Science, 1, 18, doi:10.1186/s40645-014-0018-1, 2014.

Scaife, A. A., Copsey, D., Gordon, C., Harris, C., Hinton, T. , Keeley, S. J. , O'Neill, A., Roberts, M., and Williams, K.: Improved atlantic blocking in a climate model, Geophys. Res. Lett., 38, L23703, doi:10.1029/2011GL049573, 2011.

Schiemann, R., Demory, M.-E., Shaffrey, L. C., Strachan, J., Vidale, P. L., Mizielinski, M. S., Roberts, M. J., Matsueda, M., Wehner, M. F., and Jung, T.: The resolution sensitivity of northern hemisphere blocking in four 25-km atmospheric global circulation models, submitted to J. Climate, 2016.

Scoccimarro E., Gualdi, S., and Navarra, A.: Tropical cyclone effects on arctic sea ice variability, Geophys. Res. Lett., 39, L17704, doi:10.1029/2012GL052987, 2012.

Scoccimarro E., Gualdi, S., Villarini, G., Vecchi, G., Zhao, M., Walsh, K., and Navarra, A.: Intense precipitation events associated with landfalling tropical cyclones in response to a warmer climate and increased CO2, J Climate, doi: 10.1175/JCLI-D-14-00065.1, 2014.

Shaevitz, D., Camargo, S.J., Sobel, A. H., Jonas, J.A., Kim, D., Kumar, A., LaRow, T.E., Lim, Y-K, Murakami, H., Reed, K., Roberts, M.J., Scoccimarro, E. , Vidale, P.L., Wang, H., Wehner, M. F., Zhao, M., and Henderson, N.: Characteristics of tropical cyclones in high-resolution models in the present climate, Journal of Advances in Modeling Earth Sys. , doi: 10.1002/2014MS000372, 2014.

Sein, D.V., Danilov, S., Biastoch, A., Durgadoo, J., Sidorenko, D., Harig, S., and Wang, Q.: Designing variable ocean model resolution based on the observed ocean variability, submitted to JAMES, 2016.

Shaffrey, L. C., Stevens, I., Norton, W. A., Roberts, M. J., Vidale, P. L., Harle, J. D., Jrrar, A., Stevens, D. P., Woodage, M. J., Demory, M. E., Donners, J., Clark, D. B., Clayton, A., Cole, J. W., Wilson, S. S., Connolley, W. M., Davies, T. M., Iwi, A., M., John, T., C., King, J. C., New, A., L., Slingo, J. M., Slingo, A., Steenman-Clark, L., and Martin, M.: U.K. HiGEM: the new U.K. High-Resolution Global Environment Model-model description and basic evaluation, J. Climate, 22, 1861-1896, 2009.

Small, R. J., Bacmeister, J., Bailey, D.A., Baker, A., Bishop, S., Bryan, F. O., Caron, J., Dennis, J., Gent, P. R., Hsu, H.-M., Jochum, M. , Lawrence, D. M., Munoz Acevedo, E., diNezio, P., Scheitlin, T., Tomas, R., Tribbia, J., Tseng, Y., and Vertenstein, M.: A new synoptic-scale resolving global climate simulation using the Community Earth System Model, Journal of Advances in Modeling Earth Systems, 6, 1065-1094, doiI: 10.1002/2014MS000363, 2014.

Small, R. J., Tomas, R. A., and Bryan, F. O.: Storm track response to ocean fronts in a global high-resolution climate model, Clim. Dynam., 43, 805-828, 2014.

Small, R. J., Curchitser, E., Hedstrom, K., Kauffman, B., and Large, W. G.: The Benguela upwelling system: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model, J. Climate, 28, 9409-9432, doi: 10.1175/JCLI-D-15-0192.1, 2015.

Smith, R. D., Maltrud, M. E., Bryan, F. O., and Hecht, M. W.: Numerical Simulation of the North Atlantic Ocean at 1/10°, J. Phys. Oceanogr., 30, 1532–1561, 2000.

Sperber, K. R., Sultan, H., Potter, G. L., and Boyle, J. S.: Simulation of the Northern summer monsoon in the ECMWF model: sensitivity to horizontal resolution, Mon. Wea. Rev., 122, 2461–2481, doi:10.1175/1520-0493, 1994.

Sterl A., van Oldenborgh, G. J., Hazeleger, W., and Burgers, G.: On the Robustness of ENSO teleconnenctions, Clim. Dynam., 29, 469-485, 2007.

Stevens, B., Fiedler, S., Peters, K., Kinne, S., and Mauritsen, T.: MACv2.0-SP: The MPI-M's simple plume parameterization for optical properties of anthropogenic aerosol. Tech. Report available from https://powerfolder.gwdg.de/dl/fi74MC1NbN9WYGsf63937q2R/MACv2-SP_v1-beta.tgz, 2015

Strachan, P., Vidale, P. L., Hodges, K., Roberts, M., and Demory, M. E.: Investigating global tropical cyclone activity with a hierarchy of agcms: the role of model resolution, J. Climate, 26, 133–152. doi: 10.1175/JCLI-D-12-00012.1 , 2013.

Sutton, R., and Mathieu, P.-P.: Response of the atmosphere–ocean mixed-layer system to anomalous ocean heat-flux convergence, Q. J. R. Meteorol. Soc., 128, 1259-1275, 2002.

Taylor, K.E., Stouffer, R.J., and Meehl, G.A.: An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc., 93, 485–498, 2011.

Tebaldi, C. and Knutti R.: The use of the multi-model ensemble in probabilistic climate projections, Philos. Trans. Roy. Soc., 365, 2053–2075, 2007.

Van Haren, R., Haarsma, R. J., van Oldenborgh, G. J., and Hazeleger, W.: Resolution dependence of European precipitation in a state-of-the-art atmospheric general circulation model, J. Climate, doi: 10.1175/JCLI-D-14-00279.1, 2014.

Van Haren, R., Haarsma, R. J., de Vries, H., van Oldenborgh, G. J., and Hazeleger, W.: Resolution dependence of circulation forced future central European summer drying, Env. Res. Lett., 10, 055002, doi: 10.1088/1748-9326/10/5/055002, 2015.

Vellinga, M., Roberts, M., Vidale, P. L., Mizielinski, M., Demory, M.-E., Schiemann, R., Strachan, J., Bain, C., Kettleborough, J., Good, P., Edmond, I., and Hibling, E.: Organised convection as the main carrier of Sahel rainfall variability at multi-annual timescales, Geophys. Res. Lett., doi:10.1002/2015GL066690, 2016.

Villarini G., Lavers, D.A., Scoccimarro, E., Zhao, M., Wehner, M. F., Vecchi, G., and Knutson, T.: Sensitivity of tropical cyclone rainfall to idealized global scale forcings, J. Climate, doi: 10.1175/JCLI-D-13-00780.1, 2014.

Walsh K., Lavender, S., Scoccimarro, E., and Murakami, H.: Resolution dependence of tropical cyclone formation in CMIP3 and finer resolution models, Clim. Dynam., 40, 585-599, 2012.

Walsh K., Camargo, S. J., Vecchi, G. A., Daloz, A. S., Elsner, J., K. Emanuel, Horn, J. M.,

Lim, Y-, Roberts, M., Patricola, C., Scoccimarro, E., Sobel, A., Strazzo, S., Villarini, G., Wehner, M., Zhao, M., Kossin, J. P., LaRow, T., Oouchi, K., Schubert, S., Wang, H., Bacmeister, J., Chang, P., Chauvin,F., Jablonowski, C., Kumar, A., Murakami, H., Ose, T., Reed, K. A., Saravanan, R., Yamada, Y., Zarzycki, C. M., Vidale, P. L., Jonas, J. A., and Henderson,N.: Hurricanes and climate: the
U.S. CLIVAR working group on hurricanes, Bull. Am. Met. Soc., doi: 10.1175/BAMS-D-13-00242.1, 2015.

Wang, B., Ding, Q., Fu, X., Kang, I.-S., Jin, K., Shukla, J., and Doblas-Reyes, F.: Fundamental challenge in simulation and prediction of summer monsoon rainfall, Geophys. Res. Lett., 32, doi:10.1029/2005GL022734, 2005.

Watterson, I. G., Bathols, J., and Heady, C.: What influences the skill of climate models over the continents?, Bull. Amer. Meteor. Soc., 95, 689–700, doi: 10.1175/BAMS-D-12-00136.1, 2014.

Wehner, M. F., Smith, R., Duffy, P., and Bala, G.: The effect of horizontal resolution on simulation of very extreme US precipitation events in a global atmosphere model, Clim. Dynam., 32, 241-247, doi: 10.1007/s00382-009-0656-y, 2010.

Woollings, T., Hoskins, B., Blackburn, M., Hassell, D., and Hodges K.: Storm track sensitivity to sea surface temperature resolution in a regional atmosphere model, Clim. Dynam., 35, 341–353, doi:10. 1007/s00382-009-0554-3, 2010.

Wu, R. and Kirtman, B. P.: Regimes of seasonal air-sea interaction and implications for performance of forced simulations, Clim. Dynam, 29, 393–410, doi: 10.1007/s00382-007-0246-9, 2007.

Yoshida, R. and Ishikawa, H.: Environmental factors contributing to tropical cyclone genesis over the western North Pacific, Mon. Wea. Rev., 141, 451-467, 2013.

Zappa, G., Shaffrey, L., and Hodges, K.: Can polar lows be objectively identified and tracked in the ECMWF operational analysis and the ERA-Interim reanalysis?, Mon. Wea. Rev., 142, 2596–2608, doi: 10.1175/MWR-D-14-00064.1, 2014.

Zhang, Y., Maslowski, W., and Semtner, A. J.: Impact of mesoscale ocean currents on sea ice in high-resolution Arctic ice and ocean simulations, J. Geophys. Res., 104, 18409–18429, doi:10.1029/1999JC900158, 1999.

Zhao, M., Held, I. M., Lin, S. J., and Vecchi, G. A.: Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50km Resolution GCM, J. Climate, 33, 6653-6678, 2009.

Zhu, Y. and Newell, R. E.: A proposed algorithm for moisture fluxes from atmospheric rivers, Mon. Wea. Rev., 126, 725–735, 1998.

Zhu, Z., Bi, J., Pan, Y., Ganguly, S., Anav, A., Xu, L., Samanta, A., Piao, S., Nemani, R. R., and Myneni.: Global data sets of vegetation leaf area index (LAI) 3g and fraction of photosynthetically active radiation (FPAR) 3g derived from global inventory modeling and mapping studies (GIMMS) normalized difference vegetation index (NDVI3g) for the period 1981 to 2011, Rem. Sens, 5, 927–948, 2013.

Zuidema, P., Chang, P., Medeiros, B., Kirtman, B.P., Mechoso, R., Schneider, E. K., Toniazzo, T., Richter, I., Small, R. J., Bellomo, K., Brandt, P., de Szoeke, S., Farrar, J. T., Jung, E., Kato, S., Li, M., Patricola, C. M., Wang, Z., Wood, R., and Xu, Z.: Challenges and Prospects for Reducing Coupled Climate Model SST Biases in the eastern tropical Atlantic and Pacific Oceans: The US CLIVAR Eastern Tropical Oceans Synthesis Working Group, Bull. Am. Met. Soc., doi: 10.1175/BAMS-D-15-00274.1

66. Potential applications of HighResMIP simulations

Given the relatively short time period for integration and small ensemble size, we must give careful consideration to the applications for which the HighResMIP simulations can be used.

Below is a non-exhaustive list of issues than can be addressed by HighResMIP:

Extremes. The HighResMIP simulations may allow for a better assessment and attribution of the changes in extreme events that are already occurring and of near future changes (for instance related to the hydrological cycle and atmospheric dynamics). This

will provide useful information for regional climate adaptation strategies and other users of climate model output such as infrastructure investments that have a time horizon up to 30 years. The benefit relates to the increased physical plausibility and reliability of simulating the circulation-driven aspects of the weather extremes, which are more biased in coarser resolution climate models. The ensemble could aid in developing scenarios of potential future weather events to which society is vulnerable (Hazeleger et al., 2015) and used for impact studies such as ecosystem studies, meteo-hydrological risks and landslides.

Detection and attribution. Several studies on detection and attribution of changes of weather and seasonal climate extremes would benefit from having an ensemble up to 2050 and for this shorter-term period the exact emission scenario chosen is not such a significant factor. Although the ensemble size of any single model will be small, it can be complemented over time, and the multi-resolution multi-model ensemble can be a starting point for assessing the occurrence of events within the distribution of the ensemble. Again, the increased resolution will likely result in more plausible and reliable results.

Detection and attribution.

Time of emergence. The same principle applies to the time of emergence studies: many studies show time of emergence (ToE) now or in the next few decades (depending on the variable and regions of course) – e.g. Hawkins and Sutton (2012). It seems reasonable to assume that having high-resolution simulations could help to achieve this for large scale precipitation-related events.

Decadal fluctuations. The recent climate record contains several phases in which the global mean surface warming rate is lower in the observed record than predicted by models, and the multi-model multi-resolution ensemble might give insight in this. For instance, to reassess the possible causes for the recent global warming hiatus. In particular, the role of ocean heat uptake simulated by an eddy-permitting OGCM can be examined.

Time of emergence.

Decadal fluctuations.

Scale interactions. The relation between the simulation of small scale phenomena and the correct representation of large scale features of the global atmospheric circulation can be robustly assessed through the HighResMIP ensemble: existing high-resolution atmosphere simulations suggest that the characteristics of the jet stream (Hodges et al.,

2011) and blocking (Jung et al., 2012) will be improved by higher resolution.

Human health.

Climate services. Climate services in different sectors such as agriculture, energy production and consumption could benefit from user-relevant diagnostics computed from high resolution future projections.

Climate service

Ocean model biases. Existing high-resolution ocean simulations suggest that eddy-mean flow interactions can have positive impacts on typical ocean model biases such as North West corner cold bias, Gulf Stream path, warm bias in upwelling zones, warm bias in the Southern Ocean, and deep ocean bias and model drift. Such benefits may be especially seen in eddy-resolving ocean models.

Another potential use of these simulations is to give a baseline of the forced response only (using the best estimate of the SST forced response and the RCP radiative forcing) for near-term decadal predictions.

This can then be combined with coupled decadal predictions (or statistical modelling) that also include the ocean variability and its influence. See for instance Hoerling et al. (2011) as a first attempt to do this with low-resolution models.