REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE: Ireland

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Project title: HARMONIE Climate (HCLIM) Regional Downscaling Simulations for Ireland for SSP5–8.5

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** IEMCGO	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2022	
Would you accept support for 1 year only, if necessary?	YES X	NO

Computer resources required for 2022-2024: (To make changes to an existing project please submit an amended version of the original form.)		**2022**	**2023**	**2024**
High Performance Computing Facility	(SBU)	25 million		
Accumulated data storage (total archive volume)[2]	(GB)	50,000		

[1] The Principal Investigator is the contact person for this Special Project

This project is a 1-year continuation of the HCLIM Regional Downscaling Simulations for Ireland project (spiemcgo) which is due to finish this year. The aim of the original project was to produce and assess a set of future climate projections for Ireland by downscaling CMIP6 EC-Earth climate data using HCLIM (Belusic et al. 2020), a regional climate model based on the HARMONIE NWP modelling system (Bengtsson et al., 2017). A two-stage approach was taken, with the global data first downscaled to a 12 km domain over the North Atlantic and Western Europe using HARMONIE-ALADIN physics, and subsequently downscaled to a 4 km domain over Ireland and the UK using HARMONIE-AROME physics. The domains are shown in Fig.1.

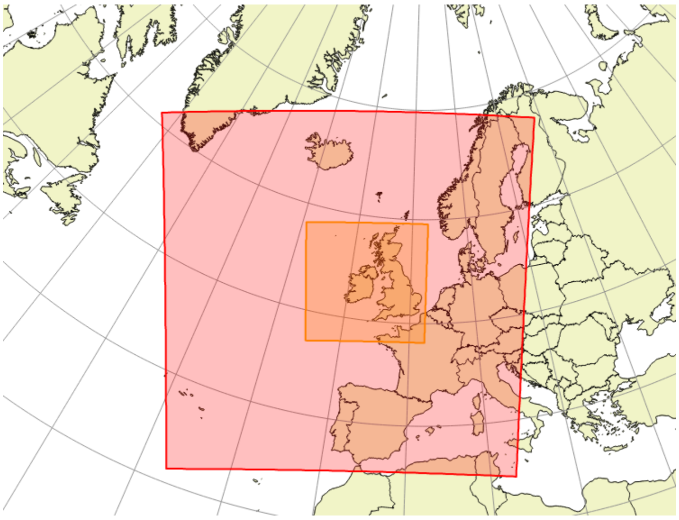

Fig. 1 *Domains of the 12 km resolution (red) and 4 km resolution runs (orange)*

Three experiments were originally planned:

Experiment 1:
HCLIM driven by lateral boundary conditions from ERA5 for the period 1981-2000. This run is used to validate Experiment 2.

Experiment 2:
HCLIM driven by lateral boundary conditions from an EC-Earth CMIP6 ensemble member for the present-day period 1981-2015. This run is used as a reference for Experiment 3.

Experiment 3:
HCLIM driven by lateral boundary conditions from an EC-Earth CMIP6 ensemble member for the "future" period 2015-2100, simulated using two ScenarioMIP "Tier 1" shared socioeconomic pathways (SSPs); SSP2–4.5 and SSP5–8.5.

Note: a brief overview of Shared Socioeconomic Pathways (SSPs), Representative Concentration Pathways (RCPs), and how the various ScenarioMIP cases (e.g. SSP2–4.5 and SSP5–8.5) were constructed is given in Annex 2 at the end of this proposal.

Due to computational constraints, it was decided in 2020 to focus on completing Experiments 1, 2, and half of Experiment 3, namely downscaling the SSP2–4.5 scenario. This was necessary due to a miscalculation in the original proposal and higher than anticipated costs when running HCLIM in default mode (see the Computational Resources section on the next page). The SSP2–4.5 scenario was chosen as it represents the medium part of the range of future forcing pathways (O'Neill et al., 2016); it was decided that this would be the most appropriate choice when focusing on a single future SSP scenario.

The original spiemcgo project is on track to complete its redefined set of goals by the end of 2021. This falls short of the original goal of also downscaling the SSP5–8.5 scenario. Downscaling this future scenario will enable users of the project's data to consider a credible high emission future scenario (O'Neill et al., 2016) for research purposes or when developing climate services for Ireland.

The output from downscaling the SSP5–8.5 scenario will be of benefit for Met Éireann's research project TRANSLATE. TRANSLATE aims to standardise Ireland's national climate projections and develop a range of climate services to meet the Irish adaptation sector's climate information requirements. The output will also feed into a range of other research projects both within Met Éireann and externally, such as extreme weather impact studies and studies of mid-latitude cyclones.

We therefore request a 1-year continuation of the spiemcgo project with the goal of downscaling the originally planned EC-Earth CMIP6 SSP5–8.5 scenario.

Computational Resources

When running on cca/ccb at ECMWF HCLIM can be configured in essentially two modes: the default or standard mode, which involves running the main Forecast module across a relatively high number of nodes (38) and results in the quickest runtime; or a cost-saving mode, which involves running the Forecast module across fewer nodes (10) and results in significant savings in computational costs at the expense of increasing the runtime by approximately a factor of two.

Due to delays in completing the EC-Earth CMIP6 simulations along with HCLIM bugs discovered when running at ECMWF, the main spiemcgo downscaling runs were delayed until Q4 2020. With a large SBU quota remaining for 2020 which could not be carried into 2021, the decision was taken to run HCLIM in default mode in order to make use of the available 2020 units. This enabled Experiments 1 and 2 to be completed, however at a relatively high cost of 31.6 MSBU. For a detailed breakdown of the computational costs see Annex 1 at the end of this proposal.

With fewer computational resources but greater available running time in 2021, the decision was taken to switch to running HCLIM in cost-saving mode for the SSP2–4.5 component of Experiment 3. The total cost for this run is approximately 30 MSBU (see Annex 1), 22.5 MSBU of which was supplied by the project's 2021 allocation (18 + 4.5 MSBU) while 7.5 MSBU was provided by the Met Éireann research account. As of the writing of this proposal (June 2021), this experiment has reached the year 2080 and is due to complete by the end of August 2021.

As with the SSP2–4.5 component of Experiment 3, approximately 30 MSBU will be required to run the SSP5–8.5 component, the goal of this proposal. Met Éireann is in a position to contribute 5 MSBU of the cost, leaving an outstanding balance of 25 MSBU. We therefore wish to apply for 25 MSBU for this proposal with a storage capacity of 50 TB.

**** Note that the remainder of this document contains the original project proposal. ****

Extended abstract

Aim

The overall aim of the proposed project is to assess the future projections of Ireland by downscaling CMIP6 EC-Earth climate data, using the climate mode of HARMONIE model (Bengtsson et al., 2017), HCLIM. This will comprise an assessment of the quality of HCLIM at the 4km scale to provide insight into the added value of climate simulations in the grey zone near the kilometre scale. The future projections will be validated against observations, and will serve to update previous downscaled CMIP5 climate projections for Ireland, and provide a basis for analysis and further research of Ireland's climate.

1. Scientific Background

In a changing warming climate, small-scale effects of climate change, such as windstorms, high temperatures and heavy rainfall have a large impact on society.

Numerous studies have demonstrated that high-resolution RCMs improve the simulation of precipitation (Bieniek et al., 2016; Kendon et al., 2014; Lucas-Picher et al., 2012) and topography-influenced phenomena and extremes with relatively small spatial or short temporal character (Feser and Barcikowska, 2012; Flato et al., 2013). Another advantage is that physically based RCMs explicitly resolve more small-scale atmospheric features and provide better representation of convective precipitation (Rauscher et al., 2010) and extreme precipitation (Kanada et al., 2008). Other examples of the added value of RCMs include improved simulation of near-surface temperature (Di Luca et al., 2016), European storm damage (Donat et al., 2010), strong mesoscale cyclones (Cavicchia and von Storch, 2011), North Atlantic tropical cyclone tracks (Daloz et al., 2015) and near-surface wind speeds (e.g. Kanamaru and Kanamitsu, 2007).

The added value of RCMs in the simulation of cyclones is particularly important as cyclones are the main delivery mechanism for precipitation in Ireland. The International Panel on Climate Change (IPCC) have concluded there is ‘high confidence that downscaling adds value to the simulation of spatial climate detail in regions with highly variable topography (e.g. distinct orography, coastlines) and for mesoscale phenomena and extremes’ (Flato et al., 2013).

High-resolution 21st Century regional projections of Ireland's climate are important for policy-makers, farming and climate services. Ensemble climate projections for Ireland (e.g., Nolan, 2017) show an overall warming; an increase in mean annual temperature (1-1.6 degrees), and reduction in number of frost days by ~50% by the mid-21st Century (2041-2060), compared to the reference 1981-2000 period. A 20% increase in heavy precipitation events is also expected, while the number of dry periods is predicted to increase by between 12 and 40%. These projections were obtained by downscaling an ensemble of CMIP5 RCP4.5 and RCP8.5 global data. Representative Common Pathways (RCPs) are greenhouse gas concentration trajectories adopted by the IPCC in 2014.

Regional Climate Models (RCMs) such as WRF and COMSO-CLM (e.g. O'Sullivan, 2015; Nolan, 2017), and RACMO2 (e.g. Lenderink, 2015) have demonstrated improved skill in the simulations of small-scale effects when compared with global climate model simulations. More recently, the climate mode of the HARMONIE NWP model (HCLIM) has been implemented and tested for downscaling (e.g., Lind, 2015).

The purpose of this project is to carry out the first downscaling projections of Ireland and Europe with HCLIM. This will serve to update the mid-century climate ensemble projections downscaled from CMIP5 data (e.g., Nolan 2017). These projections will also be a base for further study and analysis of the future Irish climate. Examples of this are the effects of climate change on the frequency and intensity of windstorms and heavy rainfall events in Ireland.

One of the first uses of HCLIM was for downscaling on a Euro-CORDEX domain (Lindstedt, 2015) at two resolutions, 6 km – within the 'grey-zone' regime - and 15 km, over 10 years. The RCM was driven by ERA-interim lateral and surface boundary conditions, for the 1997-2008 period (Lindstedt 2015). HCLIM has a convection scheme designed to operate in the 'grey-zone' 3-8 km resolution regime, which increases realism and accuracy of the time and spatial evolution of convective processes compared to more traditional parametrisations. The 6 km resolution run was compared to other European RCMs run in Euro-CORDEX, and performed well.

Lind 2015 examined summer precipitation in the Alps with HCLIM, at 15 km and 6.25 km. The regional climate was represented very well and higher order climate statistics and smaller scale spatial characteristics of precipitation were in good agreement with observations. The 'grey-zone' 6- km resolution run reproduced the frequency and intensity of high-intensity precipitation events with higher skill compares with the 15 km resolution and is in closer agreement with observations. For the proposed project, the future climate of Ireland will be simulated at ~ 4-km resolution. As part of the project the quality of HCLIM at the 4km scale will be assessed and provide insight into the added value of climate simulations in the grey zone near the kilometre scale.

Met Eirean researchers will carry out the HCLIM by downscaling EC-Earth CMIP6 data. Analysis will also be carried out by researchers in the climate services ERA4CS project. These runs will allow differences between current and future climate to be examined.

EC-Earth

The 6th phase of the Coupled Model Intercomparison Project (CMIP6) (Eyring, 2016) will play a key part in the 6th IPCC report. EC-Earth (Hazeleger et al., 2012) contributed to CMIP5, and is currently contributing to the CMIP6 project. EC-Earth consists of the ECMWF IFS atmospheric model, NEMO/LIM ocean and sea-ice model, a vegetation model and biogeochemistry model.

Met Éireann and ICHEC will carry out EC-Earth CMIP6 ScenarioMIP runs; with RCP 2.6, 4.5, 6 and 8.5, at T255L91-ORCA1L46 (80 km resolution in the atmosphere). CMIP6 also includes June 2019 Page 3 of 8HighResMIP runs, at T511-ORCA025L75 resolution (~39km resolution in the atmosphere). SSP -based RCPs are new CMIP6 versions of the RCPs based on the Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2014). Five new SSPs have been developed to give descriptions of future societal conditions that serve as the basis, both for deriving forcing pathways and for characterizing vulnerability and mitigative capacity important for IAV (impacts, adaptation and vulnerability). EC-Earth data has been downscaled using a range of RCMs, such as RACMO (Lenderink, 2017), COSMO-CLM and WRF (Nolan 2017). To date, HCLIM has been used to downscale ERA-Interim data. It has also been used to downscale EC-Earth datasets, run at 20 km resolution with ALARO, and also at 2km with AROME. This project would downscale the new CMIP6 EC-Earth data using HCLIM.

HCLIM

HCLIM is the climate version of the NWP non-hydrostatic meso-scale HARMONIE model (Bengtsson et al., 2017). The HARMONIE model over Ireland has performed well, and this is promising for using the climate version of HARMONIE for downscaling. Part of this project will assess the quality of HCLIM at the 4km scale to provide insight into the added value of climate simulations in the grey zone near the kilometre scale. Work on this will start in the second half of 2019 (see section 3 timeline).

Cycle 38 is the present stable version used for downscaling, and will be used in this project. Development work on the next version HCLIM, cycle 43, is being carried out. The core of the model is similar to that in NWP mode, with some differences. The surface parametrisation in HARMONIE is taken into account in SURFEX model (Masson et al., 2013). HCLIM has been run with a diffusion scheme as standard soil scheme, for example at KNMI and SMHI. At SMHI, they have used diffusion as the surface model setup at all resolutions and turned on TEB (town energy balance model) for resolutions less than 4 km. The diffusion scheme will be used for these simulations.

In the context of HCLIM ALARO refers to the used physics in an otherwise unchanged non-hydrostatic core. It has generally been recommended not to use HCLIM-ALARO in cy38, because of problems with coupling to the surface model. SMHI, for example, do not use, nor recommend to use it.

HCLIM-ALADIN should generally be used for resolutions greater than 10 km, though some use it even at 5 km. HCLIM has been run with ALADIN and AROME to downscale to 3 km; ALADIN down to 12 km, AROME down to 3 km. In order to downscale global data, it is suggested to use a two-stage downscaling. In the first step, EC-Earth 80 km resolution data would be downscaled down to 12 km using ALADIN physics, and in the second step, AROME physics to downscale further. Here it will to run at 4 km resolution and quality of HCLIM at the 4km scale to provide insight into the added value of climate simulations in the grey zone near the kilometre scale.

2. Simulations

This project will serve to update the mid-century climate ensemble projections carried out with CMIP5 data (e.g., Nolan, 2017), and to examine local climate change effects. The projections will also be useful for climate services for Ireland, and will be made available to third level institutions, policy makers, researchers and climate services (e.g. ERA4CS).

The domain of the proposed 4-km simulations will include UK and Ireland (see Fig. 2).

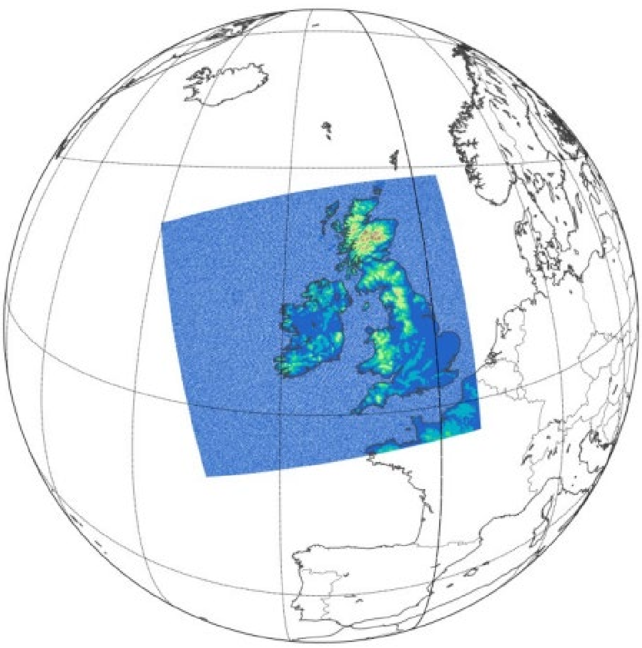

Fig.2 Ireland HARMONIE domain

These simulations will consist of an ERA-5 boundary condition run to validate the present-day climate, a present-day run using Historical EC-Earth data as input, and Future runs using RCP4.5 and RCP8.5 EC-Earth data as input.

In order to run the EC-Earth data simulations, preparations for HCLIM for EC-Earth have been and are taking place. Config files are being adapted. EC-Earth data needs to be compatible with HCLIM; working scripts are used to post process the data to make it compatible with HCLIM. The runs to be carried out are:

Experiment 1:

The lateral boundary conditions for HCLIM are taken from ERA 5, 1981-2000. This run will be used to validate the present-day run.

Experiment 2:

Present day Run with as input EC-Earth data over the 1981-2015 34-year reference period, from the historical EC-Earth run. This run will be used for comparison with the future runs.

Experiment 3:

Future 21st century Two future (2015-2100) HCLIM runs will be carried out at RCP4.5 and RCP8.5.

Validation

Experiment 1 will be validated against the gridded E-OBS observation dataset. Downscaled ERA5 will be compared to E-OBS temperature data. Experiment 2 will be validated with respect to the ERA5 run. Once experiments 1 and 2 are validated, mid- 21st century HCLIM runs will be carried out (exp 3).

3. Timeline

Work on this project was expected to start in 2019. As the EC-Earth simulations have been delayed to later than previously thought, however, I have focused on preparing for this up to now (monitoring, cmorisation...). It is thus expected the HCLIM work will commence over the summer, and continue in the latter half of this year and 2020; I will focus on the HCLIM work then.

As was suggested by the reviewers, it is proposed to first simulate Exp1 and 2 and make availability of the resources for Exp 3 dependent on explicit expectations and evaluations of these experiments.

4. Justification of computational resources

HCLIM will be used to downscale EC-Earth CMIP6 data. CMIP6 simulations have been delayed until June, later than previously thought, due to issues with the latest version of EC-Earth. In light of this in 2019 I have thus been working on EC-Earth, analysing EC-Earth data for validation & preparing (monitoring, cmorisation) the global data for downscaling with HCLIM.

I am keeping my account SBUs for the HCLIM work which will commence over the summer, and continue in the latter half of this year and 2020. I will focus on the HCLIM work then.

Experiments 1 and 2 will be performed in the second half of 2019, and it is envisaged that experiment 3 to start end 2019 or start 2020. Once Experiments 1 and 2 are carried out, an update will be made regarding the availability of the resources for Exp 3 in 2020.

A model run on an Ireland domain at 2.5 km resolution costs ~ 70 kSBU per month. This results in ~ 5 MSBU for 20 years at 4 km resolution, ~ 9 MSBU for 34 years, and ~ 23 MSBU per 85-year run.

The corresponding amount of output data is 15 TB.

For a detailed breakdown of the number of simulation years, computational costs and archive needs see Table 1 below.

	Description	Simulation yrs.	Total SBUs	Total Archive
Experiment 1 (2019-20) ***	ERA-5	20	5 million	5 TB
Experiment 2 (2019-20) ***	Present day	34	9 million	10 TB
Experiment 3 (2020)	Future	170	46 million	30 TB
Total			60 million	45 TB

Table 1. A breakdown of the number of simulation years, total SBU cost and total archive needs for each experiment

Annex 1: Computational Costs

Despite the limited time in Q4 2020, it was possible to complete both Experiments 1 and 2 of the original spiemcgo projet by running HCLIM in default mode. The total cost was approximately 31.6 MSBU. This cost was covered by a combination of the additional 10 MSBU granted in 2020, the initial project allocation of 20 MSBU, and 1.6 MSBU from the Met Éireann research account.

The costs of running in default mode are as follows:

12 km cost ~ 12 kSBU/month
4 km cost ~ 35 kSBU/month
Total cost ~ 47 kSBU/month

Each experiment requires a spin-up year in order to bring the model to a stable equilibrium. This results in 252 simulation months (21 years) needed to complete Experiment 1 and 420 simulation months to complete Experiment 2 (35 years). The total cost of both experiments is therefore:

(252 + 420) * 47 kSBU = 31.6 MSBU

For 2021 we had the initial project allocation of 18 MSBU combined with an additional 4.5 MSBU granted in April 2020, as well as additional units from the Irish research allocation. Given the limited number of resources and comparatively longer available runtime (all of 2021, versus Q4 2020) we switched to the cost-saving running mode. The associated costs are as follows:

12 km cost ~ 6.5 kSBU/month
4 km cost ~ 22.5 kSBU/month
Total cost ~ 29 kSBU/month

1032 simulation months (86 years) are needed to complete the SSP2–4.5 experiment, which results in a cost of approximately 30 MSBU. Combining the remaining project resources (22.5 MSBU) with additional units from the Irish research allocation (7.5 MSBU) we will have sufficient computational resources to complete this experiment by the end of August 2021.

The SSP5–8.5 experiment has the same cost as the SSP2–4.5 experiment, or approximately 30 MSBU when running in cost-saving mode.

Annex 2: RCP, SSP and ScenarioMIP

Representative Concentration Pathways (RCPs) are greenhouse gas concentration trajectories adopted by the IPCC. Four pathways were used for the IPCC fifth assessment report (AR5), namely RCP2.6, RCP4.5, RCP6 and RCP8.5. These pathways correspond to radiative forcing values in the year 2100 of 2.6, 4.5, 6 and 8.5 W/ m^2, respectively.

Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. There are five defined pathways, namely SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-fueled Development). The SSPs provide narratives describing alternative socio-economic developments, and have been used in phase 6 of the IPCC's Coupled Model Intercomparison Project, CMIP6.

The Scenario Model Intercomparison Project (ScenarioMIP) is the primary activity within CMIP6 that will provide multi-model climate projections based on alternative scenarios of future emissions and land use changes produced with integrated assessment models. SSPs can be combined with climate simulations from CMIP6 and a forcing pathway stabilizing at a certain W/m^2 value, e.g. 4.5 W/m^2 (O'Neill et al., 2016).

The full set of SSPs and forcing outcomes forms a matrix of possible integrated scenarios (van Vuuren et al., 2012, 2014; Kriegler et al., 2012). Each row contains climate model simulations based on a forcing pathway (e.g., a 4.5 W/m^2 pathway), which can be used in combination with the societal conditions described by any of the SSPs, as long as it is feasible that SSP emissions could be made consistent with that forcing pathway. These scenarios are referred to as SSPx–y, where x is the specific SSP and y represents the forcing pathway.

For example, SSP2–4.5 represents SSP2 (Middle of the Road) on a forcing pathway that stabilises at 4.5 W/m^2. This scenario represents the medium part of the range of future forcing pathways and updates the RCP4.5 pathway. SSP5–8.5 on the other hand, represents SSP5 (Fossil-fueled Development) on a forcing pathway that stabilises at 8.5 W/m^2. This scenario represents the high end of the range of future pathways in the Integrated Model Assessment (IAM) literature and updates the RCP8.5 pathway.

The ScenarioMIP experiments focus on a subset of all possible SSP and forcing pathway combinations. These scenarios are arranged into two tiers: Tier 1, which spans a wide range of uncertainty in future forcing pathways and includes new SSP-based scenarios as continuations of the RCP2.6, RCP4.5, and RCP8.5 forcing levels; and Tier 2, which includes additional scenarios of interest as well as additional ensemble members and long-term extensions.

Tier 1 consists of four scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. All four scenarios were used for the recent EC-Earth CMIP6 ensemble simulations. From these four scenarios, the original proposal aimed to downscale the EC-Earth SSP2-4.5 and SSP5-8.5 simulations. These two scenarios were chosen as they represent what can be considered as medium and high emission scenarios respectively (O'Neill et al., 2016).

References

Belušić, D., and Coauthors (2020). HCLIM38: a flexible regional climate model applicable for different climate zones from coarse to convection-permitting scales, *Geosci. Model Dev.*, 13, 1311–1333.

Bengtsson, L., and Coauthors (2017). The HARMONIE-AROME model configuration in the ALADIN-HIRLAM NWP system, *Mon. Weather Rev.*, 145(5), 1919-1935.

Bieniek, P., Bhatt, U., Walsh, J., Rupp, T., Zhang, J., Krieger, J., and Lader, R. (2016). Dynamical downscaling of ERA-interim temperature and precipitation for Alaska. *J. Appl. Meteorol. Climatol.* 55(3): 635–654.

Cavicchia, L., and von Storch, H. (2011). The simulation of medicanes in a high-resolution regional climate model. *Clim. Dyn.* 39: 2273–2290.

Daloz, A.S., Camargo, S.J., Kossin, J.P., Emanuel, K., Horn, M., Jonas, J.A., Kim, D., LaRow, T., Lim, Y.K., Patricola, C.M., and Roberts, M. (2015). Cluster analysis of downscaled and explicitly simulated North Atlantic tropical cyclone tracks. *J. Clim.* 28(4): 1333–1361.

Di Luca, A., Argüeso, D., Evans, J.P., de Elía, R., Laprise, R. (2016). Quantifying the overall added value of dynamical downscaling and the contribution from different spatial scales. *J. Geophys. Res. Atmos.* 121: 1575–1590.

Donat, M., Leckebusch, G., Wild, S., Ulbrich, U. (2010). Benefits and limitations of regional multi-model ensembles for storm loss estimations. *Clim. Res.* 44: 211–225.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.*, 9, 1937-1958.

Feser, F., and Barcikowska, M. (2012). The influence of spectral nudging on typhoon formation in regional climate models. *Environ. Res. Lett.* 7: 014024.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., and Rummukainen, M. (2013). Evaluation of Climate Models. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds). Cambridge University Press: Cambridge, UK.

Hazeleger, W., X. Wang, C. Severijns, S. Ştefănescu, R. Bintanja, A. Sterl, K. Wyser, T. Semmler, S. Yang, B. van den Hurk, T. van Noije, E. van der Linden, and van den Wiel, K. (2012). EC-Earth V2: description and validation of a new seamless Earth system prediction model. *Clim. Dyn.*, 39, 2611-2629.

Kanamaru, H., and Kanamitsu, M. (2007). Fifty-seven-year California reanalysis downscaling at 10 km (CaRD10). Part II. Comparison with North American regional reanalysis. *J. Clim.* 20: 5572–5592.

Kanada, S., Nakano, M., Hayashi, S., Kato, T., Nakamura, M., Kurihara, K., and Kitoh, A. (2008). Reproducibility of maximum daily precipitation amount over Japan by a high-resolution non-hydrostatic model. *SOLA* 4: 105– 108.

Kendon, E.J., Roberts, N., Fowler, H., Roberts, M., Chan, S., and Senior, C. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Change* 4: 570–576.

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., and Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways, *Global Environ. Chang.*, 22, 807–822/

Lenderink, G., and Attema, J. (2015): A simple scaling approach to produce climate scenarios of local precipitation extremes for the Netherlands, *Environ. Res. Lett.*, 10:8, 085001

Lindstedt, D., Lind, P., Kjellström, E., and Jones, C. (2015). A new regional climate model operating at the meso-gamma scale: performance over Europe, *Tellus A*, 67:1, 24138

Lind, P., Lindstedt, D., Kjellström, E., and Jones, C. (2016): Spatial and temporal characteristics of summer precipitation over Central Europe in a suite of high-resolution climate models, *J. Clim.*, DOI: 10.1175/JCLI-D-15-0463.1

Lucas-Picher, P., Wulff-Nielsen, M., Christensen, J., Adalgeirsdottir, G., Mottram, R., and Simonsen, S. (2012). Very high resolution regional climate model simulations over Greenland: identifying added value. *J. Geophys. Res.* 117: D02108.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A. and co-authors. (2013). The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.* 6(4), 929#960. DOI:10.5194/gmd-6-929 2013.

Nolan, P., O'Sullivan, J., & McGrath, R. (2017). Impacts of climate change on mid-twenty-first-century rainfall in Ireland: a high-resolution regional climate model ensemble approach. *Int. J. Climatol.*

O'Neill, B., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., and van Vuuren, D.P. (2014). A new scenario framework for climate change research: the concept of shared socio economic pathways. *Climatic Change, Special Issue*, Nakicenovic N, Lempert R, Janetos A (eds) A Framework for the Development of New Socioeconomic Scenarios for Climate Change Research.

O'Sullivan, J., Sweeney, C., Nolan, P., and Gleeson, E., (2015). A high-resolution, multi-model analysis of Irish temperatures for the mid-21st century. *Int. J. Climatol.*

Rauscher, S.A., Coppola, E., Piani, C., and Giorgi, F. (2010). Resolution effects on regional climate model simulations of seasonal precipitation over Europe. *Clim. Dyn.* 35: 685–711

van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S. K., and Arnell, N. (2012). A proposal for a new scenario framework to support research and assessment in different climate research communities, *Global Environ. Chang.*, 22, 21–35, 201