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Achievements in 2021

Towards an "eddy-resolving" decadal prediction system

In the last reporting period, MPI-M has performed a prototype ensemble of multiyear hindcast simulations with the ocean eddy-resolving MPI-ESM1.2-ER model setup (Gutjahr et al., 2019, MPI-ESM-ER in the following) and has preliminary evaluated its performance with a focus on the predictability of the 2015 North Atlantic record "Cold Blob". Our aim is to investigate potential improvements due to resolving ocean eddies in interannual to decadal climate variability and in the prediction skill of the North Atlantic circulation and climate of the regions impacted by it (Europe, Nordic Seas, and Arctic).

The MPI-ESM-ER setup is employing an "eddy-resolving" ocean component with a global resolution of 10 km and an atmospheric component with a resolution of 100 km (T127). We are comparing these "eddy-resolving" simulations with similar MPI-ESM1.2-HR experiments conducted within the CMIP6 DCPP-A framework (Marotzke et al., 2016) employing an "eddy-permitting" ocean configuration of 0.4° (~40km). Since both the radiative forcing (CMIP6), the assimilation procedure and ensemble generation are exactly identical, it allows us to isolate the effect of resolving oceanic eddies (and topographic features) in the MPI-ESM-ER prediction system.

Besides performing three ensemble members of historical+ SSP2-4.5 scenario simulations with MPI-ESM-ER covering the period 1950 to 2100, we have conducted a set of multiyear hindcast simulations covering the period 1992 to 2014. To use the supercomputing resources efficiently, the strategy so far was to spawn hindcasts every other year from an MPI-ESM-ER assimilation run conducted over the period 1992-2014. To assess the performance of the MPI-ESM1.2-ER prediction system, we have therefore conducted 12 ensembles of hindcast simulations that are 3-years long each. For the North Atlantic record "Cold Blob'' case study of 2015 we have expanded the MPI-ESM-ER hindcast ensemble to 10 members. These hindcasts used the same assimilation technique and data as the hindcasts performed with MPI-ESM1.2-HR within the CMIP6 DCPP-A project (Pohlmann et al., 2019) with all three climate system components initialised from observations: 3D oceanic temperature and salinity anomalies from ECMWF's Ocean Reanalysis System 4 (ORA S4, Balmaseda et al., 2012); atmospheric full field data from ECMWF's Reanalysis ERA40 (Uppala et al., 2005) and ERA-Interim (Dee et al., 2011); anomaly sea ice initialisation from the National Snow and Ice Data Center (Bunzel et al. 2016; Pohlmann et al., 2019)). To account for the different SST climatology in the MPI-ESM-HR configuration, the MPI-ESM-ER configuration and the observations, we also bias-correct the hindcasts. The bias-correction removes, for each lead time, the time mean of the respective lead time series constructed from the ensemble-mean hindcasts initialized every second year between 1992 and 2014.

Predictive skill of the North Atlantic subpolar gyre SST in the MPI-ESM based "eddy-permitting" and "eddy-resolving" forecast systems

The North Atlantic sea surface temperature (SST) has a strong influence on the climate of Europe (e.g. Årthun et al., 2017) and is one of the regions where models achieve a high predictability (e.g. Matei et al., 2012; Müller et al., 2012; Marotzke et al., 2016). Beside other factors, such as the assimilation technique or the type of assimilation data, the model resolution was found to affect the predictive skill as well (Prodhomme et al., 2016). Prodhomme et al. (2016) increased the ocean resolution from 1° to 0.25° and found improvements of model biases and also of the prediction skill. Here we go beyond and analyse improvements of prediction skill in the MPI-ESM1.2 prediction system resulting from an "eddy-resolving" (0.1°) oceanic component. In the following, we summarize the results comparing these MPI-ESM-ER hindcasts described above with five members of the MPI-ESM-HR hindcasts.

Figure 1 depicts the time series of annual mean SST averaged over the North Atlantic subpolar gyre (60°E-15°W and 50°- 65°N). The SST time series from the observations show both the distinct abrupt strong warming shift of 1995 and the cooling trend in the 2010s that culminated with the record cold blob conditions of 2015 (Duchez et al., 2016). Comparing the lead year 1 (first year after initialisation) time series of the hindcasts from MPI-ESM-ER with MPI-ESM-HR, there is a clear reduction in the systematic model bias by using an "eddy-resolving" ocean component in MPI-ESM-ER (Fig. 1a). All MPI-ESM-HR hindcasts are approximately 1°C too warm, but the MPI-ESM-ER hindcasts ensemble is very close to the observations. Reducing the SST bias in the North Atlantic will have implications for other quantities than SST, such as storm tracks or blocking events over Europe. This improvement of the SST bias in MPI-ESM-ER was also reported by Gutjahr et al. (2019) for a 1950 control simulation with MPI-ESM-ER. Although all simulations are able to reforecast the warming in the mid 1990s and the cooling from about 2010 onwards, the warming is less in the first half of the 1990s than observed one, particularly in the MPI-ESM-HR prediction system.

After removing the model systematic bias, the reforecasted SST anomalies agree well with the observations to a first order (Fig. 1b). However, again we note that the warm anomaly in the mid1990s is slightly less than in the observations, but consistent in all hindcasts, whereas there is much more uncertainty (spread of the hindcasts) for the sharp cold blob anomaly in 2015.

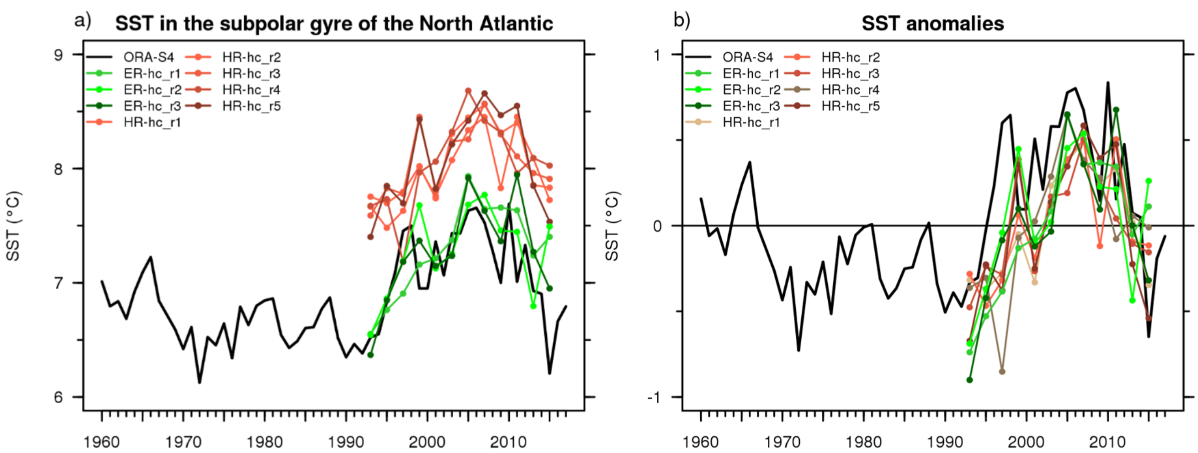

Figure 1: Time series of (a) absolute sea-surface temperature (SST) and (b) SST anomalies in the North Atlantic subpolar gyre (60° to 15°W and 50° to 65°N) over the period 1960-2017 from observations (ORA-S4) and MPI-ESM1.2 hindcasts (1995-2015) with MPI-ESM-ER and MPI-ESM-HR setups at lead time one year.

Case study: North Atlantic record "Cold Blob" and European heat waves in the summer of 2015

Because of this large uncertainty of the hindcasts in 2015 due to the chaotic nature of the atmosphere and its particular sensitivity to the initial values, we have made a more detailed comparison for the development of the two strong anomalies that coexisted in 2015: the record "Cold Blob" in the North Atlantic and the summer heat-waves over Europe. From Fig. 1 we conclude that both prediction systems are capable of reproducing a cold anomaly over the North Atlantic in 2015, but the strength of the anomaly is subject to great uncertainty. Only two of the five MPI-ESM-HR members are able to reforecast the magnitude of the cold anomaly closer to the observed value (Fig.1b). The reason why the spread of the hindcasts increase in 2015 is that the models first need to simulate a persistent strong NAO+ phase during the winter and spring of 2015, resulting in a westerly flow that constantly removes heat from the ocean to produce the "Cold Blob", and second the right timing of blocking events over Europe by a high pressure ridge that lead to the heat waves in the summer of 2015. Such complex conditions require a large ensemble of hindcasts to increase the signal-to-noise ratio. Understanding the reasons behind this challenge in successfully forecasting the North Atlantic "Cold Blob" event and associated impacts over European continent are currently subject to sustained efforts in the decadal prediction research community (e.g. Maroon et al., 2021). Particularly, the Blue-Action project has identified this impact-relevant extreme climate event as a test-bed for future development of multi-year-to-decadal prediction systems.

Four ensemble members initialized in November 2014 in MPI-ESM-ER configuration and two ensemble members in MPI-ESM-HR configuration simulate relatively cold anomalies in the entire subpolar North Atlantic in 2015 and warmer SSTs in 2016, thus a subpolar SST minimum in 2015 (upper panels in Figure 2; these members are shown by solid lines). As the observed absolute SST minimum in summer 2015 was strongest in the eastern part, we also assess the bias-corrected SST averaged over the eastern subpolar North Atlantic (lower panels in Figure 2). Regarding MPI-ESM-HR configuration, two ensemble members simulate an eastern subpolar SST minimum in 2015 (as for the entire subpolar North Atlantic), though the respective ensemble members are not identical (solid lines in left panels in Figure 2). Regarding MPI-ESM-ER configuration, one additional ensemble member simulates a subpolar SST minimum in 2015 in the eastern part (green lines in right panels in Figure 2), and another ensemble member simulates relatively cold anomalies in eastern subpolar SST in both 2015 and 2016 (dashed magenta line in lower right panel in Figure 2). Thus, six ensemble members in MPI-ESM-ER configuration simulate an eastern subpolar North Atlantic "Cold Blob" in 2015. One of these ensemble members even reproduces the full observed strength of the "Cold Blob" (solid red line in lower right panel in Figure 2), underlining the potential of high-resolution climate predictions.

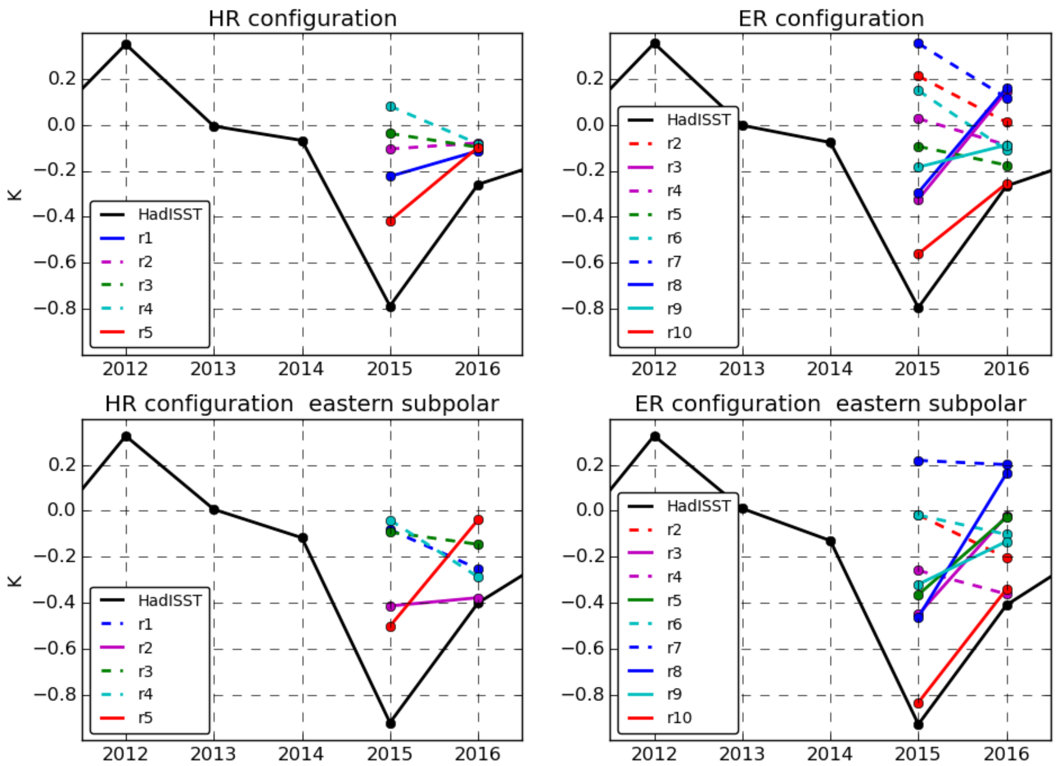

Figure 2: Annual mean SST averaged over the entire subpolar (60°W-15°W, 50°N-65°N; upper panels) and eastern subpolar (40°W-15°W, 50°N-65°N; lower panels) North Atlantic. North Atlantic SST in observations (anomalies with respect to 1992:2:2014, black line) and in the bias-corrected hindcasts initialized in November 2014 for MPI-ESM-HR configuration (0.4°ocean resolution; left panels) and MPI-ESM-ER configuration (0.1°ocean resolution; right panels). The bias-correction is based on the ensemble-mean hindcasts initialized every second year between 1992 and 2014.

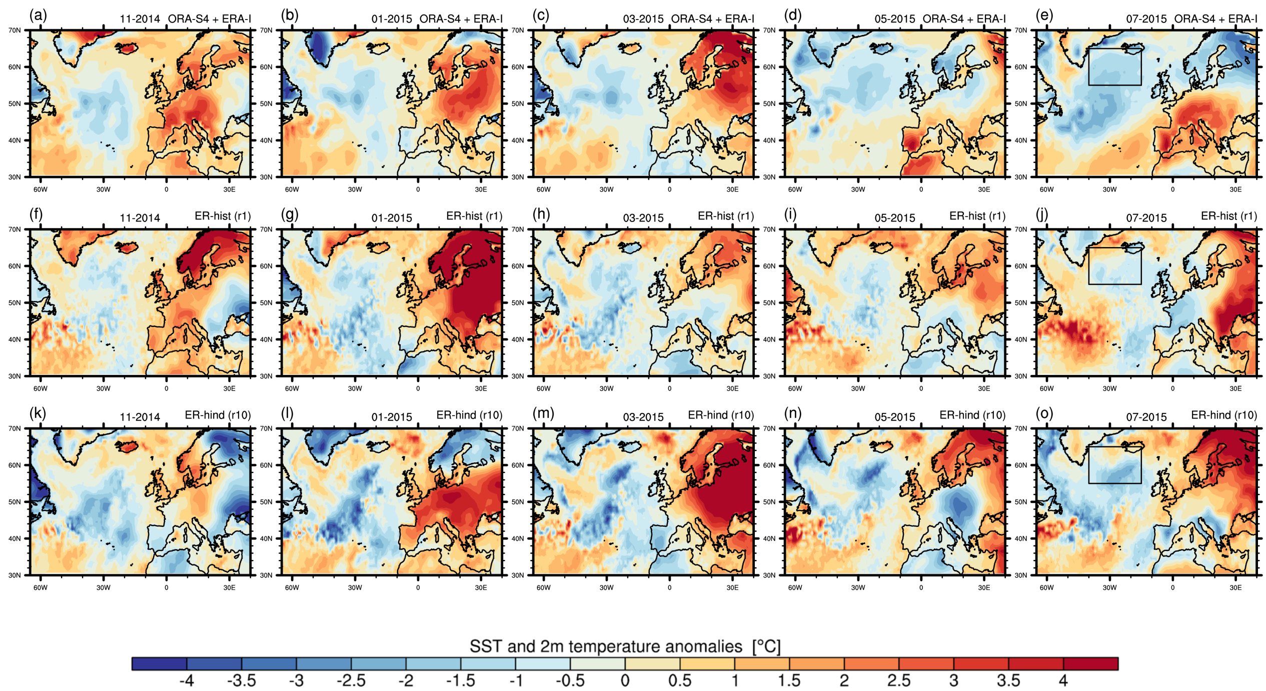

Figure 3: Monthly mean anomalies of sea surface temperature (SST) and 2m temperature from November 2014 to July 2015 relative to the mean 1981-2010. Top row: a composite of SST from ORA-S4 and 2m temperature from ERA-Interim. Middle row: first ensemble member of the MPI-ESM-ER historical simulations (ER-hist). Bottom row: one ensemble member of the MPI-ESM-ER hindcasts initialised on 1st November 2014. The black boxes in the last column illustrate the center of the SST cold anomaly in the North Atlantic and of the heat wave over central Europe.

We have further explored the development of the 2015 Cold Blob and its associated climate impacts over Europe. Figure 3 shows the evolution of the observed SST (over ocean) and 2m temperature (over land) and how it has changed from November 2014 to July 2015. Already at the beginning of November a -2°C colder anomaly ("cold blob") (Fig. 3a) has been developed in the observations. Its maximum extent and intensity was reached in July 2015. This cold blob developed due to a persistent strong wind forcing in an anomalously strong NAO+ phase that was maintained for about 6 months and caused a large heat loss to the atmosphere. Figure 4 (top row) shows a strong meridional gradient of the 850hPa geopotential over the North Atlantic that caused a strong western flow, which removed a large amount of heat from the ocean. This almost zonal flow remained until approximately March, when it had already become unstable and was blocked by a high pressure system that moved over Europe. This high pressure ridge then caused very weak wind conditions and shuffled warm air masses to central Europe, which resulted in a very strong heat wave over Europe (Fig. 3e) within the top 10 of the last 65 years (Russo et al., 2015).

We have further checked whether the observed development of the "Cold Blob" and its associated impacts are captured by the MPI-ESM-ER initialised and historical model simulations. Results are presented here from only one ensemble member of the historical and one of the 2014 initialised hindcast with the MPI-ESM-ER. The selected historical simulation coincides to some degree by chance with the observations for this period, while the other historical ensemble members do not. This preliminary analysis is currently being extended to the full 10-member MPI-ESM-ER hindcast ensemble. Both the historical and the hindcasts with MPI-ESM-ER reproduce the cold anomaly in the North Atlantic, although less pronounced than observed, and maintain a "Cold Blob" until March 2015, before the anomaly vanishes. Without simulating a correct strong cold anomaly, the meridional pressure gradient weakens too early so that the high pressure ridge moves northward either too early (Fig. 4n, MPI-ESM-ER_01) or has a wrong location (Fig. 4j, MPI-ESM-ER-hist).

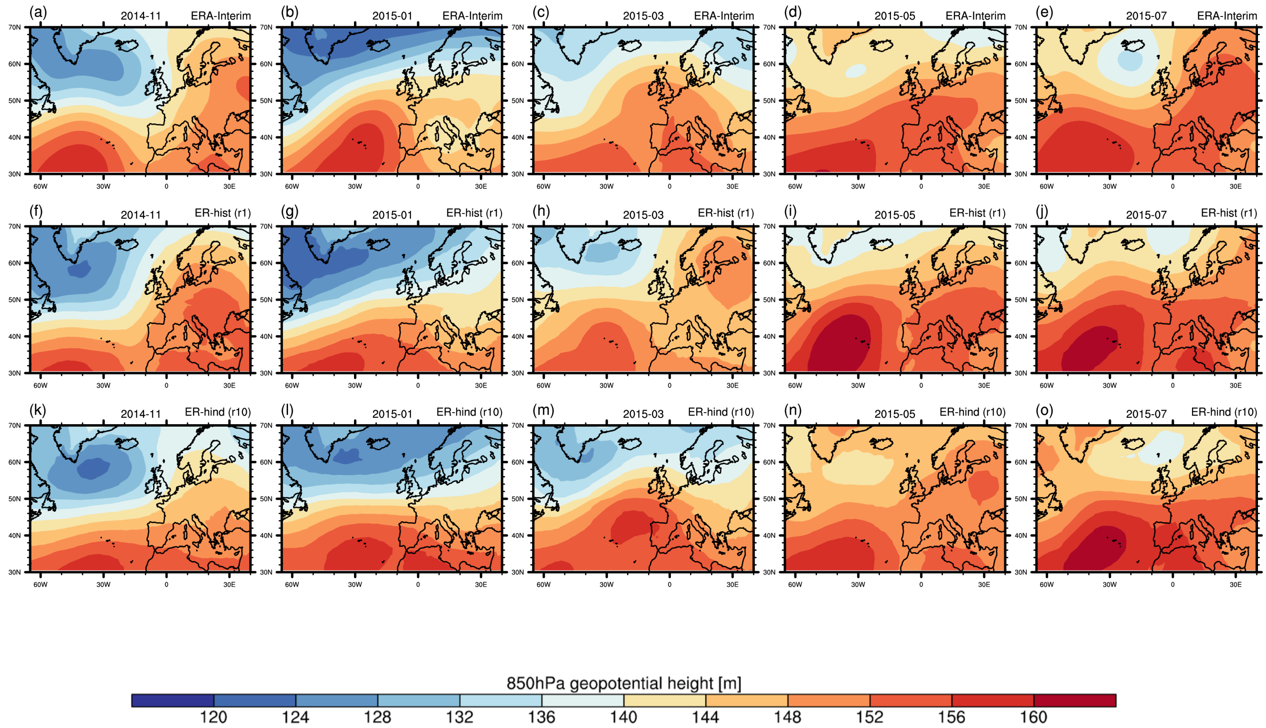

Figure 4: Monthly means of the 850 hPa geopotential height from November 2014 to July 2015 in observations and model simulations. Top row: from reanalysis ERA-Interim. Middle row: first ensemble member of the MPI-ESM-ER historical simulations (MPI-ESM-ER-hist). Bottom row: one ensemble member of the MPI-ESM-ER hindcasts initialised on 1st November 2014.

Predicting such extreme coupled climate phenomena over the North Atlantic-European region has proven to be very challenging for state-of-art prediction systems (Maroon et al, 2021). However, we could demonstrate that our prediction system is able to reproduce the observed anomalies but in years where it is absolutely necessary to forecast the atmosphere conditions too, it will require a large ensemble of hindcasts (of the order of 10 or more). We could also demonstrate that using an eddy-resolving ocean (0.1°) considerably improves the model systematic bias over the North Atlantic subpolar gyre. Based on these promising results, we plan to investigate other phenomena such as storm frequencies or blocking events over Europe, but also forecasting the Arctic sea ice.

References

Århun, M., Eldevik, T., Viste, E., Drange, H., Furevik, T., Johnson, H.L., Keenlyside, N. S., 2017: Skillful prediction of northern climate provided by the ocean. Nature Communications, 8, 15875, doi: 10.1038/ncomms15875.

Bunzel, F., W. A. Müller, T. Stacke, S. Hagemann, M. Dobrynin, J. Baehr, K. Fröhlich, H. Pohlmann, 2018: Improved seasonal prediction of European summer temperatures with new 5-layer soil-hydrology scheme. Geophys. Res. Lett., 45, 346-353.

Duchez, A. et al. (2016), Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. Environ. Res. Lett., 11, 074404, doi: 10.1088/1748-9326/11/07/074004.

Gutjahr, O., Putrasahan, D. A., Lohmann, K., von Storch, J.-S., Jungclaus, J. H., Brüggemann, N., Haak, H., Stössel, A., 2019: Max Planck Institute Earth System Model (MPI-ESM1.2) for High-Resolution Model Intercomparison Project (HighResMIP). *Geoscientific Model Development*, 12, 3241-3281, doi: 10.5194/gmd-12-3241-2019.

Matei, D., H. Pohlmann**,** J. Jungclaus, W. Müller, H. Haak, J. Marotzke, 2012: Two tales of initializing decadal climate prediction experiments with the ECHAM5/MPI-OM model. *J. Climate*, 25, 8502-8523.

Maroon, E., S. Yeager, G. Danabasoglou, N. Rosenbloom, 2020: Was the 2015 North Atlantic subpolar cold anomaly predictable? , submitted to *J. Climate*.

Marotzke, J., Müller, W. A., Vamborg, F. S. E., Becker, P., Cubasch, U., Feldmann, H., Kaspar, F., Kottmeier, C., Marini, C., Polkova, I., and others: MIKLIP - a national research project on decadal climate prediction. Bull. Amer. Meteor. Soc., 97, 2379-2394, doi: 10.1175/BAMS-D-15-00184-1.

Müller, W. A., Baehr, J., Haak, H., Jungclaus, J. H., Kröger, D., Matei, D., Notz, D., Pohlmann, H., von Storch, J.-S., Marotzke, J., 2012: Forecast skill of multi-year seasonal means in the decadal prediction system of the Max Planck Institute for Meteorology. Geophys. Res. Lett., 39, L22707, doi: 10.1029/2012GL953326.

Pohlmann, H., Müller, W.A., Bittner, M., Hettrich, S., Modali, K., Pankatz, K., Marotzke, J., 2019: Realistic quasi-biennial oscillation variability in historical and decadal hindcast simulations using CMIP6 forcing. Geophys. Res. Lett., 46, 14118-14125, doi: 10.1029/2019GL084878.

Prodhomme, C., Batté, L., Massonnet, F., Davini, P., Bellprat, O., Guemas, V., Doblas-Reyes, F.J., 2016: Benefits of increasing the model resolution for the seasonal forecast quality in EC-EARTH. J. Climate, 29, 9141-9162, doi: 10.1175/JCLI-D-16-0117.1.

Russo et al. (2015), Top ten European heatwaves since 1950 and their occurrence in the future. Environ. Res. Lett., 10, 123003, doi: 10.1088/1748-9326/10/12/124003.