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Deliverable D10.2

Comparison of statistics of selected meteorological events in CMIP5, CORDEX and in PRIMAVERA models

Deliverable Title	*Comparison of statistics of selected meteorological events in CMIP5, CORDEX and in PRIMAVERA models*	
Brief Description	*Assess and compare statistics of selected extreme events by constructing distributions from observations, from climate model ensembles and from PRIMAVERA simulations Stream 1 and (early) Stream 2.*	
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1. Executive Summary

This report describes the effect of changed model resolution on a set of climate indices and processes. This is done for the PRIMAVERA Stream1 models, but also CMIP5 and CORDEX models. The report studies how the simulated climate is affected by model resolution and if it is possible to evaluate which resolution that performs best compared to reanalyses. Furthermore the report analyses some specific processes (precipitation, storm tracks and hydrological indices) and how they are affected by model resolution.

In general higher model resolution leads to more detailed and more realistic climate, even though it is sometimes difficult to quantify the improvement. The largest differences between low and high model resolution are for precipitation, especially extreme precipitation, and extreme temperature. For specific processes it is easier to evaluate the effect of increased model resolution. Higher model resolution better reproduces high precipitation intensities. Higher model resolution also better reproduces extra tropical cyclones, both in terms of cyclone tracks and intensities. For some hydrological indices the PRIMAVERA high resolution model compares well, and even outperforms, high resolution regional models over central Europe.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Part B Section 1.1) WP numbers are in brackets:

No.	Objective	Yes	No
A	To develop a new generation of global high-resolution climate models. *(3, 4, 6)*		
B	To develop new strategies and tools for evaluating global high-resolution climate models at a process level, and for quantifying the uncertainties in the predictions of regional climate. *(1, 2, 5, 9, 10)*	X	
C	To provide new high-resolution protocols and flagship simulations for the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP6) project, to inform the Intergovernmental Panel on Climate Change (IPCC) assessments and in support of emerging Climate Services. *(4, 6, 9)*		
D	To explore the scientific and technological frontiers of capability in global climate modelling to provide guidance for the development of future generations of prediction systems, global climate and Earth System models (informing post-CMIP6 and beyond). *(3, 4)*		
E	To advance understanding of past and future, natural and anthropogenic, drivers of variability and changes in European climate, including high impact events, by exploiting new capabilities in high-resolution global climate modelling. *(1, 2, 5)*		
F	To produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in process understanding. *(2, 3, 5,*	X	

	6, 10)		
G	To engage with targeted end-user groups in key European economic sectors to strengthen their competitiveness, growth, resilience and ability by exploiting new scientific progress. *(10, 11)*	X	
H	To establish cooperation between science and policy actions at European and international level, to support the development of effective climate change policies, optimize public decision making and increase capability to manage climate risks. *(5, 8, 10)*		X

3. Detailed Report

Introduction

Climate adaptation is usually done at local to regional scale which increases the demand for detailed climate data. High resolution climate models provide more details than low resolution models, which in itself is of value. The simulated climate is more realistic when represented by many grid points (as in high resolution simulations) than by few (as in low resolution simulations). Is the simulated climate also “better” at high resolution, and not just more detailed? For example, dynamical and physical processes should be better resolved with higher resolution, like the breaking of atmospheric waves in the upper-atmosphere or the formation of clouds, which would lead to a better representation of these processes. There are some practical problems when evaluating the potential benefits of increased model resolution. Station-based observations represent local conditions and cannot be directly compared with model data, even if it is a high resolution model, since the latter will represent an area average rather than a point value. Furthermore, it is difficult to directly compare model simulations (and reanalyses) of different resolutions. If we want to study the effect of resolution it is desirable to keep the original resolution of each model, which means that it is impossible to compare two simulations grid point by grid point. Thus, it can sometimes be difficult to detect the added value of increased resolution even if it is there.

In this report we look at the PRIMAVERA Stream1 climate models to estimate the effect of increased resolution. The low and high resolution model versions are compared to each other for each model. The Stream1 models are also compared to reanalysis datasets to see how they compare to the observed climate. Reanalyses rather than point observations are used since they are gridded and thus easier to compare with model data. The problem of comparing data sets of different resolution described above applies also for this type of comparison. The Stream1 simulations are put in a wider climate model perspective by also including other global simulations (CMIP5 simulations at 150-250 km) and regional simulations (CORDEX simulations at 12.5-50 km). The focus of this report is on the observed climate.

1 Stream1 simulations

1.1 Models

The report is mainly based on results from the PRIMAVERA Stream1 models. Five global climate models are run for the recent past with a low resolution and a high resolution version. The resolutions vary between models; low resolution is about 80-160 km, high resolution 40-80 km. Table 1 in the appendix lists all models, details about the models can be found at: http://proj.badc.rl.ac.uk/primavera-private/wiki/Model_Specs

1.2 Potential for added value

At first we take a look at how the different model versions simulate temperature and precipitation and how the fields compare to one another.

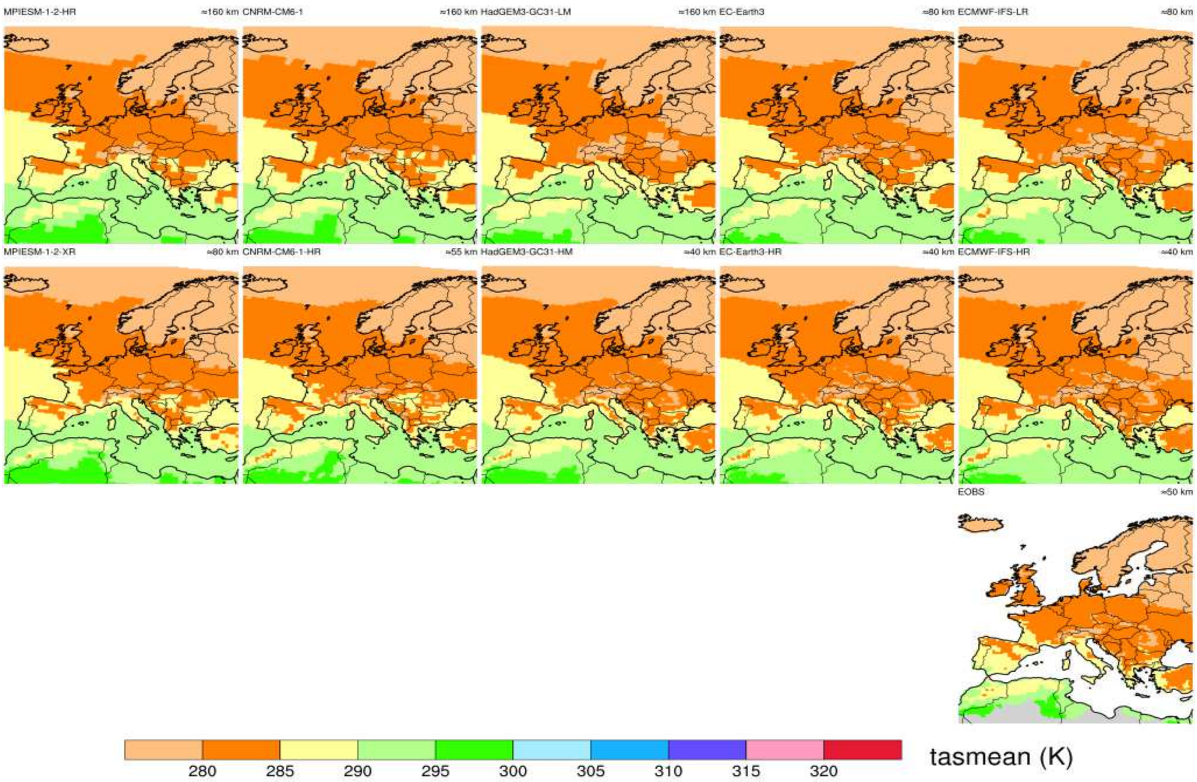


Figure 1. Mean annual temperature 1971-2000 (tasmean, K) in Stream1 simulation in the low resolution versions (top row) and high resolution versions (middle row). Bottom row shows reanalysis from EOBS.

Higher horizontal resolution generally gives a more detailed picture. Figure 1 shows average temperature 1971-2000 in five Stream1 models at low and high resolution. Higher resolution gives more details and more realistic features of for example coastlines and mountain ranges. The overall patterns of temperatures as well as the temperature values are, however, similar in both resolutions. Figure 2 shows annual mean precipitation for the same models. As for temperature higher resolution gives a more detailed picture, but with an even bigger importance of resolution. At low resolution precipitation is spread over large grid boxes, this means that precipitation is displaced and that the amount of precipitation is smaller than at higher resolutions where the precipitation is distributed in smaller grid boxes. Compare for example the Norwegian west coast and the Alps at low and high resolutions. The difference between models is bigger for precipitation than for temperature. As an example the amount of precipitation in CMRM-CM6-1 is larger than in HadGEM3-GC31, not only in the areas with large precipitation amounts but in general. The importance of resolution is even larger for extreme precipitation, here illustrated by the largest one-day precipitation (rx1day, Fig 3). Since extreme precipitation is more scattered than mean precipitation the size of the grid boxes is more important for the appearance of the field. With higher resolution more grid boxes have larger amount of extreme precipitation making extreme precipitation more extreme in higher resolution; however, the differences between models are large, larger than the difference between low and high resolution.

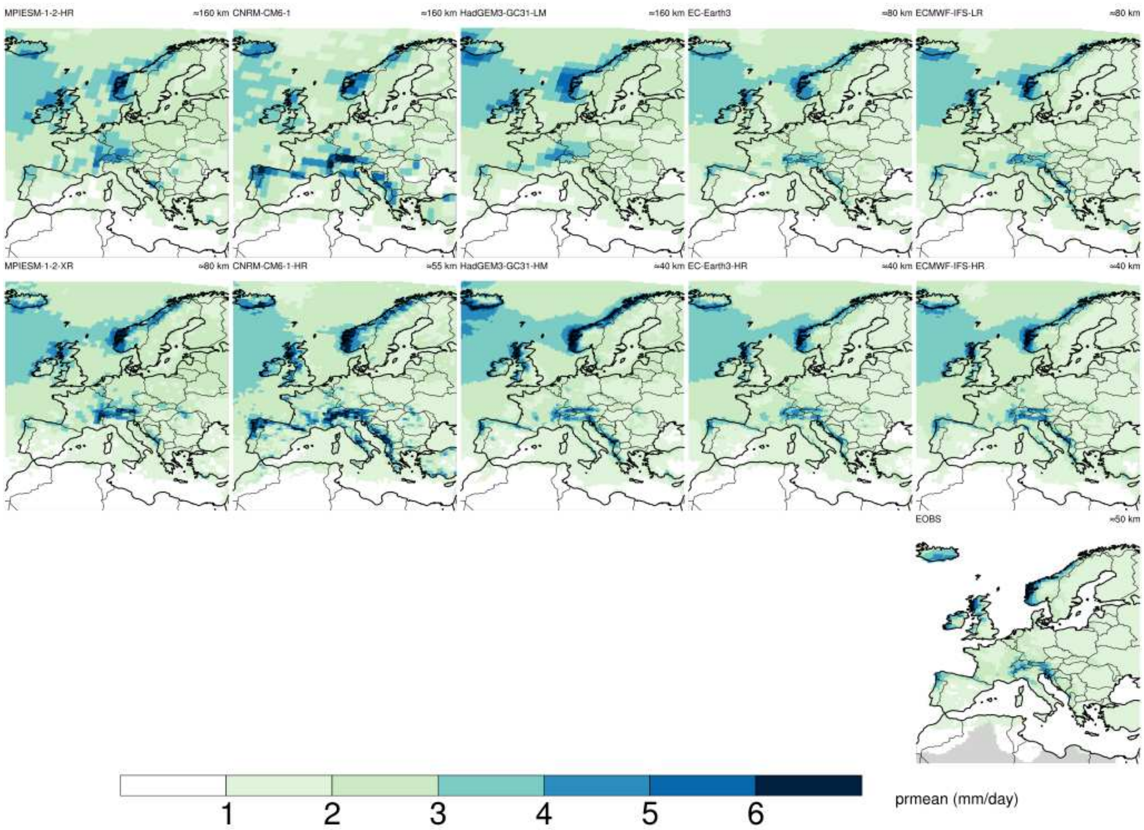


Figure 2. Mean annual precipitation 1971-2000 (prmean, mm/day) in Stream1 simulation in the low resolution versions (top row) and high resolution versions (middle row). Bottom row shows reanalysis from EOBS.

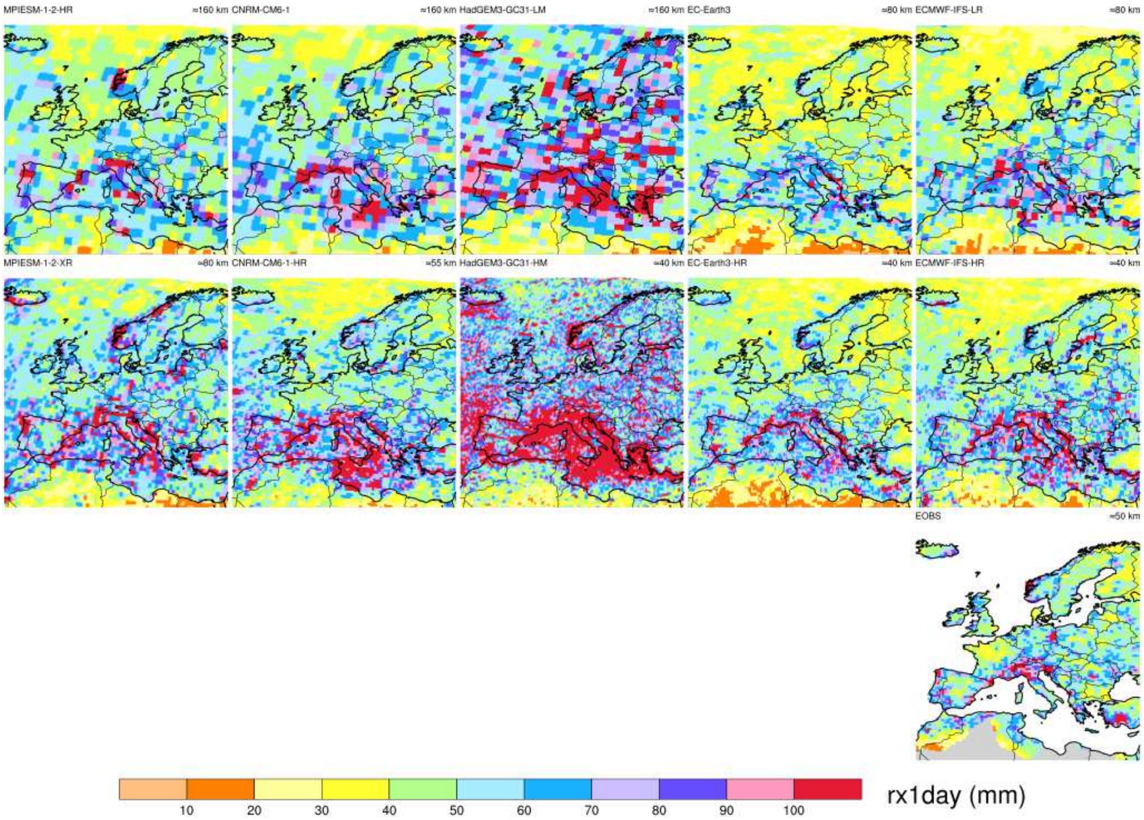


Figure 3. Maximum one day precipitation 1971-2000 (rx1day, mm) in Stream1 simulation in the low resolution versions (top row) and high resolution versions (middle row). Bottom row shows reanalysis from EOBS.

The previous sections show that there are differences in the simulated climate due to differences in model resolution, at least when looking at the simulated fields. The next step is to quantify the difference. A first way to test the value of higher resolution is to compare the low and high resolution version of each respective Stream1 model; if the models give significantly different results that tells something about the potential for added value by higher resolution. Note that this comparison does not tell which model version is the best, only if they are different or not.

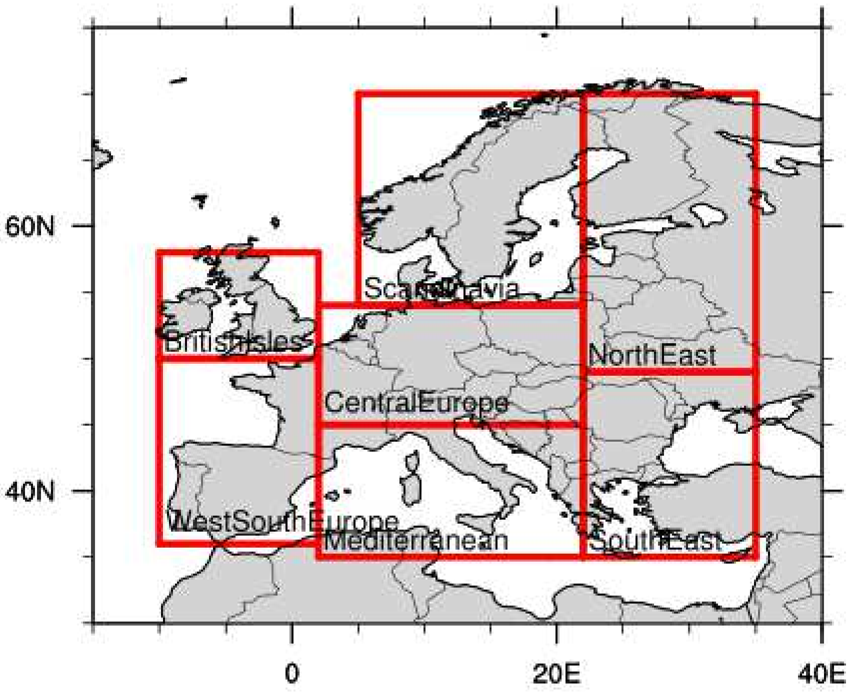


Fig 4. Regions used in the analysis. British Isles (BRI), Scandinavia (SCA), North East Europe (NEE), Central Europe (CEE), West South Europe (WSE), Mediterranean (MED), South East Europe (SEE).

For each sub-region (Fig. 4) data for all grid points in one model are treated as a data set. When two model versions are compared a Kolmogorov-Smirnov test (Chakravarti et al., 1967) is used to see if the two data sets are taken from the same distribution. The Kolmogorov-Smirnov test tells if we can reject the hypothesis that the two data sets are from the same distribution. Every pair of high and low Stream1 model versions are compared (Table 1 in Appendix). A significance level of 0.05 is used. For every region and parameter (listed in Table 2 in appendix) the differences between all model pairs are estimated. The interpretation is that resolution is more important for the simulated parameter if many model pairs are statistically different. The number of statistically significant different model pairs is used as an estimate of the potential for added value with higher resolution.

Table 3 in Appendix shows the number of models that show significant differences between resolutions. Precipitation based parameters (prmin to cwd) show the greatest potential for added value; especially different measures of extreme precipitation with 5-7 (out of 7) different model pairs in all regions. Different measures of average precipitation show a slightly smaller number of different pairs (5-6). Minimum precipitation (prmin) is the exception, but for a good reason; since it is always close to zero there is not much room for improvement. For wind based parameters (sfcWindmin to sfcWindmax) the number of different pairs is smaller than for precipitation (4-6). Minimum and maximum wind speeds show the greatest potential for added value resolution; 5-7 model pairs are different. Temperature based parameters (tasmin to su) generally show less differences between model pairs, but also larger spread between regions (2-6 model pairs different). For example tropical nights (tr) shows values from 0 to 7, and the 99th percentile of mean temperature 0-6. The temperature parameter with the largest differences is maximum temperature (tasmax) where 4-7 pairs are different. The reasons for pairs being different or not different can be many. In the case of indices based on fixed thresholds, such as tropical nights or summer days, systematic differences may prevent differences to show in the index. For example if the model has a cold or warm bias. The effect of increased resolution also differs between regions. The effect of increased resolution over all regions could be modest even if there is a clear improvement in some regions.

It is difficult to tell that the potential for added value is different in different regions in a systematic way. In a region, a low (high) value for one parameter is compensated by a high (low) value for another. No region appears to have a particular low or high potential for added value. The average potential for added value across all parameters is similar in all regions.

The behaviour of the individual models is analysed in box plots showing mean and spread of the same indices and regions as in Table 2. For mean temperature (tasmean) the mean value and quartiles of a region are similar in both low and high resolution, but there is a tendency for increased distance between minimum and maximum values in the high resolution simulations. For extreme temperature (here exemplified by maximum temperature, tasmax) the differences between model resolutions seem to be larger, but not in a systematic way (Fig. 4). For some models the higher resolution version gives higher temperature, for others the lower resolution version gives higher temperature. The differences are dependent on the region. In some regions, for example the Mediterranean region, the differences between model versions are small; in others, like the Central European region, they are larger. For surface winds (mean and maximum) there are differences between model versions, but it is hard to tell whether model resolution impact surface winds in any systematic way. For mean precipitation the differences between model versions are small, although the distance between minimum and maximum is larger in the high resolution versions. For different indices of maximum precipitation there is a clear shift towards higher values in the high resolution simulations.

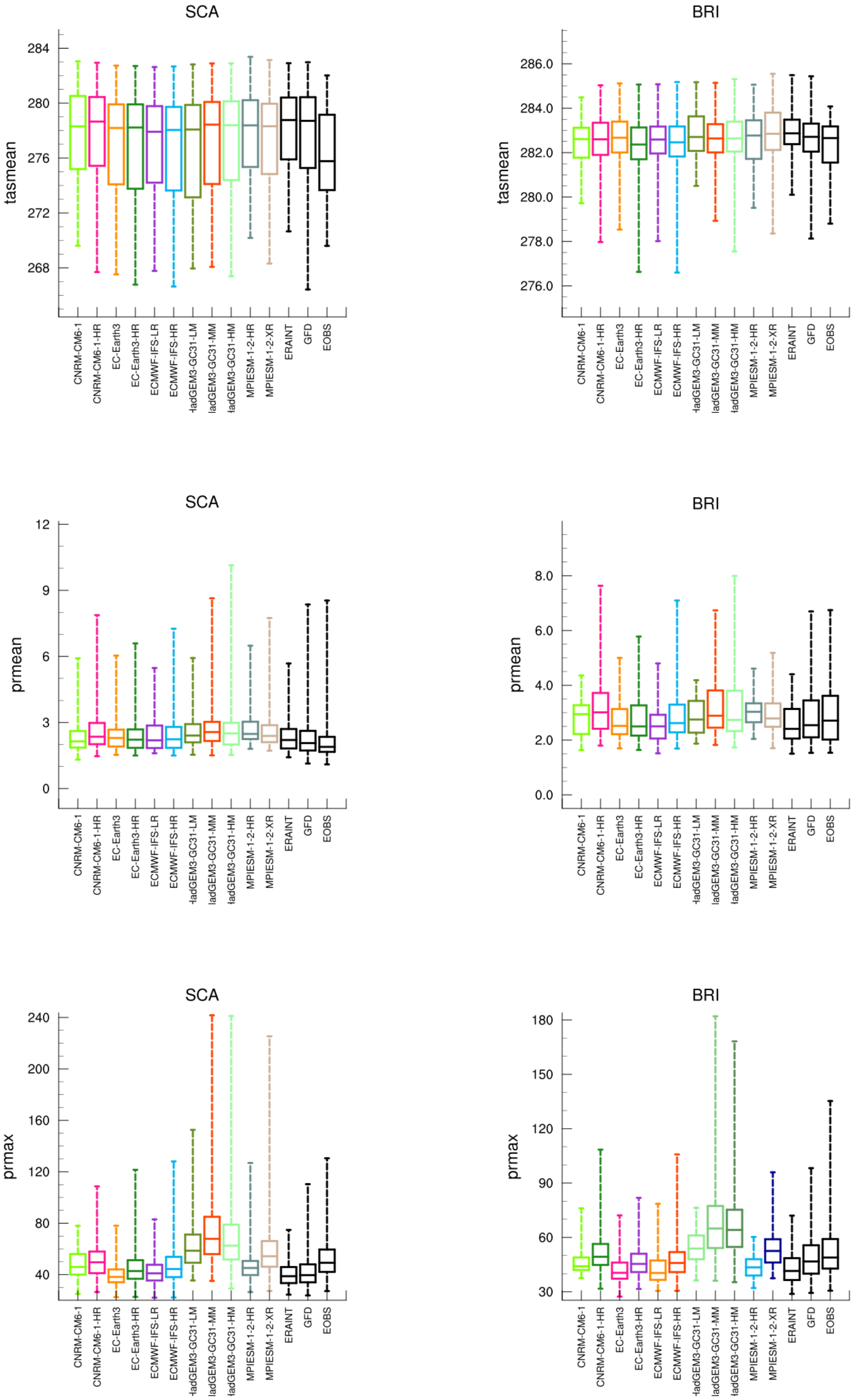


Figure 4. Some examples of indices across models (coloured boxes) and reanalyses (black boxes) in Scandinavia (SCA, left column) and the British Isles (left column) for average temperature (tasmean, top), average precipitation (prmean, middle) and maximum precipitation (prmax, bottom). Dashed vertical lines show the range from minimum to maximum value, the box spans the quartiles and the line

inside the box the median.

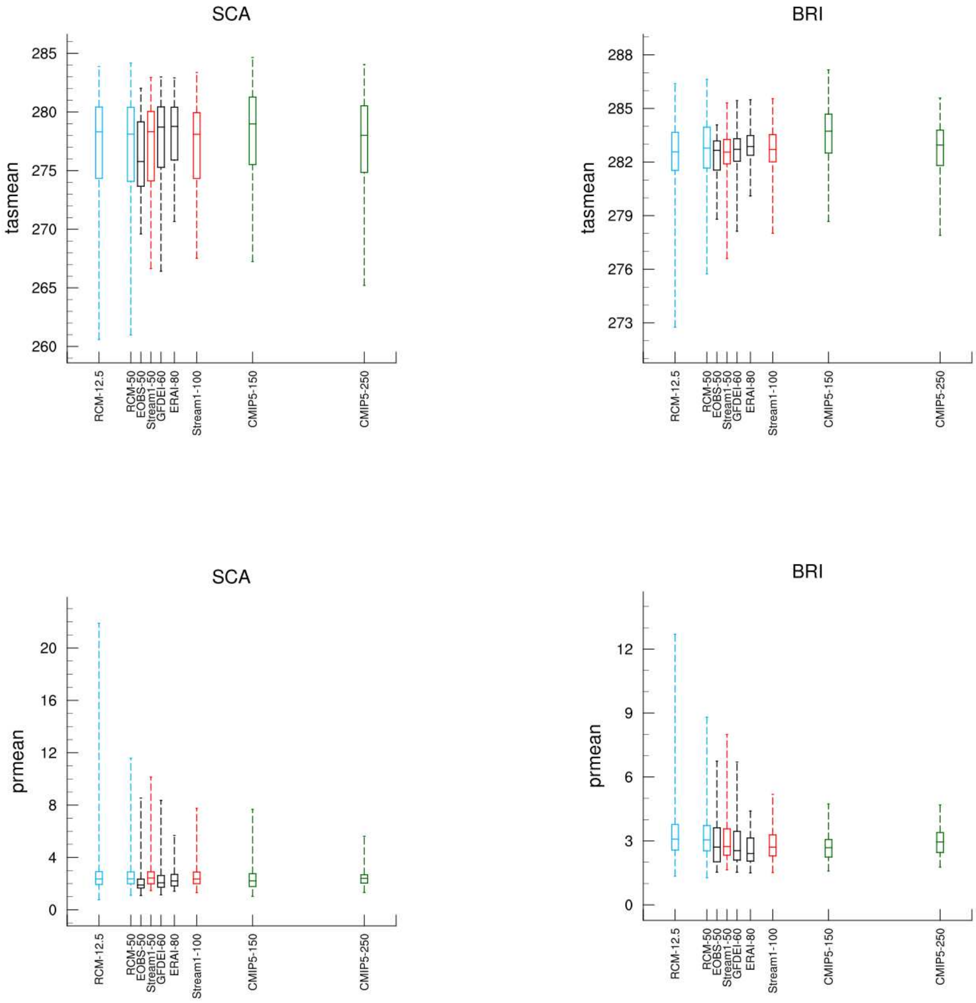
In the case of clear differences between low and high model versions, which one is the best? The model simulations are compared with three different reanalysis data sets with resolutions similar to the high resolution model versions (ERAINT (~80 km, Dee et al., 2011), GFD (~50 km, Berg et al., 2017), EOBS9.0 (~50 km, Haylock et al., 2008)) to see if the simulated climate improves with higher resolution. A root mean square error where each model simulation is compared to all three reanalyses is calculated to quantify the possible improvement in the simulated climate. In many cases, but far from all, the simulated climate is improved by increased resolution, especially for extreme precipitation. For average temperature and precipitation the difference between the resolutions is small. On the regional scale used here it is difficult to say that higher model resolution obviously leads to a climate that compares better with observations. For example, a model with a wet bias will not be improved by higher resolution; since higher resolution tends to give larger precipitation amounts the comparison with reanalyses will worsen. Does this mean that the high resolution model versions are worse than the low resolution versions? Or at least that it is not worth the effort of doing high resolution modelling? Not necessarily. Higher model resolution gives a more realistic picture of the climate (see Figs. 1-3). This is true even if the comparison to reanalyses does not improve.

In the case of precipitation the question of added value requires a more detailed analysis. Other studies within PRIMAVERA show that extreme precipitation is better reproduced in high resolution simulations. The highest precipitation intensities are only captured in the high resolution models (For more details see delivery report D2.2 Quantification of the benefits of increased model resolution in the Stream 1 simulations. See also section 3.1 below).

1.3 Stream1 compared to observations and other models

To put the findings from above in perspective they are compared with model simulations from CMIP5 (Taylor et al., 2011) and CORDEX (e.g. Jones et al., 2011; Gutowski et al., 2016). CMIP5 offers global simulations in the range 150-250 km and CORDEX offers European simulations in the range 12.5-50 km, this means that we have the possibility to study the impact of resolution over a wider range of resolutions than in the Stream1 simulations. This comparison corroborates the findings from above. Temperature based indices (here exemplified by average temperature, tasmean) are not much influenced by resolution, but the range between minimum and maximum values is larger in the CORDEX ensembles. There is, however, not a clear relationship between resolution and range since the ranges in the CMIP5 ensembles are larger than in the Stream1 ensembles. For indices based on average precipitation (such as average precipitation, prmean) higher resolution means a larger range between minimum and maximum values, which basically is a result of increased maxima; even though the median values are similar across resolutions (Fig. 5). For maximum precipitation and indices based on that, the maximum values increases with higher resolution just like for average precipitation, but there is also a tendency for increased median values.

In general there is an agreement between the model ensembles in how model resolution affects the simulated climate. The low resolution Stream1 ensemble behaves similarly to the CMIP5 ensemble of corresponding resolution; and the high resolution Stream1 ensemble behaves similarly to the reanalysis and CORDEX ensembles of corresponding resolution. At the edges of the range the high resolution CORDEX ensemble and low resolution CMIP5 ensemble fall into the picture of how the simulated climate relates to model resolution.



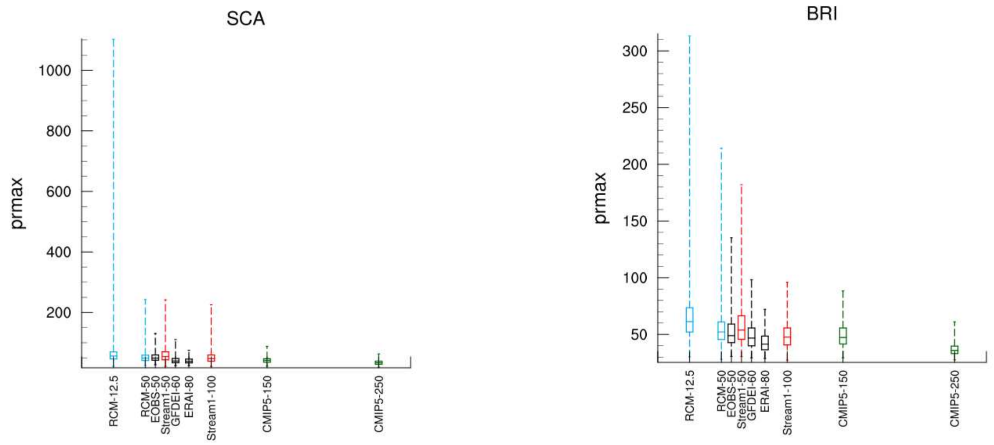


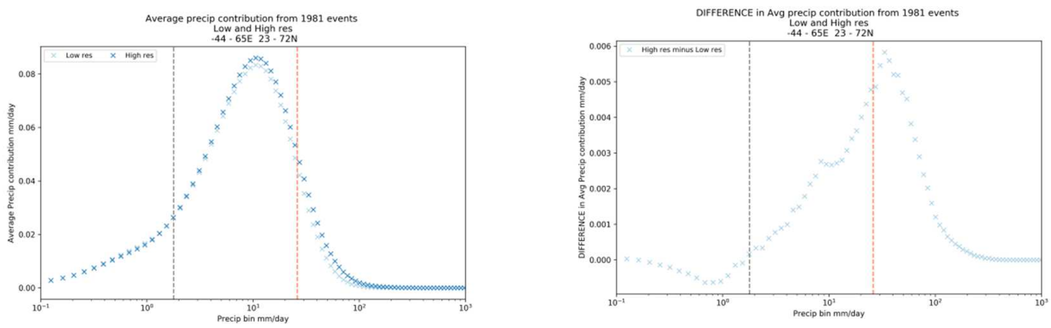
Figure 5. Some examples of indices across model ensembles (CORDEX in blue, Stream1 in red, CMIP5 in green) and reanalyses (black boxes) in Scandinavia (SCA, left column) and the British Isles (left column) for average temperature (tasmean, top), average precipitation (prmean, middle) and maximum precipitation (prmax, bottom). Dashed vertical lines show the range from minimum to maximum value, the box spans the quartiles and the line inside the box the median. The x-scale indicates resolution size, from 12.5 km (RCM-12.5) to 250 km (CMIP5-250).

2 Part II – specific processes

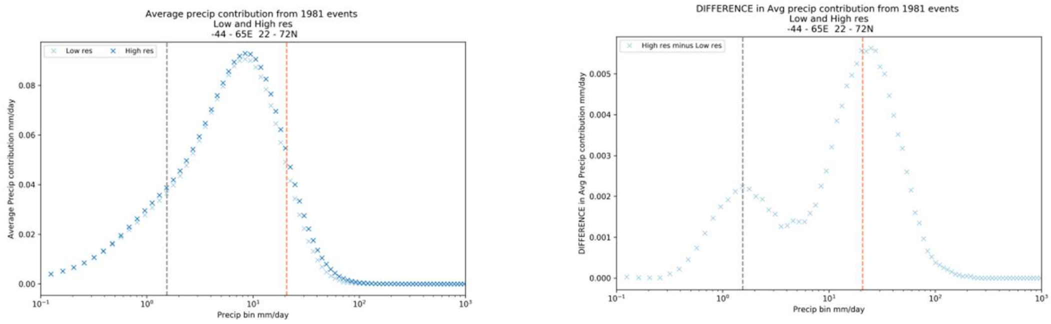
2.1 Precipitation dynamics

In this section we look especially on the effect from resolution on the intensity of precipitation. This is done using the ASoP (Analyzing Scales of Precipitation) software (Klingaman et al., 2017), which measures the spectrum of precipitation intensities. Here, the low and high resolution versions of the Stream1 simulations are analysed and compared. The analysis shows in which intensities precipitation changes depend on resolution. Figure 6 shows how the different precipitation intensities contribute to the total amount of precipitation, and how the intensities differ between model versions. This is done for the whole European domain. The distributions are calculated for each model land grid point and then averaged over the European domain.

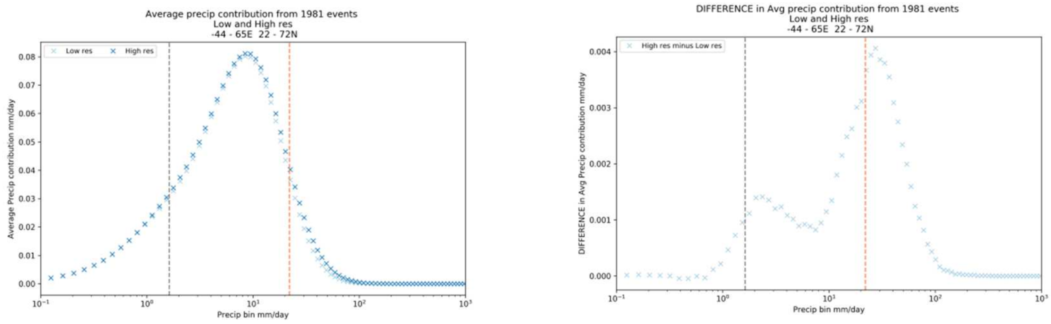
CNRM-CM6-1



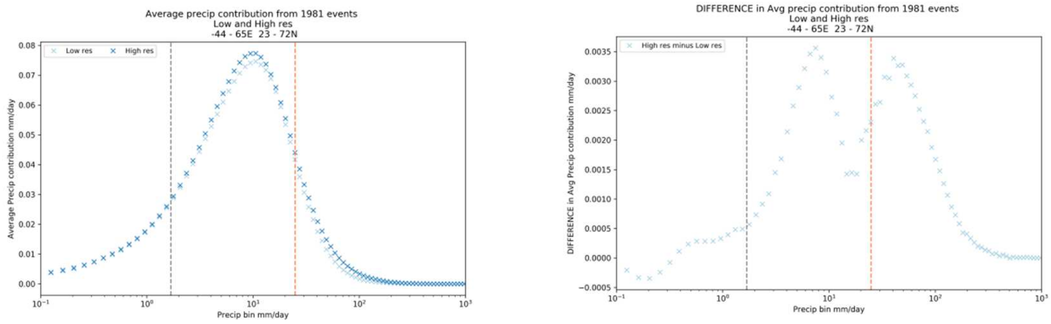
EC-Earth3



ECMWF-IFS



HadGEM3-GC31



MPIESM-1-2

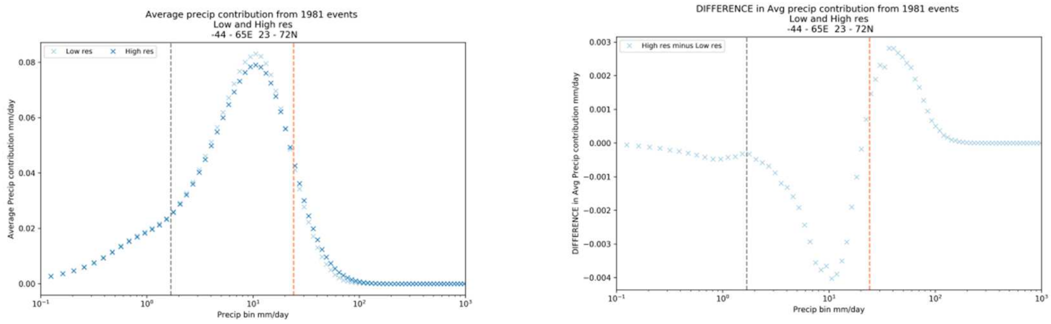


Figure 6. Precipitation contributions to different intensities. Y-axes show precipitation amount in mm/day, x-axes show precipitation intensity in mm/day. Left column: precipitation amounts in absolute values for low resolution (light blue crosses) and high resolution (dark blue crosses). Right column: Difference in precipitation amount (high resolution – low resolution). Gray vertical line marks median precipitation amount, red vertical line marks the 99th percentile.

The overall precipitation distribution is similar in all models and all resolutions (left column in Fig 6). There are, however, some notable differences between the high and low resolution versions (right column in Fig. 6). In all models but MPIESM-1-2 the total amount of precipitation is higher in high resolution than in low resolution (values in the right column are mostly above zero); the largest difference is seen at high intensities, all models have a peak in the difference curve at around the 95th percentile. EC-Earth3 and ECMWF-IFS also have peaks at the median, while HadGEM3-GC31 has a peak between the median and the 99th percentile. It's a clear feature that higher model resolution gives more intense precipitation. In all cases but one this is not a result of a shift in how the intensities are distributed, i.e. that the high intensities grow on the expense of lower intensities, but on an overall increase in precipitation. This means that when it rains in the high resolution version it rains more; but not more often, since the number of precipitation days (days with at least 1 mm of precipitation) is similar in low and high resolution simulations.

2.2 Storm tracks

2.2.1 Introduction

As part of WP11, interviews were conducted with 8 participants from the insurance industry, to discover how they might benefit from high resolution global climate models (see PRIMAVERA deliverables 11.6 and 10.1). Their main concerns were wind storms and flooding, since these are the highest loss hazards covered by property insurance policies. Due to the lack of sufficient observational data, climate models can be used to augment observational datasets to estimate long return period losses. PRIMAVERA models could prove very useful for this purpose if it can be shown that they realistically simulate wind storms and flooding. Since extra-tropical cyclones (ETCs) are the main cause of winter European wind storms, as well as being associated with flooding in this document we compare ETC characteristics between 2 re-analysis datasets and PRIMAVERA models, and also with CMIP5 models to see if PRIMAVERA shows any improvement.

2.2.2 Method

The PRIMAVERA models analysed here are the present day AMIP runs at the highest resolution currently available. Only one ensemble member has been analysed from each modelling centre. TRACK (Hodges 1995) has been used to track all the ETCs. The TRACK algorithm tracks maxima in the 850hPa relative vorticity field filtered to T42 resolution. Tracks are retained for ETCs which last at least 2 days, travel >1000km and have a maximum relative vorticity >10^{-5} s^{-1}. The CMIP5 present day AMIP runs from the same modelling centres (where available) and ERA-Interim (Dee et al 2011) as well as MERRA 2 (Gelaro et al. 2017) re-analysis datasets have been tracked in the same way (tracks from the ERA Interim data kindly provided by Kevin Hodges and Robert Lee and from the MERRA2 data by Malcolm Roberts). All the results presented here are for winter (DJF) ETCs over the period common to all datasets (1979/80 – 2007/08 for the ERA Interim based analyses and 1980/81 – 2007/2008 for the MERRA2 analyses). Table 3 summarises the models analysed in this document and their resolutions.

Modelling centre	PRIMAVERA model analysed	CMIP5 model analysed
CMCC	CMCC-CM2-HR4 (100km)	CMCC-CM (70km)
CNRM	CNRM-CM6-1-HR (45km)	CNRM-CM5 (100km)
ECEARTH	ECEARTH3-HR (25km)	ECEARTH (80km)
MOHC	HadGEM3-GC31-HM (25km)	HadGEM2-A (90km)
MPI	MPI-ESM-1-2-XR (50km)	MPI-ESM-MR (130km)
ECMWF	ECWMF-IFS-HR (25km)	Unavailable

Table 3. Summary of models analysed in this poster with approximate horizontal resolutions at mid latitudes (50ºN). CMIP5 resolutions from https://portal.enes.org/data/enes-model-data/cmip5/resolution

2.2.3 ETC locations (track densities)

Track densities from each model were calculated by counting the number of storms each month passing within a 6.3º radius of each grid point, as in Economou et al. (2015) (Figures 7 and 8 for ERA Interim and figure 9 and 10 for MERRA 2). Figure 11 shows the reduction in bias from CMIP5 to PRIMAVERA (|CMIP5 bias| - |PRIMAVERA bias|) for each model, while figure 12 shows the same change in terms of biases from the MERRA2 reanalysis. Red areas (positive reduction) show where there is improvement.

Results are mixed (look at figure 7 and 8): ECEARTH and MPI show large areas of reduced bias in PRIMAVERA, but CMCC shows an increased bias in northern Europe (although the very high resolution CMCC model has not been tracked yet).

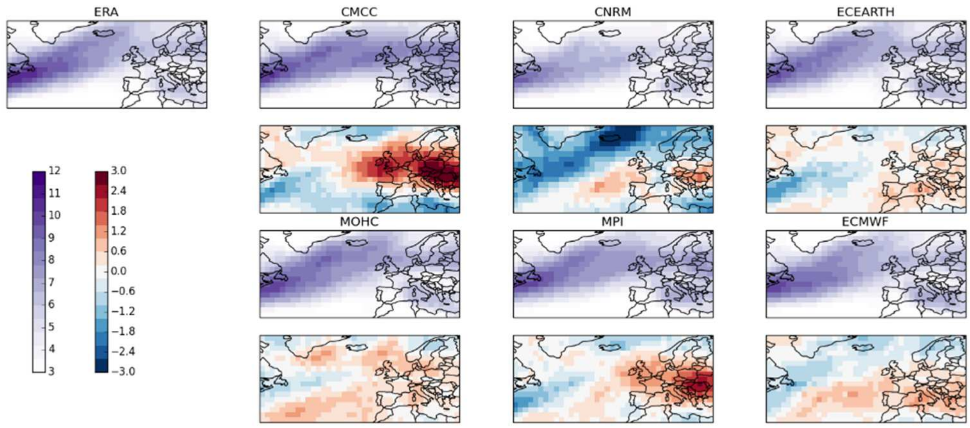


Figure 7. North Atlantic/European track densities of ERA (left) and PRIMAVERA models (right). The plots indicate the mean monthly number of storms passing around each grid point for the winter season (purple colors) and the biases between the model simulated number of storms and the respective reanalysis simulated number of storms (red-blue colors).

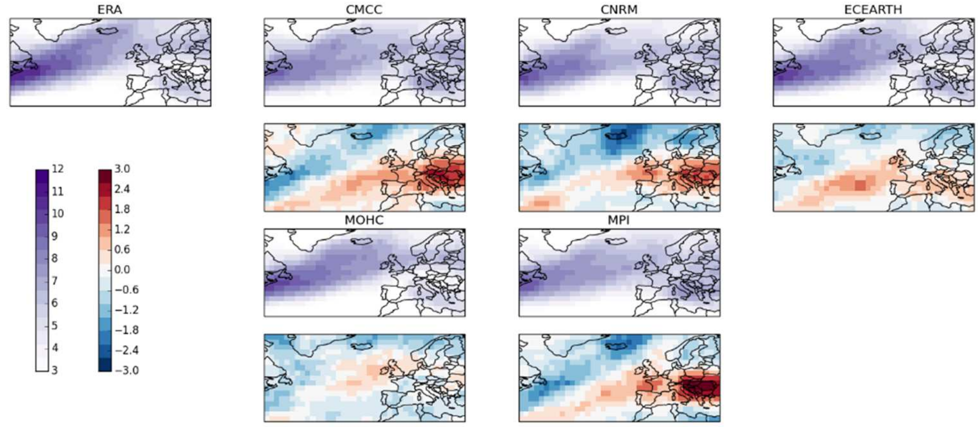


Figure 8. As for Figure 7, but CMIP5 models. The model bias (model – ERA, red-blue colour scale) is shown beneath each track density plot.

The same comparison was also made with the MERRA 2 reanalysis dataset (½° latitude by ⅝° longitude, or approx. 50km in latitudinal direction) which has a finer resolution compared to the ERA Interim data (0.75˚ resolution, or approx. 80 km), see figure 9 and 10.

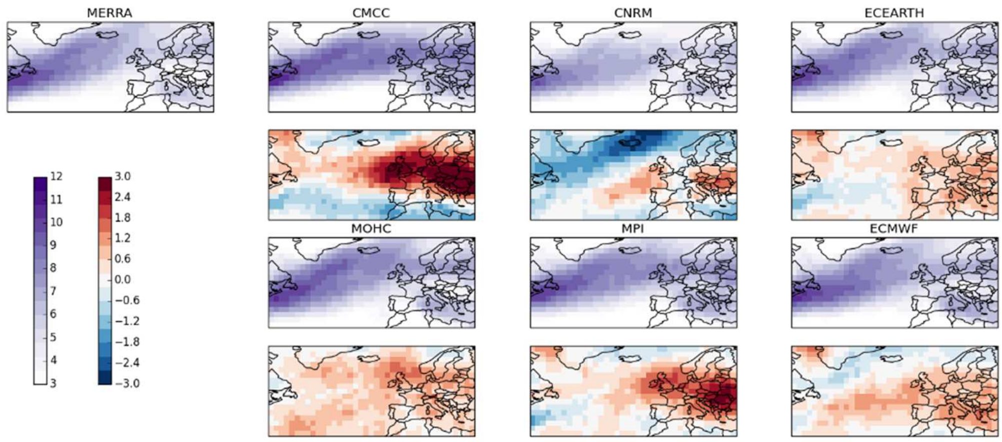


Figure 9. North Atlantic/European track densities of MERRA2 (left) and CMIP5 models (right).

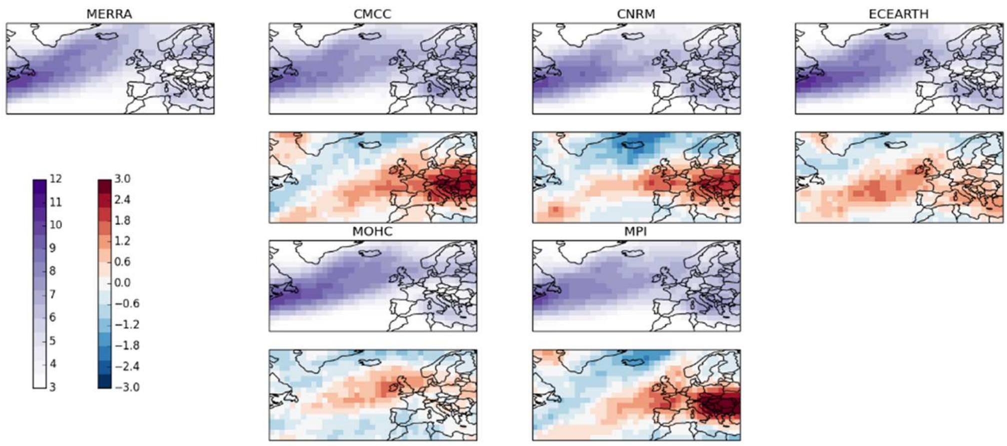


Figure 10. North Atlantic/European track densities of MERRA2 (left) and CMIP5 models (right). The model bias (model – MERRA, red-blue colour scale) is shown beneath each track density plot.

Looking at figures 9 and 10 the PRIMAVERA models are characterised by smaller biases overall compared to the CMIP5 models. One exception is the CMCC model which has a higher resolution in the CMIP5 set of models. The patterns of the biases are similar for the MPI and CNRM models, while it differs for the MOHC, the EC-Earth and the CMCC models.

The improvement in terms of bias from the ERAI or MERRA2 reanalyses that can be found within the PRIMAVERA models compared to the CMIP5 models can be seen in figures 11 and 12.

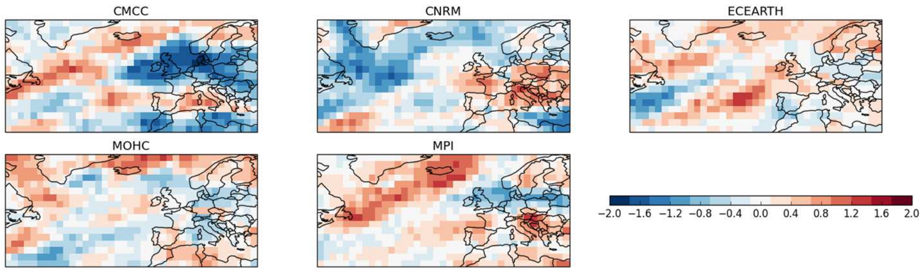


Figure 11. Change in storm track bias (as compared to ERAI) between CMIP5 and PRIMAVERA models measured in mean monthly number of storms.

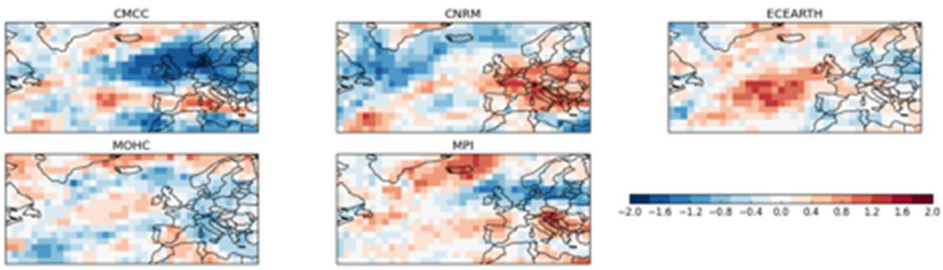


Figure 12. Change in storm track bias (as compared to MERRA2) between CMIP5 and PRIMAVERA models (red = reduction in bias for PRIMAVERA models).

There is a greater improvement of the PRIMAVERA models compared to the CMIP5 models when considering the changes in biases from the MERRA 2 storms, one exception is the CMCC model

2.2.4 ETC variability

It is important for the insurance industry that models capture the variability in ETCs striking Europe each year. Figures 13 and 14 show the number of ETCs entering a European domain (-15˚E to 25˚E, 35˚N to70˚N) each winter for the period 1979/80 – 2007/08, for PRIMAVERA and CMIP5 models, with ERA ETCs plotted in the thick black line. All models have similar standard deviation in ETC numbers and compare well to ERA – See figures 13 and 14.

Similar comparison was made also between the PRIMAVERA and CMIP5 models and the MERRA2 reanalysis based storm frequencies (Figs 15 and 16). The standard deviation of the storm numbers vary to a greater extent around the MERRA storms standard deviation. Similarly to the comparison with ERA Interim based storms the PRIMAVERA models show somewhat higher number of storms entering the European domain (Figure 15)

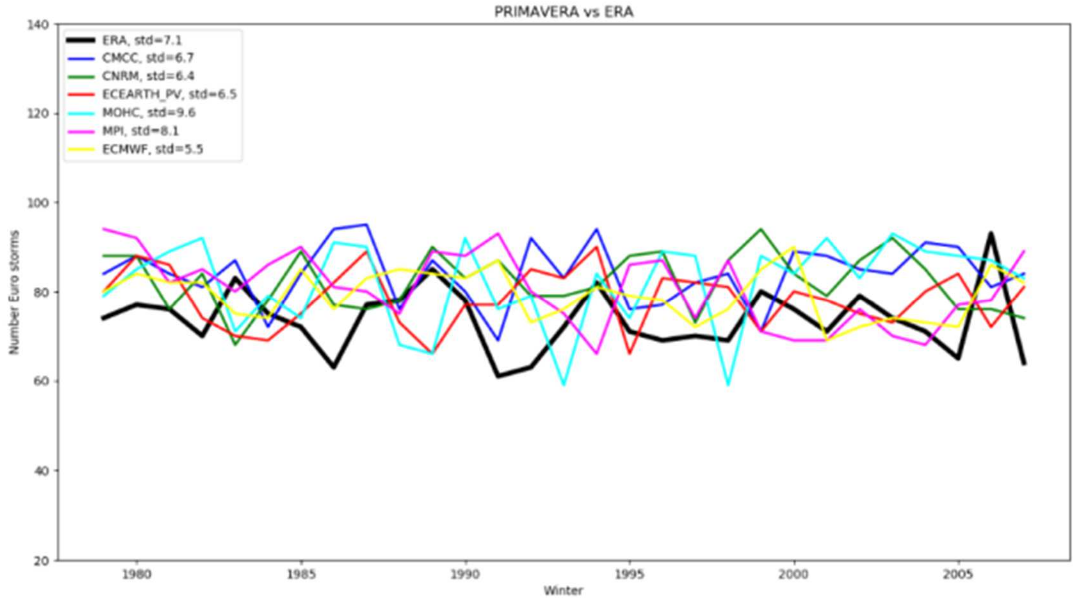


Figure 13. Numbers of ETCs entering Europe each winter for PRIMAVERA models.

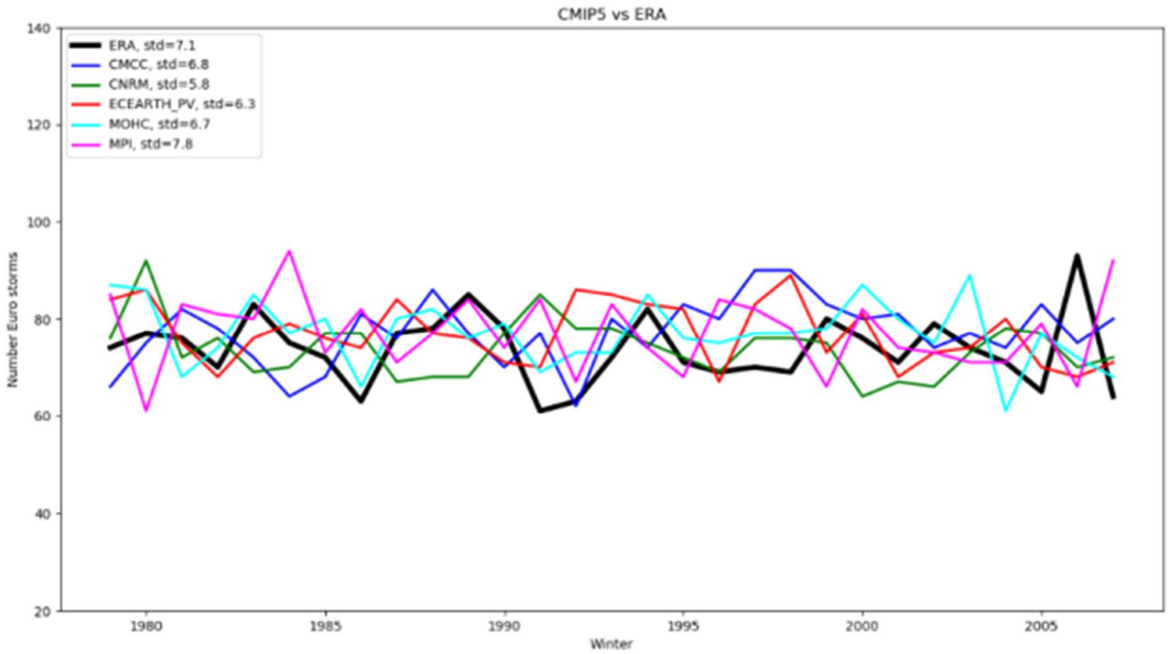


Figure 14. As Fig 13 but for CMIP5 models. The numbers for ERAI are shown in black.

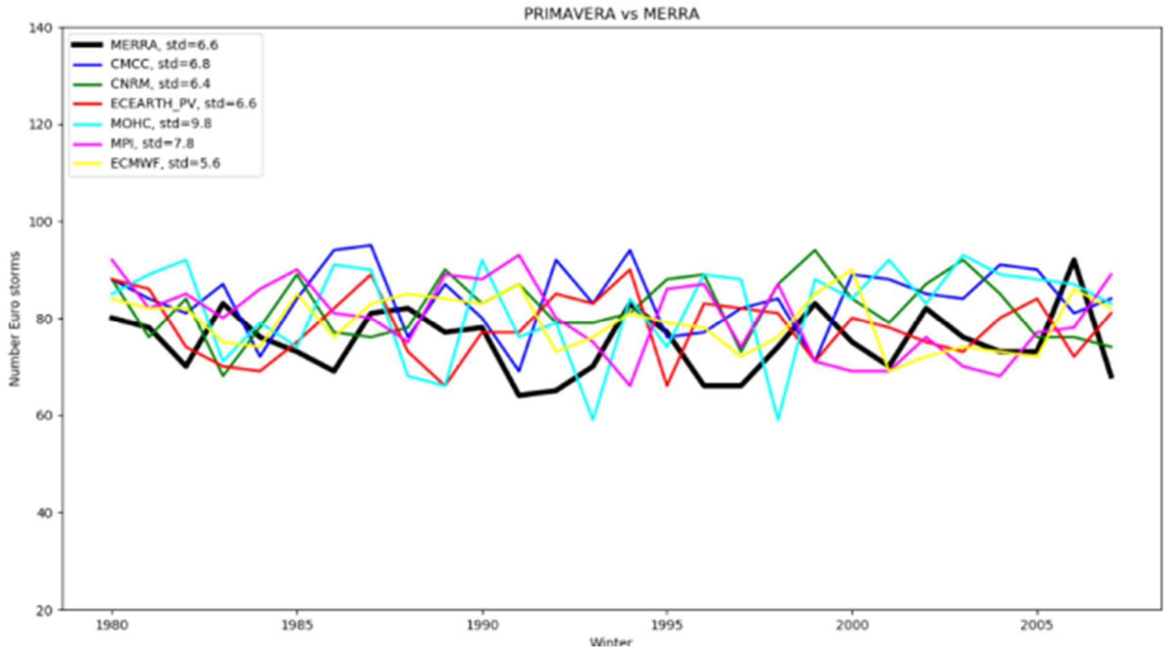


Figure 15. Numbers of ETCs entering Europe each winter for PRIMAVERA models

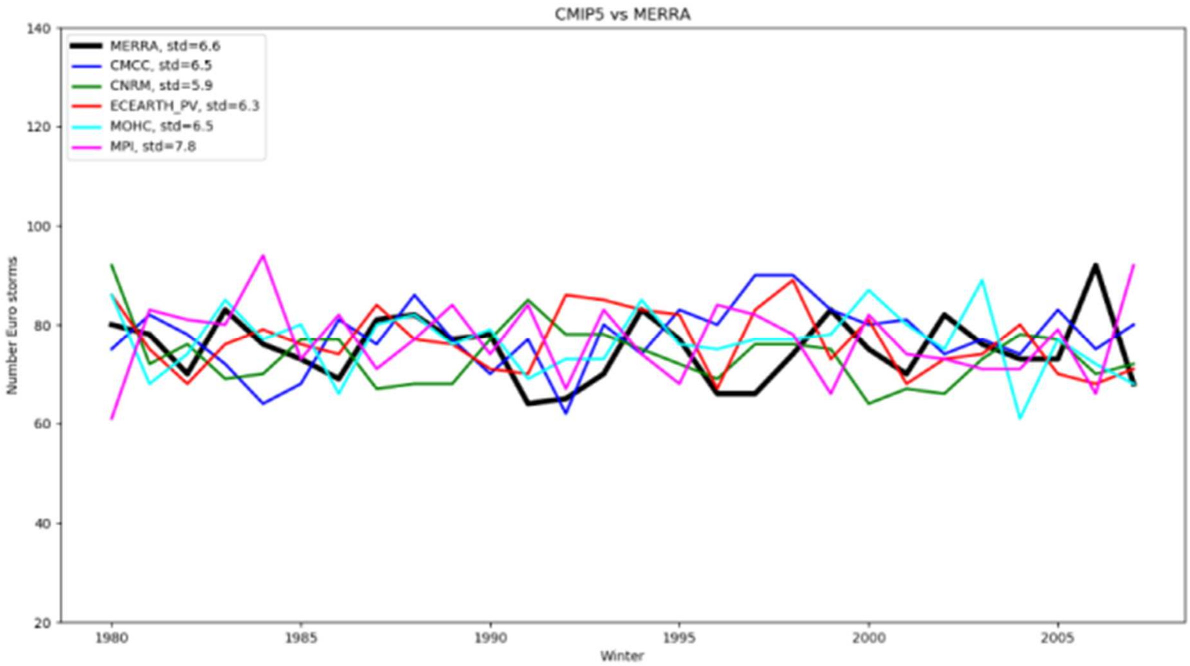


Figure 16. Same as in fig. 15 but for CMIP5 models. The number of MERRA ETCs is shown in black.

The CMIP5 models compare favourably to the MERRA reanalysis based storms frequencies and standard deviation values (Figure 16)

2.2.5 ETC intensity – Criterion: Minimum SLP of an ETC

Figures 17 and 18 show frequency anomalies of the minimum MSLP of ETCs entering Europe (-15˚E to 25˚E, 35˚ to 70˚N), for PRIMAVERA and CMIP5 models compared to the MERRA reanalysis. CMIP5 models tend to underestimate the number of extreme ETCs in Europe (min MSLP < 970hPa). This bias is reduced in PRIMAVERA models, although some PRIMAVERA models underestimate the number of weaker ETCs. In general, the differences are small. The CMCC PRIMAVERA model seems to be an outlier.

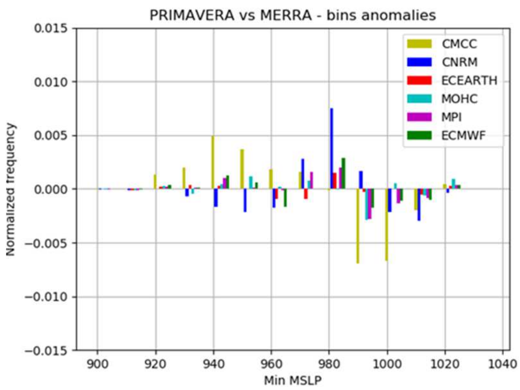


Figure 17. Frequency anomalies of minimum MSLP of ETCs entering Europe for PRIMAVERA models.

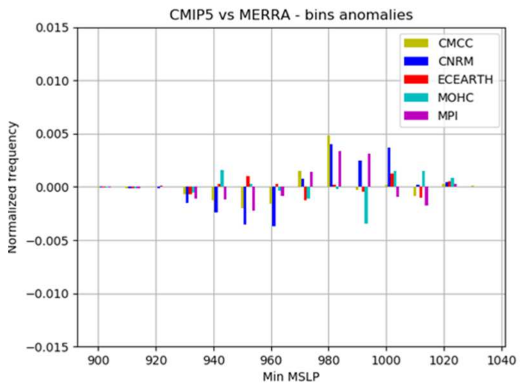


Figure 18. As for Fig 17, but CMIP5 models. Both comparisons are vs MERRA 2 storms.

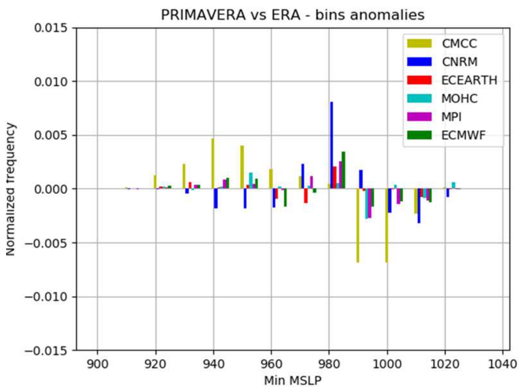


Figure 19. Frequency anomalies of minimum MSLP of ETCs entering Europe for PRIMAVERA models.

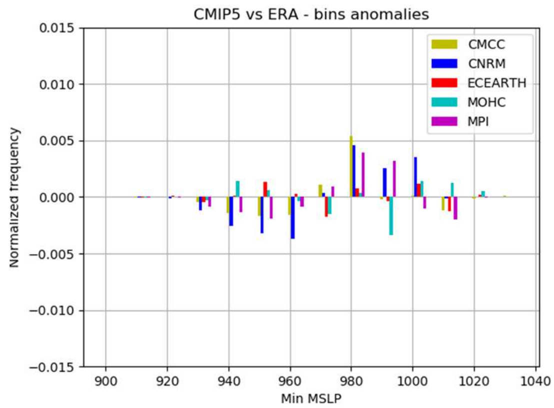


Figure 20. Same comparison but for CMIP5 models. Both comparisons are vs ERA storms.

The same comparisons were also performed using the tracked ERA data (figures 19 and 20). The results indicate that again the CMIP5 models underestimate the number of extreme storms with lower min MSLP; while some of the PRIMAVERA models overestimate the number of storms with low min MSLP (below 980 hPa), especially the CMCC model, and fewer models underestimate the number of intense storms, which is an improvement compared to the CMIP5 models. In addition the PRIMAVERA models underestimate the number of weaker storms, similarly to the above comparison.

2.2.6 ETC intensity – Criterion: Maximum vorticity of an ETC

In the comparisons to the MERRA2 reanalysis - the CMIP5 models seem to underestimate the frequency of more extreme storms with higher vorticity, while overestimating the frequency of lower vorticity storms. These biases are largely reduced in the PRIMAVERA models especially regarding the underestimation of the stronger storms with higher vorticity (Figures 21 and 22).

In the comparison to the ERA Interim reanalysis based storms the CMIP5 models underestimate the frequency of the stronger storms with higher vorticity and overestimate the frequency of the storms with lower vorticity. The PRIMAVERA models have overcome to a great extent these biases (Figures 22 and 23).

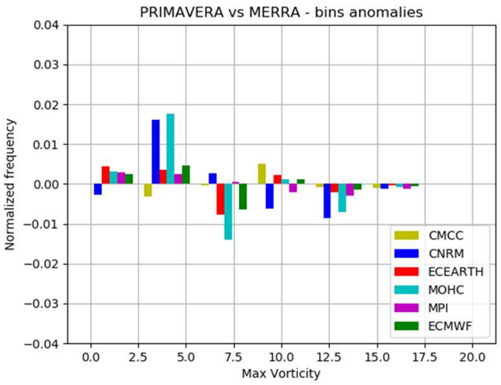


Figure 21. Frequency anomalies of maximum vorticity of ETCs entering Europe for PRIMAVERA models.

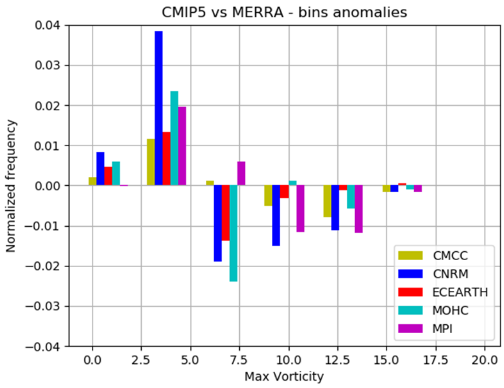


Figure 22. Same as figure 21 but for CMIP5 models. Both comparisons are vs MERRA reanalysis

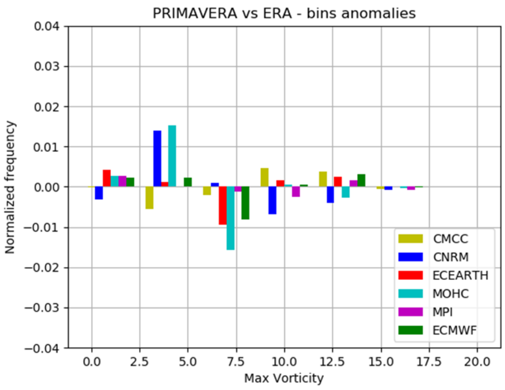


Figure 23. Frequency anomalies of maximum vorticity of ETCs entering Europe for PRIMAVERA models.

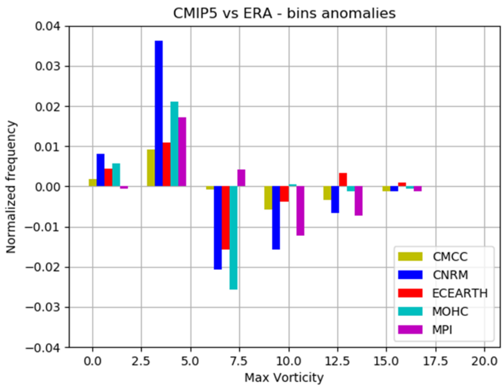


Figure 24. Same as figure 23 but for CMIP5 models. Both comparisons are vs ERA reanalysis

2.2.7 ETC intensity – Criterion: Maximum 925hPa winds of an ETC

Several PRIMAVERA models overestimate the upper section of the wind distribution – indicating overestimation of the wind speeds towards stronger winds. Some models underestimate the lower end of the distribution – representing lower frequencies of lower wind speeds at 925hPa level. The biases are much smaller compared to the biases evident when the PRIMAVERA models are compared to the ERA Interim (Figure 25), where the model distributions are shifted towards the higher wind speeds (Figure 26, right panel).

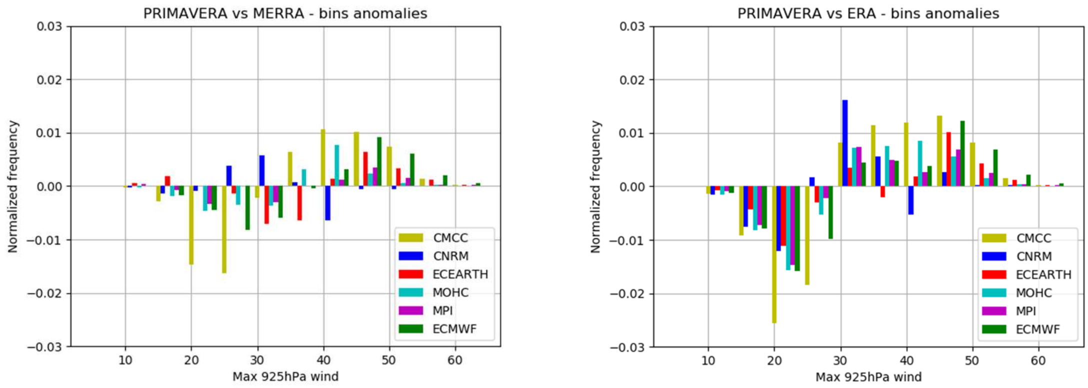


Figure 25. Frequency anomalies for maximum 925hPa wind of ETCs entering Europe for PRIMAVERA models –MERRA comparison (left) and ERA comparison (right)

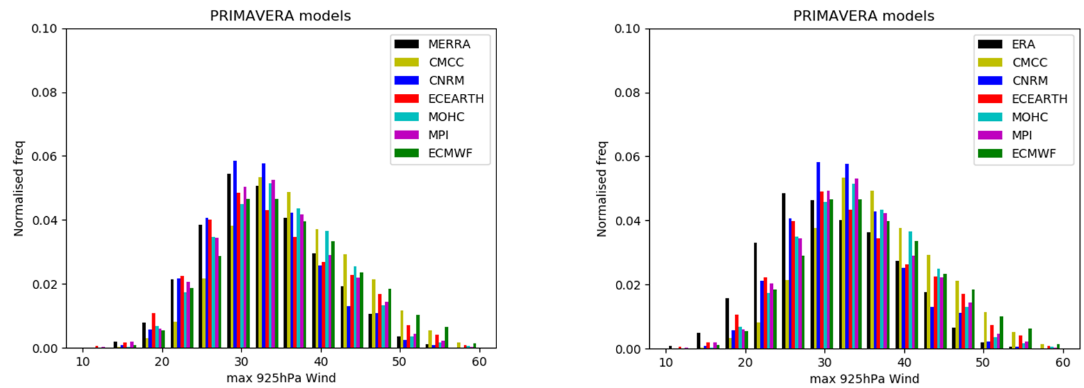


Figure 26. Side by side distribution histograms – Primavera models vs MERRA to the left and PRIMAVERA models vs ERA to the right.

2.2.8 Conclusions

The characteristics of ETCs in PRIMAVERA models compare well to the MERRA2 and the ERA reanalyses. A large improvement compared to CMIP5 is seen in the distribution of ETC intensities as measured by minimum MSLP and maximum vorticity, as PRIMAVERA models better simulate more extreme ETCs. Regarding track densities, the PRIMAVERA models are characterised by overall smaller biases compared to the CMIP5 models.

2.3 Data for hydrological impact research over the Upper Danube basin

2.3.1 Introduction and Motivation

Productive assessments of climate change impact on river discharge and hydropower generation require reliable climate model simulations. Recent initiatives in dynamical downscaling for Europe, in the ENSEMBLES and CORDEX frameworks, provided large ensembles of Regional Climate Model (RCM) data for impact research, at increased horizontal resolution and with improved dissemination to data users. Higher spatial resolution and improved process representation yielded some progress in the representation of historical climate for the main variables of interest in the context of hydrology and hydropower, precipitation and temperature. However, substantial model biases remain even in the most recent generation of RCM data.

Global Climate Model (GCM) simulations with high spatial resolution are currently produced in the framework of the PRIMAVERA project, with one of its objectives being to provide robust and reliable climate simulations to the impact research community. To demonstrate and enhance usability and effectiveness of the generated climate modelling results, selected data users are involved in an early project phase to apply climate model data in their impact modelling. This contribution showcases an application of some initial PRIMAVERA climate modelling results in a hydrological model for the Upper Danube basin upstream of Vienna. Historical simulations of precipitation and temperature from different PRIMAVERA GCMs at low, medium and high resolutions, and for both forced and coupled versions of the climate model are used. The initial objective of the application is the evaluation of the skill of the different GCM simulations to represent the regional climate at the temporal and spatial scales of the hydrological model. The respective results will also be compared with previous results applying ENSEMBLES and CORDEX RCM data in the same hydrological modelling setup for the Danube at Vienna.

In particular, this section also includes an evaluation of raw simulations from historical PRIMAVERA, CMIP5 and CORDEX for their skill to reproduce basin-scale climate.

2.3.2 Objectives of this section

This section covers only a portion of the work conducted as part of this use case, focused on the comparison of PRIMAVERA simulations with other datasets over the Upper Danube River basin. Therefore, it is centred around the following objectives:

- To compare the skill of raw (not bias-corrected) PRIMAVERA simulations to represent the historical mean climate and its variability over the Danube basin with that simulated in CMIP5 (low resolution GCMs) and CORDEX (RCMs).
- To compare the above points with the results obtained using outputs from other projects such as ENSEMBLES and CORDEX, after being subjected to bias correction (Stanzel and Kling, 2018).

2.3.3 Data

PRIMAVERA

The PRIMAVERA runs from the UK Met Office/Hadley Centre HadGEM3-GC3.1 model were considered at low, medium and high resolutions. The low-resolution version was later discarded. Additionally, the coupled versions of these simulations also had to be discarded because bugs were found in the model setup and a re-run is being performed. PRIMAVERA runs for ECMWF-IFS and CMCC-CM2 models at low and high resolution were considered. The historical coupled runs from CMCC-CM2 haven't been finalized, so only the coupled runs from ECMWF-IFS could be included in the analysis. In every case, a single ensemble member was considered at each resolution for the historical period 1950-2014. Monthly temperature at 2m and precipitation were the variables evaluated here.

CMIP5

Historical simulations of 46 CMIP5 GCMs were considered in the analysis for the period 1950-2005. A single ensemble member was used in each case.

CORDEX

Historical regional climate simulations from 9 EURO-CORDEX runs at 0.11^0 resolution were considered. They were generated using combinations of 5 GCMs and 6 RCMs.

OBSERVATIONS

Two datasets were considered to represent the true climate of the Danube basin: CRU TS3.25, a global 0.5^0 resolution gridded dataset; and a set of station data gathered by Pöyry Austria. In both cases, monthly temperature at 2m and monthly precipitation were used. Given the gridded nature of the model data, we argue that it is fairer to compare their output with the CRU dataset than with station data, so only those results are presented here.

2.3.4 Climate Analysis Description

The evaluation of raw historical climate simulations was performed using a compound metric (adapted from Stanzel and Kling, 2018) for temperature (T) and precipitation (P) monthly mean climate and variability for each model run (i), that can be described as the sum of the total errors:

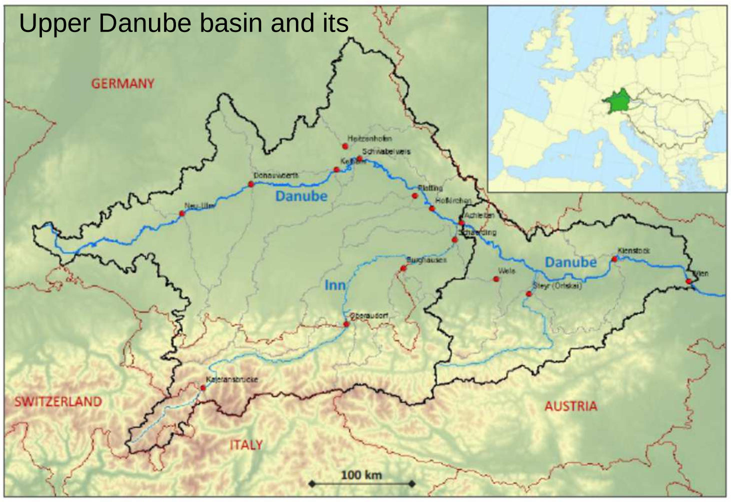
$$Etot_i = EP_i + ET_i$$

Where, for X being either T or P, this can be expressed as:

$$EX_i = E\_MX_i + E\_VX_i = RMSE(MX_{im}) + RMSE(VX_{im})$$

The first term accounts for the error in the mean value and the second term accounts for the error in the variability (expressed as the standard deviation). The RMSE is performed along months.

To compare the models, this total error metric is normalized by the multi-model median. As a result, the models exhibiting a metric higher than 1 are worse than the median and the ones with a metric lower that one are better than the median model.



To account for the potential impact of the low resolution of some of the models, the evaluation was performed for three domains: the basin, the basin + a 30km buffer zone, the basin + 50km buffer zone. This means that for each model, all the grid points included in the polygons for those 3 regions were averaged before their performance was evaluated. In the case of the observations, it was observed that the correlations between the time series obtained from the three domains remained very high for temperature (above 0.99) and high for precipitation (above 0.96) so they could all be considered representative of the basin.
Results from this analysis were also compared with the results obtained by Pöyry, evaluating each model with a similar compound metric but at 61 hydrological units in the basin (instead of the basin average) and after a bias correction process that accounted for the height of the terrain, which is a complex feature of the study region.

2.3.5 Results

The following summarizes the preliminary results obtained from the analysis of the performance metrics over the period 1950-2005, which was the longest period common to most models. The results summarized here (and the corresponding figures) refer to the comparison with CRU TS3.25 data, but they are in very good agreement with the results obtained from a comparison with station data collected by Pöyry for the Danube Basin (not shown).

PRIMAVERA atmosphere-only runs were shown to outperform most other models (both GCMs and RCMs), regardless of the selection of the domain, when raw model output is considered over the Upper Danube basin. In particular, high-resolution PRIMAVERA runs performed better than mid/low-resolution ones for the HadGEM and CMCC models, but not for the ECMWF-IFS model. This model was the worst performing of the PRIMAVERA set.

The coupled runs from the ECMWF-IFS model are slightly worse in the overall error, but the high-resolution version remains better than the multi-model median. These coupled runs have larger errors for temperature (comparable to those on most CORDEX simulations), but smaller errors in precipitation (Figure 27). CORDEX raw temperature output performs worse than a lot of GCMs, despite its high resolution. This arises from very strong cold biases in temperature over this region (Figures 27-29).

In the case of temperature, PRIMAVERA runs do much better at representing the variability than the mean climate (Figures 30 and 31). The errors in these components are similar when it comes to precipitation, depending on the specific experiment (Figures 32 and 33). When a similar evaluation was performed comparing PRIMAVERA runs with EURO-CORDEX and ENSEMBLE runs after a height-dependent bias correction and at the hydrological regions, PRIMAVERA's skill declined sharply, being on average below the median skill (Stanzel et al., 2018). Nonetheless, raw model output from PRIMAVERA runs (especially at high resolution) outperform RCM output over this region, both for temperature and precipitation, despite the RCM's much higher resolution.

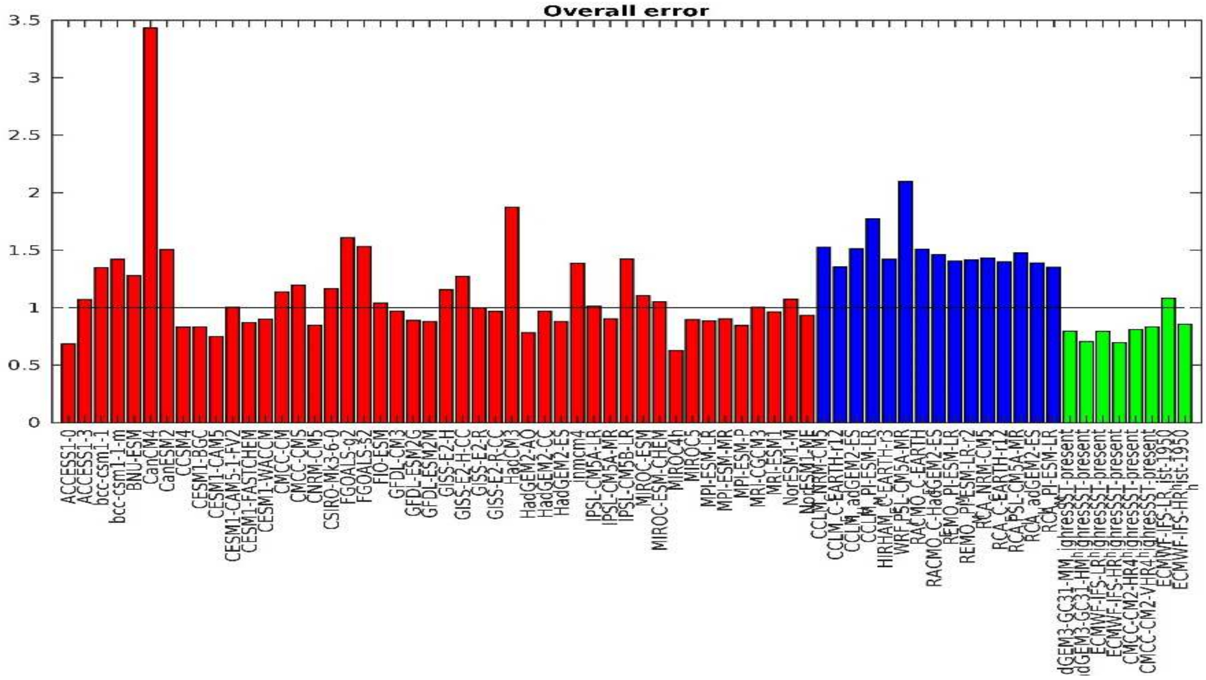


Figure 27. Normalized overall error as compared with CRU TS3.25 at the basin scale. Values lower than one imply a performance that is better than the multi-model median. Red bars: CMIP5 models, blue bars: CORDEX models, green bars: PRIMAVERA models.

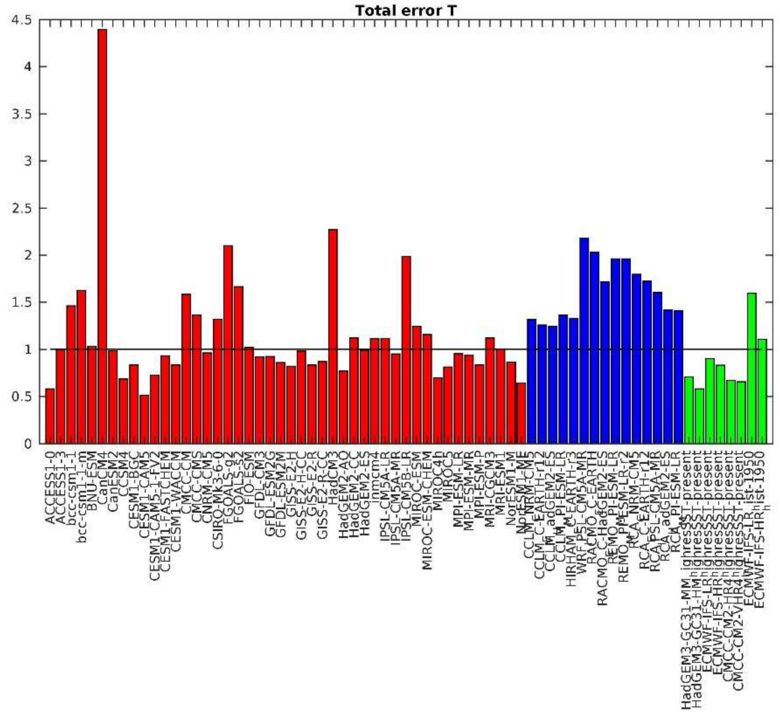


Figure 28. Same as Fig. 27 but for the total error in temperature.

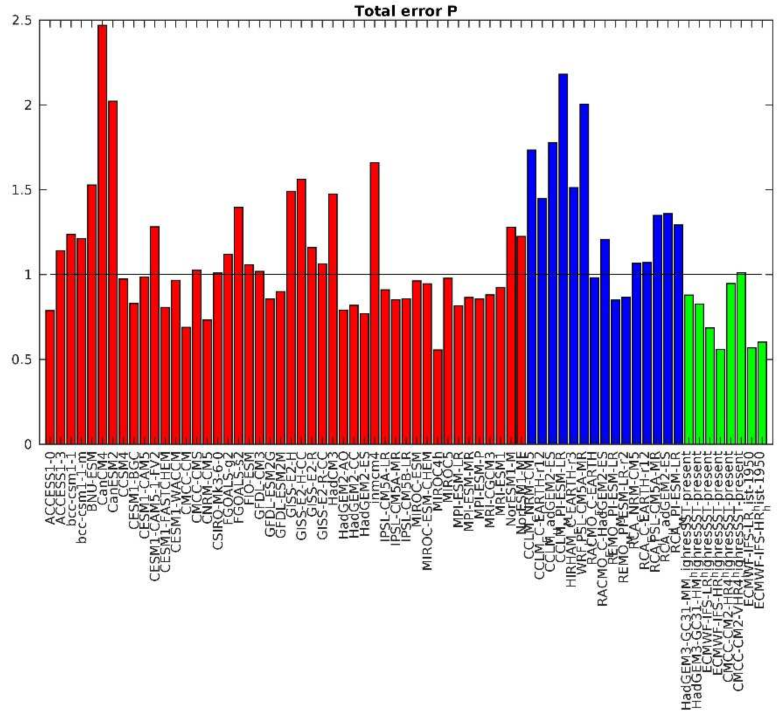


Figure 29. Same as Fig. 27 but for the total error in precipitation.

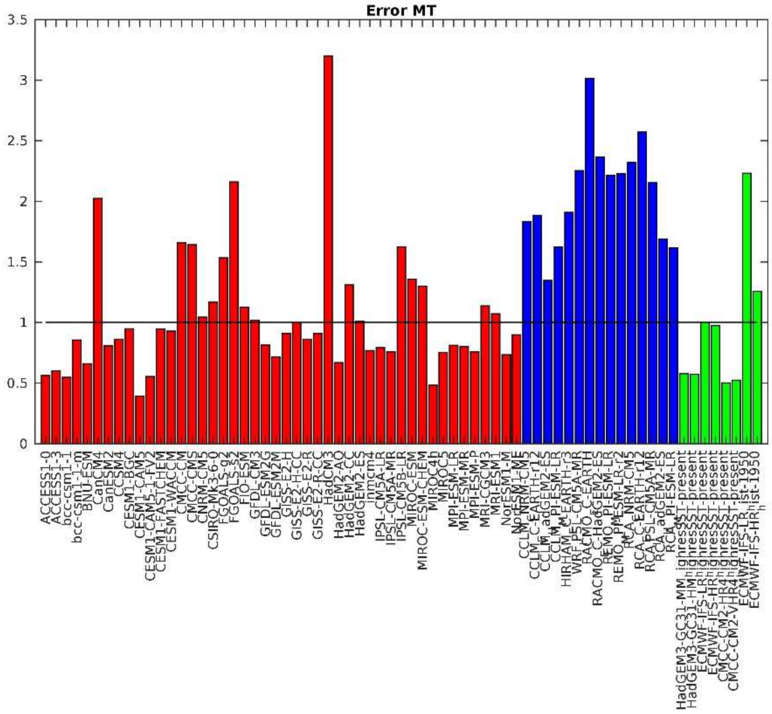


Figure 30. Same as Fig. 27 but for the error in mean temperature.

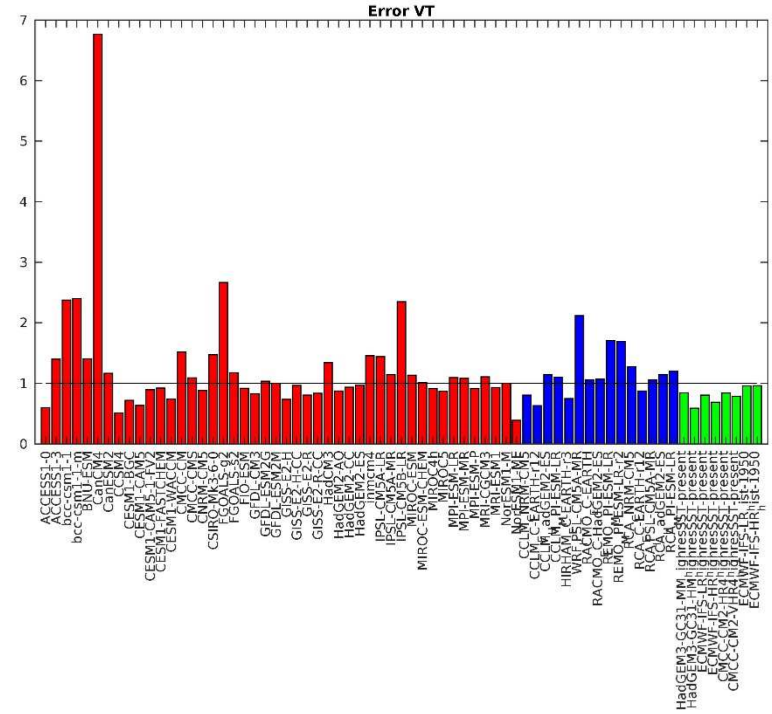


Figure 31. Same as Fig. 27 but for the error in temperature variability.

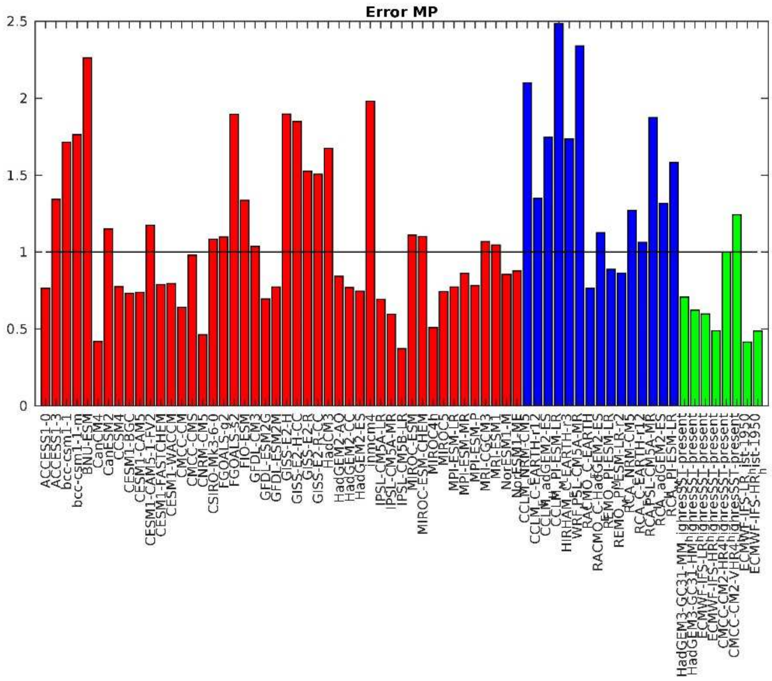


Figure 32. Same as fig. 27 but for mean precipitation.

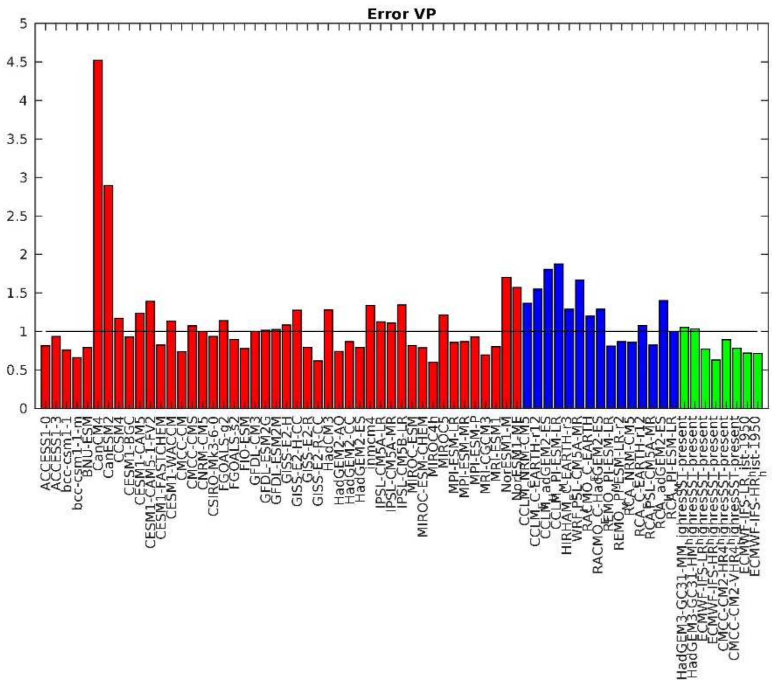


Figure 33. Same as Fig. 27 but for the error in precipitation variability.

2.3.6 Value for User

The users had both published and ongoing work on the representation of hydrological variability of the Upper Danube Basin using RCM data from the EURO-CORDEX project and were keen to complement the analysis with the use of

PRIMAVERA models. The study of future projections over the basin is part of their consulting work for the German and Austrian Hydrological Services, but while the PRIMAVERA future runs are not released, they were keen to perform a model comparison over their study region. Preliminary results of this study were already presented at EGU 2018; a new abstract has been submitted to be presented at ECCA 2019 by the Pöyry team.

3 Conclusions

Does increased model resolution mean that the simulated climate improves? That depends on the definition of improvement and how improvement is measured. It is clear that higher resolution gives a more detailed and more realistic picture of the simulated climate, which in itself could be worth the effort. Local climate is better described if the simulated climate represents a region of 40×40 km instead of a region that is 100×100 km large. Over a larger region this does not necessarily translate into a different climate. Indices based on average temperature and wind are similar, over a larger region, in both the low and high resolution versions of the Stream1 models. The largest differences between model resolutions are found for precipitation, extreme precipitation in particular, and extreme temperature. That the low and high resolution versions are different does not mean that the high resolution versions are better. It is, however, not straightforward to quantify the improvement. If, for example, a high resolution simulation gives an increase in precipitation compared to the low resolution version, that could mean that the high resolution version deviates more from observations if the model from the beginning has a wet bias; nevertheless, the high resolution version may have a better representation of how precipitation is distributed in a region. Still, the difference between model versions with different resolution is often smaller than the difference between models with the same resolution, which suggests that in a multi-model ensemble the resolution is not the most important uncertainty factor. The Stream1 simulations fall in the picture of how the simulated climate depends on model resolution; from CMIP5 simulations at around 200 km to CORDEX simulations at 12.5 km.
When it comes to specific processes the benefit of higher resolution is easier to quantify. This report shows that extreme precipitation is better reproduced by high resolution models. Furthermore Extra Tropical Cyclones (ETC) are better represented in the PRIMAVERA models compared to CMIP5 (which are of lower resolution), for both intensities and cyclone tracks. A study over the Danube basin shows that the PRIMAVERA models even outperform the CORDEX RCM for a selection of climate variables.

4 Planned publications

Strandberg et al., How does increased model resolution impact precipitation intensities?

Squintu et al., The impact of model resolution on the representation of heat and cold extremes over Europe

4. Lessons Learnt

This report has used some methods to compare model simulations of varying resolutions that may be of use to other parts of the project.

5. Links Built

WP10 has close connection to WP11. The results from this report will be used in WP11 for user cases and dissemination.

5 References

Berg, P., Donnelly, C., and Gustafsson, D.: Near-real-time adjusted reanalysis forcing data for hydrology, Hydrol. Earth Syst. Sci., 22, 989-1000, https://doi.org/10.5194/hess-22-989-2018, 2018.

Chakravarti, Laha, and Roy, (1967). Handbook of Methods of Applied Statistics, Volume I, John Wiley and Sons, pp. 392-394.

Dee et al (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, QJRMetSoc, doi: 10.1002/qj.828

Economou et al (2015), Serial clustering of extratropical cyclones in a multi-model ensemble of historical and future simulations, QJRMetSoc, doi: 10.1002/qj.2591

Gelaro, R. and others, 2017: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). J. Climate, 30, 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1

Gutowski Jr., W. J., Giorgi, F., Timbal, B., Frigon, A., Jacob, D., Kang, H.-S., Raghavan, K., Lee, B., Lennard, C., Nikulin, G., O'Rourke, E., Rixen, M., Solman, S., Stephenson, T., and Tangang, F.: WCRP COordinated Regional Downscaling EXperiment (CORDEX): a diagnostic MIP for CMIP6, Geosci. Model Dev., 9, 4087–4095, https://doi.org/10.5194/gmd-9-4087-2016, 2016.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D. and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J. Geophys. Res., 113, 0119, doi:10.1029/2008JD010201, 2008.

Hodges (1995), Feature tracking on the unit-sphere, Mon Wea Rev, doi: 10.1175/1520-0493(1995)123<3458:FTOTUS>2.0.CO;2

Jones, C., Giorgi, F., and Asrar, G.: The Coordinated Regional Downscaling Experiment: CORDEX, An international downscaling link to CMIP5, CLIVAR Exchanges, 56, 34–40, 2011.

Klingaman, N. P., Martin, G. M., and Moise, A.: ASoP (v1.0): a set of methods for analyzing scales of precipitation in general circulation models, Geoscientific Model Development, 10, 57–83, doi:10.5194/gmd-10-57-2017, 2017.

Stanzel P., Kling H.:From ENSEMBLES to CORDEX: Evolving climate change projections for Upper Danube River flow. Journal of Hydrology, Volume 563, p. 987-999; doi:10.1016/j.jhydrol.2018.06.057, 2018.

Stanzel P., Gonzalez P., Kling H., Brayshaw D.: Use of high-resolution GCM simulations for hydrological and hydropower impact research in the Upper Danube basin. Geophysical Research AbstractsVol. 20, EGU2018-13170, 2018. EGU General Assembly, 2018.

Taylor K E, Stouffer R J and Meehl G A 2011 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98

6 Appendix

Low resolution version		High resolution version	
CNRM-CM6-1	~160 km	CNRM-CM6-1-HR	~55 km
EC-Earth3	~80 km	EC-Earth3-HR	~40 km
ECMWF-IFS-LR	~80 km	ECMWF-IFS-HR	~40 km
HadGEM3-GC31-LM	~200 km	HadGEM3-GC31-MM	~100 km
HadGEM3-GC31-LM	~200 km	HadGEM3-GC31-HM	~40 km
HadGEM3-GC31-MM	~100 km	HadGEM3-GC31-HM	~40 km
MPIESM-1-2-XR	~160 km	MPIESM-1-2-XR	~80 km

Table 1. Low and high resolution versions of Stream 1models. Note that for HadGEM3, which is available in three different resolutions, three comparisons are made.

Name	Definition	Unit		
prmin	Minimum precipitation	mm/day		
prpctl1	1st percentile of precipitation	mm/day		
prpctl5	5th percentile of precipitation	mm/day		
prpctl10	10th percentile of precipitation	mm/day		
prmean	Mean precipitation	mm/day		
prpctl90	90th percentile of precipitation	mm/day		
prpctl95	95th percentile of precipitation	mm/day		
prpctl99	99th percentile of precipitation	mm/day		
prmax	Maximum precipitation	mm/day		
rr1	No. of days with precipitation over 1 mm	days		
r10mm	No. of days with precipitation over 10 mm	days		
r20mm	No. of days with precipitation over 20 mm	days		
rx1day	Maximum one day precipitation	mm		
rx5day	Maximum five day precipitation	mm		
cdd	Consecutive dry days	days		
cwd	Consecutive wet days	days		
sfcWindmin	Minimum surface wind	m/s		
sfcWindpctl1	1st percentile of surface wind	m/s		
sfcWindpctl5	5th percentile of surface wind	m/s		
sfcWindpctl10	10th percentile of surface wind	m/s		
sfcWindmean	Mean surface wind	m/s		
sfcWindpctl90	90th percentile of surface wind	m/s		

sfcWindpctl95	95th percentile of surface wind	m/s		
sfcWindpctl99	99th percentile of surface wind	m/s		
sfcWindmax	Maximum of surface wind	m/s		
tasmin	Minimum temperature	K		
tasminmax	Maximum of minimum temperature	K		
tasminmean	Mean of minimum temperature	K		
tasminmin	Minimum of minimum temperature	K		
tasminpctl1	1st percentile of minimum temperature	K		
tasminpctl5	5th percentile of minimum temperature	K		
tasminpctl10	10th percentile of minimum temperature	K		
tasminpctl90	90th percentile of minimum temperature	K		
tasminpctl95	95th percentile of minimum temperature	K		
tasminpctl99	99th percentile of minimum temperature	K		
cfd	Consecutive frost days	days		
fd	Frost days	days		
tr	Tropical nights	nights		
taspctl1	1st percentile of mean temperature	K		
taspctl5	5th percentile of mean temperature	K		
taspctl10	10th percentile of mean temperature	K		
tasmean	Mean temperature	K		
taspctl90	90th percentile of mean temperature	K		
taspctl95	95th percentile of mean temperature	K		
taspctl99	99th percentile of mean temperature	K		
tasmaxmin	Minimum of maximum temperature	K		
tasmaxpctl1	1st percentile of maximum temperature	K		
tasmaxpctl5	5th percentile of maximum temperature	K		
tasmaxpctl10	10th percentile of maximum temperature	K		
tasmaxmean	Mean of maximum temperature	K		
tasmax	Maximum temperature	K		
tasmaxmax	Maximum of maximum temperature	K		
tasmaxpctl90	90th percentile of maximum temperature	K		
tasmaxpctl95	95th percentile of maximum temperature	K		
tasmaxpctl99	99th percentile of maximum temperature	K		
csu	Consecutive summer days	days		
id	Ice days	days		
su	Summer days	days		

Table 2. Definitions of climate indices.

	BRI	CEE	MED	NEE	SCA	SEE	WSE	AVG
prmin	3	3	3	2	3	3	3	2,9
prpctl1	5	5	6	6	7	6	6	5,9
prpctl5	5	5	6	6	7	6	6	5,9
prpctl10	5	5	6	6	7	6	6	5,9
prmean	4	3	7	5	7	5	5	5,1
prpctl90	5	4	4	5	6	4	6	4,9
prpctl95	3	3	5	5	4	6	5	4,4
prpctl99	7	4	7	7	6	5	6	6
prmax	7	7	7	6	7	6	7	6,7
rr1	5	7	6	6	7	5	7	6,1
r10mm	5	4	5	6	4	5	6	5
r20mm	7	5	5	6	6	5	5	5,6
rx1day	7	7	7	6	7	6	7	6,7
rx5day	7	6	7	5	7	4	7	6,1
cdd	6	7	6	7	6	5	6	6,1
cwd	3	6	4	7	6	5	6	5,3
sfcWindmin	6	7	7	6	7	5	6	6,3
sfcWindpctl1	6	7	5	6	6	6	5	5,9
sfcWindpctl5	6	6	4	6	5	6	5	5,4
sfcWindpctl10	6	6	5	6	5	7	3	5,4
sfcWindmean	5	5	4	6	4	5	4	4,7
sfcWindpctl90	5	6	4	6	4	5	6	5,1
sfcWindpctl95	5	6	4	4	4	3	6	4,6
sfcWindpctl99	6	6	4	5	4	3	6	4,9
sfcWindmax	5	7	6	7	6	3	5	5,6
tasmin	5	7	5	7	5	5	6	5,7
tasminmax	5	7	5	7	6	6	6	6
tasminmean	3	5	3	2	0	2	3	2,6
tasminmin	4	6	6	7	6	5	3	5,3
tasminpctl1	5	6	4	7	3	4	2	4,4
tasminpctl5	4	4	3	6	4	3	3	3,9
tasminpctl10	4	6	3	7	3	3	3	4,1
tasminpctl90	3	3	4	6	4	2	5	3,9
tasminpctl95	4	4	4	6	4	3	5	4,3
tasminpctl99	5	5	4	6	4	5	5	4,9
cfd	6	6	2	5	5	4	4	4,6

0
1
2
3
4
5
6
7

fd	5	4	4	4	3	3	3	3,7
tr	0	5	4	7	4	3	5	4
taspctl1	4	6	5	7	3	4	3	4,6
taspctl5	4	4	3	6	3	3	2	3,6
taspctl10	5	5	3	5	3	3	3	3,9
tasmean	2	5	2	2	2	1	3	2,4
taspctl90	3	6	5	4	4	5	3	4,3
taspctl95	2	6	4	5	3	5	3	4
taspctl99	0	6	4	6	3	6	2	3,9
tasmaxmin	5	7	6	7	5	5	2	5,3
tasmaxpctl1	5	6	5	7	3	4	3	4,7
tasmaxpctl5	4	4	3	6	4	4	3	4
tasmaxpctl10	4	5	3	6	3	3	3	3,9
tasmaxmean	3	4	3	2	0	2	3	2,4
tasmax	5	6	6	7	5	6	4	5,6
tasmaxmax	5	6	5	7	6	6	5	5,7
tasmaxpctl90	2	2	5	6	3	3	4	3,6
tasmaxpctl95	3	3	5	6	3	4	4	4
tasmaxpctl99	4	5	4	6	3	5	4	4,4
csu	0	2	4	2	1	4	1	2
id	5	4	4	3	2	3	4	3,6
su	0	1	5	2	0	4	1	1,9
AVG	4,3	5,1	4,6	5,6	4,3	4,4	4,4	

Table 3. Number of models with a statistically significant difference between the low and high resolution versions