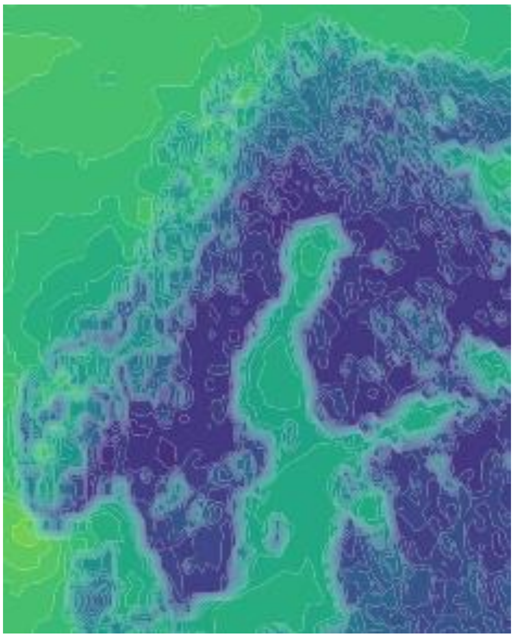

The impact of climate change on Swedish wind power production

Master’s thesis in Industrial Ecology

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DEPARTMENT OF SPACE, EARTH, AND ENVIRONMENT
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Gothenburg, Sweden 2020
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MASTER’S THESIS 2020

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Cover: [The average capacity factor for the Nordic countries for year 2006 generated from the model MOHC with scenario RCP2.6]

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The impact of climate change on Swedish wind power production

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Abstract

Global warming is now a fact, making it significant to model the future climate to be as prepared as possible. The aim of this study was to investigate if and how a warmer climate will affect the Swedish wind power. Wind power profiles were assessed with focus on recurrence of low wind periods, to see if they have a risk of becoming more frequent or longer or perhaps both. The investigation was conducted by analysing wind speed data from two different global climate models, HadGEM2-ES and MPI-ESM-LR, with the time scope of 2006 to 2099, and the temporal resolution of 3 h and 6 h, respectively. Both models with the scenarios RCP2.6 and RCP8.5.

The study found a decrease of about 3% of the yearly electricity production from an average Swedish wind turbine, by the end of the century in the worst-case scenario, corresponding to a 5℃ increase. However, the two models were ambiguous as to whether it is the duration of low wind events or the number low wind events which increase. The study reached the conclusion that to be able to say anything for sure, whether a warmer climate does affect the wind patterns, or not, data from only two models are not enough. It also recommend that for future work it would be of interest to not only see how many and how long these low wind events are, but also to see how close to each other they are since this is a major factor when deciding the substituting energy source when wind turbine are not producing enough, for this study this is partly handled by using moving averages of 12 h and 24 h, when analysing the profiles.

However, the result from the scenario where the global warming is kept below 1.5℃, shows no visible change for electricity production from an average Swedish wind turbine.

Nevertheless, the overall results from this study do not indicate any substantial risk for future wind power owners of being directly affected by the change in production from the wind turbines as an effect of global warming.

Keywords: Wind power, low wind events, HadGEM2-ES, MPI-ESM-LR

Acknowledgements

Firstly, I would like to express my gratitude to both my supervisors, Viktor Walter and Emil Nyholm and my examiner Lisa Göransson for guiding me through this study. But, what I'm most grateful for, is your support and understanding during a tough period of my life. Thanks for not giving up on me. I would also like to thank Elena Maltz for the guidance through the code. Lastly, thank you Henrik Hodel, for all the coffee, it was more than appreciated.

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Introduction

Background

As of today, the concept of climate change is widely known. According to Nasa, as many as 18 of the 19 warmest years since 1884, have all occurred 2001 and later [1]. The temperature increase is already up about 1 degree Celsius since preindustrial time. Global warming is not only affecting the temperature. For example, it also impacts the currents in the seas, wind patterns and cloud patterns (e.g. thickness, altitude, and coverage), to mention a few of them. All these factors that affect the climate on Earth are highly interconnected. However, they will all respond to an increased level of greenhouse gases in different ways. Making modelling them a very hard task, but even more of paramount interest.

The Intergovernmental Panel on Climate Change (IPCC) are using Representative Concentration Pathways (RCP) based scenarios when modelling future climate [2]. Two of these are RCP2.6 and RCP8.5. Where the first one mentioned is a scenario where the CO_2-emissions will culminate around 2020 and the second where the CO_2-emissions will continue to increase up to triple todays emission. These scenarios are used together with a global climate model (GCM) and a regional climate model (RCM) resulting in a climate model.

The future climate is unknown, it is therefore of great interest to model it to be prepared to possible changes. Not speaking on a personal level, e.g. changing diet and traveling means, but instead on an energy system level. Imagine what effect it can have on future windfarm sites if we already today can predict where it will be the most suitable to station them, where it will be less. Or the possible effect it can have on the energy system if we can see that wind power will be more or less beneficial, as an effect of global warming. This could help prepare the energy system change. Tobin et al. have looked at how climate change can impact the power generation from an average wind farm in 2050s Europe [3]. They found it to be a likely decrease of up to 3% in the annual energy yield, for all their nine climate models [4]. Their work includes wind speed data taken from seven different GCMs combined with seven different RCMs resulting in nine different models in total. Tobin et al. state that their model's performance is better over ocean than over land. One reason for this is because they use windspeed at 10m height and therefore must scale it to the desired height, commonly the hub height. Wohland et al. have used five GCM when investigating what impact climate change can have on the backup energy in a future renewable electricity system [5]. Out of these five GCM, only one GCM is not used in the work performed by Tobin et al. Wohland et al. only used one RCM, however it is the same one that Tobin et al. uses for three of their scenarios. On the contrary they found it to be an increase of up to 7% of background energy in Europe. They both have in common that they used data for RCP8.5 and the drawback of only having data from 10m height.

Wind power is an intermittent source of energy, that historically has had a smaller part in the energy system. It is, however, a source with very low greenhouse gas emissions, therefore making it significant for future energy systems. The Swedish Energy Agency has looked closer at four scenarios of how the future energy system might look [6]. Where one of the scenarios suggest that the annual electricity generation for wind power even surpass that of hydropower. Since wind power has a potential for expansion in installed capacity today [7], it more often than not runs at full effect, limited by wind or installed capacity. As the installed capacity continuous to increase the role of wind power will most likely shift from today's role towards being of a greater role. As of today, there is about 4100 wind turbines in Sweden, with an installed capacity of almost 9000 MW, which are placed throughout the country from north to south [8]. In year 2019 wind power stood for 12% of the total electricity production in Sweden [9]. Forecasts shows that this percentage is assumed to increase the coming years due to increase in installed capacity [8][7], making the modelling of future electricity production from wind power both important and interesting.

Aim

The aim of the thesis is to investigate if and how the Swedish wind power will be affected by a warmer climate. The focus of the work is on wind power properties which impact the interaction between wind power and the rest of the electricity system, including the annual wind power production as well as its distribution over time. Especially interesting is to see if the recurring low wind periods have a risk of becoming more frequent or longer, or even both. Results from the study indicate which output from the climate models that is relevant to understand the climate impact on wind power. The work is intended to provide a first indication on how climate change impact the cost-competitiveness of wind power and wind power integration challenges, but is limited by the availability of results from the climate models which concern parameters central to wind power production.

Limitations

The geographical boundaries: the work will only touch upon the impacts on the wind power electricity generation in Sweden.

The thesis will be limited to the two models, Hadley Global Environment Model 2, and Max Planck Institute Earth System Model, both with two scenarios, RCP2.6 and 8.5. Since these two models are the only models that currently have wind data for the more relevant hight of 100m.

The models used in the study have the time scope 2006 to 2099, therefore this will be the time limitation of the study, with the exception for one scenario, (MPI RCP2.6) that has the time scope 2006 to 2060. The Hadley Global Environment Model 2 has the temporal resolution of 6h and the Max Planck Institute Earth System Model has a 3h temporal resolution.

Theory

Representative Concentration Pathways

RCP are scenarios for how the greenhouse effect will develop in the future [10]. There are four different scenarios that are more commonly referred to: 8.5, 6.0, 4.5 and 2.6 (W/m^2). They are named after their respective level of increased radiation at year 2100.

RCP8.5 is the worst-case scenario, where the CO_2-emissons at 2100 are increasing up to tripled todays. The human population will continue to increase which will not only lead to an amplified pressure on the agriculture but also an increase demand for energy originating from fossil fuel, due to insignificant investment in renewable energy. In scenario RCP 6.0 everything is a little bit better off than in RCP8.5. Not as big increase in population hence not as big pressure on agriculture and energy demand. The CO_2-emissions will not increase until year 2100 instead the annual emissions will start to decrease about year 2060. Which at year 2100 will result in a CO_2 concentration increase of 25% from today's value. RCP 4.5 is also better off than previous one, due to increased climate politics and not as big increase in population, to mention a few. The emissions of CO_2 will increase until 2040. RCP2.6 is the best-case scenario, where the CO_2-emissions will culminate about 2020. And at year 2100 there will be negative emissions, meaning capturing and storing more than what is emitted. In Figure 1 the associated temperature increase to each RCP scenario can be seen. It is clear that scenario RCP8.5 is likely to end far above the 2 °C target [11]. Whereas both scenarios RCP2.6 and RCP 4.5 are likely to end around or below 2.5 °C, as can be seen in *Figure 1*.

However, it is important to remember that these are scenarios of what *can* happen at emission levels from different development pathways, *not* predictions.

As mentioned previously the temperature increase is already up about 1 °C since preindustrial time, however the temperature increase is not equally distributed around the earth. The most substantial temperature increase has happened at the Northern hemisphere [12]. One major reason for this is the loss of sea ice, since the absence of ice (lower albedo) leads to more heat from the sun being absorbed. The origination of wind is the uneven absorption of solar radiation by the surface on Earth [13], since this leads to different temperature in the air and further to differences in atmospheric pressure. This change in atmospheric pressure due to increased absorption of heat is one potential source to a change in wind pattern. Exactly how climate change will affect wind speed, and wind currents etcetera are unknown. The only thing known is that it is likely to change in some way. Zeng et al. [14] and Roderick et al. [15] have both looked closer at windspeed and have contrary result. However, Zeng et al. have studied the windspeed over the United States and Roderick et al. over Australia. Zeng et al. finds that the windspeed is going to increase and Roderick et al. that it will decrease. This is not proof of the unknown effect of global warming; it is only to emphasize that the change does not have to be unanimous around the Earth.

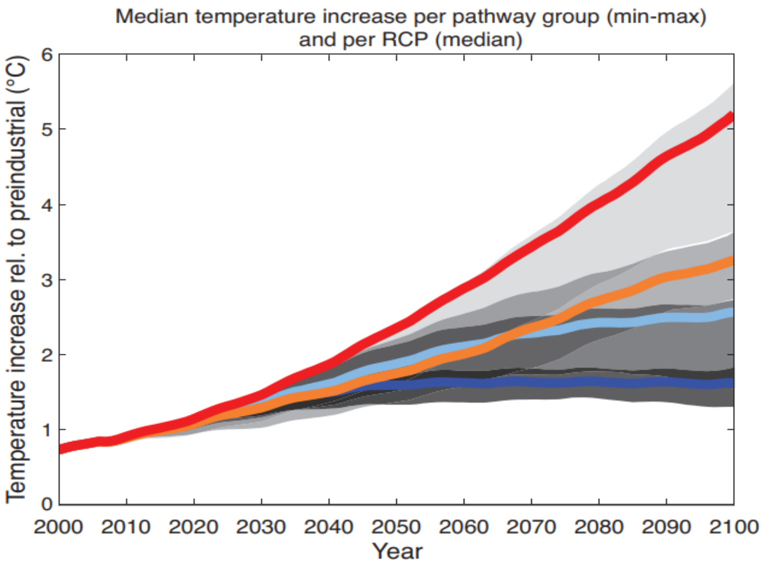

Figure 1 Global temperature relative to pre-industrial for the pathways, RCP8.5 (red), RCP 6.0 (orange), RCP 4.5 (light blue) and RCP2.6 (navy) [16].

Weather vs climate

"Weather is the physical condition of the atmosphere (particularly the troposphere) at specific time and place with regard to wind, temperature, cloud cover, fog and precipitation (the collective word for rain hail, snow, etc.)." [13]

Weather is only temporary. Climate on the other hand describes the average weather in a region for 30 years or more. Therefor modelling these are different. When modelling the future weather, the current atmosphere and oceanic conditions are used [17]. Together with information about temperature, wind speed and geographic location to mention a few parameters. This information is used with forecast models that provides a short time (only a few days ahead), high resolution (down to km resolution) result of the future weather. Simplifying it, climate models are stretched-out weather forecast over several decades, that does not only consider the current weather conditions. However, they do not have the same resolution, instead climate models are usually on a scale of hundreds of km (that in order to be used more locally must be downscaled with the use of RCM). Compared to weather forecast they are a lot more complex and do not only consider variables like temperature and wind speed, but they also include for example information about melting glaciers.

Method

This study involved two main tasks, processing the wind data collected from Centre for Environmental Data Analysis (CEDA) [18], and using the processed data to calculate the chosen indicators, yearly production, seasonal production and number of low wind events and their average length. In order to get a better understanding of the data used for this study a brief introduction to the two climate models and their scenarios will begin this part, *Models and scenarios*. Followed by a methodical explanation of the processing of this data, *Processing the data*. The last section, *Indicators*, consists of an explanation of the role of wind power in the energy system and an explanation of the chosen indicators.

Models and scenarios

The data used for the analyses in this study are collected from Earth System Grid Federation (ESGF) portal at CEDA [18]. As previously mentioned, the data is from two different models with two RCP scenarios each. The first GCM is Hadley Global Environment Model 2 – Earth System (HadGEM2-ES), with wind speed at 100 m height at a six-hourly temporal resolution [19], later this model will be referred to as MOHC. The second GCM is Max Planck Institute Earth System Model at base resolution (MPI-ESM-LR) with wind speed at 100 m height at a three-hourly temporal resolution [20], later referred to as MPI. They both use the RCM RegCM4-6 for both scenario RCP2.6 and RCP8.5. As mentioned in the Background section both Tobin et al. and Wohland et al. used data from 10 m height from the same two GCM, MOHC and MPI, among others [3], [5]. However, these two models (MOHC and MPI) were chosen since they now have 100 m wind speed data which is closer the wind turbines hub height and therefore eliminating the need for scaling employed by predecessors [21], [22]. A result of both GCMs having two scenarios each (RCP2.6 and RCP8.5), is that it will be possible to both see the (possible) different effects on electricity generation from wind power and to compare the two GCMs with each other.

Processing the data

Two sets of data were provided from ESGF for every scenario, one for northward wind and one for eastward wind. Each set of data had the format of a three-dimensional matrix. However, for this study the absolute wind speed was desired, rather than the direction. Therefore, Pythagoras theorem was used to convert the two sets of data into one set, see *Equation 1*. The output form was a single three-dimensional matrix for each scenario, with the absolute wind speed as output from the matrix. The parameters in the three-dimensional matrix, $[t, x_n, y_n]$, is time (t), latitude (x_n) and longitude (y_n).

Equation 1

$$\text{absolute wind speed} = \sqrt{(northward\ wind\ speed)^2 + (eastward\ wind\ speed)^2}$$

Due to miss match in geographical location and dissimilar matrix conversion of the data had to be conducted. The required matrix was of size [α, 231, 181] where α is an arbitrary number representing time, the matrix's provided from ESGF had the size [α, 526, 526] and therefore the extra positions for wind speeds had to be removed. The 231x181 unique coordinates does not overlap with the coordinates provided from ESGF and nor are they based on the same coordinate system. ESGF based their data on a spherical coordinate system and the coordinate system used in the calculation models are a cartesian coordinate system. The result of this can be seen in *Figure 2.*

The closest coordinate combination from ESGF (x_n and y_n) was coupled to each point in wind power models (x_o and y_o). Resulting in in a matrix (231,181) with references to x_n and y_n. It would have been possible to weight the point around each coordinate in order to get a matrix with higher accuracy, but it was decided that simpler coupling mechanism would result in a matrix that was accurate enough.

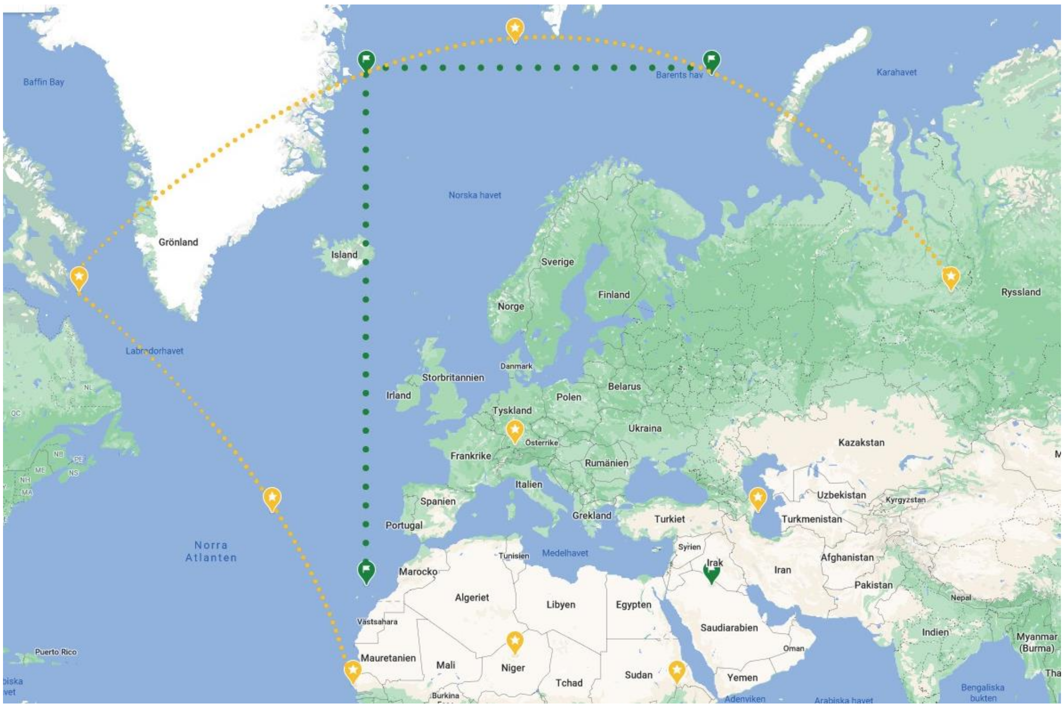

Figure 2. A conventional (flat) map with the two different matrixes route marked. The one created with data from ESGF in yellow, with 12km between every point, clearly depicts the arced path that is the result from the spherical coordinate system. The one who the calculation models requires is marked in green, which has 0.25° step.

After this the data was ready to be processed to wind profiles. There were existing models for conversion of wind speed to wind power production data that were predetermined to be used for this study. The calculations for electricity production from wind turbines were provided from Johansson and Thorson, in depth explanation can be found in section *3.3.2* of their work [23].

In short, running the code with the data generate Excel files conforming to the wind profiles for each EPOD region, SE1, SE2, SE3 and SE4, see *Figure 3*. Since all these regions does not have the same usable area, the data is weighed against the area, see

Equation 2 and *Table 1*, in order to find values for Sweden in total. This weighing calculation is performed per data point since every point has different sizes and unusable areas as lakes and reserved national areas e.g. national parks.

Figure 3. The four EPOD regions in Sweden.

Equation 2

$$FLH_{y,m} = \frac{W_m * \sum_t \sum_\alpha CapacityFactor_{\alpha,t,y,m} SE_\alpha}{SE_1 + SE_2 + SE_3 + SE_4}$$

In *Equation 2*, the full load hours for a specific year and model are calculated. In the equation the y stand for year, m for model, t for time step and α for region (see *Table 1).* Since the two models used in this study does not have data with a temporal resolution of 1 h, the variable W_m, either 3 or 6 depending on the model's temporal resolution, was used. The values for the four different SE regions can be found in *Table 1*: Usable area in the four regions, where areas corresponding to e.g. lakes and natural reserved areas are removed.. Usable area refers to surface of land that can be used for wind turbines. The resulting, FLH is the average FLH for Sweden for that year and modelled scenario. This was also calculated on a seasonal level where winter were considered to be December, January and February. For spring the months of March, April and May was used. June, July and August were counted to summer and lastly, autumn were considered to be September, October and November.

Table 1: Usable area in the four regions, where areas corresponding to e.g. lakes and natural reserved areas are removed.

Region	Usable area [km^2]
SE_1	11,000
SE_2	145,000
SE_3	59,600
SE_4	107,600

Indicators

The focus of the work is on wind power properties which impact the interaction between wind power and the rest of the electricity system. The interaction between wind power and the rest of the electricity system are mainly determined by the annual wind power production and its distribution over time. The annual wind power production is central to the cost-competitiveness of wind power relative to other generation technology options. Even though a higher installed capacity of wind power is of advantage for the energy system in order to meet the 2℃ target, it still involves difficulties. The production needs to occur when there is a demand, it is easy to curtail wind when it is windy but no demand, however it gets trickier when there is no wind but a high demand. In Sweden it is windier during the winter half-year compared to the summer half-year [24]. This correlates well with the fact that the energy demand is higher during the winter half-year and lower during the summer half-year. However, a major disadvantage for wind power is that it is not always windy, therefore complements are crucial, especially in an energy system with wind as a central energy source. This system must therefore be designed with complementing electricity production in order to be ready for longer periods without wind. It is this design that can be affected in different ways depending on how the electricity production from wind might change. Therefore, it is of interest to be able to look at the duration of low wind periods. It had to be defined what “low wind” is. To have a good range, three different threshold values were chosen 20%, 30% and 40%, these corresponds to when the production is x% of installed capacity or lower. Next was to determine how long average duration to look at. It was decided that it was most interesting to look at the longer duration since variations of short duration can be managed by batteries or gas turbines to a low cost. Thus, variations with a duration of at least 12 h and 24 h duration were investigated.

The threshold values were used together with a rolling average, the duration, 12 h and 24 h. Resulting in six different cases for each model and scenario. For example, with a rolling average of 12 h and 30% threshold value and model MPI, 3 h resolution, this means calculating the average of four consecutive values (x) and if the average of those does not surpass 0,3 (30%) flag it, see *Equation 3*. To calculate the total duration of the low wind events, the consecutive flags were summed up. The events were then allocated to a season, by the time stamp it ended in. This made it easy to sum up how many and how long events there were in each year and season.

Equation 3

$$AVERAGE(x_1 + x_2 + x_3 + x_4) \leq 0.3 \rightarrow 1$$

Results

The overall results show a stable electricity production from wind. No major risks can be seen for the possibility that the electricity production from wind would see radical changes due to global warming in the future. However, results from RCP8.5 do indicate a decrease in production of about 3%, which is in direction with the findings from Tobin et al. [3]. Other results from these two models, indicate that it is plausible the wind pattern researched in this thesis will stay the same. Notice that all results listed below regards only the production in Sweden.

Yearly production

As both scenarios for RCP2.6 shows very slight changes, or non, these results have been transferred to the appendix (see *Result).* However, as mentioned before, RCP2.6 is a scenario where the CO_2 emissions culminate around 2020 [10], and therefore making substantial changes less likely to occur. For further information about these results (MOHC RCP2.6 and MPI RCP2.6), please refer to the *Appendix.*

In *Figure 1*, the yearly production for MOHC RCP8.5 and MPI RCP8.5 is depicted. A decrease in the yearly production of about 3% and 1.8% respectively, can be seen until the end of the century.

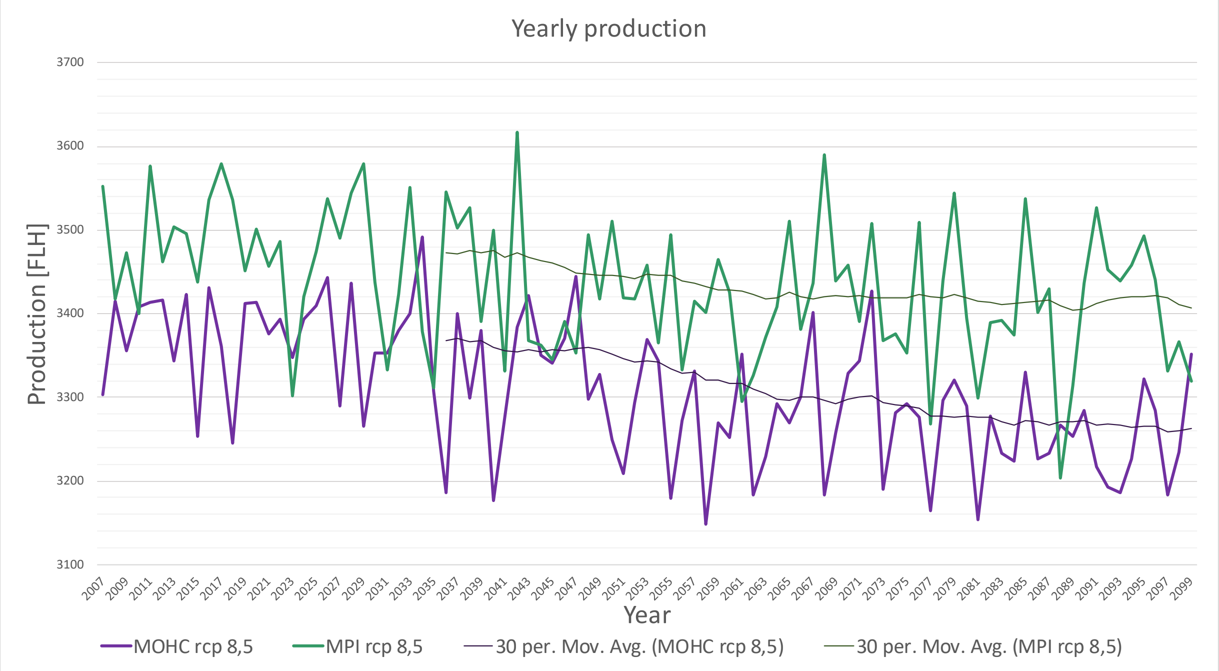

Figure 4 Yearly production for MOHC RCP8.5 and MPI RCP8.5. Including 30 years moving average trend line. OBS! The vertical axis is trimmed.

Even though the two models do not agree upon the average production, (average value of the first thirty years for MPI is 3480 FLH and for MOHC is 3360 FLH) MOHC RCP8.5 is on an average 4% lower in production than MPI RCP8.5, they do however both indicate a decrease in production. Since these models are not to be used for predicting future weather but instead to indicate a possible direction for the future climate this gives us a first glance at how the production is likely to change in the future.

Seasonal production

Looking closely at

Figure 5a to *Figure 5* d it is visible that both scenarios for the two models do capture changes within the seasons winter and spring. MOHC also shows a decreased production within autumn. The biggest change can be seen for both models during winter, see

Figure 5a, with a decrease of almost 4.2% for MOHC and a decrease of 2.4% for MPI. As can be seen in

Table 2 MOHC has a larger decrease for all season, except summer, compared to MPI. However, they do both indicate decrease in all four seasons.

Another interesting thing that can be seen in

Figure 5a and *Figure 5* b, is that even though the yearly average production for MOHC is lower than for MPI, this is not the case when looking closer at winter and spring season. For winter,

Figure 5a, the production pretty much overlap in the first four decades and first after that they start to go apart MPI has a higher average. And for Spring, *Figure 5* b, they have more or less the same average throughout the whole time scope, MPI has an average of 873 FLH and MOHC as an average of 874 FLH for the entire period.

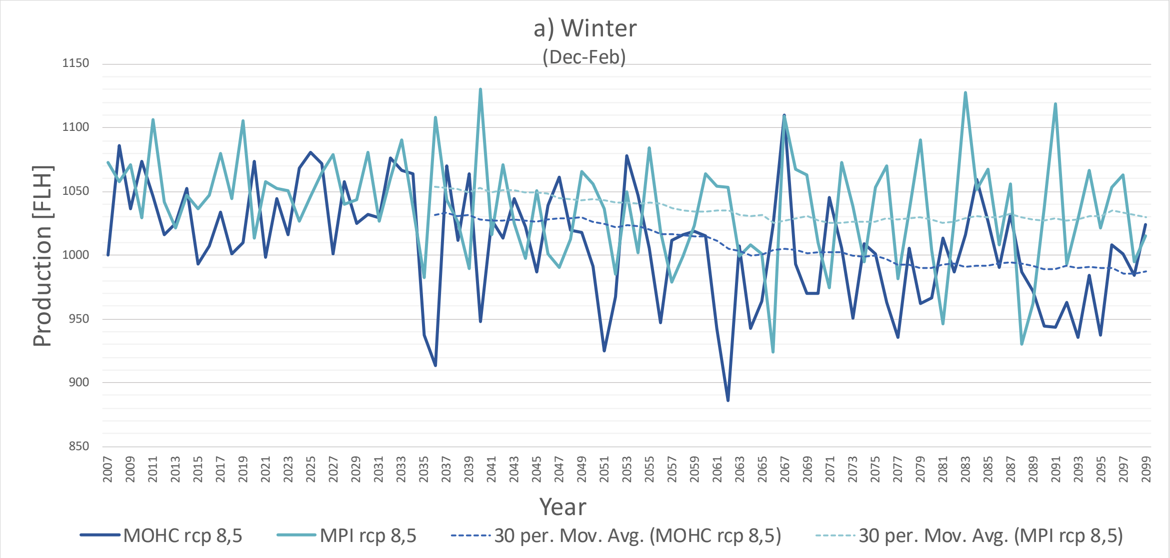

Figure 5a) Production during winter for MOHC RCP8.5 and MPI RCP8.5. OBS! The vertical axis has been trimmed.

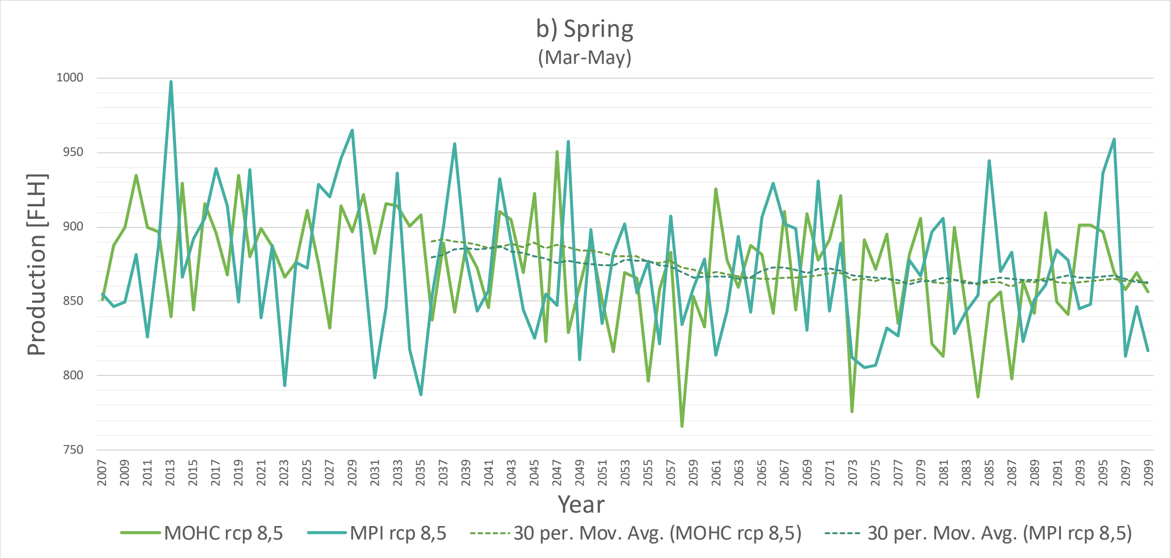

Figure 5 b) Production during spring for MOHC RCP8.5 and MPI RCP8.5. OBS! The vertical axis has been trimmed.

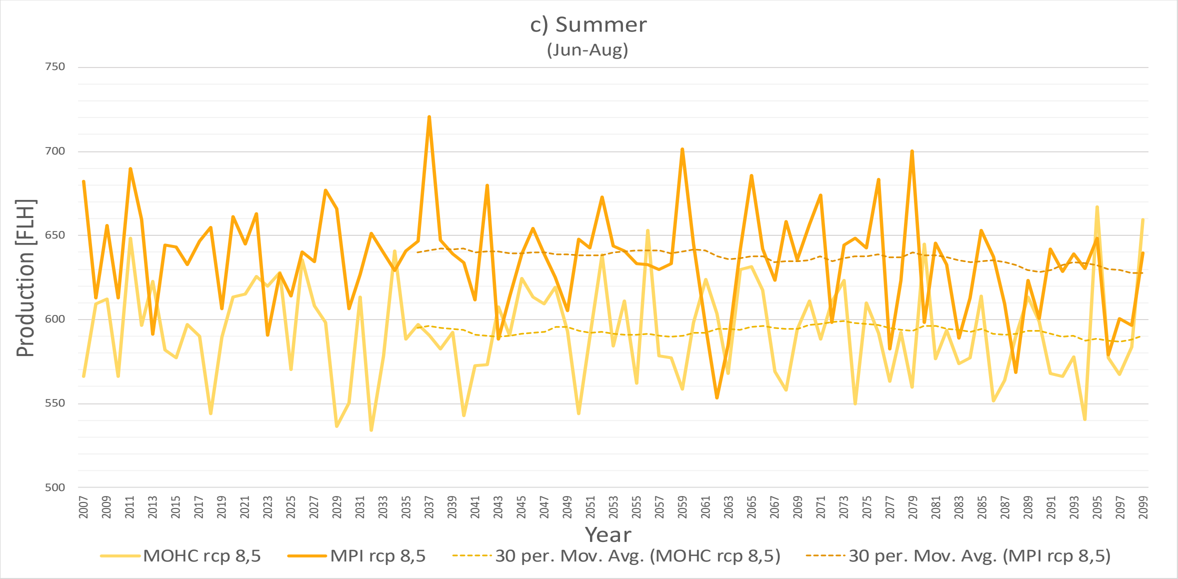

Figure 5 c) Production during summer for MOHC RCP8.5 and MPI RCP8.5. OBS! The vertical axis has been trimmed.

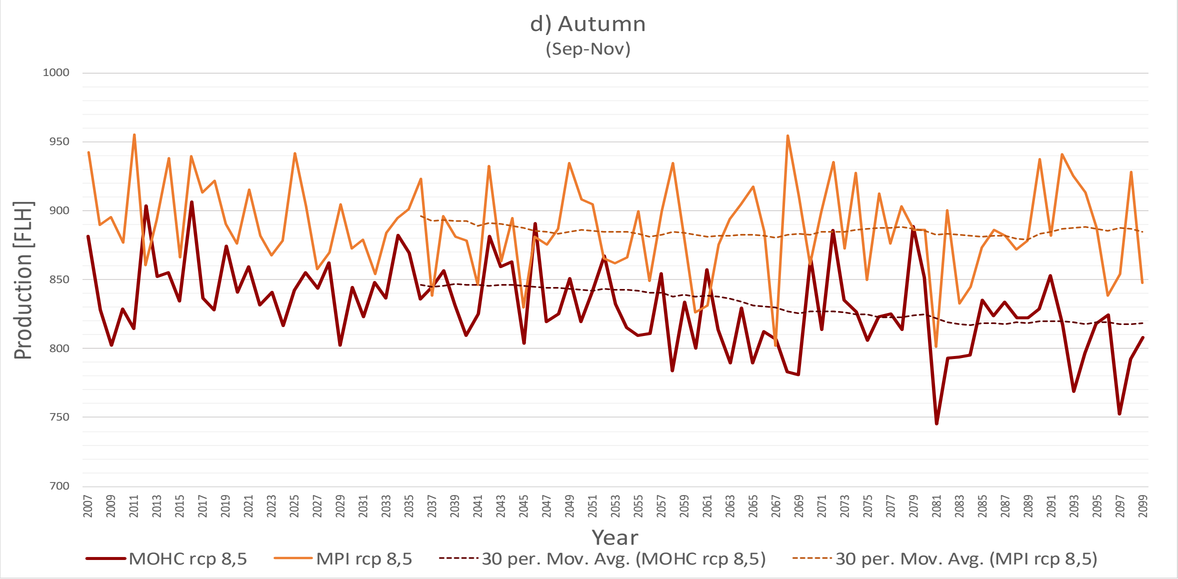

Figure 5 d) Production during autumn for MOHC RCP8.5 and MPI RCP8.5. OBS! The vertical axis has been trimmed.

Table 2. Changes within season

Season	MOHC RCP8.5	MPI RCP8.5
Winter	-4.2%	-2.4%
Spring	-2.8%	-2.0%
Summer	-0.8%	-1.6%
Autumn	-3.5%	-1.3%

Looking closer at *Figure 5* c the result shows a neglectable change for MOHC, and a decrease of 1.6% for MPI. Looking even closer it is visible that most of that decrease happens during the two latter decades. The production is, compared to the other seasons, low during the summer, in north of Europe [25][26]. It is, therefore, very unlikely that a future energy system will be built to rely on energy production from wind during summer hence this small, but visible possible outcome for wind during summer will not be a new burden for the energy system.

However, looking closer at the last season autumn, see *Figure 5* d, this is the only season where the two models do not agree to the same level. Even though MPIs moving average does indicate a decrease. The decrease MOHCs moving average depicts, is more pronounced.

Nevertheless, these indications of a decrease in production are small.

Low wind events and their average length

In order to give an answer to,

“ … to see if the recurring low wind periods have a risk of becoming more frequent or longer, or even both.”

- Aim, p.2

we will look closer at the results from the moving average and threshold value calculations. Once again is not all the result of major interest. In the report the results from using threshold value 30% and a moving average of 24 h for both models, MOHC RCP8.5 and MPI RCP8.5 are examined further, since they were considered to capture the variations with greatest impact on the energy system design, for more information about results regarding other threshold values and moving average, please refer to *Appendix Result*.

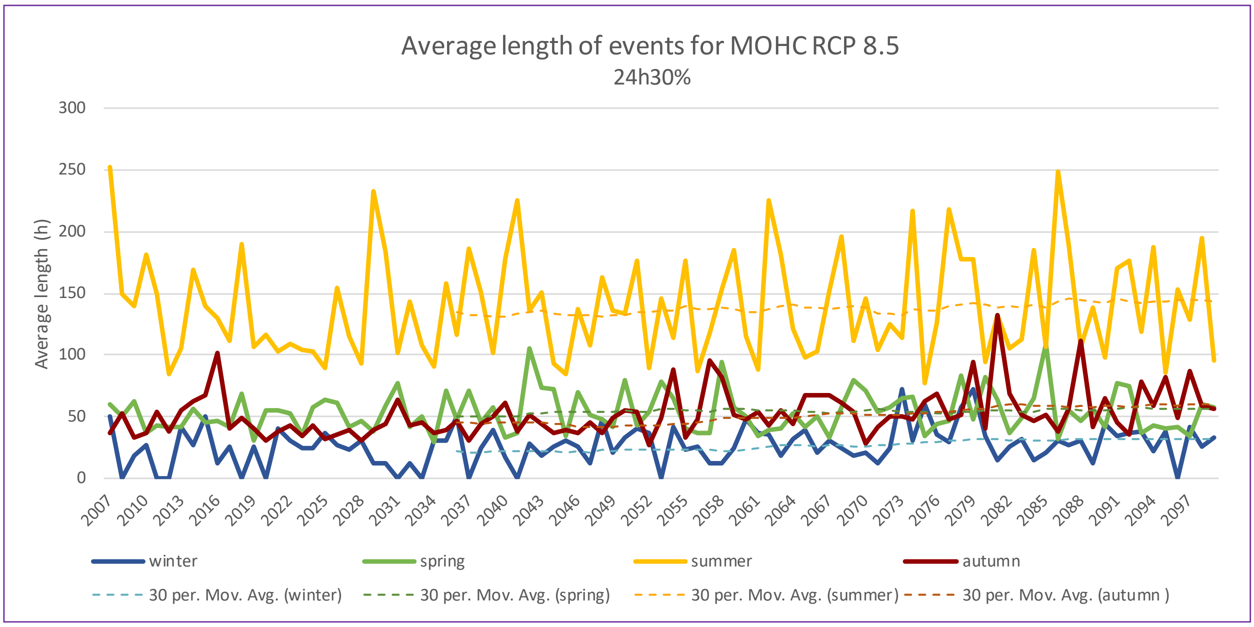

Figure 6. Average length of the events in all four seasons for MOHC RCP8.5 with a moving average of 24 h and a threshold value of 30%.

A gradual increase over time, of the average length (h) of the low wind events can be seen in *Figure 6*. For winter, the increase is about 10 h, spring 6 h, summer 10 h and for autumn 15 h. The corresponding number of events can be seen in *Figure 7*. However, there is only an increase in number of events during the winter and spring, of about one event per year respectively, resulting in three events during winter and seven events during spring. The increase for winter is the change that has the biggest potential of becoming expensive, due to the high energy demand. Even though the average length of the events is just above 30 h, this would in total correspond to an increase in low production hours of four days (96 h). During spring, the average length increases by a few hours, from 50 h to 56 h, together with the increase of one extra event per year it results in an increase of almost four days (92 h), resulting in 16.5 days of low wind in total. Even though the average length of the events increases during summer, by 10 h, this is not enough to counteract the decrease of one event per year, resulting in a decrease of one day in total (25 h). However, it is still on average 66 days of the summers total 92 that the production is 30% or less. For autumn, the increase in number of events is less than a day but the increase in average length is 15 h resulting in an increase to 6 days in total.

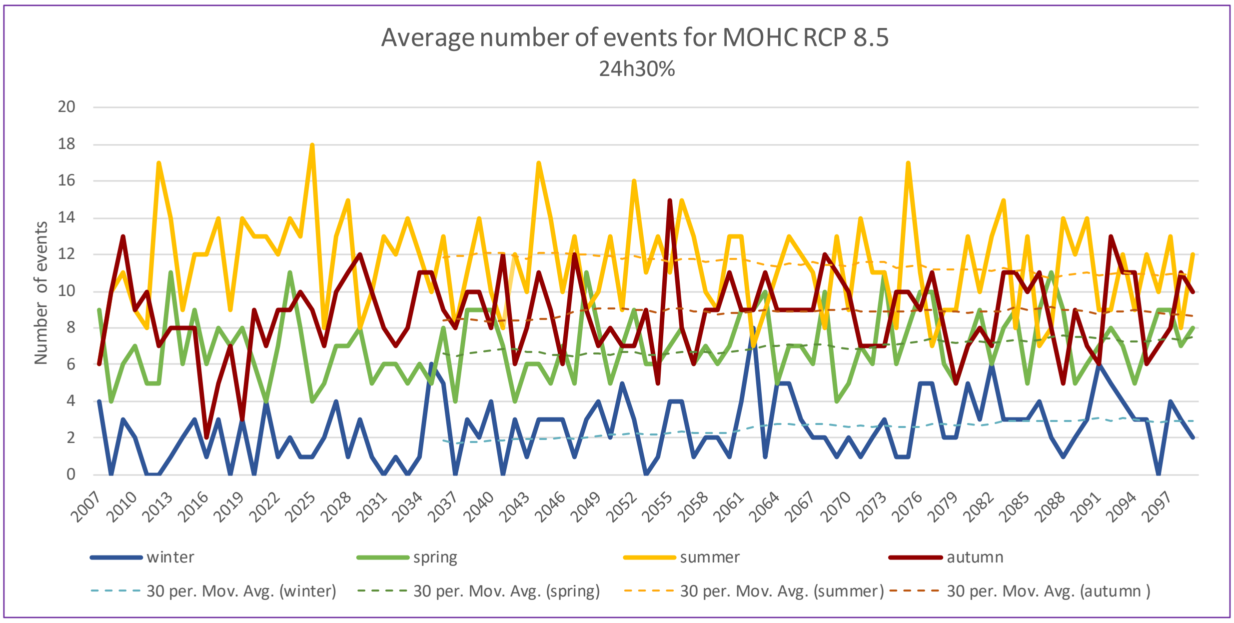

Figure 7. Number of events for all four seasons for every year in the time scope for MOHC RCP8.5 with a moving average of 24 h and a threshold value of 30%.

In *Figure 8* and *Figure 9* the corresponding results for MPI RCP8.5 can be seen. The average length of the events increases 6 h for winter, decreases 2 h for spring, increases 6.5 h for summer and increases 5 h for autumn. The number of events on the other hand increases by one for winter and spring, decreases by one for summer and stays the same for autumn. This results in 3 days during winter, increased by 1.5 day. During spring, the total is increased by one day resulting in 13 days of wind power production below the threshold. For summer, the result is decreased by one day resulting in 42.5 days. Autumn is the only season with no change in events, however, the total result is still increased by 2.5 days resulting in 12.5 days due to the increase in average length of low production periods.

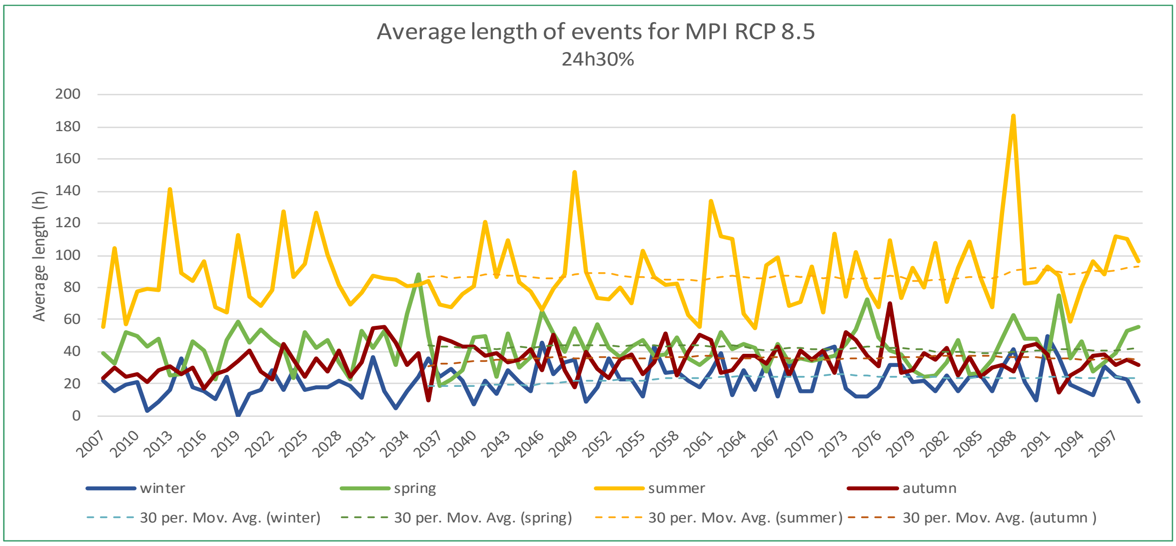

Figure 8. Average length of events for all four seasons for MPI RCP8.5, with a moving average of 24 h and a threshold value of 30%.

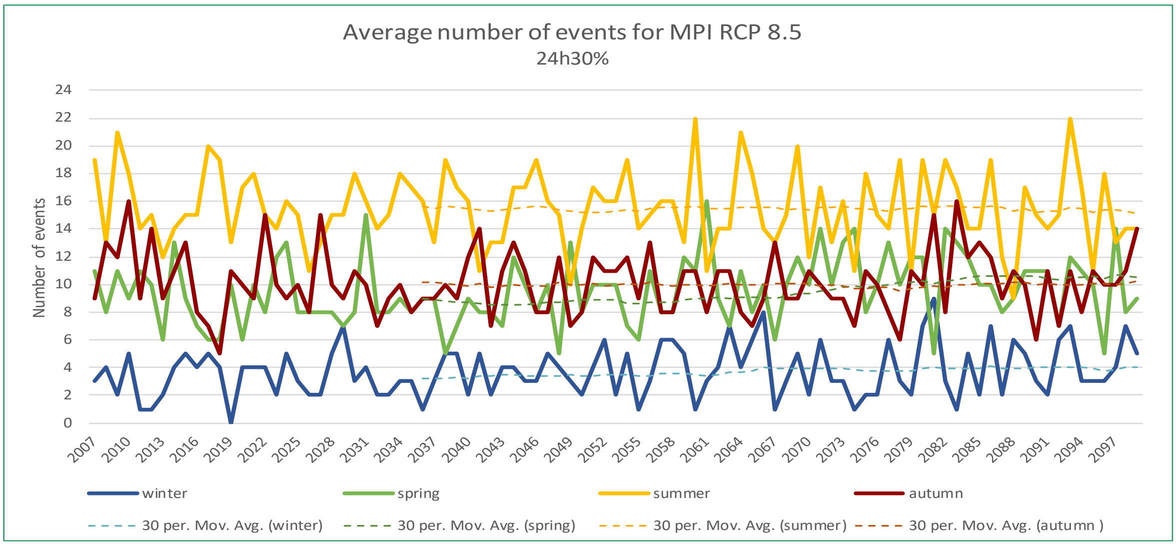

Figure 9. Number of events for all four seasons for MPI RCP8.5, with a moving average of 24 h and a threshold value of 30%.

For easier comparison with the results from MOHC and MPI, this paragraph will concern *Figure 6*, *Figure* 7, *Figure* 8 and Figure 9. The two models do have different output. While MPI is visibly higher in number of events, MOHC has apparent longer events. Multiplying the average length with number of events, demonstrate that MOHC has, for all four seasons, more hours that the electricity production is 30% or less. They differ from each other the most during summer, multiplying the average length with number of events conclude that it is 24 days (out of total 92) more in MOHC that has as low electricity production as 30% or less of installed capacity. Both the models indicate an overall increase of low production hours; the models are ambiguous as to whether it is the duration of events or number of events which increase. If these events do not occur too close to each other this would entail that the events still are manageable, therefore, no indication of a critical risk. N.B., this does still entail a need for either a bigger energy storage or more complementing electricity production techniques. However, data from only two models are not enough to say anything for sure, whether a warmer climate does affect the wind patterns studied in this thesis, or not.

Discussion

This study shows two main results. First one is that if the global warming is kept below 1.5℃ the results from this study indicates no visible change in wind power production at all. The second result is for RCP8.5 which corresponds to a global warming of about 5℃, which shows a 3% decrease in yearly production, by the end of the 21st century. The result from RCP8.5 is in line with the result from previous work, carried out by Tobin et al. Who also see a 3% decrease of wind power production for RCP8.5 [3].

In this study two moving average values, 12 h and 24 h where used together with three different threshold values, 20%, 30% or 40%. It was discovered that with a higher threshold value than 30%, the risk of the whole summer becoming one big event got too high to provide any useful information for this study. Opposite, a smaller threshold value than 30% could be used if the intention is to look at the summer by itself or if the aim is to look at the need for reserve capacity. A favourable thing with having these values for moving average and threshold value was that it gave a good overview of the suitability of energy storage as a mean of substitution.

To evolve the work even further it is of interest to not only see how many low production events there is, but also how close to each other they are, since this impact the choice for substitute for the low production hours. If the events are sparsely distributed the potential for energy storage are good, on the other hand, if they are close to each other that could imply that the storage will not have time to charge in between the events. Combining this with the indicators for average length of event and number of events are of great interest. Since it would provide extra information which would make it easier to decide what kind of storage that is useful, what size it need to have in order to be able to substitute the majority of the events, to give a few examples.

Possible sources for error

As for all studies there are likely sources for error and during this one the following once have been detected.

When evaluating the events during summer, with a threshold value of 40% there is a risk of it expanding throughout summer into the autumn. Since the “event count” count the event to the season the event ends in, these very long events risk to be counted to autumn instead of summer, where the majority of the event elapse. However, this is the case for both models and scenarios and therefor it should affect the result uniformly.

Another source for misinterpretation is the lack of data from several climate models. This study was conducted on only two models. It would be more appropriate to draw conclusions from a cluster of results from several models since it instils higher credibility to the results.

A quite interesting thing that is visible in *Figure 4* is that the “starting value” do vary quite a bit between the different models and scenarios. Even though the result is from two different models, they should still look pretty much the same from the start since they are supposed to model the future climate from the same initial values. Considering changes within seasons, seen in

Table 2, it does not appear to be a shift in value since the percental change does not follow the same pattern, even though the change is similar for most cases. This is a sign of that the wind power production in Swedish is not what they calibrated their models after. Keeping in mind that wind power is the windspeed in cubic, meaning that it is not unlikely that it is a small difference in the models that give this result. Nevertheless, this implies that future models would benefit by area specific calibration of wind power production.

In the calculation phase for production it was discovered that the data for 2006 was repetitive, some tens of rows were repeated after and after, therefor it was decided to exclude the year 2006 from all the calculations, however it is very hard to tell if this repetitive data was merely an error from when the data was uploaded, something that whet wrong when calculating the windspeeds or if it origins from an error already in the scenario, when calculating the original data. Therefore, it is hard to assess how much this have affected the study. However, if the first case is the reason, it would only be about one year out of 90, which would have an extremely low impact.

Conclusion

With the results provided from this study, it has been studied how a warmer climate will affect the electricity production from wind turbines in Sweden. For future research, this work proposes the use of 100m wind speed data, or higher, when calculating electricity production since this eliminate the scaling procedure and is closer to hub height. Further, a rolling average of 24 h together with a threshold value of 30%, is recommended to provide a general result of low production hours, however these numbers do vary depending on what the aim of that study is.

A slight decrease in production can be seen on both a yearly and seasonal level, for both models and their respective scenarios. Which indicate that it is likely that the production from wind power will decrease as an effect of a warmer climate.

Looking closer at the low wind events and their average length it was found that in many cases the number of events might increase and/or the average length of the event might increase. In the cases where the number of events decreased the average length of the event increased and thereby counteracted that possibility for an increase in production. Combining this with the overall decrease in production it implies that the low production hours are not compensated for by more high production hours. However, the result from the two models are ambiguous as to whether it is the duration of events or number of events which is the source to the increase in low production hours, or perhaps a mixture of both.

However, the overall results from this study do indicate that future wind power owners do not pose a high risk of being directly affected by the change in production from the wind turbines, as an effect of global warming. Nevertheless, there are indirect effects that are not evaluated in this study that might have an impact.

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Appendix

A. Result

Sadly, the scenario of RCP2.6 for model MPI only had the time scope of 2006 to 2060. The result from scenario are therefore not as easy to compare with MOHC RCP2.6 as they were for scenario RCP8.5. And the moving average therefore do not go as far into the future and the result are less pronounced. However, there are still some visible changes for MOCH RCP2.6 that are worth mentioning. A slight decrease can be seen for the yearly production and this decrease cuts through the most in summer and autumn. Notice that all the vertical axes has been trimmed in order for the result to be easier to read. All graphs in this section has the Production [FLH] on the vertical axis and the year on the horizontal axis.

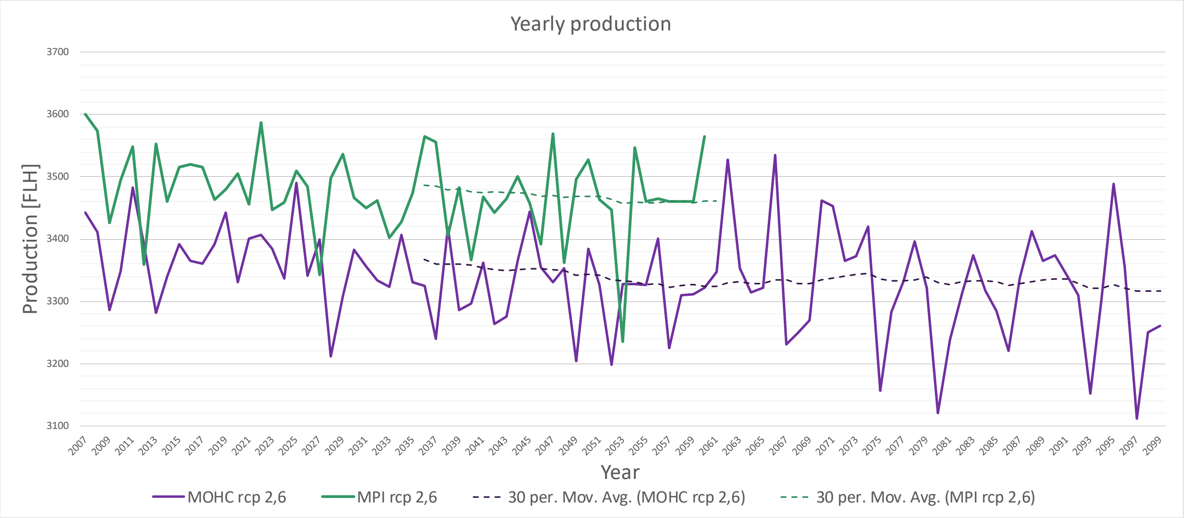


Figure A. 1 Yearly production for MOHC RCP2.6 and MPI RCP2.6.

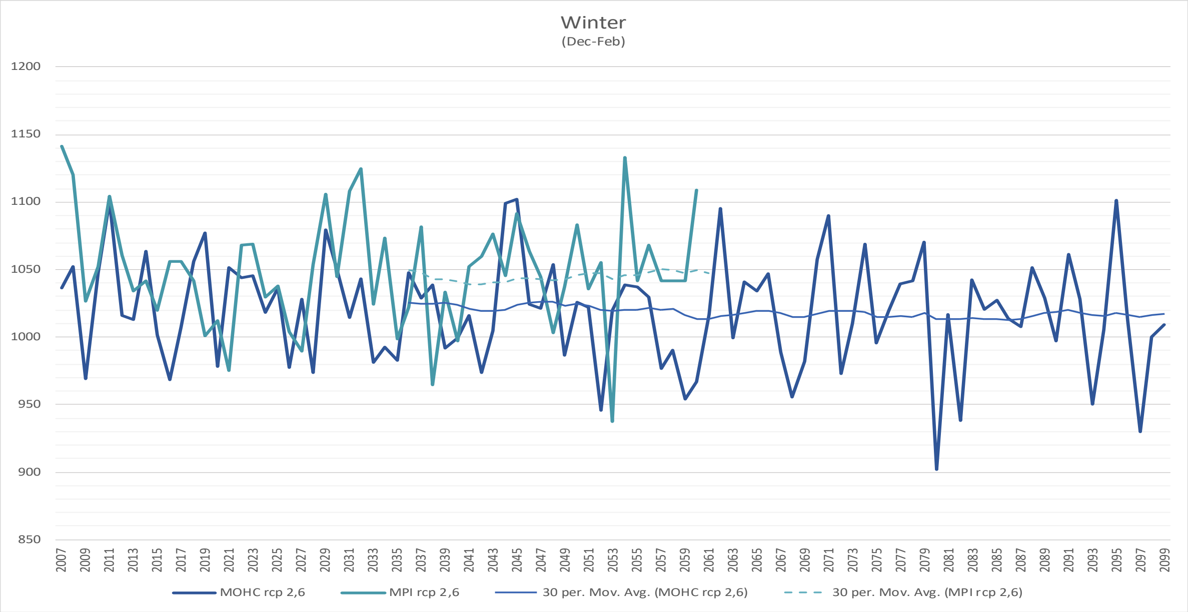


Figure A. 2 The production for MOHC RCP2.6 and MPI RCP2.6 during winter season (December to February).

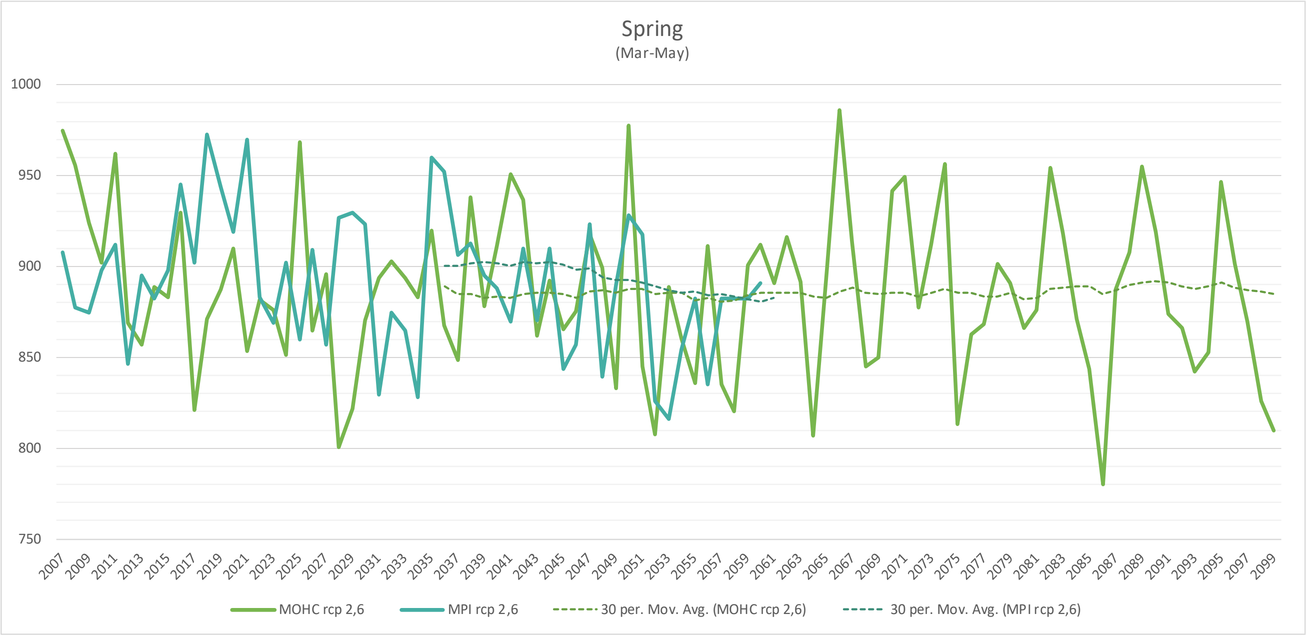


Figure A. 3 The production for MOHC RCP2.6 and MPI RCP2.6 during spring season (Match to May).

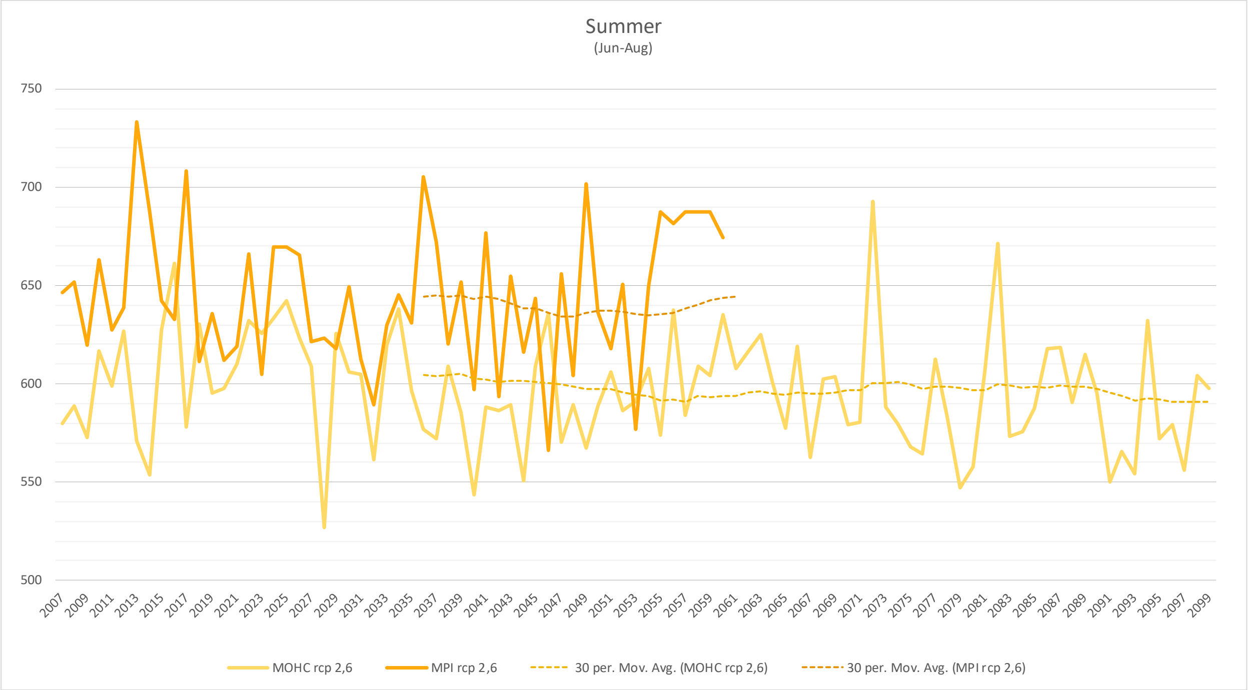


Figure A. 4 The production for MOHC RCP2.6 and MPI RCP2.6 during summer season (June to August).

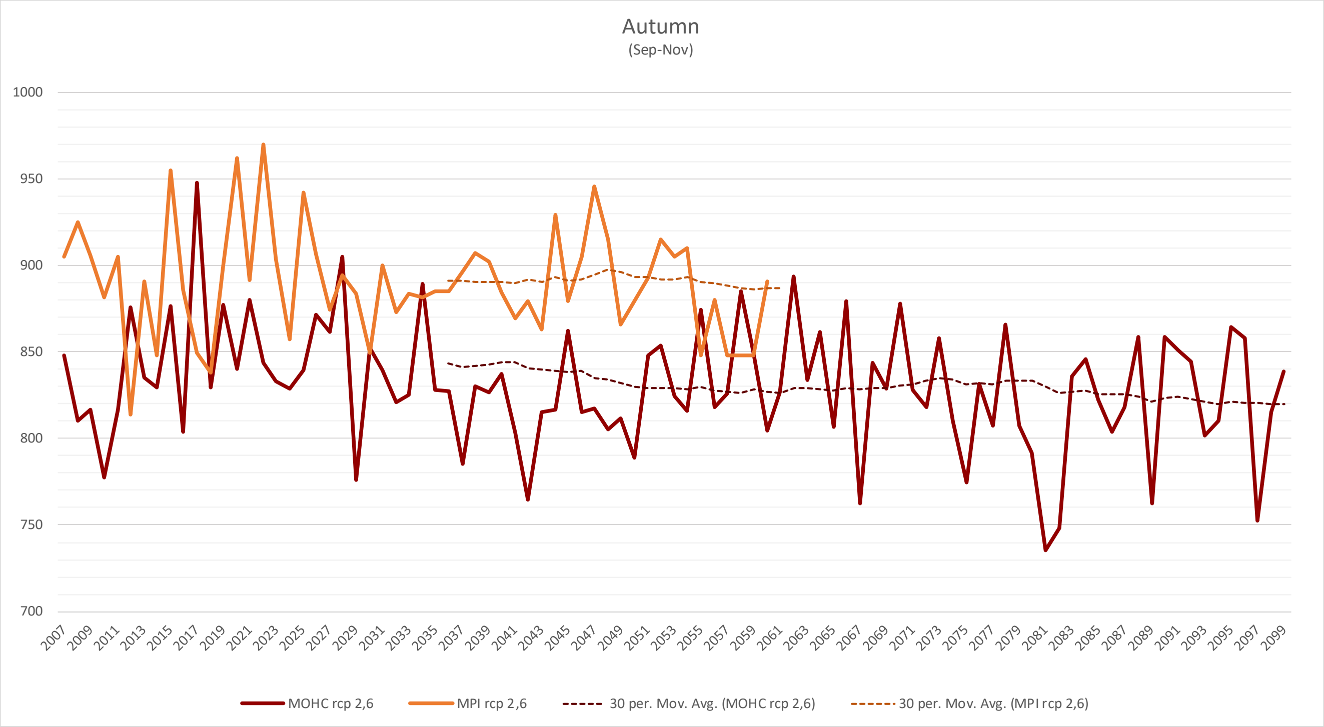


Figure A. 5 The production for MOHC RCP2.6 and MPI RCP2.6 during autumnal season (September to November).

B. Result

In this section the result for the indicators for MOHC RCP2.6 and MPI RCP2.6 can be found. All graphs representing result for MOHC are presented with a purple border and the result for MPI with a green border. In all graphs the years runs along the horizontal axis and on the vertical axis are either the number of events or the average duration of the event [h]. The information of what moving average and what threshold value that is being presented is found n the heading.

MOHC RCP2.6 - number of events

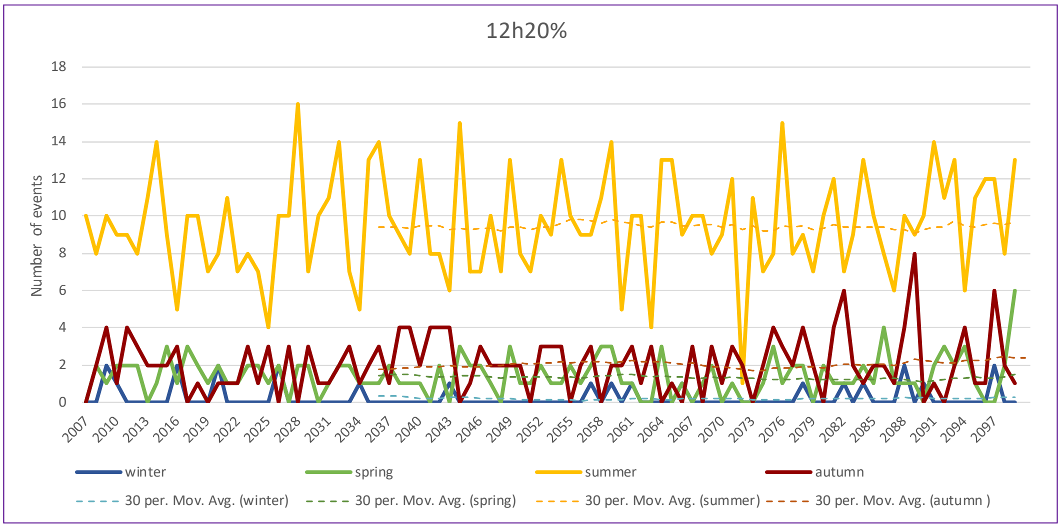


Figure B. 1. Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 12 h and a threshold value of 20%.

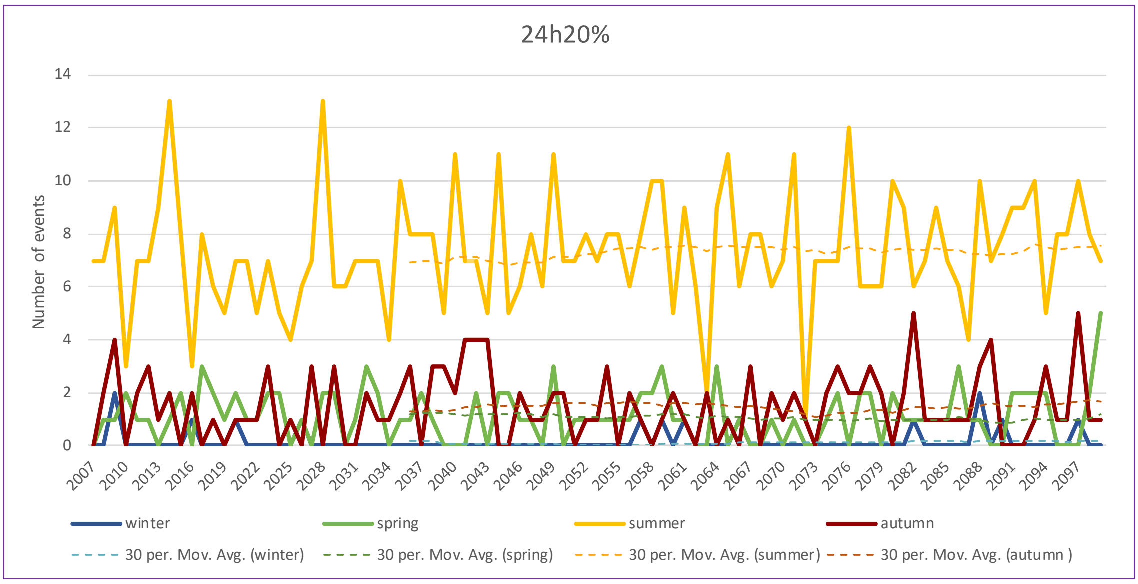


Figure B. 2. Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 24h and a threshold value of 20%.

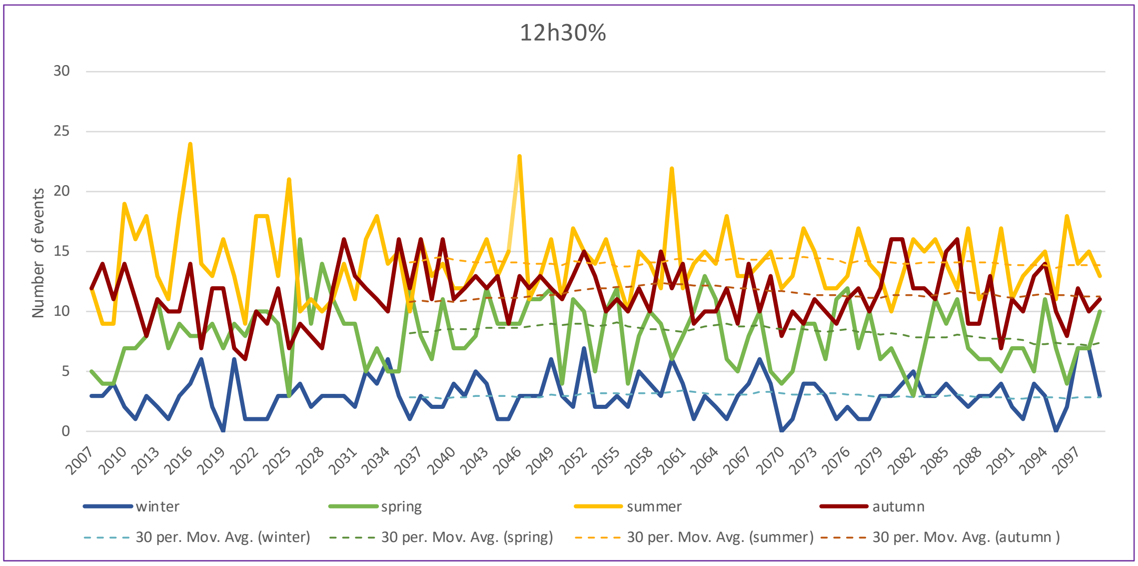


Figure B. 3. Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 12 h and a threshold value of 30%.

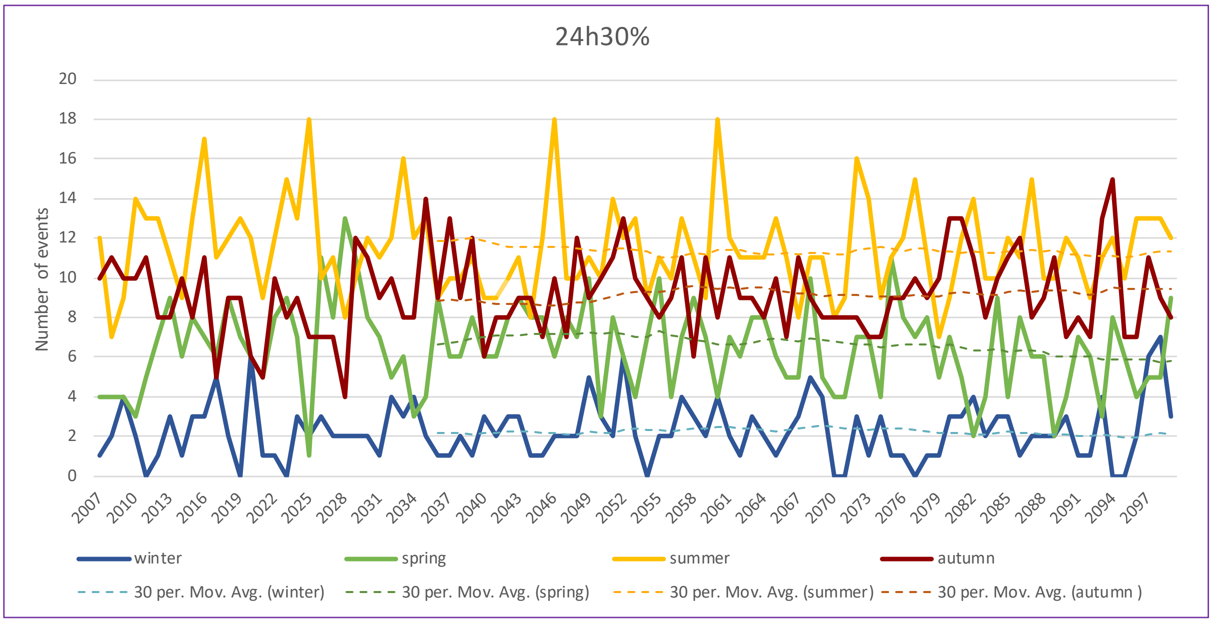


Figure B. 4 Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 24h and a threshold value of 30%.

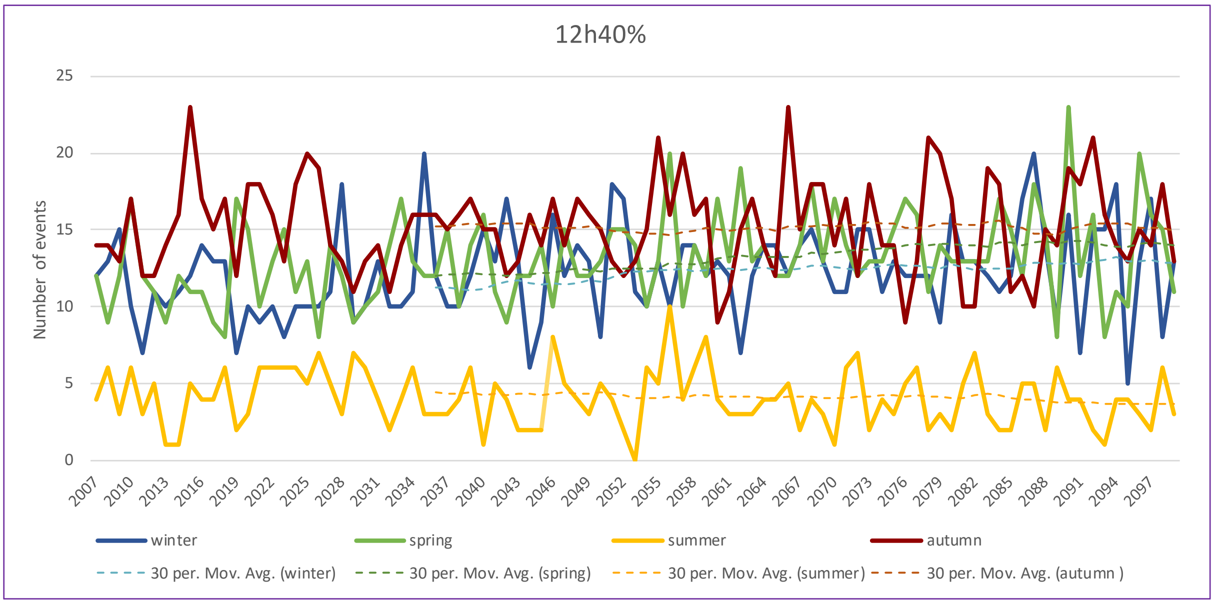


Figure B. 5 Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 12h and a threshold value of 40%.

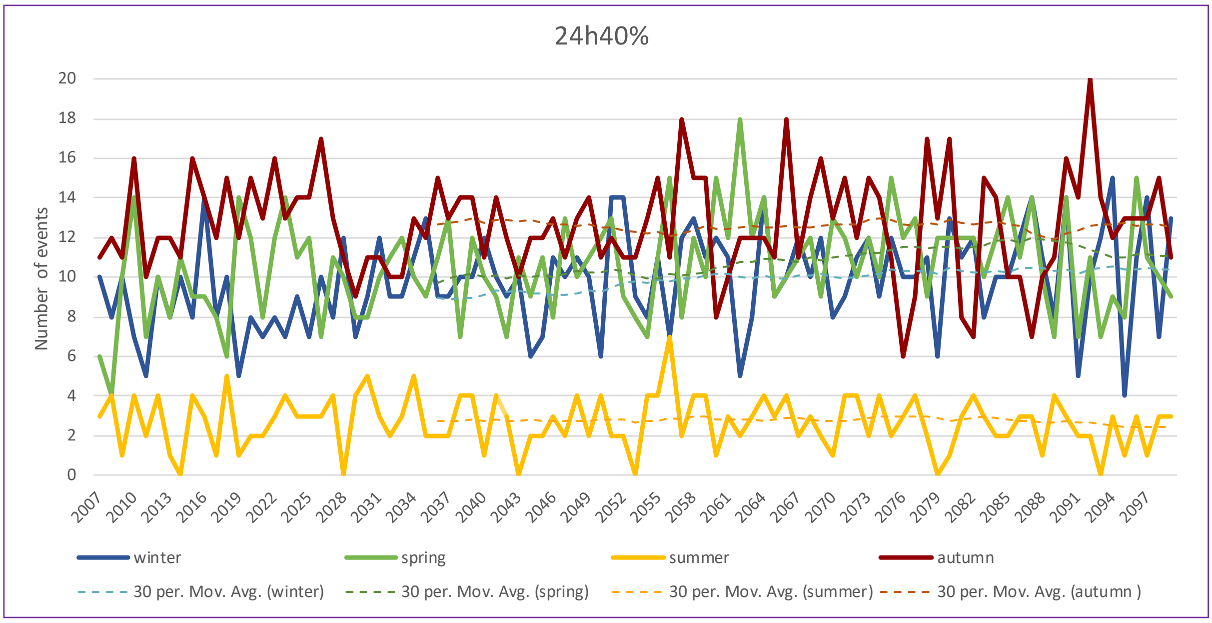


Figure B. 6 Number of events for each season for every year in the time scope for MOHC RCP2.6 and a moving average of 24h and a threshold value of 40%.

MOHC RCP2.6 - average length of events

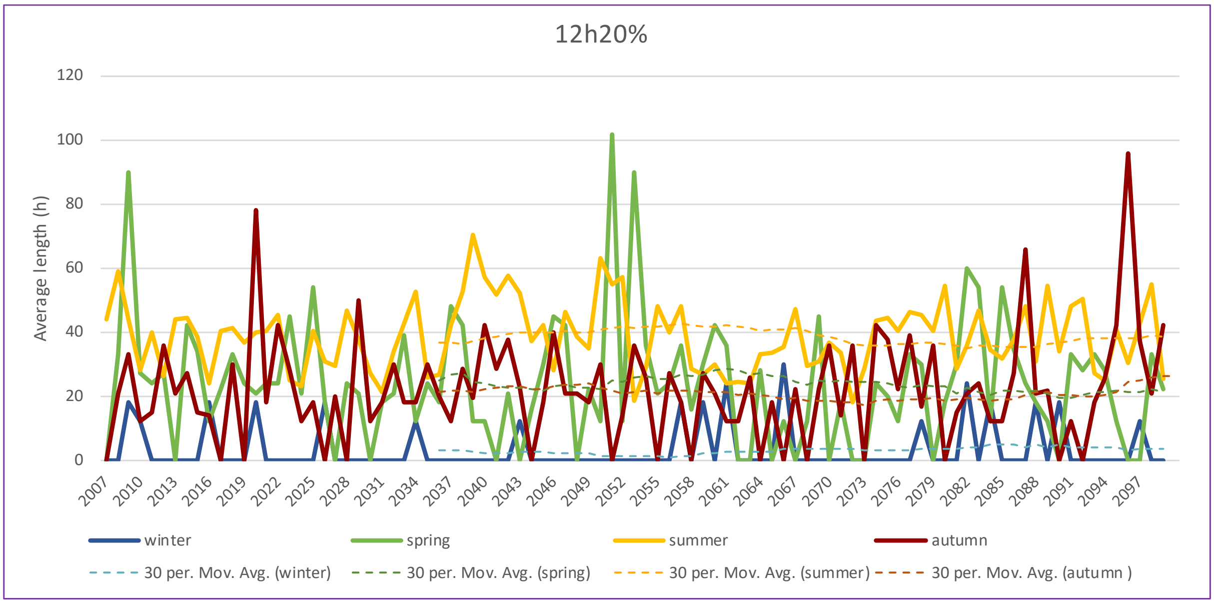


Figure B. 7 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 12h and a threshold value of 20%.

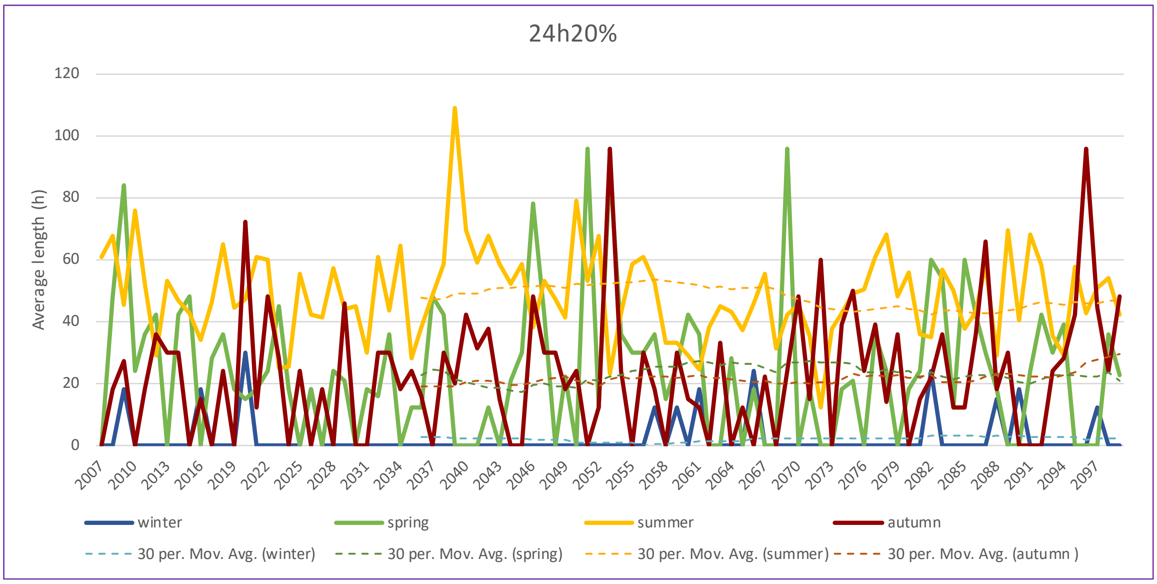


Figure B. 8 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 24h and a threshold value of 20%.

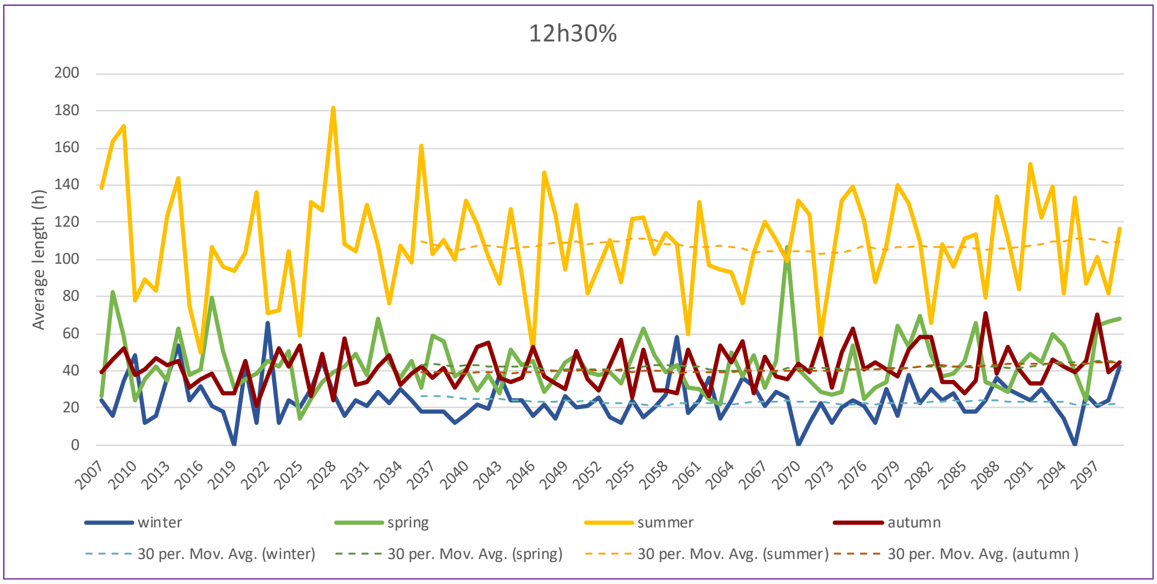


Figure B. 9 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 12h and a threshold value of 30%.

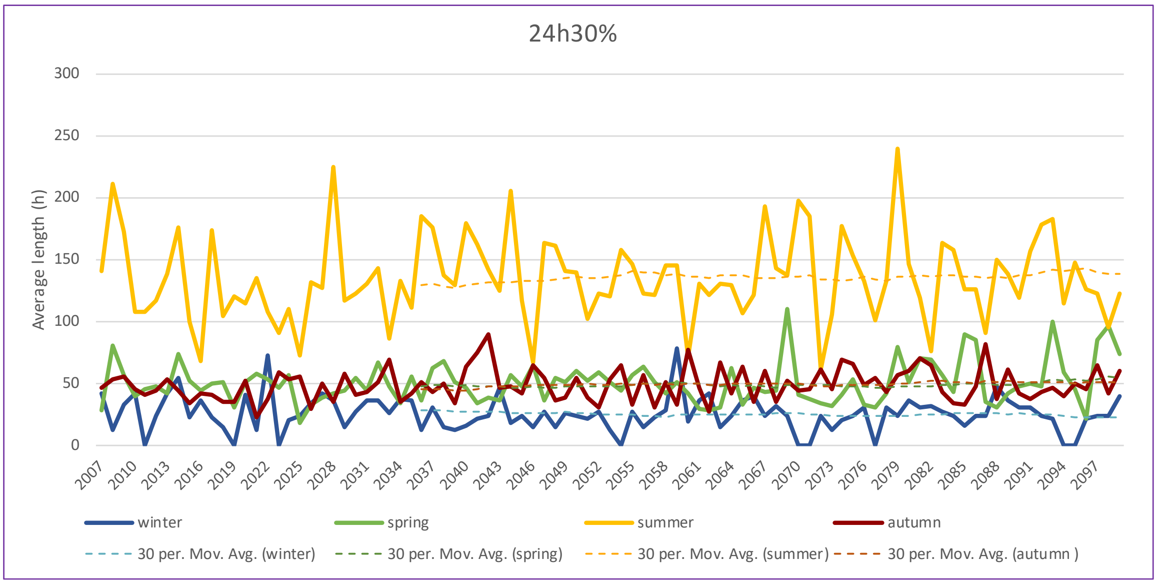


Figure B. 10 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 24h and a threshold value of 30%.

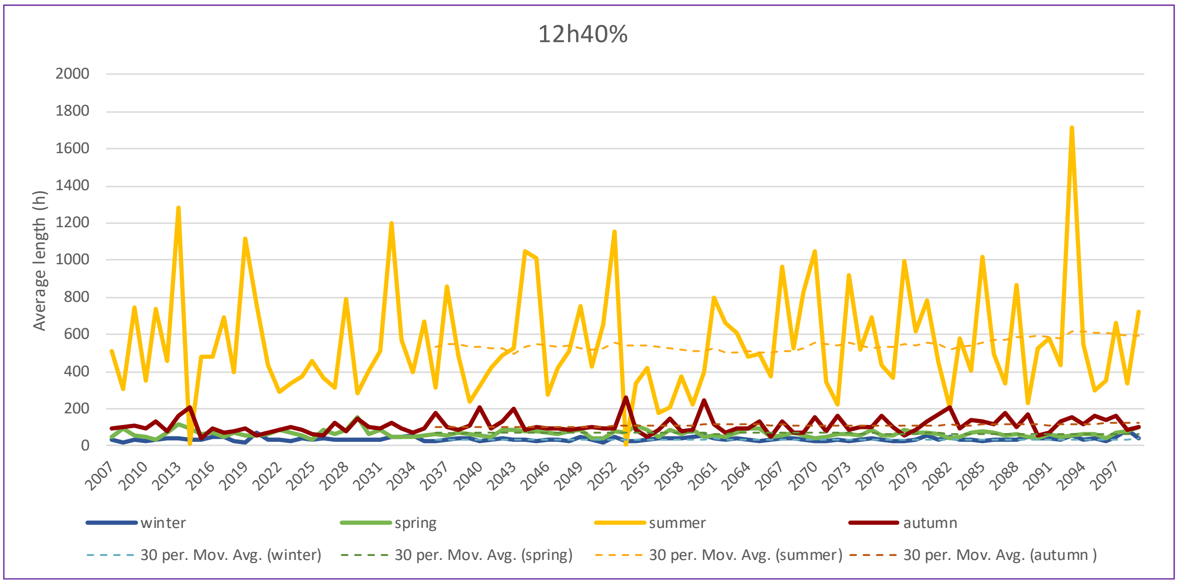


Figure B. 11 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 12h and a threshold value of 40%.

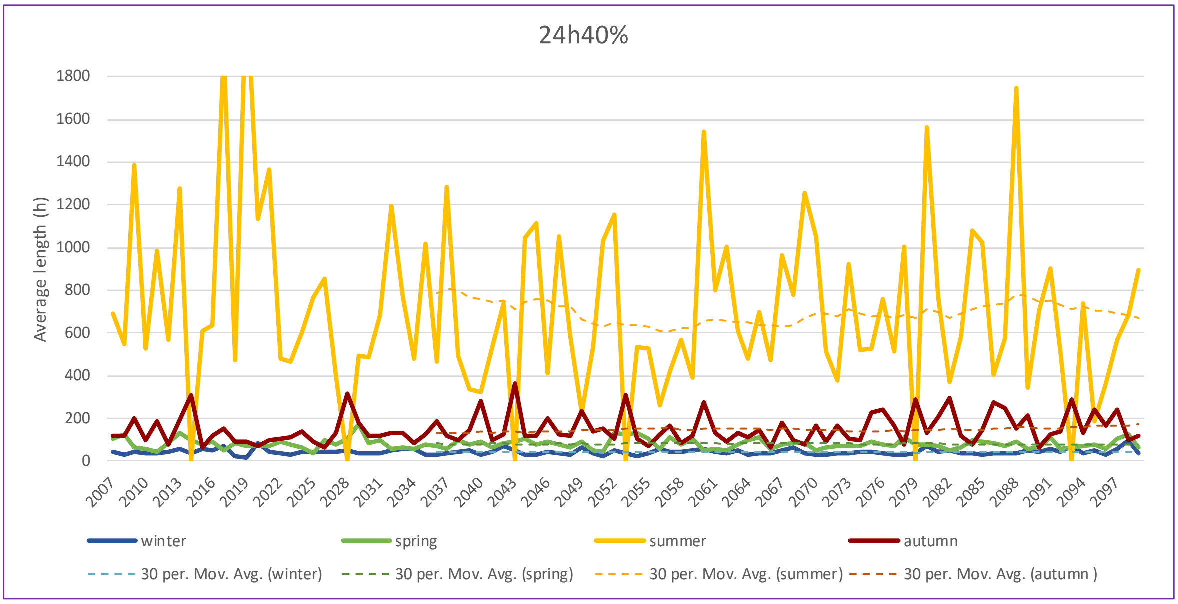
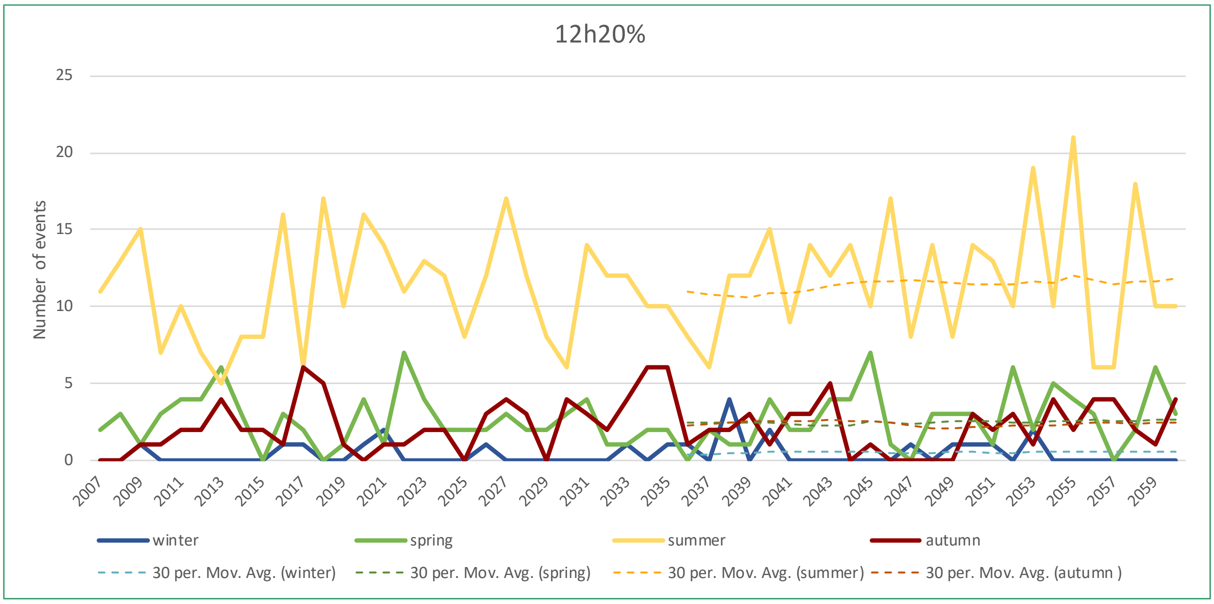
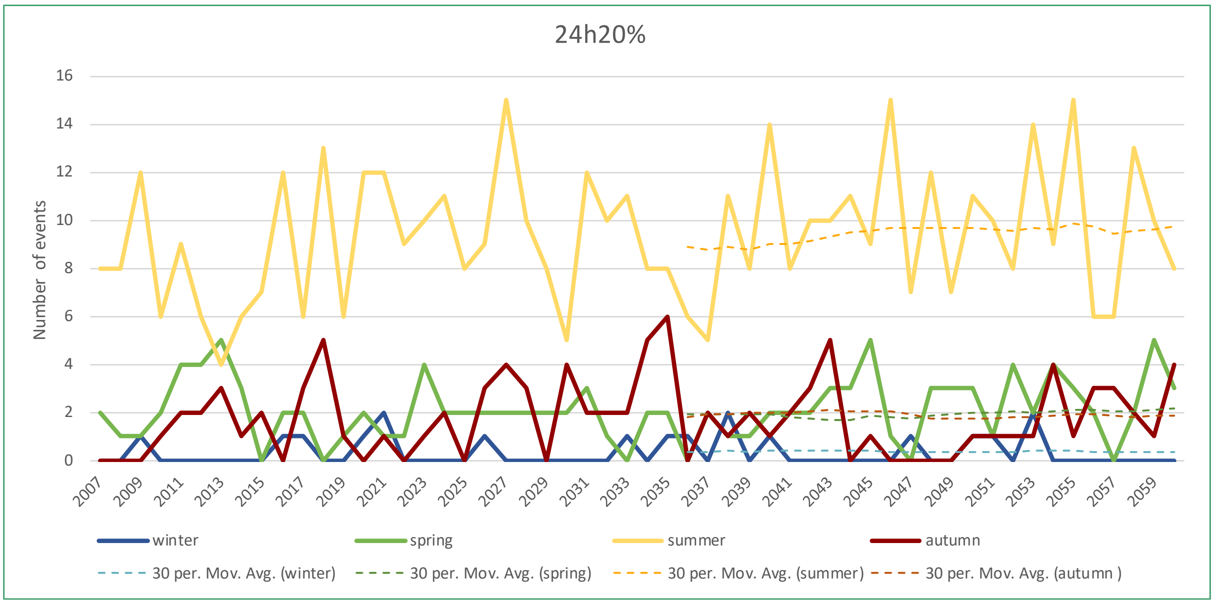
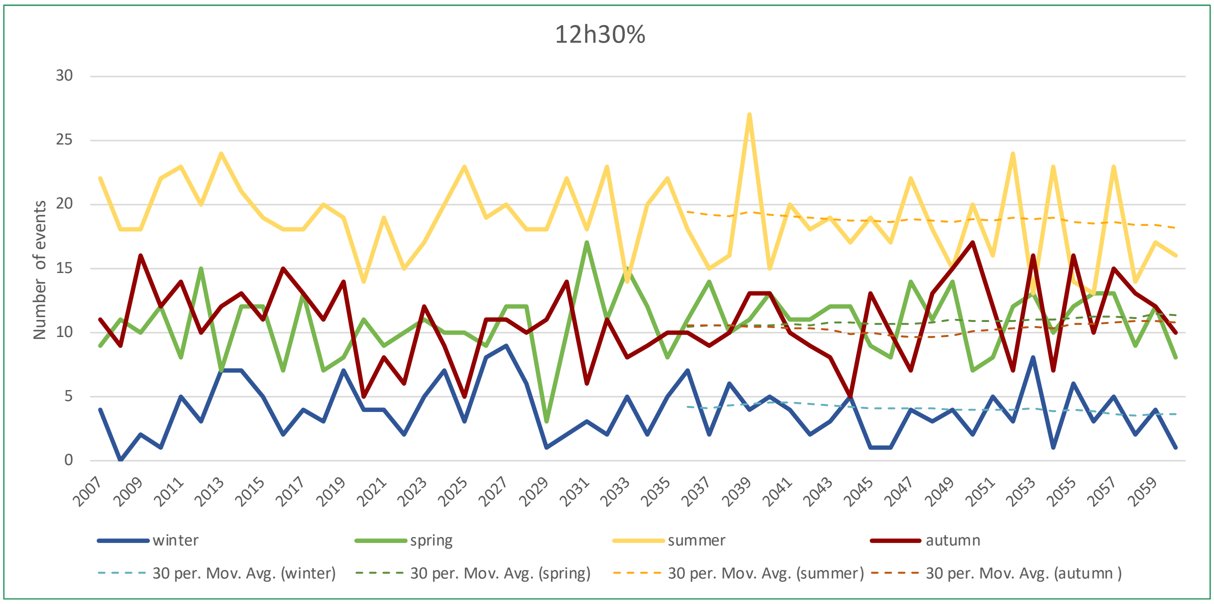


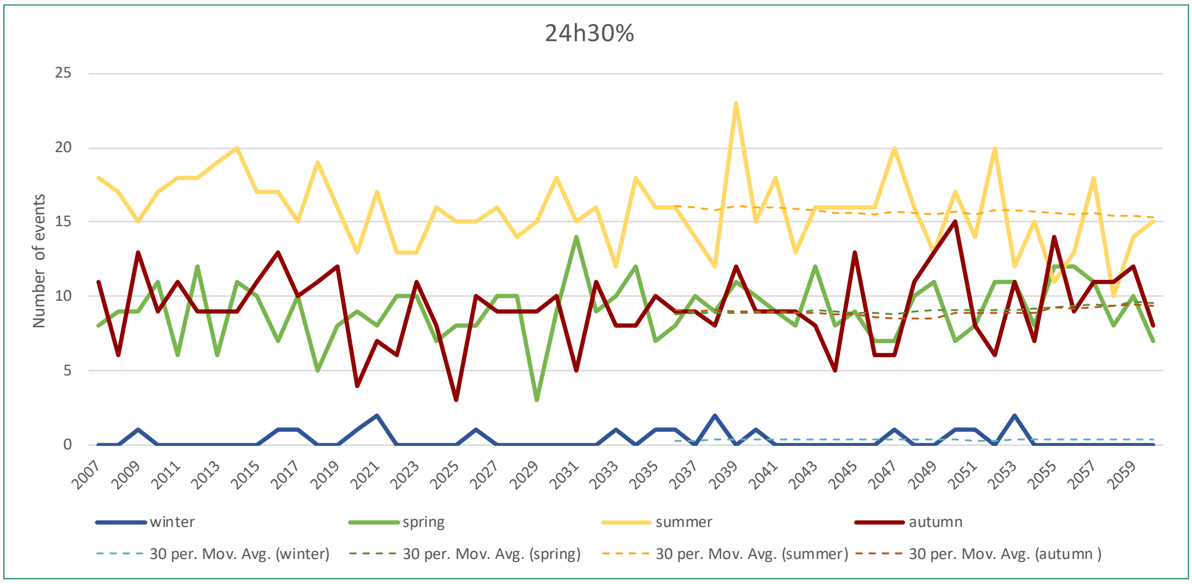
Figure B. 12 Number of events for each season for every year in the time scope for MPI RCP2.6 and a moving average of 24h and a threshold value of 40%.

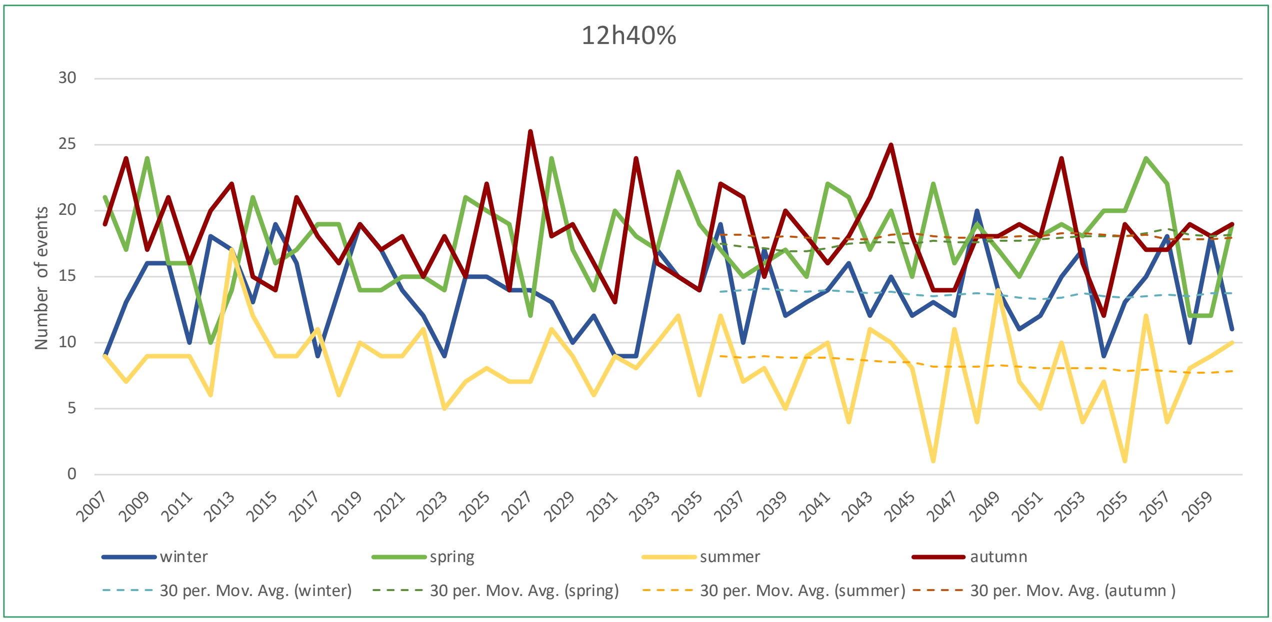
MPI RCP2.6 - number of events

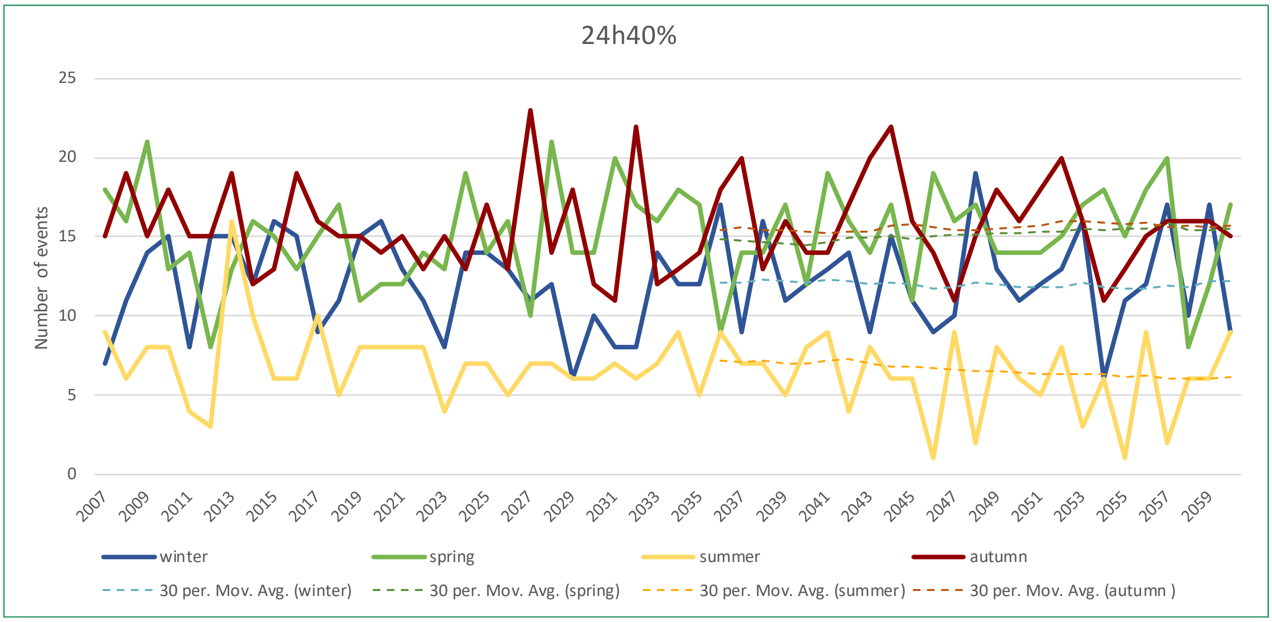



24h20%
Number of events
0
2
4
6
8
10
12
14
16
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


12h30%
Number of events
0
5
10
15
20
25
30
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


24h30%
Number of events
0
5
10
15
20
25
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


12h40%
Number of events
30
25
20
15
10
5
0
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


24h40%
Number of events
25
20
15
10
5
0
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
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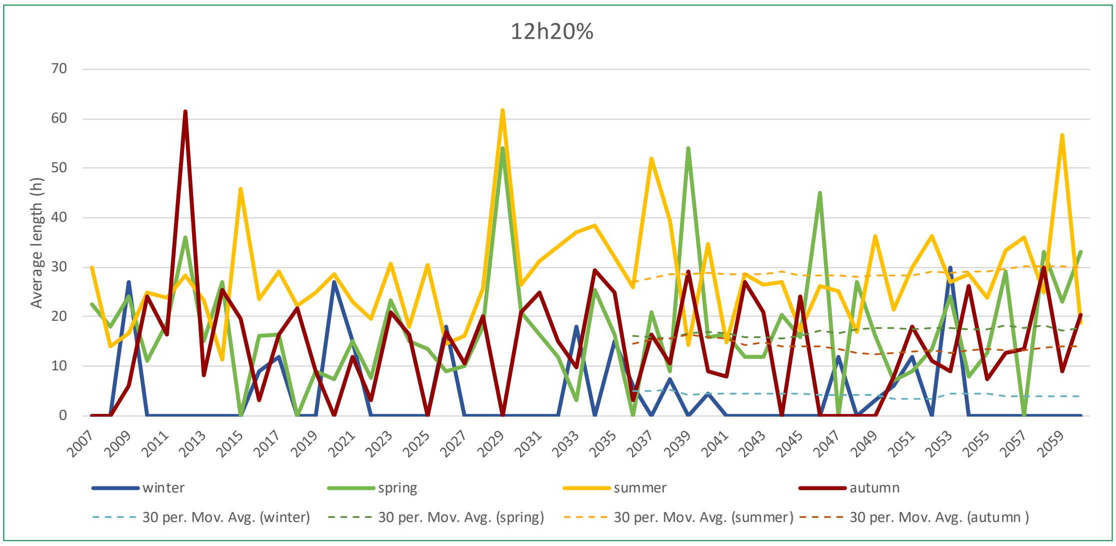
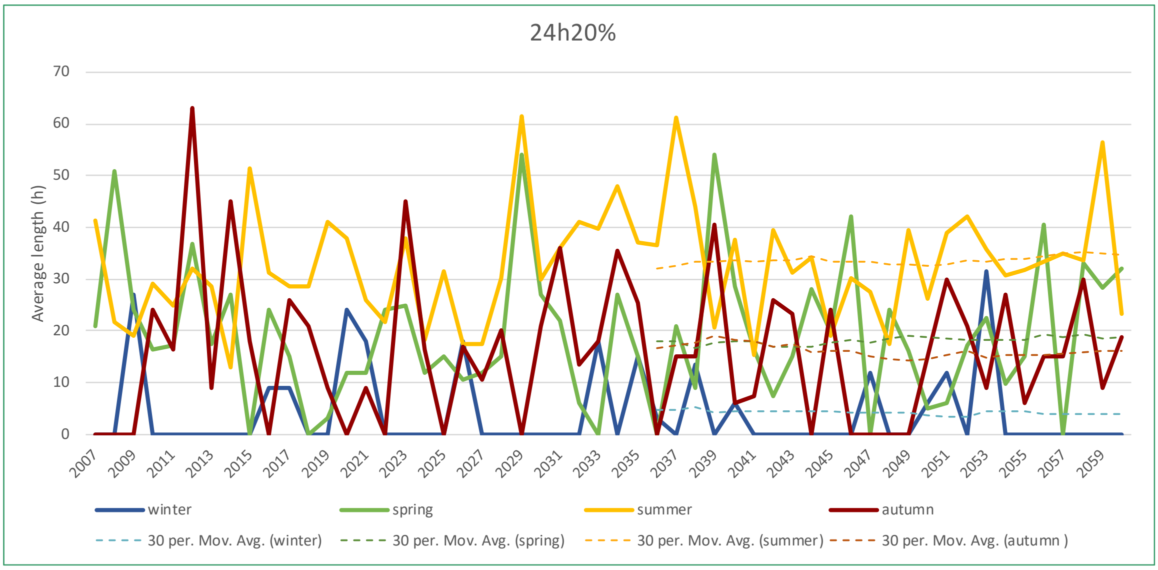
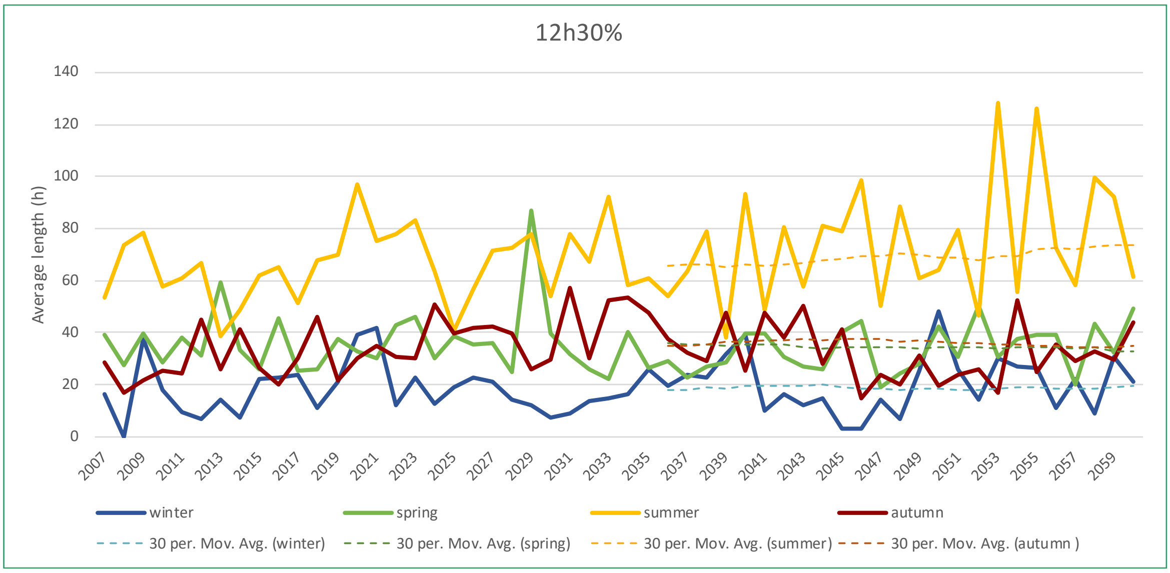
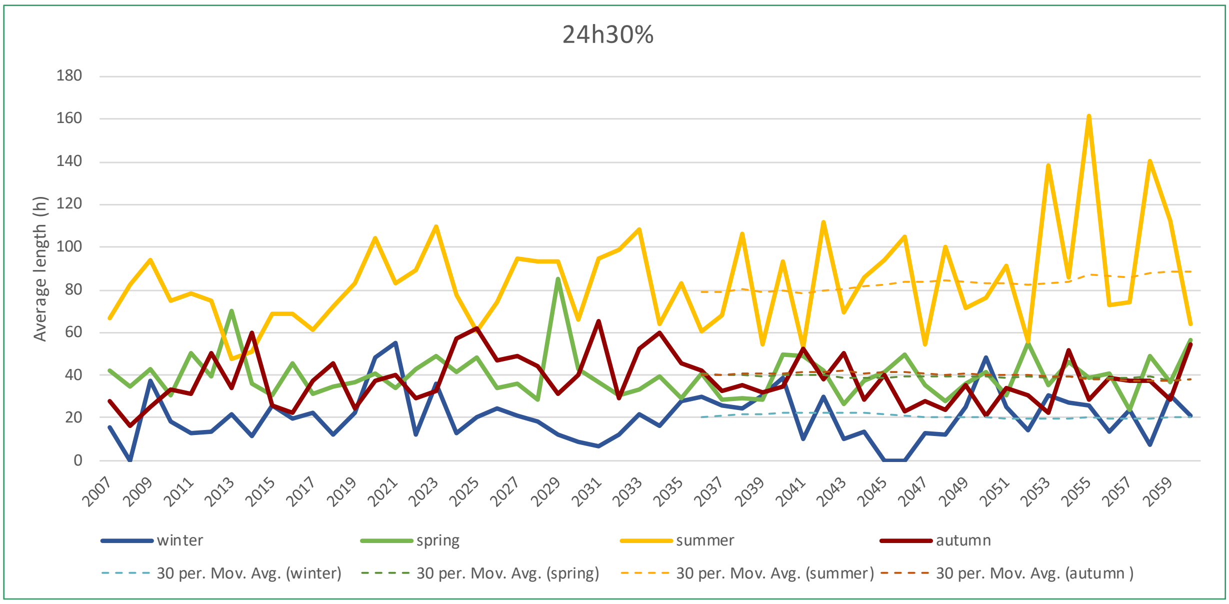
2045
2047
2049
2051
2053
2055
2057
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)

MPI RCP2.6 - average length of events








24h30%
Average length (h)
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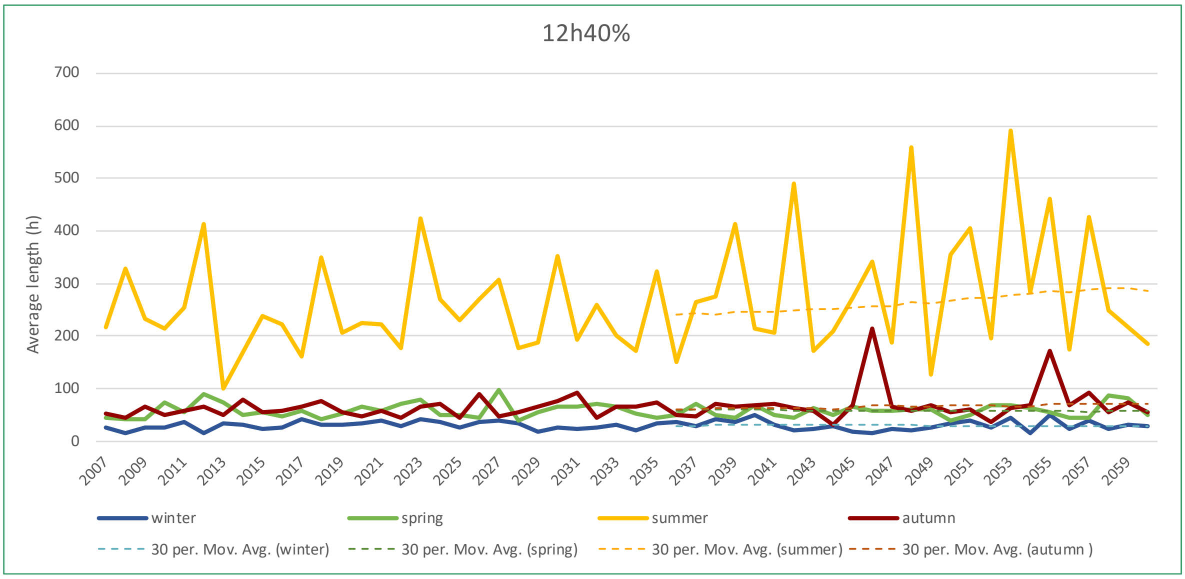
2059
winter
spring
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


12h40%
Average length (h)
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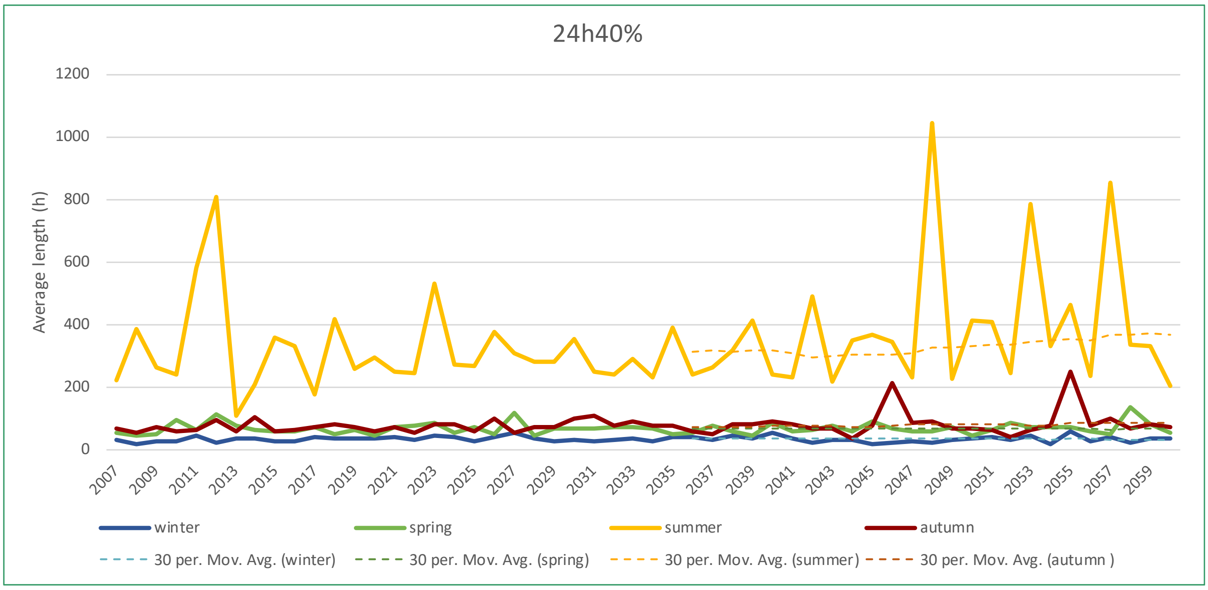
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


24h40%
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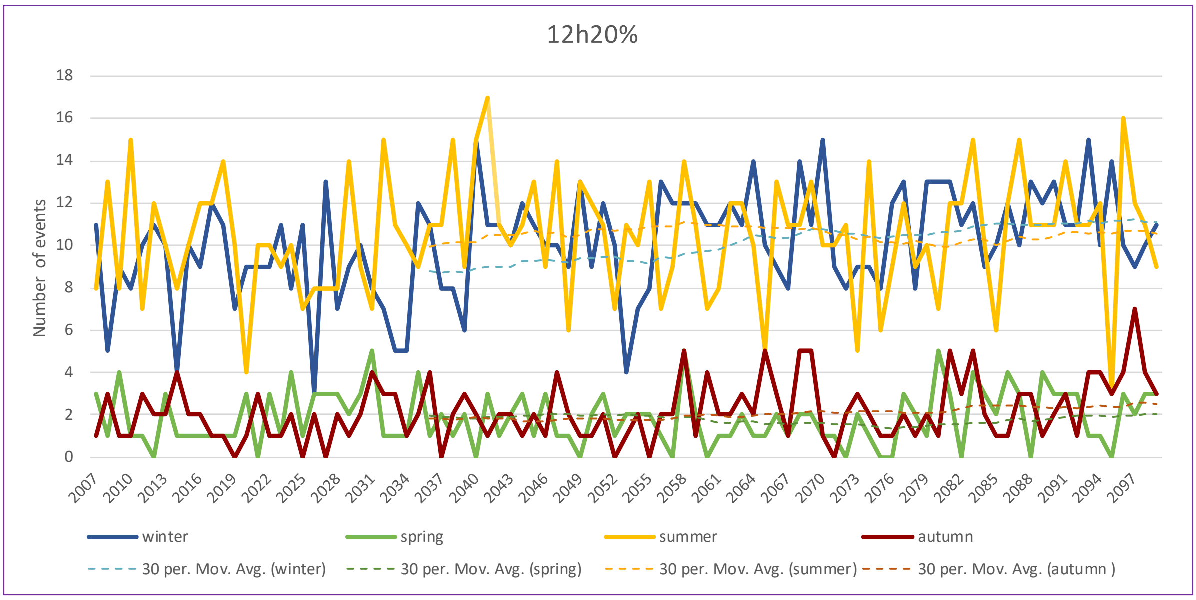
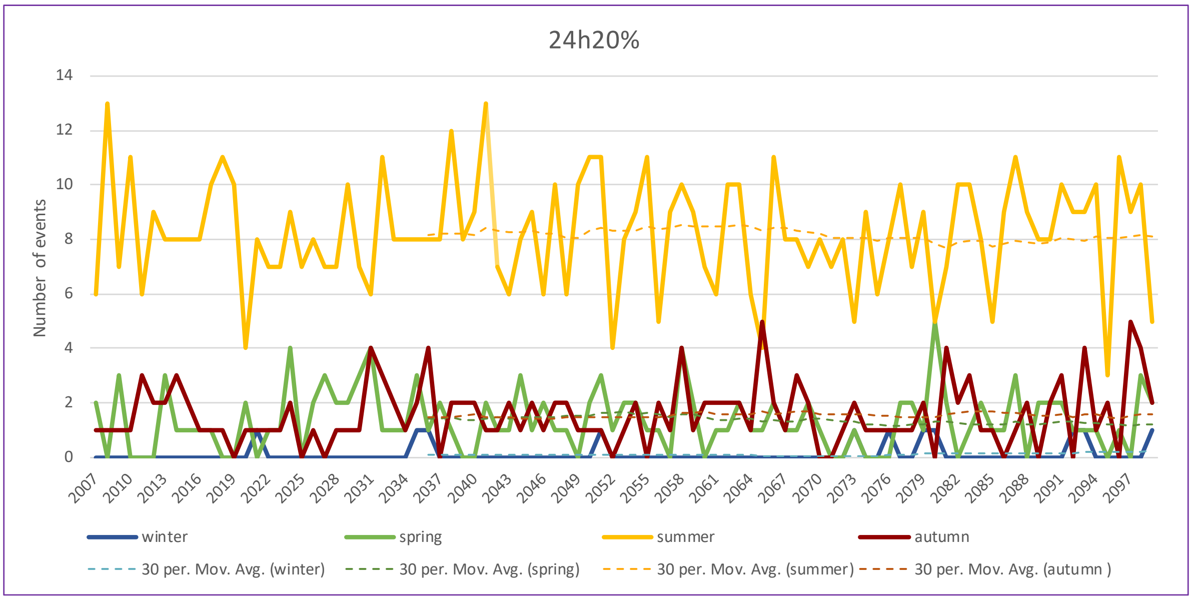
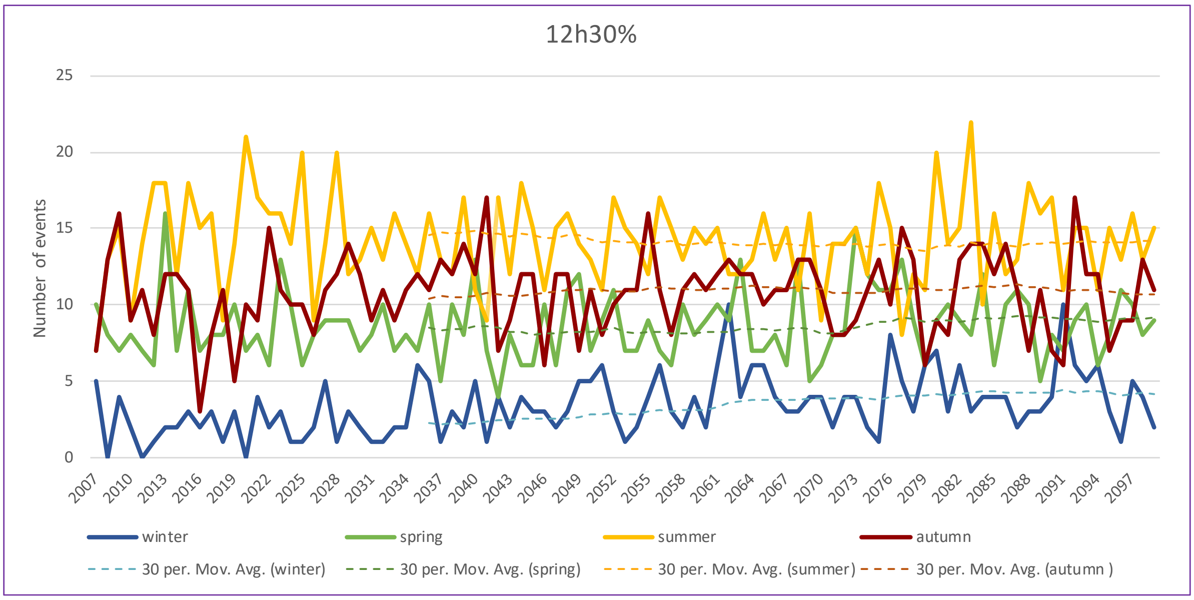
summer
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)

MOHC RCP8.5 - number of events



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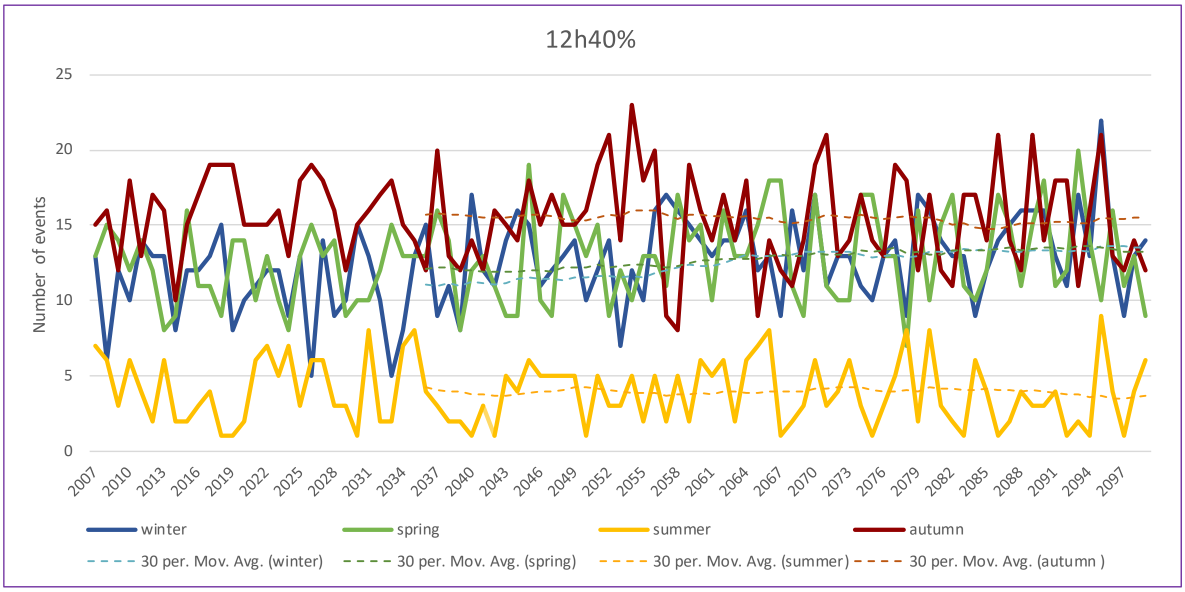
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)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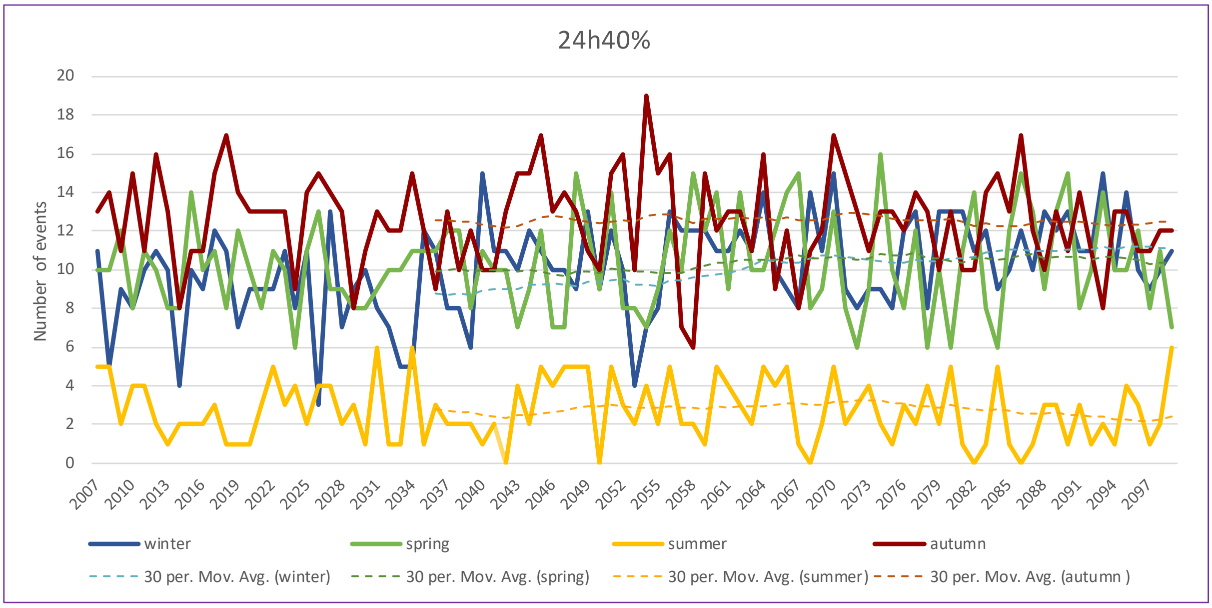
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)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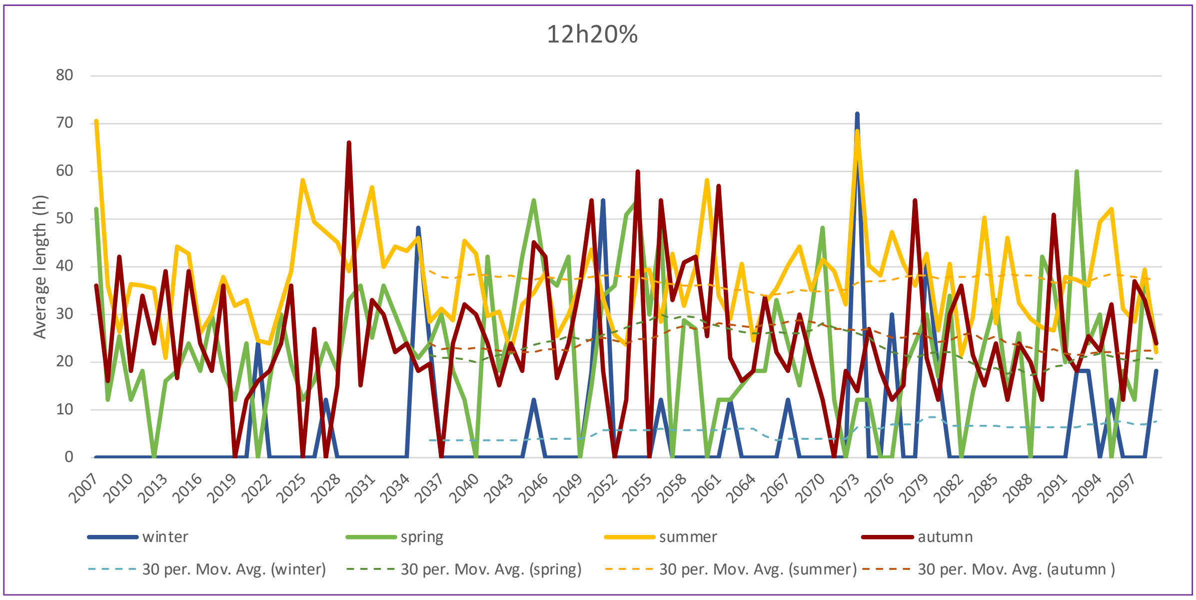
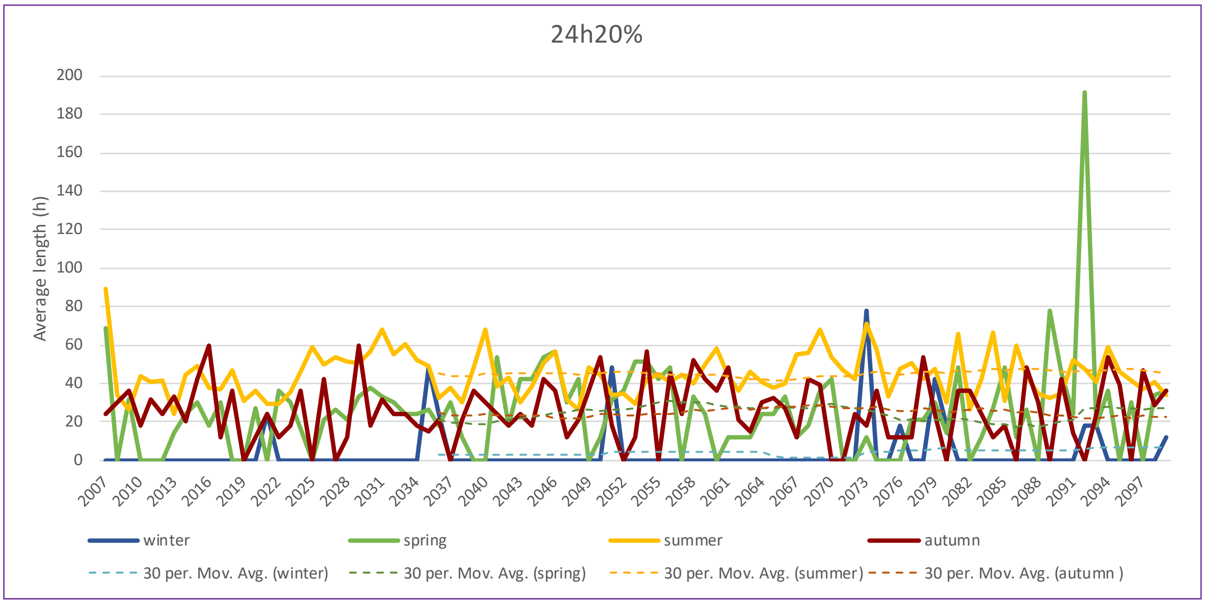
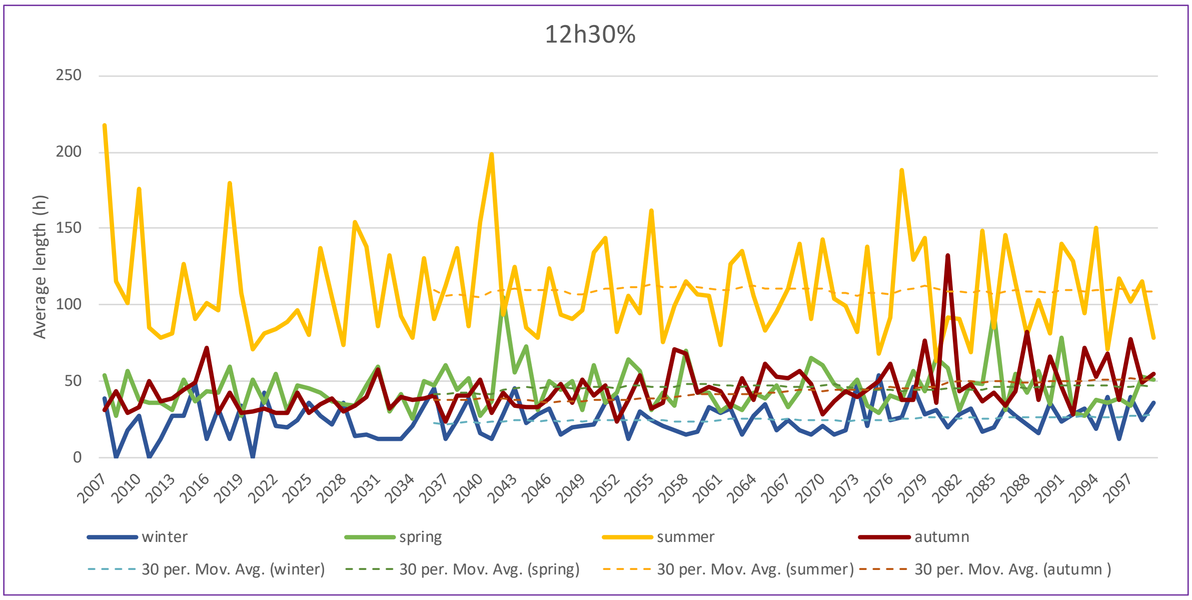
autumn
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)

MOHC RCP8.5 - average length of events



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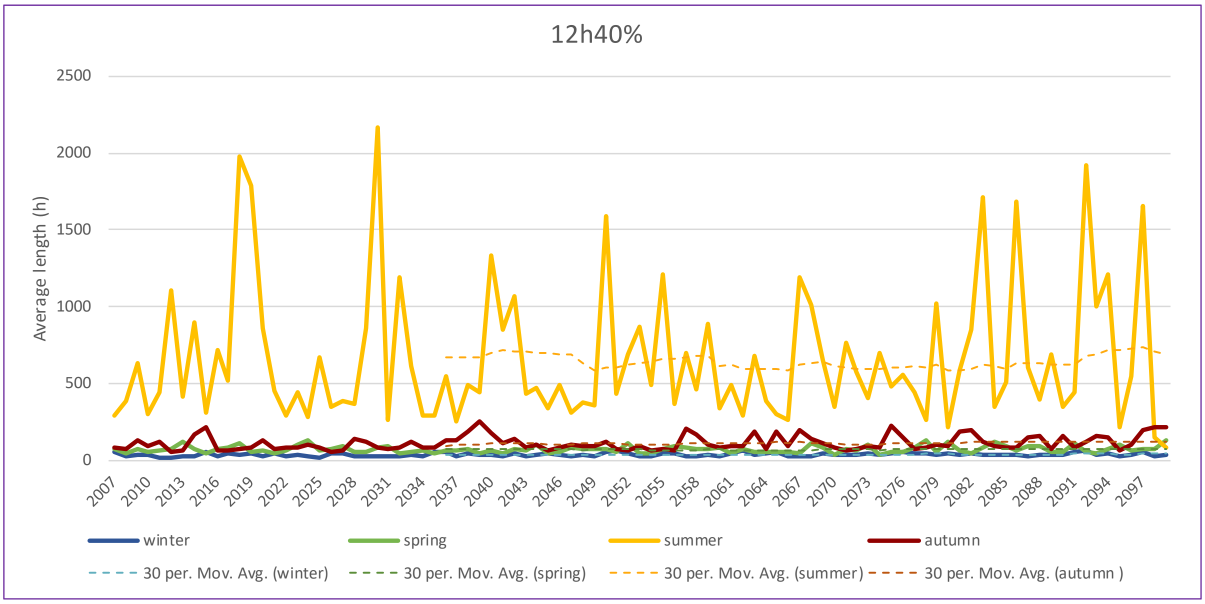
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


12h40%
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30 per. Mov. Avg. (winter)
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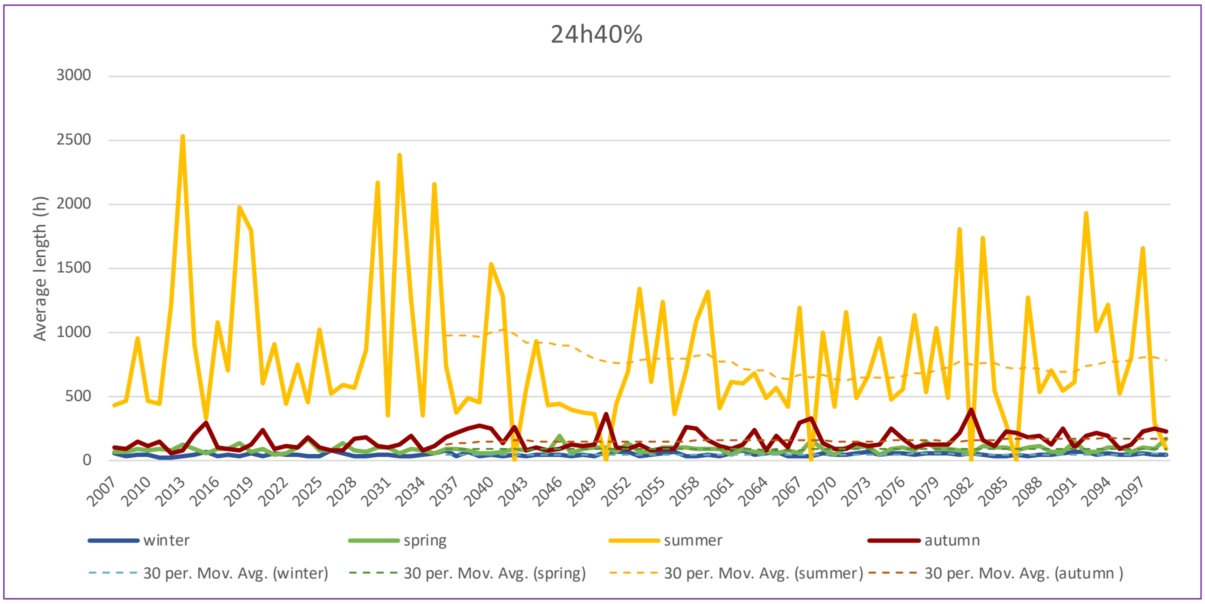
30 per. Mov. Avg. (autumn)


24h40%
Average length (h)
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30 per. Mov. Avg. (winter)
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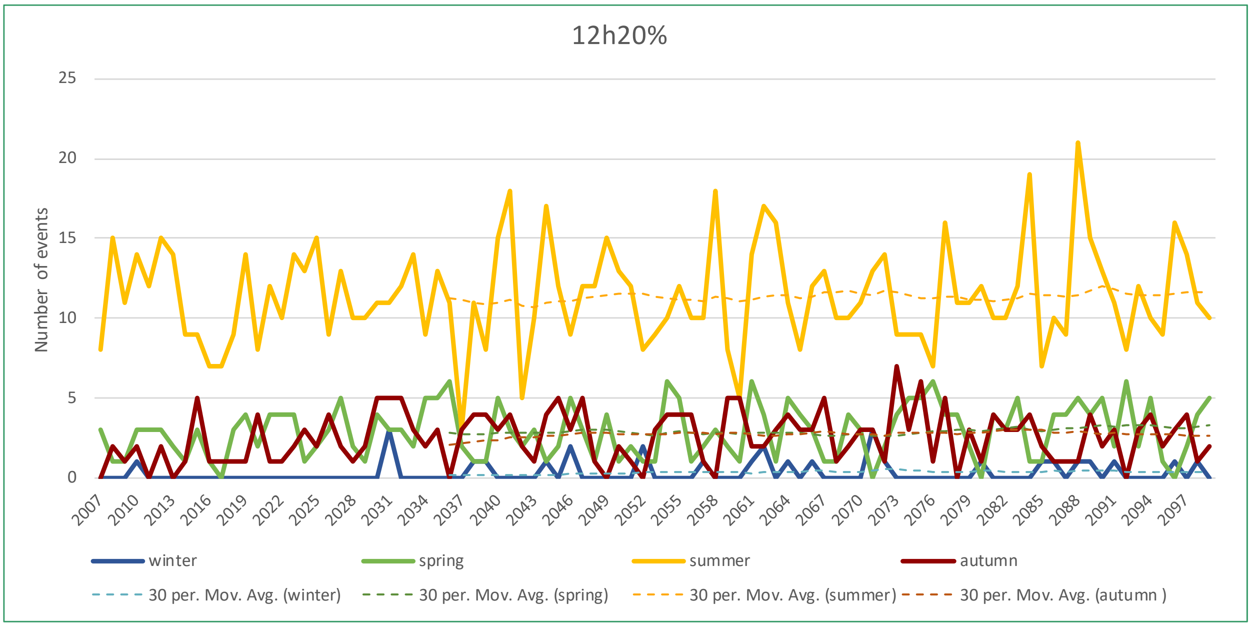
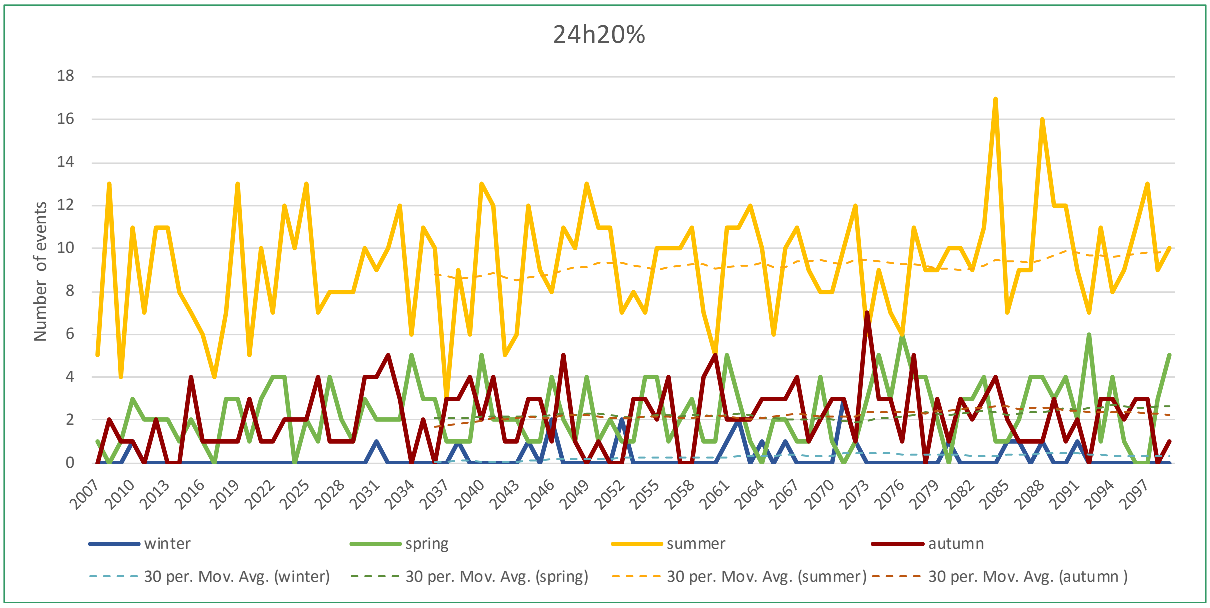
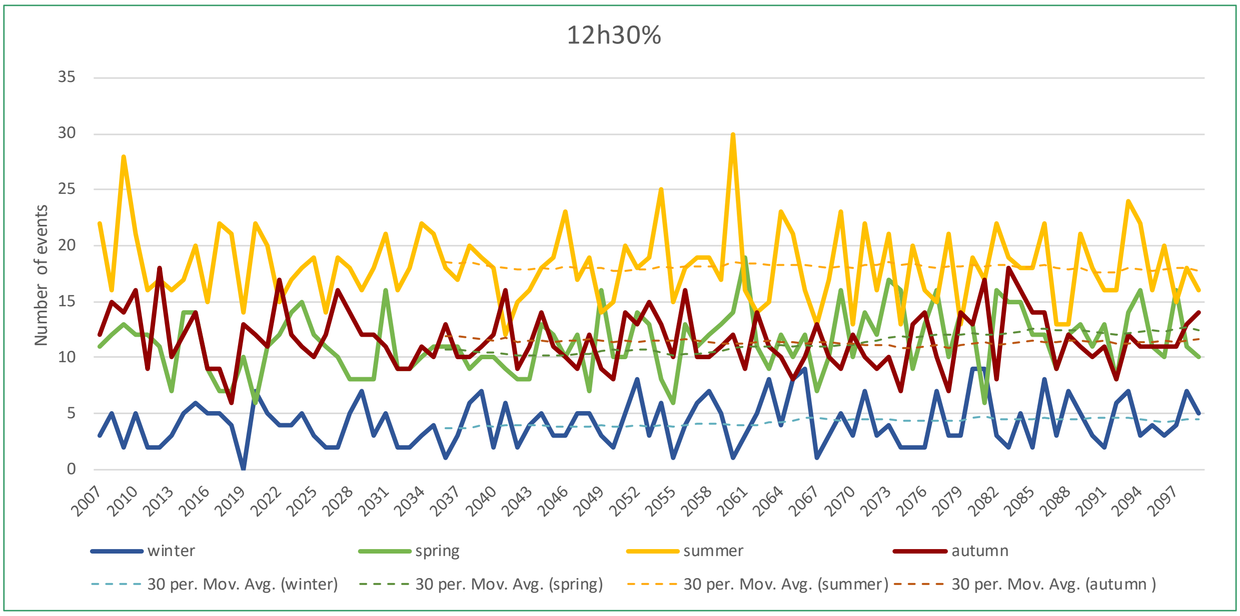
30 per. Mov. Avg. (autumn)

MPI RCP8.5 - number of events



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30 per. Mov. Avg. (winter)
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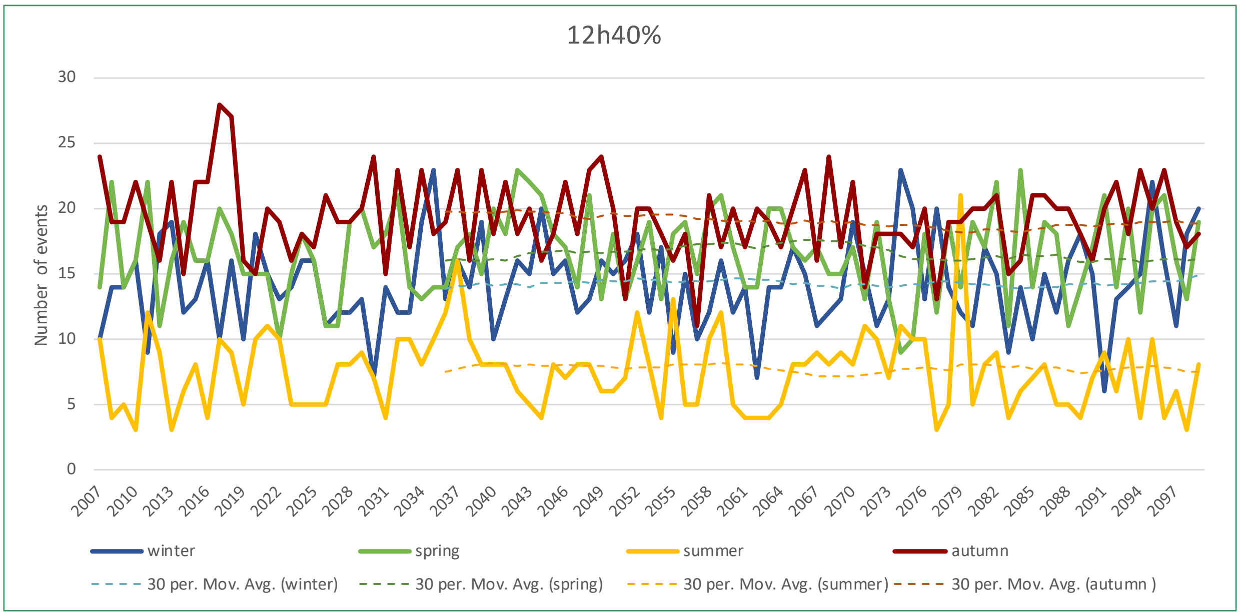
30 per. Mov. Avg. (autumn)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30 per. Mov. Avg. (winter)
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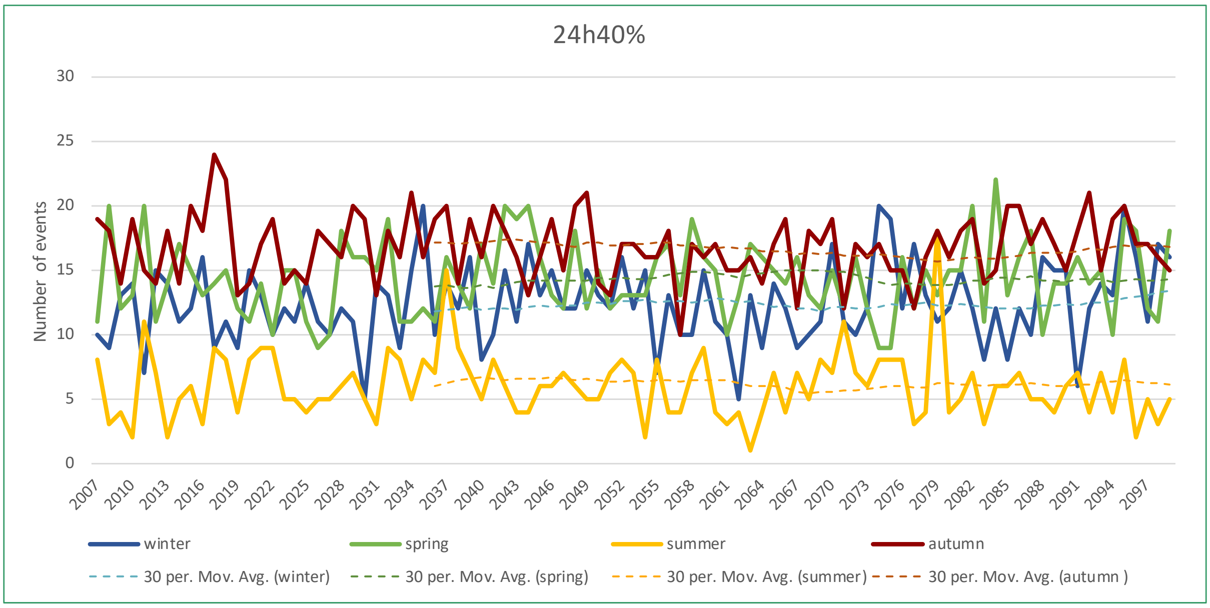
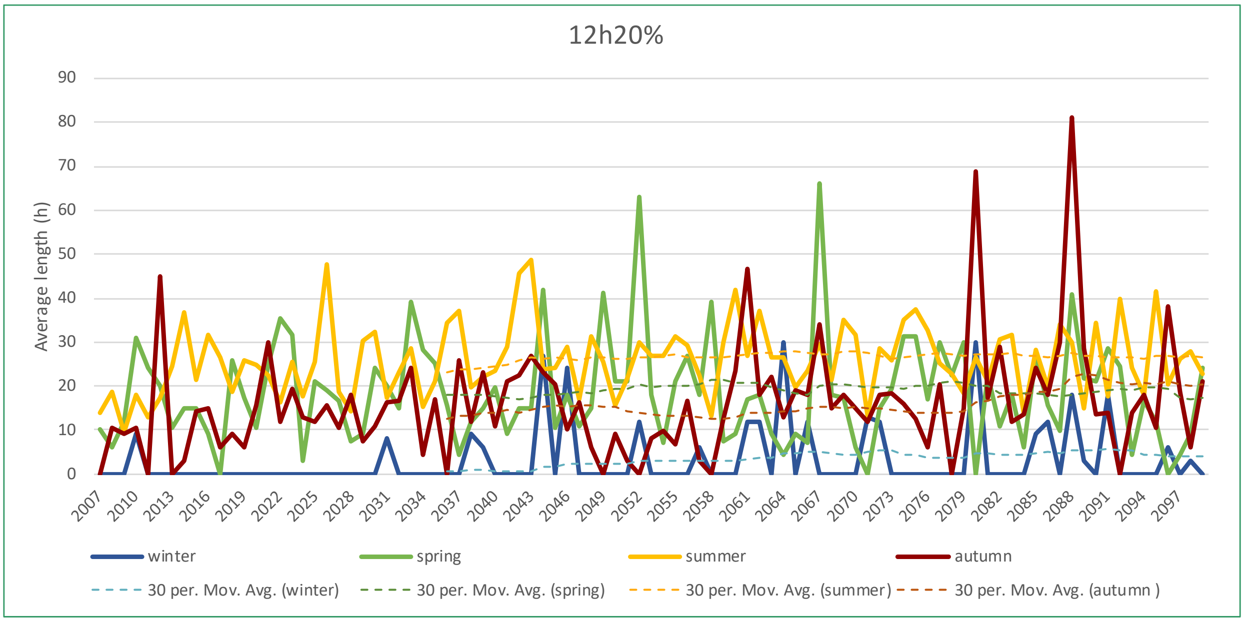
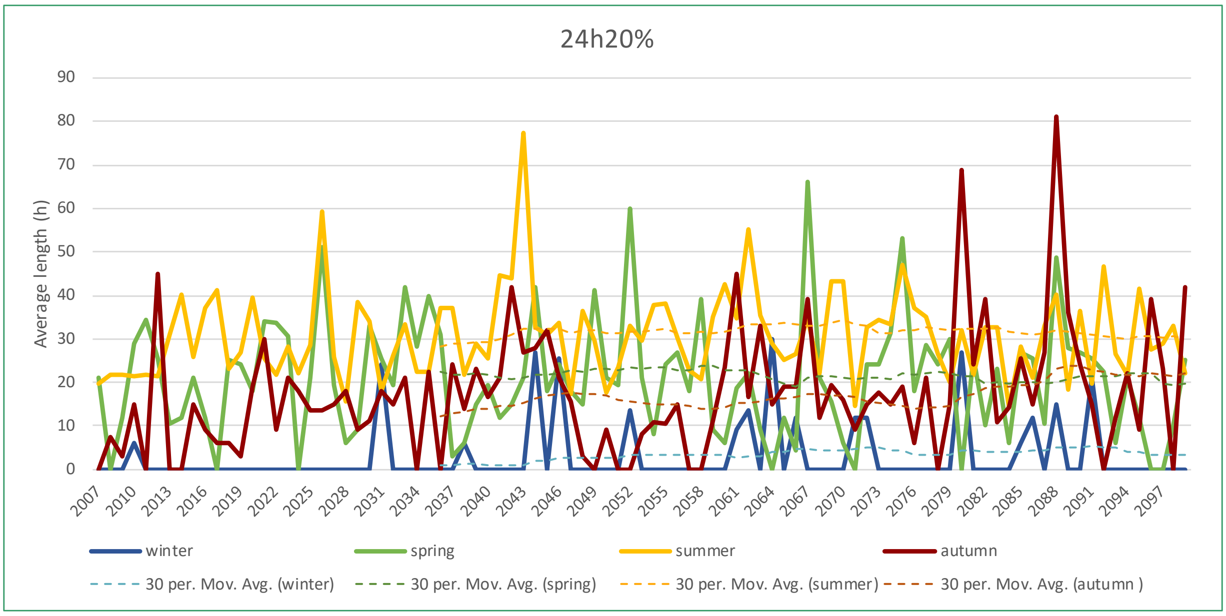
30 per. Mov. Avg. (autumn)



MPI RCP8.5 - average length of events

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Average length (h)
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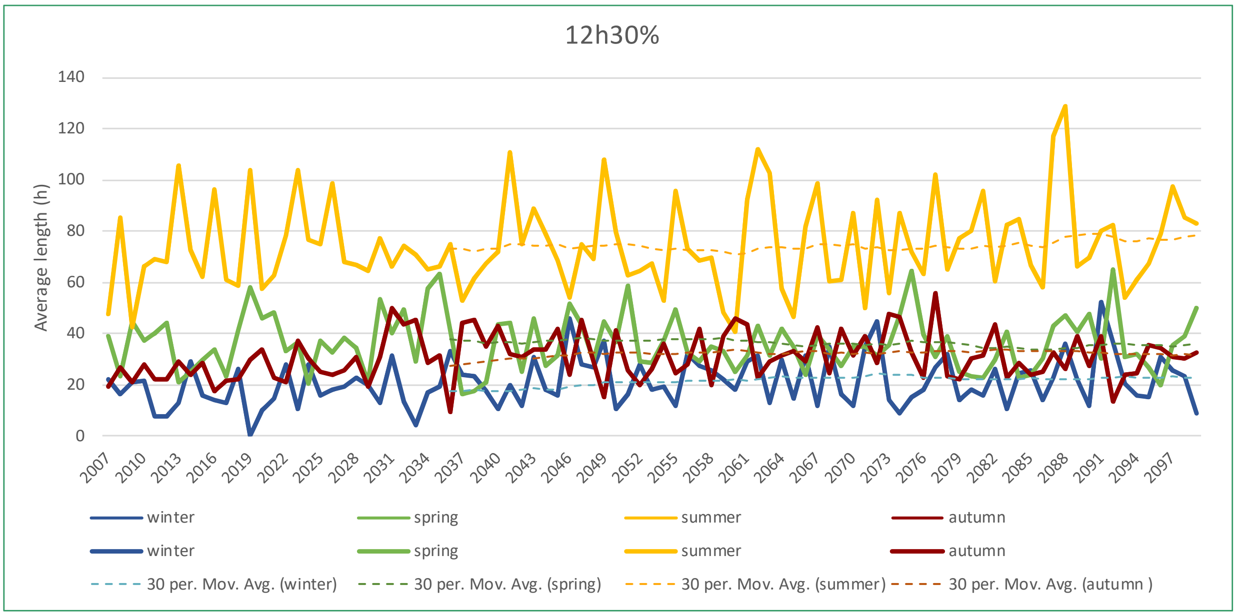
30 per. Mov. Avg. (winter)
30 per. Mov. Avg. (spring)
30 per. Mov. Avg. (summer)
30 per. Mov. Avg. (autumn)


12h30%
Average length (h)
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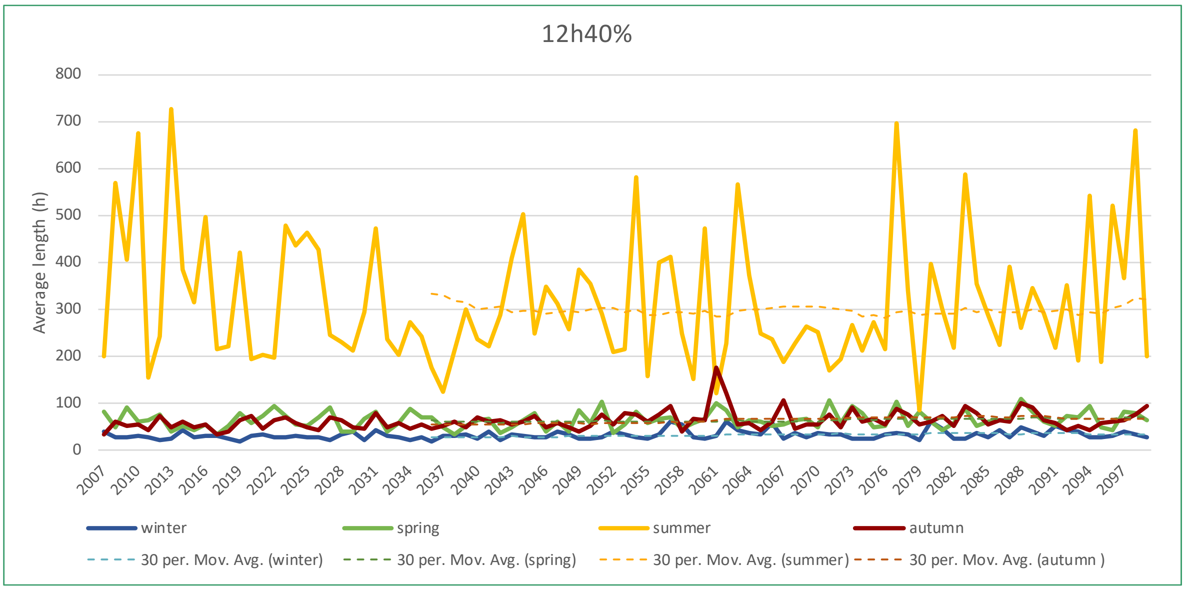
30 per. Mov. Avg. (autumn)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30 per. Mov. Avg. (spring)
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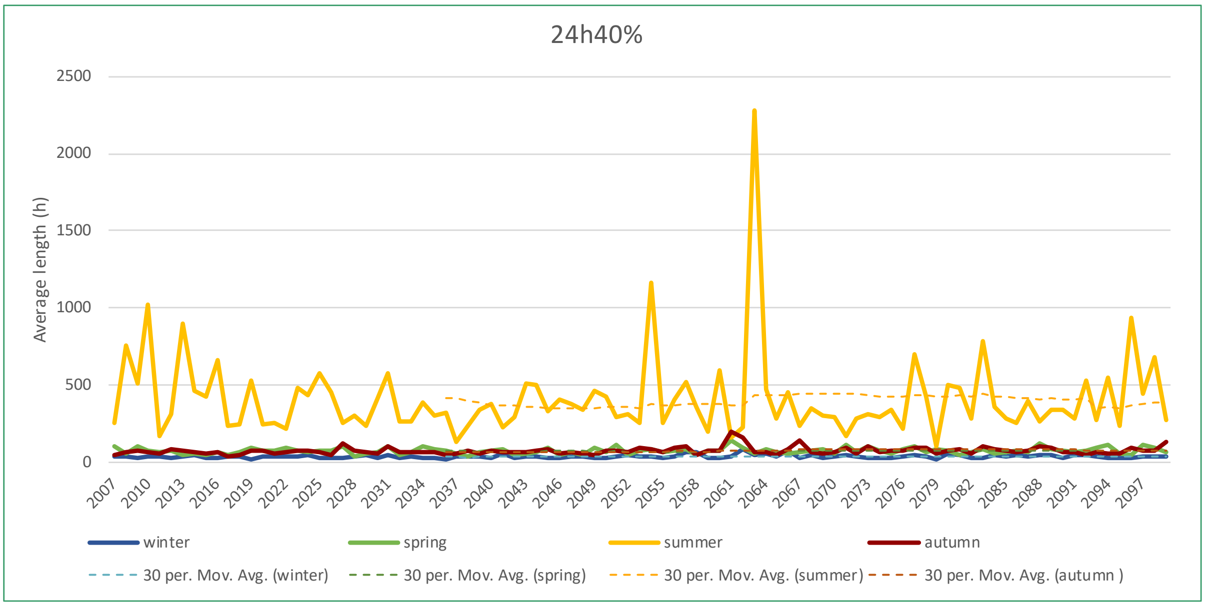
30 per. Mov. Avg. (autumn)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