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Storm activity and climate change in northern Europe

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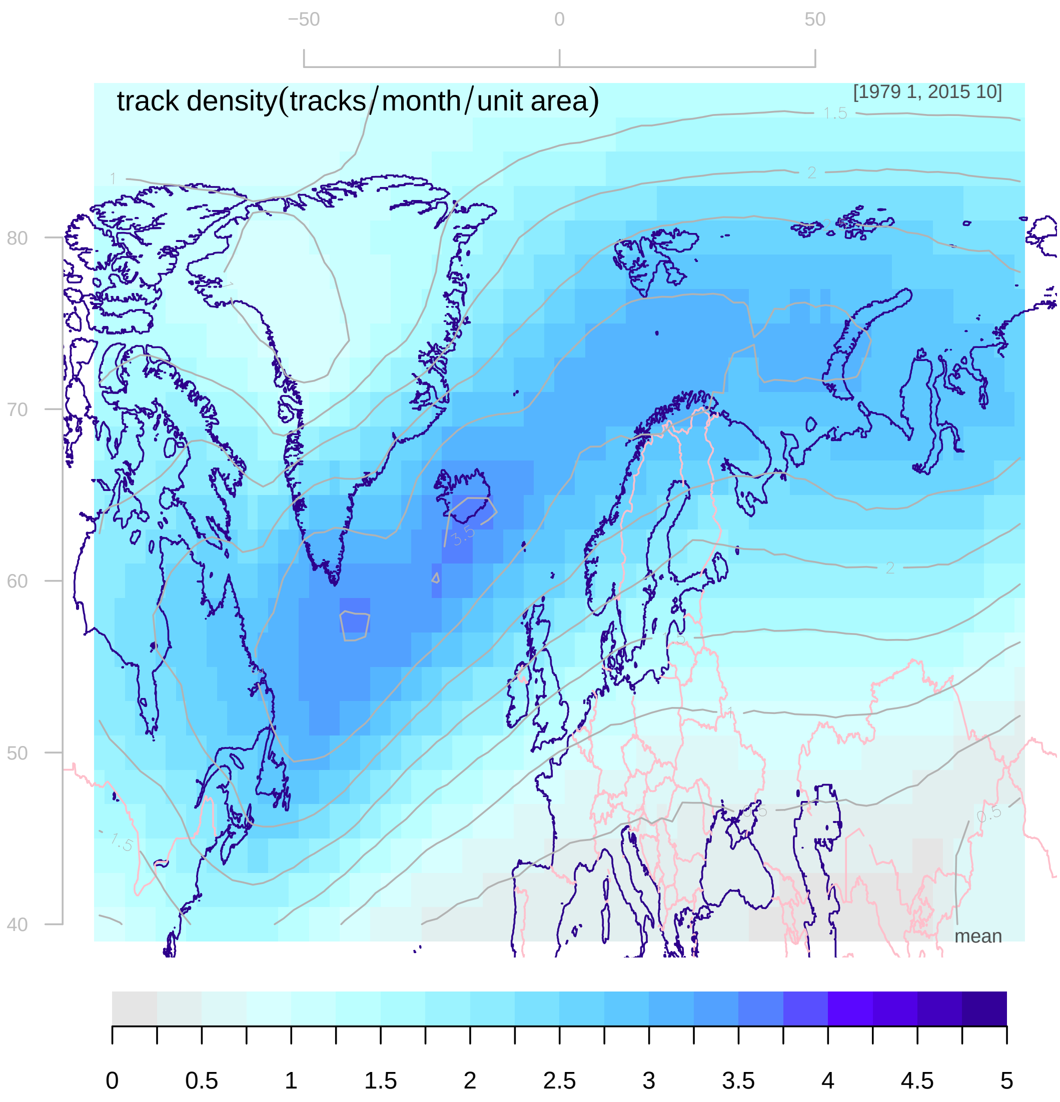

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Abstract

Storm activity in northern Europe.

Keywords

Storm tracks, cyclone identification, empirical statistical downscaling, climate change.

Disciplinary signature
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Contents

Abstract

We present an analysis of the north Atlantic storm tracks, focusing specifically on the relationship between cyclones and the climate conditions in Norway and Sweden. Using a new way of applying empirical-statistical downscaling to the storm tracks, we estimate the cyclone activity in the near and far future based on CMIP5 models. The projections indicate an increase in storm activity in northern Norway and the Barents region as a result of anthropogenic climate change.

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1 Introduction

Mid-latitude cyclones are associated with extreme precipitation, flooding and high wind speeds and can have disastrous effects on societies and infrastructure. They are also important for the water cycle and transporation of heat and moisture. There are many meteorological phenomena that give rise to precipitation, e. g., convection, orographic lifting and stratiform frontal systems associated with low pressure systems. All these processes contribute to transporting humidity from regions of evaporation to where the precipitation takes place. In Norway, frontal systems and low pressure systems have a large spatial range (synoptic scale) and influence precipitation statistics year round, while rain from convective clouds occur mostly in the summer over short time and spatial scales (mesoscale). The study of low pressure systems can thus provide important information regarding the hydrological conditions in the region.

2 Background

Low pressure systems are commonly referred to as storms or cyclones because of the cyclonic circulation of the air about its center (counter-clockwise on the northern hemisphere). Cyclones tend to form in certain geographical regions, such as over the North Atlantic, and follow each other like pearls on a string. The paths along which low pressure systems commonly occur are often referred to as storm tracks. High pressure systems (anti-cyclones) may block the path of storms, thus causing either heatwaves in the summer or cold spells in the winter.

Cyclones are formed as a result of unstable atomspheric situations (baroclinic instability) where there is a strong horizontal temperature gradient (*Chang et al.*, 2002; *Klein*, 1958; *Wallace et al.*, 1988). Surface level low pressure systems are also closely connected to upper atmospheric wind patterns (jet streams) and the upper an lower level atmospheric streams can be understood as an intergrated whole. There are, however, many unkowns related to what makes the storm tracks move polward or eastward, what extends or shorten the life time of storms, and what affects the precipitation associated with the low pressure systems. It is still an open question whether systematic atmospheric changes control the storms on climate time scales or if they are steered by unpredictable chaotic dynamics.

Historical studies of storm activity in the Baltic and Scandinavian region, using cyclones identified from reanalysis data or proxies such as wind speed or pressure tendency at observational stations, show no longterm trend since the 19th century but significant multidecadal variability (*Bolle et al.* (2015) and references therein, e. g. *Bärring and Fortuniak* (2009); *Lehmann et al.* (2011)). Previous studies using GCMs indicate that the location and intensity of storms are expected to change considerably in the future while the change in the total number of cyclones will be small (*Bengtsson et al.*, 2006; *Leckebusch et al.*, 2006; *Löptien et al.*, 2008; *Pinto et al.*, 2009; *Raible et al.*, 2008; *Wang et al.*, 2006).

3 Data and methods

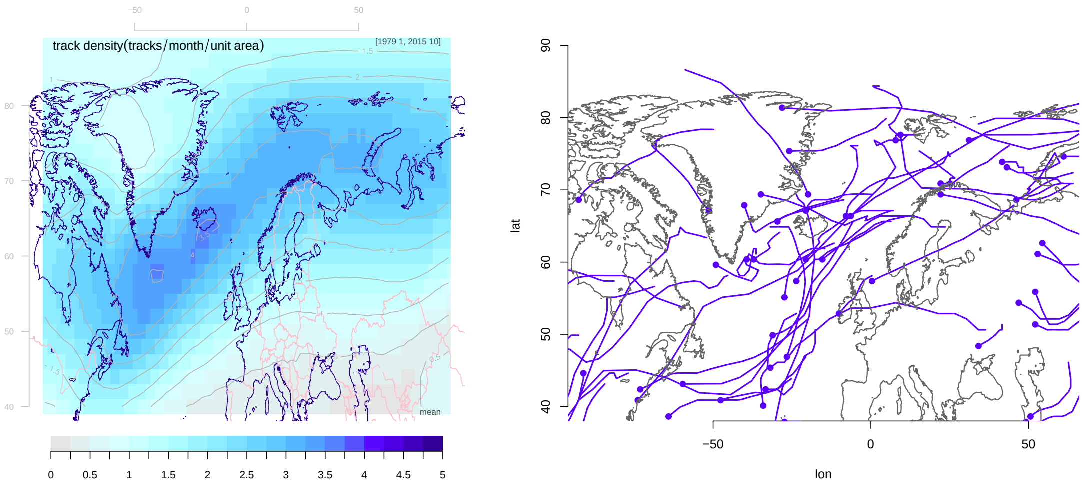
There are two common methods of representing cyclone activity, the Lagrangian approach in which cyclones are identified and tracked throughout their lifetime (*Hodges*, 1994; *Sinclair*, 1997), and the Eulerian approach in which the storm-track activity is described in terms of variance and covariance statistics (*Blackmon*, 1976; *Chang et al.*, 2002). The first is computationally intensive and sensitive to the algorithm and grid resolution but provides much information. Different algorithms vary in their identification of weak cyclones and thus the total number of storms, while strong cyclones and the spatial and interannual variations are more consistently portrayed (*Neu et al.*, 2014). The second approach is more easily reproducible but conflates the cyclone frequency and intensity and does not provide information of extreme values and individual cyclones and anticyclones. For the purpose of this study, we chose the Lagrangian approach, identifying and tracking cyclones in 6-hourly reanalysis sea level pressure (SLP) data. However, when evaluating the storm tracks in the CMIP5 models, we instead apply a new downscaling method to obtain projections of the future storm density.

3.1 Cyclone identification and tracking

Cyclone identification and tracking algorithms are included in the `'esd'`-package which is a suite of climate analysis and statistical downscaling tools for the R-environment, developed at Met Norway (*Benestad et al.*, 2015). The package is open source and availble at GitHub (http://www.github.com/metno/esd) and FigShare (http://dx.doi.org/10.6084/m9.figshare.1454425). A data base of cyclone trajectories in the Northern Hemisphere have been prepared by applying these methods to 6-hourly ERAinterim reanalysis sea level pressure (SLP) data (*Dee et al.*, 2011).

The calculus based cyclone identification algorithm (CCI) locates low pressure centers in a gridded sea level pressure field, typically reanalysis data (*Benestad and Chen*, 2006). Pressure minima are identified by representing the pressure profiles in the meridional and zonal direction as Fourier series and finding the points where the first derivative is zero and the second derivative is positive.

The cyclone centers are then connected in order to track the storms throughout their lifetimes. The tracking algorithm searches for continuations of a cyclone track within a distance of 1000 km of a cyclone center, and the most likely (i.e., smoothest) trajectories are found by minimizing the change in direction and change in displacement in three subsequent time steps. Trajectories shorter than 8 time steps (2 days) or a total distance of less than 1000 km from the point of cyclogenesis to cyclolysis are excluded from further analysis. An example of the trajectories identified with this method is shown in the right hand side of Figure 1.



(a) Cyclone trajectory density, 1979-2015.

(b) Cyclone trajectories for December 2015.

Figure 1: Two maps showing the North Atlantic storm tracks in terms of (a) the average trajectory density for the period 1979-2015, and (b) cyclone trajectories for a single month (December 2015). The cyclone trajectories have been identified and tracked from ERAinterim data as described in Section 3.1, and the density (i.e., the number of cyclones per month and unit area) was calculated based on the identified cyclone trajectories for each 2°x2° grid box.

3.2 Empirical-statistical downscaling of storm characteristics

The coarse resolution of climate models can be a problem when studying storm tracks based on cyclone identification and tracking. Here, we explore empirical-statistical downscaling as an alternative to identifying cyclones directly from model output. The downscaling approach has the added benefit of being more computationally efficient than CCI.

The downscaling methods included in the `'esd'` package are based on representing the large scale climate patterns by Empirical Orthogonal Functions (EOF). EOF analysis decomposes the reanalysis data into a set of dominant spatial modes and time series (principle components, PC) that describe the variations in these spatial patterns. The next step of the downscaling is to use multiple linear regression to establish a connection between the *predictand* (the time series that you want to downscale) and the *predictor*, i.e., the principle components of the reanalysis data. In order to apply the statistical model to a second predictor data set, e.g., a GCM output, the same patterns must be identified in both predictor data sets through common EOF analysis. The *predictand* may be a time series of observations from a single station or, if you are downscaling a set of stations or gridded data, the *predictands* can be principle components describing the most important modes of variability among the predictand data.

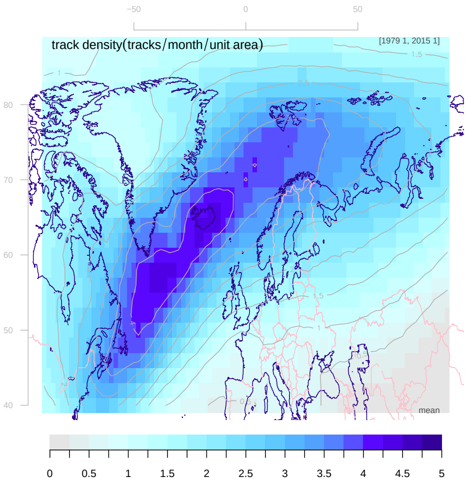
In order to downscale the characteristics of the North Atlantic storm tracks they must be represented in a suitable way, i.e., as one or a few time series. One of the ways this can be done is to calculate the trajectory density (a gridded field of the number of cyclones per month and unit area) from the cyclone trajectory data set, apply EOF analysis and then downscale the leading principle components. Here, we downscale the PCs of the trajectory density using as predictor the NCEP Reanalysis data (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ (*Kalnay et al.*, 1996)). It may seem circular to predict the storm tracks, which are calculated from reanalysis SLP data (6-hourly ERAinterim), with another SLP data set as predictor (monthly mean NCEP). However, the point of the downscaling procedure is to find a shortcut that allows the state of the storm tracks to be estimated from monthly instead of 6-hourly SLP data and from SLP with coarser spatial resolution. The downscaling may also shed some light on the connection between large scale climate patterns and the position of the North Atlantic storm tracks.

Empirical statistical downscaling of storm track characteristics depends on two implicit assumptions. First of all, the large scale climate patterns that are used as predictor have to contain the necessary information to reproduce the storm tracks. This assumption can be verified through cross-validation. Here, we apply a five-fold cross-validation in which different parts of the data are repeatedly withheld (five times) from model tuning to be used for independent comparison with the downscaled values. A connection between the storm tracks and large scale circulation patterns is expected since synoptic scale disturbances are associated with large scale baroclinic waveguides (*Chang et al.*, 2002; *Klein*, 1958; *Wallace et al.*, 1988) and linked to the planetary flow (*Chang et al.*, 2002; *Held et al.*, 1989). The second assumption is that the climate models have a realistic representation of the large scale patterns of the predictor. This point can be adressed by comparing the large scale climate patterns of GCMs to the corresponding patterns of reanalysis data sets.

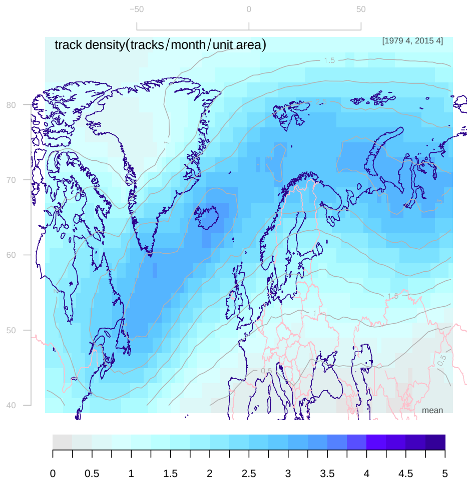
4 Storms and precipitation in northern Europe

4.1 The North Atlantic storm tracks

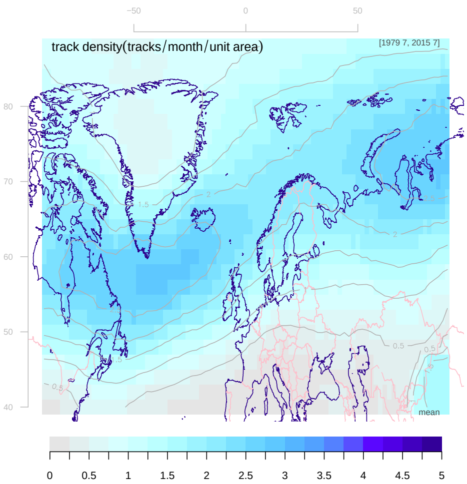
Cyclones in the North Atlantic region tend to travel along a north-easterly band towards Iceland and the Barents region or along a more zonal path towards northern or central Europe. Figure 1 shows the North Atlantic storm tracks in terms of the cyclone density for the period 1979-2015 and the cyclone trajectories for a single month (December 2015). Although most cyclones take a northerly path along Iceland and towards the Barents Sea, the cyclone density is quite high in the whole Scandinavian region, especially in the northernmost part and along the coast. The highest frequency of mid-latitude cyclones occur in the winter season while the storm tracks are weak and more zonal in the summer (Figure 2).



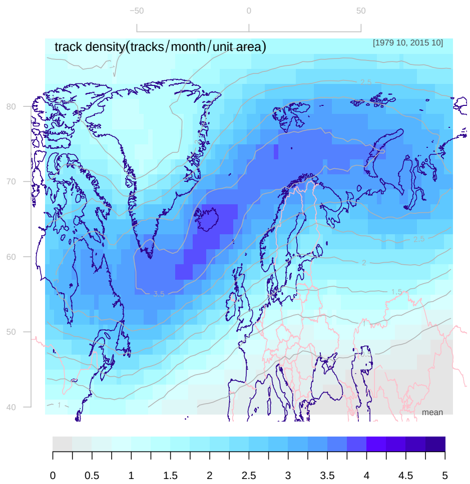
(a) Winter (DJF).



(b) Spring (MAM).



(c) Summer (JJA).

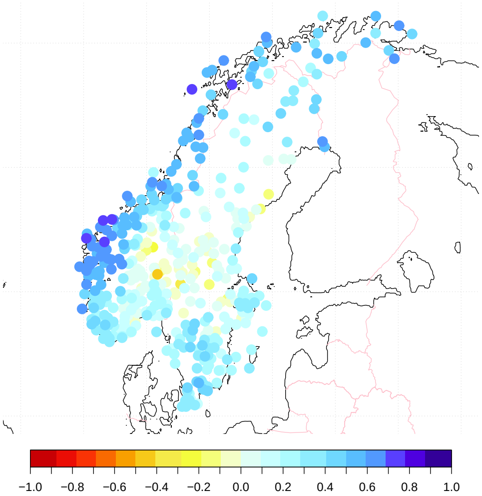


(d) Fall (SON).

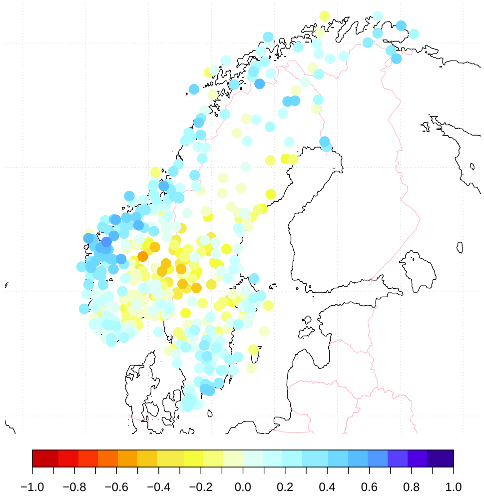
Figure 2: Cyclone density for the North Atlantic region for (a) winter, (b) spring, (c) summer, and (d) fall. See Figure 1(a) for annual density.

4.2 Cyclones and precipitation

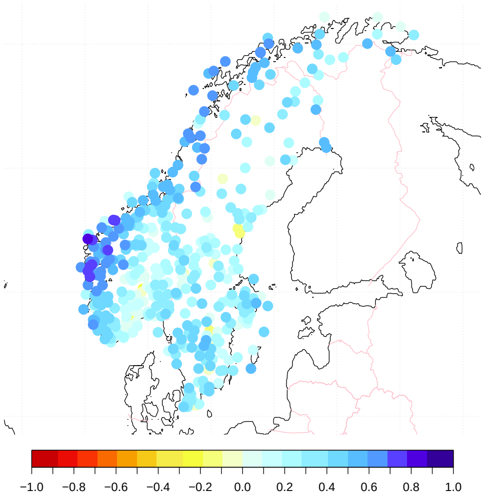
Cyclones are associated with clouds and precipitation. In the Scandinavian region, there is a positive correlation between the mean precipitation and the number of storms (Figure 3). The correlation is strongest along the west coast of Norway and weaker in the inland regions in the south-east part of Norway and the southern half of Sweden. The number of rainy days (wet-day frequency) is more closely connected to the cyclone activity than the amount of rain during rainy days (wet-day mean). In most parts of Norway and Sweden, the strongest connection between precipitation and storm activity is found in winter (Figure 4). In the summer, the correlation is weaker, possibly indicating that convective precipitation is more dominant than precipitation associated with large scale circulation.



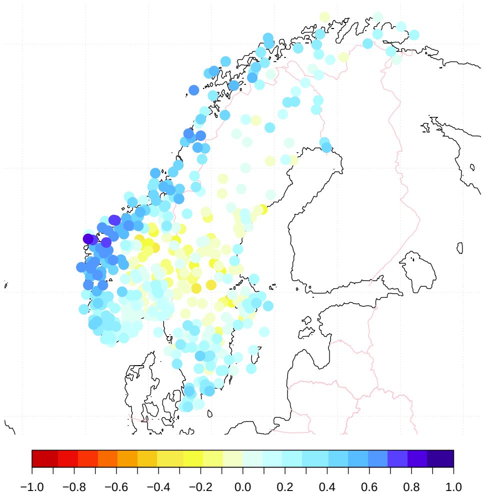
(a) Correlation of precipitation and cyclones.



(b) Correlation of wet-day mean and cyclones.

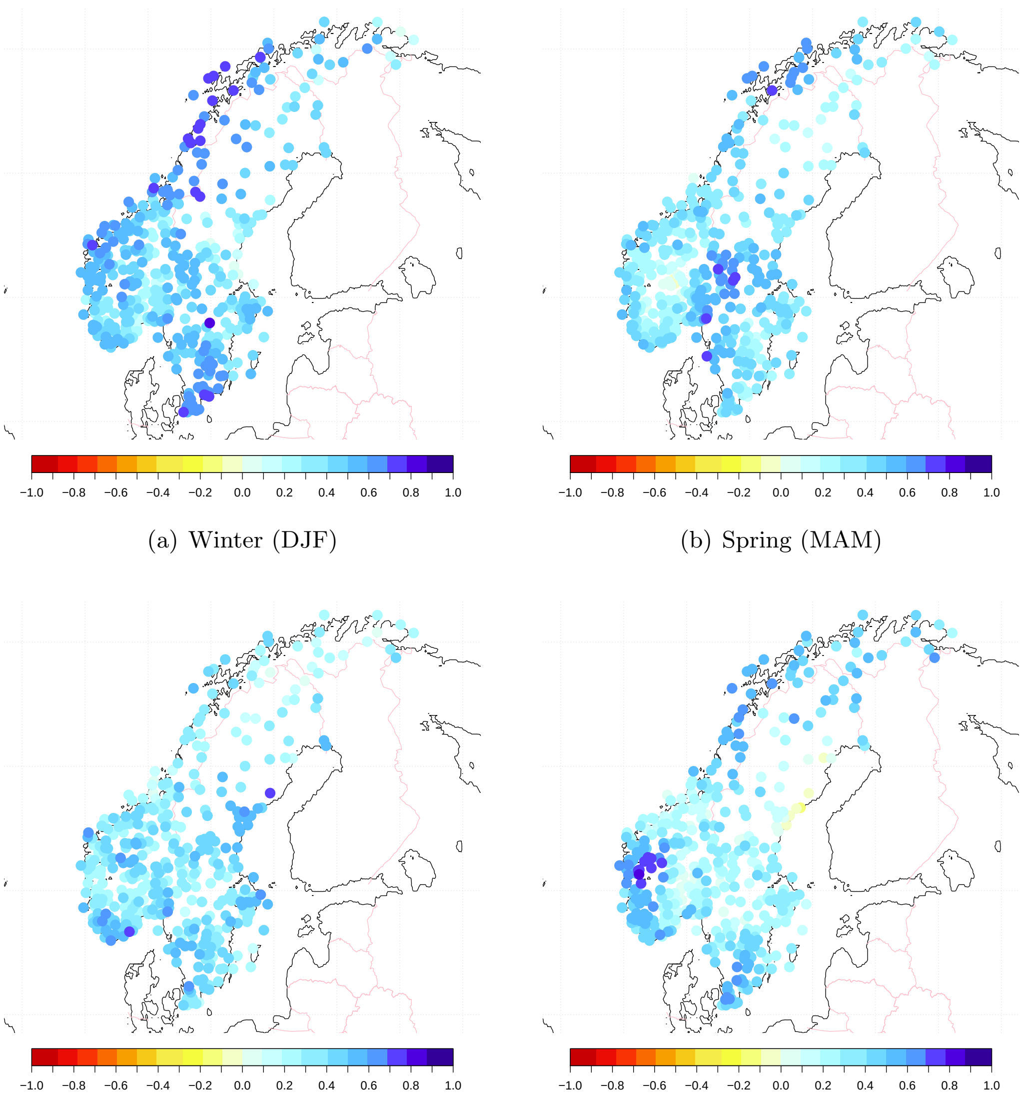


(c) Correlation of wet-day freq and cyclones.



(d) Correlation of heavy precip and cyclones.

Figure 3: Correlation between the annual mean number of cyclones and the (a) mean precipitation, (b) wet-day mean, (c) wet-day frequency (days with ≥ 1 mm precipitation), and (d) frequency of heavy precipitation (days with ≥ 10 mm precipitation) for stations in Norway and Sweden. The calculations are based on precipitation observations from the ECA&D data set and cyclones identified and tracked from ERAinterim SLP data.



(a) Winter (DJF)

(b) Spring (MAM)

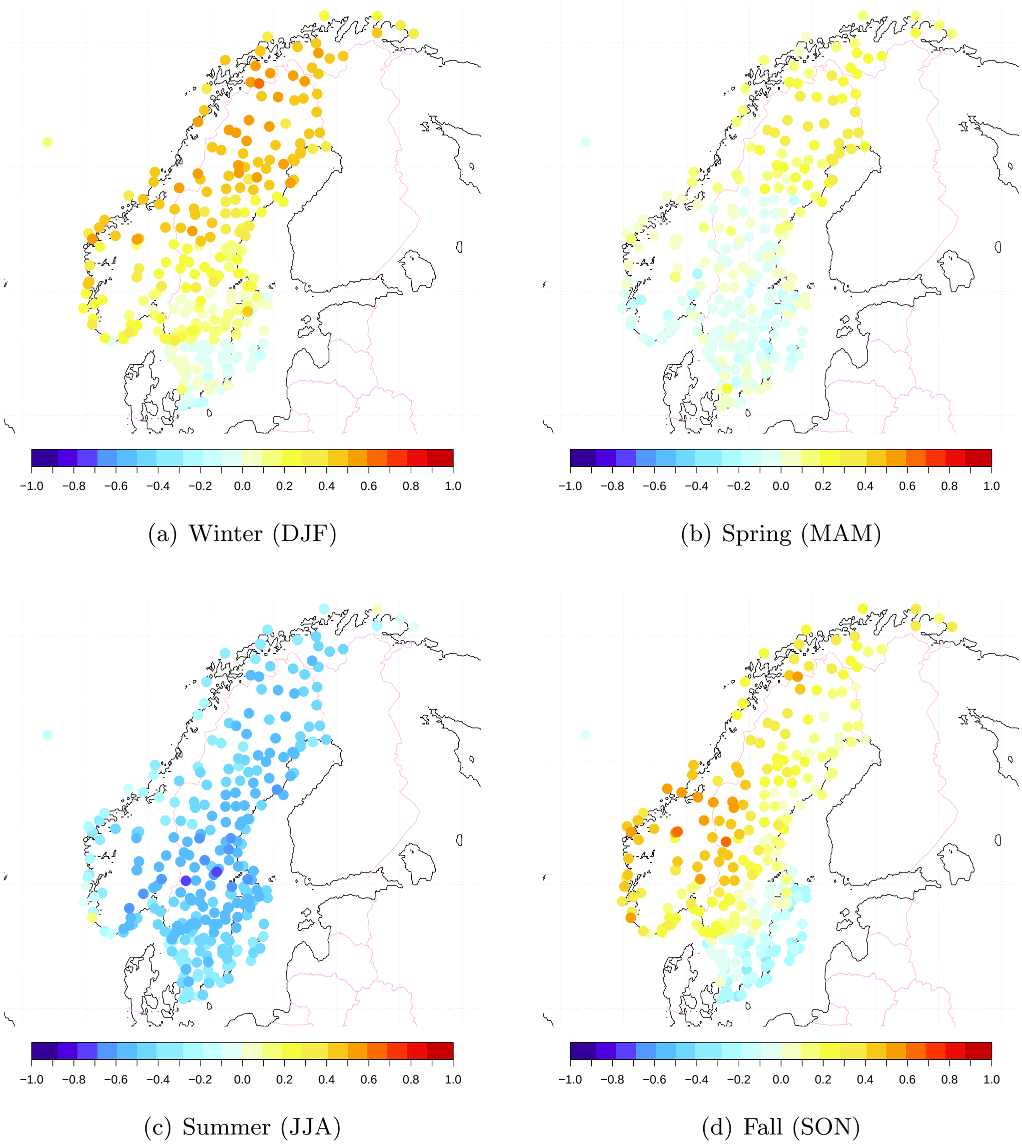
(c) Summer (JJA)

(d) Fall (SON)

Figure 4: Correlation between the precipitation in Norway and Sweden and the total number of cyclones in the region 5-30°E/55-75°N for the (a) winter, (b) spring, (c) summer and, (d) fall season. The calculations are based on precipitation observations from the ECA&D data set and cyclones identified and tracked from ERAinterim SLP data.

4.3 Cyclones and temperature

In Scandinavia, cyclones are associated with warmer than average air temperature in the winter, but colder than average in summer (Figure 5). This can be explained by the fact that clouds can be both cooling or warming, depending on the cloud characteristics, height, and the time and place they occur. Clouds absorb and re-emit outgoing longwave radiation (heat) back to earth and thus have a warming effect, but they also reflect incoming shortwave (solar) radiation back to space which has a cooling effect. In the summer, the cooling effect of clouds tends to dominate but in winter when solar irradiance is weak and days are short they instead have a net warming effect. The positive correlation between cyclones and temperature in winter can also be understood in terms of the transportation of warm airmasses. On a large scale, the temperature gradient and patterns affect the atmospheric circulation so the cause-and-effect relationship between cyclones and temperature can go both ways.



(a) Winter (DJF)

(b) Spring (MAM)

(c) Summer (JJA)

(d) Fall (SON)

Figure 5: Maps showing the correlation between the temperature in Norway and Sweden and the total number of cyclones in the region 5-30°E/55-75°N for the (a) winter, (b) spring, (c) summer and, (d) fall season. The calculations are based on temperature observations from the ECA&D data set and cyclones identified and tracked from ERAinterim SLP data.

5 Representation of the North Atlantic storm tracks and sea level pressure in CMIP5 models

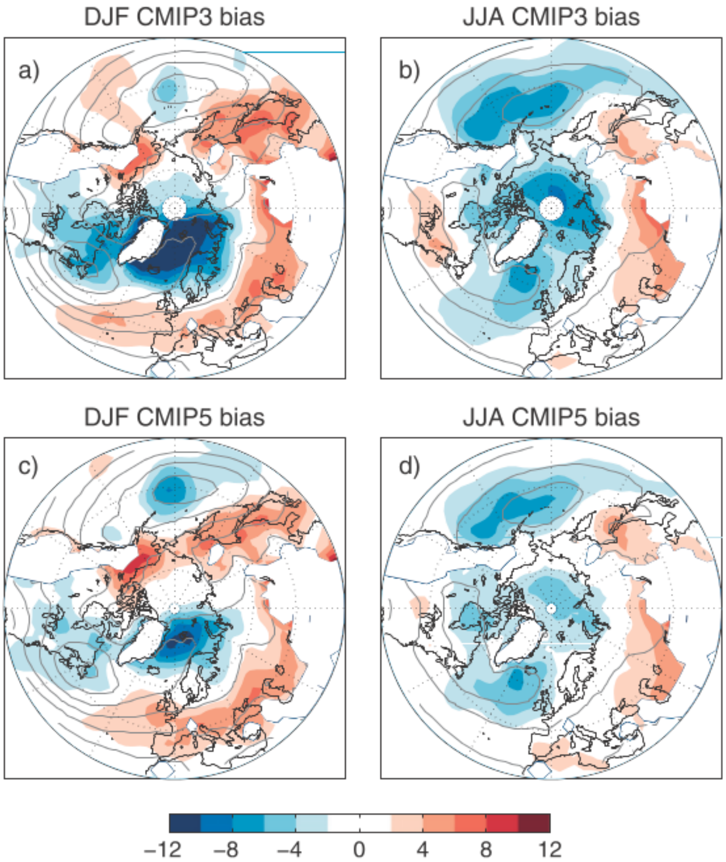


FIG. 2. Mean bias with respect to ERA-Interim (shading) in the 2–6-day MSLP std dev (10^{-1} hPa) of the control simulations of the (a),(b) CMIP3 and (c),(d) CMIP5 models for (left) DJF and (right) JJA. The ERA-Interim climatology is contoured with isolines every 1 hPa. High orography is masked.

Figure 6: Figure 2 from *Zappa et al.* (2013). The storm track biases in CMIP3 and CMIP5, respectively. The cyclone acitivity is measured by the standard deviation of the 2–6-day bandpass-filtered SLP.

Several studies have reported that GCMs tend to simulate storm tracks that are too zonal and shifted towards the equator (*Chang et al.*, 2012; *Zappa et al.*, 2013). Although the CMIP5 models are better than the CMIP3 models at capturing some features of the North Atlantic storm track, e. g., the northeastward tilt and extension of the storm track in the Norwegian Sea, still some bias remains (see Figure 2 from *Zappa et al.* (2013), shown here in Figure 6). The majority of the CMIP5 simulations have too many storms propagating towards Europe and too few that turn north towards the Norwegian Sea. Increasing the spatial grid resolution has improved the representation of storm tracks, but is not a guarantee for a realistic cyclone activity. Nevertheless, some of the CMIP5 models with high resolution do capture the North Atlantic storm tracks reasonably well, e. g., HadGEM2-ES, EC-Earth, and MRI-CGCM3 (*Zappa et al.*, 2013).

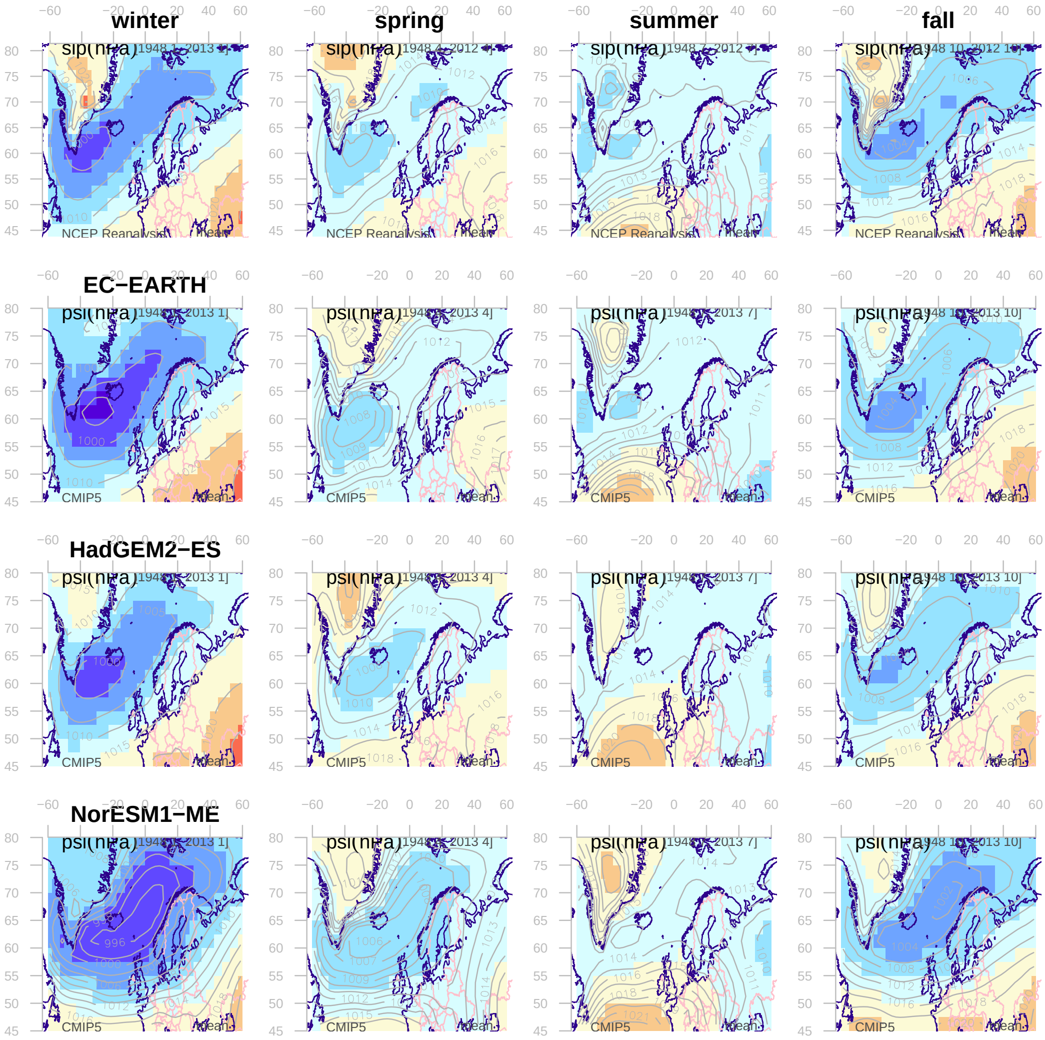


Figure 7: Average seasonal SLP patterns of the NCEP reanalysis (top) and three GCM runs, EC-EARTH (second row), HadGEM2-ES (third row), and NOR-ESM (bottom), for the period 1948–2013.

In this study, we use downscaling as a shortcut to the CMIP5 storm tracks based on monthly SLP instead of using the common Lagrangian or Eulerian estimates of the cyclone activity using 6-hourly model output. The downscaling approach is dependent on the realistic representation of the large scale patterns of the models. The tendency of models to overestimate the westerlies and underestimate blocking events could potentially cause a bias in downscaled projections (*Wojcik*, 2015). Figure 7 shows the average seasonal SLP patterns of the NCEP reanalysis and a selection of 3 GCMs from CMIP5. EC-Earth and HadGEM2-ES have SLP patterns reasonably similar to the corresponding reanalysis patterns, while the NOR-ESM SLP is slightly off both in terms of the shape, pressure gradient, location, and depth of the minima.

6 Projections of storm tracks based on downscaling

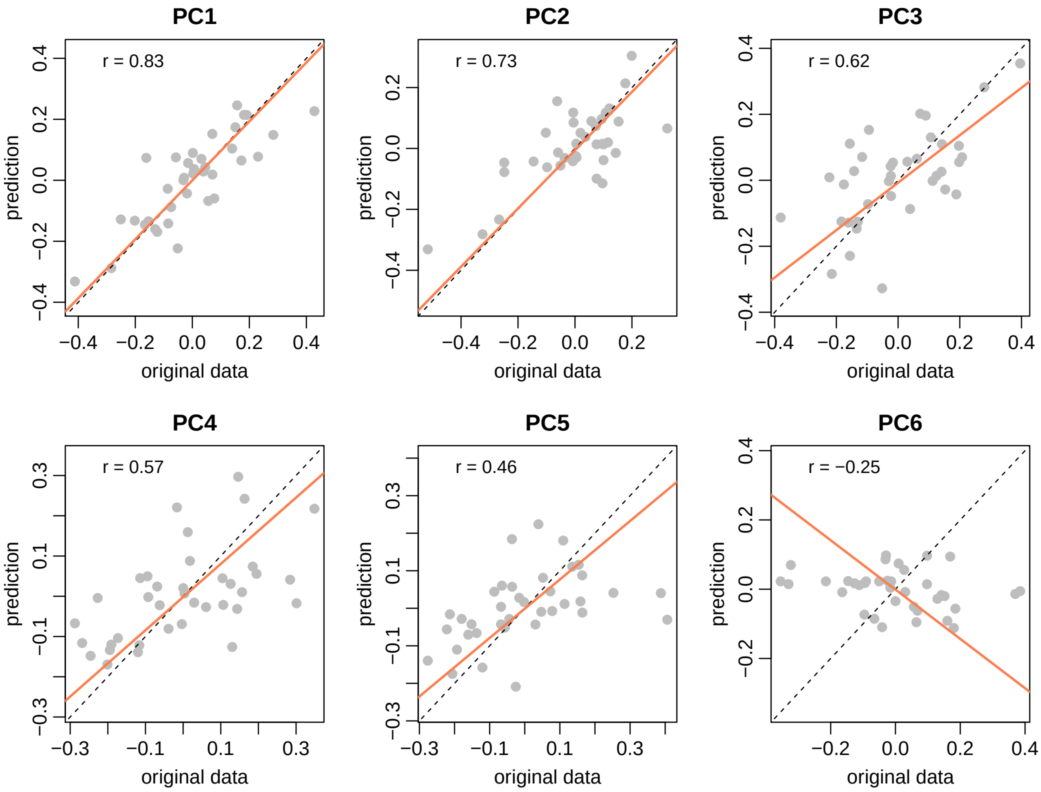


Figure 8: Cross-validation of the downscaling of the first 6 PCs of the annual mean cyclone density in the North Atlantic region. The downscaling was done using the NCEP reanalysis SLP. The x-axis shows independent data excluded from model tuning and the y-axis shows the values predicted based on the downscaling.

The principle components (PCs) of the annual mean cyclone density are downscaled using the NCEP reanalysis SLP as predictor as described in Section 3.2. Cross-validation shows that the first five PCs is predicted with some skill through downscaling while the sixth PC is not skillfully predicted (Figure 8). Comparing the original cyclone density to the corresponding field reproduced from the cross-validation PCs, we see that the first five PCs can reproduce the main features of the cyclone density field (Figure 9). In other words, the SLP patterns contain sufficient information to reproduce the annual mean storm tracks.

The downscaling skill for the first five PCs is about as high for the winter season (December, January, February) as for the annual mean. For the other seasons, fewer of the leading PCs can be downscaled with skill, as shown by very low or even negative correlation between the downscaled and original independent values of some of the PCs (not shown here). This means that the full range of variability of the storm tracks may not be reproducible based on seasonal downscaling. The downscaled results can still give some indication of the storm track changes that are associated with large scale climate patterns, but the results should be interpreted with

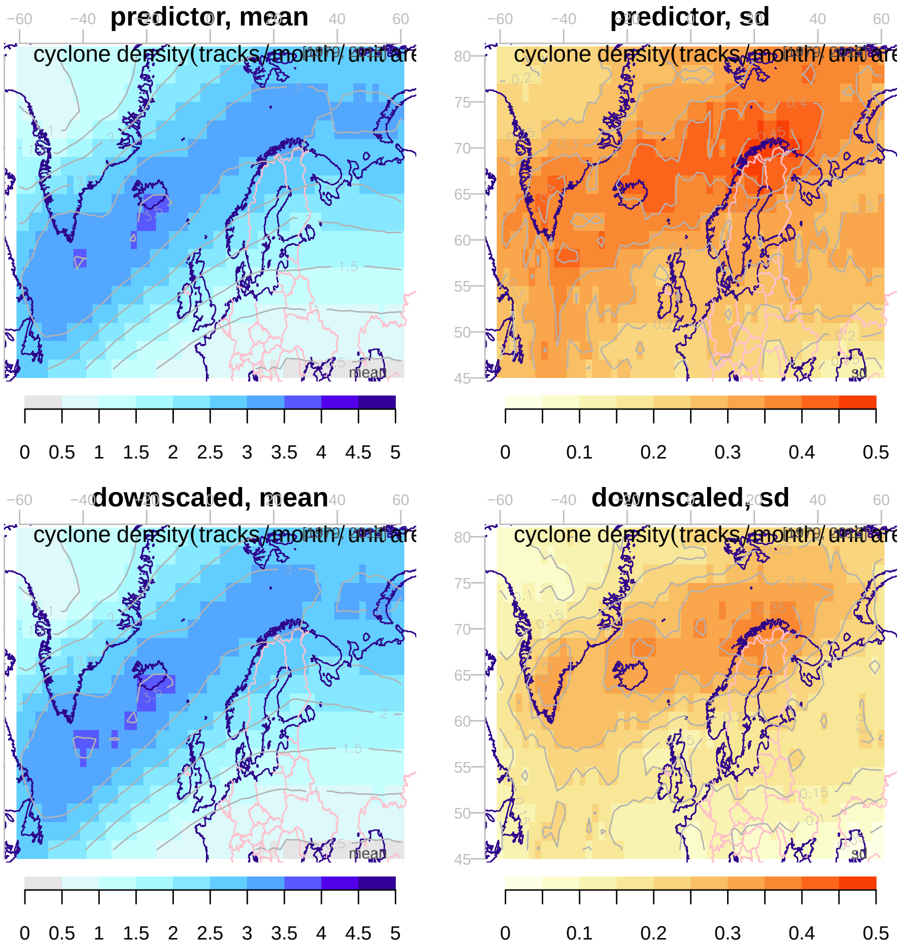


Figure 9: Cross-validation comparing the original cyclone density (upper panels) and the cyclone density recontructed from the first five independent downscaled PCs (see y-axis in Figure 8). The left plots show the mean and the right plots show the standard deviation of the cyclone density for the period 1979–2015.

caution. For now, we focus on the annual mean storm tracks, but keep in mind that winter will be dominate the picture because this is when most cyclones occur.

Downscaling of the annual mean cyclone density using the CMIP5 models as predictor indicates an increase in the storm activity in the northern part of the North Atlantic region. The projected change is stronger under the high emission scenario RCP8.5 compared to the more moderate emission scenario RCP4.5 (Figure 10). In the Barents region, the increase of the ensemble median is approximately 0.5 cyclones/month/unit area, which corresponds to around 15–20% in some parts.

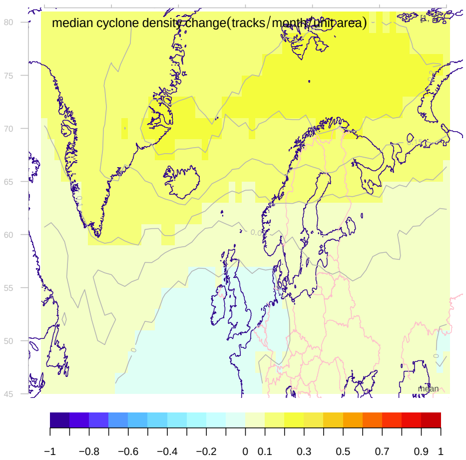
7 Summary and future outlook

The North Atlantic storm tracks and the associated weather in the Scandinavian region is investigated using the R-package `'esd'`, which includes both cyclone identification, tracking and visualisation tools. A new way of applying empirical-statistical downscaling is used to estimate the cyclone activity for the future based on CMIP5 models. Cross-validation indicates that the downscaling is skillful enough to reproduce the main features of the storm tracks based on reanalysis monthly mean SLP. Projections suggest an increase in storm activity in northern Norway and the Barents region in the far future as a result of anthropogenic climate change.

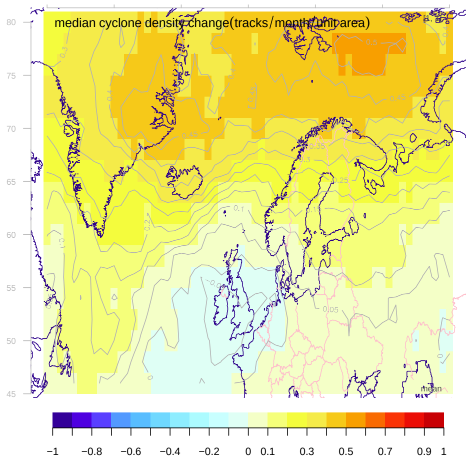
The downscaling approach to estimating cyclone activity in GCM projections needs to be further evaluated and compared to other measures of cyclone activity in GCMs, for example the standard deviation of 2-6-day bandpass-filtered SLP or cyclones identified and tracked directly from model data. The influence of the spatial resolution on all these methods should also be investigated. It is important to understand whether the improvement of storm tracks with GCM resolution reported in the literature (*Zappa et al.*, 2013) is primarily due to the resolution sensitivity of the analysis tools or because high resolution models better represent small scale atmospheric processes. A more in-depth analysis of the GCM SLP patterns, e. g., by studying the common EOFs of reanalysis and GCMs, would be helpful to further evaluate the downscaling procedure. The influence of the choice of predictor can also be investigated in terms of the included GCMs, where the choice is to use the full ensemble of available models, select a subset of the most realistic models, or apply weights to the ensemble. Other predictors than SLP could be explored, such as the 500 hPa geopotential height, which is better represented by many GCMs in some seasons (*Wojcik*, 2015).

Further analysis of the representation of storm tracks and sea level pressure patterns in GCMs could be useful to evaluate which models are likely to capture important aspects of the hydrological cycle. This analysis should be based on methods that allow the consideration of cyclone intensity and frequency separately, or at least emphasize storms that are associated with extreme weather. The storm track analysis could be extended to regional climate models (RCMs) and it would be interesting to see if dynamical downscaling improves representation of storm tracks.

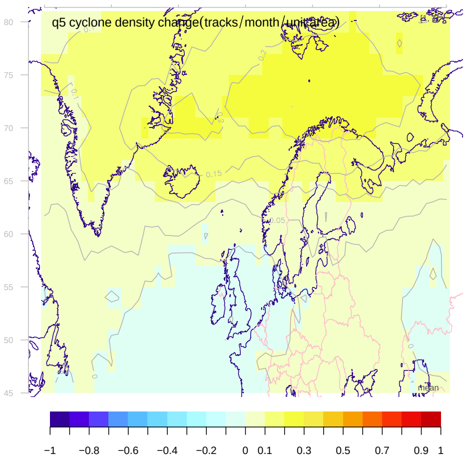
Information about storms is potentially of great interest for hydrological purposes, but in order to produce useful information we have to identify relevant cyclone characteristics and statistical measures. Here, the focus has been on the number density of cyclones in different regions and periods. In the future, we should also consider other complementary aspects that describe the intensity of cyclones and the associated extreme weather.



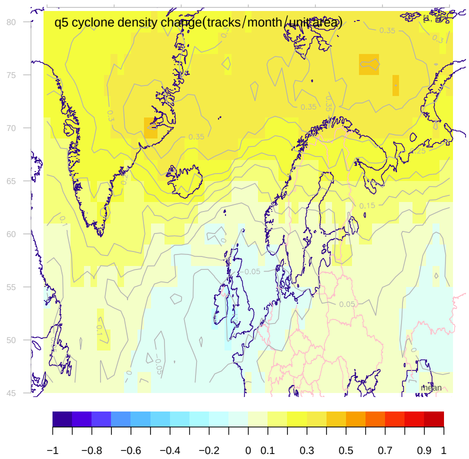
(a) RCP4.5, ensemble median.



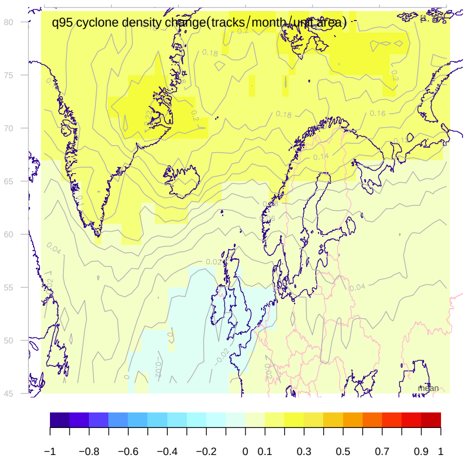
(b) RCP8.5, ensemble median.



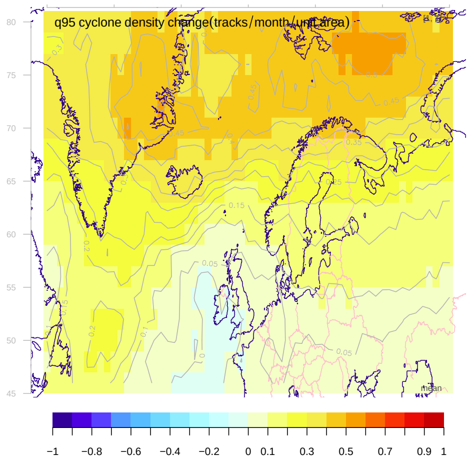
(c) RCP4.5, ensemble 5th percentile.



(d) RCP8.5, ensemble 5th percentile.



(e) RCP4.5, ensemble 95th percentile.



(f) RCP8.5, ensemble 95th percentile.

Figure 10: Projected changes in the annual mean cyclone density in northern Europe and the North Atlantic region from the present day (1980-2010) to the far future (2070-2100), based on downscaling of the CMIP5 model ensemble. The panels show the change in the median (a, d), 95th percentile (b, e), and the 5th percentile (c, f) of the model ensembles for two different scenarios, RCP4.5 (a, b, c) and RCP8.5 (d, e, f).

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