Change in Thunderstorm Activity in a Projected Warmer Future Climate: a Study over Europe

Förändring i åskaktivitet i ett varmare framtida klimat: En studie över Europa

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Abstract

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In the last 100 years, a rise in the global mean temperature has been noted, and projections show even higher temperatures in the future. The temperature rise can lead to changes in the weather patterns and therefore the thunderstorm activity in a future warmer climate has been investigated in this study. The future projections were made with an ensemble of 8 General Circulation Models downscaled with the regional climate model RCA4, developed at SMHI. Temperature and humidity data at four different levels in the atmosphere has been used to compute three different stability indices. Stability indices indicate potential for deep convection in the atmosphere, from which thunderstorms are developed.

It was found that the projections show an increase in thunderstorm potential in a warmer future climate. In Sweden, the projections show an increase with about 15 more days with risk of thunderstorms at the end of the 21st century for the RCP4.5 scenario, corresponding to an increase of 40% in the south, and an even larger increase in the north. For the RCP 8.5 scenario, the projected change in days with risk of thunderstorms corresponds to an increase about 20 days, or about 60% more thunderstorm days in south of Sweden. In other parts of Europe, the increase is expected to be even larger, mainly in the mountain regions. It was also found that the thunderstorm season is projected to be extended in the future, with more days with risk of thunder in May and September.

The increase in number of days with risk of thunderstorms is a result of the greater amount of water vapour that the atmosphere is able to hold in a warmer climate. Even if thunderstorms are projected to increase, other factors counteract, such as a decrease in the vertical temperature gradient and a decrease in the difference between moisture in the upper and the middle atmosphere. Yet, taken together the days with risk of thunderstorms are projected to become more frequent.

Key Words: Thunder, Convection, Stability Indices, Climate change, Regional Climate Model, RCA4

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Under de senaste hundra åren har medeltemperaturen på jorden ökat med cirka 1°C, vilket har medfört förändringar i klimatet. Temperaturen kommer att fortsätta stiga på grund av den redan förhöjda halten växthusgaser i atmosfären, och om växthusgaser fortsätter släppas ut kan det förväntas bli ännu varmare. I och med att temperaturen fortsätter stiga är det mycket som pekar på att vädret i allmänhet kommer förändras, som till exempel förändrat mönster i åskoväder.


Studien visar på att dagar med risk för åska förväntas öka i slutet av detta seklet med omkring 10-15 dagar per år över Sverige, med ännu fler dagar med risk för åska i södra Europa. En förhöjd åskrisk kan även förväntas vid bergskedjor så som svenska fjällen och Alperna. Den främsta anledningen till att åska förväntas bli vanligare är till följd av att temperaturstigningen möjliggör högre halt vattenånga i atmosfären, och därmed kommer fuktigheten i luften att öka. En längre åsksäsong har även noteras, med tidigare start i maj, och även förlängd i september.

Nyckelord: Åska, konvektion, stabilitetsindex, klimatförändring, regional klimatmodellering, RCA4
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1 Introduction

Thunderstorms have a significant impact on societies, and are thus essential to study; this includes lightning and hail storms, flash floods, wind gusts, and in some areas tornadoes. An assessment by The Swedish Commission on Climate and Vulnerability (SOU, 2007) has shown that electricity supplies, electronics, transportation, communication and crops take great damage by thunderstorms, which amount to large expenses every year in Europe (Faust, 2016). Electronic devices and other technological factors may be damaged by lightning as well as flooding and strong winds. Crops, however, take the greatest damage from hail and strong precipitation.

Thunderstorms have a small spatial and temporal scale, making them difficult to forecast and analyse using model data. The models generally have coarser resolution than the size of thunderstorm clouds and thus thunderstorms cannot be explicitly resolved by the models. Instead, the models parameterise convection.

Another challenge when developing models regarding thunderstorms is the limited number of observations of thunderstorm activity (Brooks, 2013). Thunderstorms are not a very common phenomenon compared to the data gathered from precipitation and temperature, and consequently, much less data exists. Lightning strikes are non-continuous, and an extensive lightning location system is needed in order make the data reliable. The need for more climate data for thunderstorms is also mentioned in SOU (2007).

In a future climate, where temperatures are projected to rise, convection and thunderstorm patterns might change as well. In a review of the link between severe thunderstorms and future climate change, Brooks (2013) concluded that studies show an increase in thunderstorm potential in a future climate. This came as a result of investigating the Convective Available Potential Temperature (CAPE) in the United States. The studies also conclude that it is difficult to determine the severity of thunderstorms due to a decrease in the vertical wind shear. Brooks (2013) also mentioned that the lack of climate data for thunderstorms makes it more difficult to give a qualified conclusion on thunderstorms in a future climate.

For thunder to develop, deep convection is needed. Three main components are necessary for deep convection: (1) instability in the atmosphere, (2) available moisture in the atmosphere and (3) a triggering mechanism for the air to be lifted (Doswell et al., 1996). One way thunderstorms can be forecast is through the use of so called stability indices, which indicate the potential for convection. The stability indices are dependent on the first two components mentioned above and are calculated using temperature and moisture data at various levels in the atmosphere (Peppler, 1988). Analysing the temperature and moisture at large scales yields an indication of the potential for thunderstorms to occur given that convection is triggered. This is true even if thunderstorms are unresolved in climate models because the factors which yield thunder clouds extend to a larger scale than the local thunderstorms (Trapp et al., 2007).

In this report, the effects of a warmer future climate on thunder activity and convection in Europe is investigated. Three different stability indices, K-index, KO-index and HH-index are calculated using temperature and humidity data from climate simulations by the Rossby Centre Regional Atmospheric Climate Model 4 (RCA4), developed by the Swedish Meteorological and Hydrological Institute (SMHI) (Kjellström et al., 2016).
This study has mainly considered the following points,

- A validation of the stability indices to indicate the risk of thunder has been done by using reanalysis-driven regional climate model data and compared results with lightning observation (from the lightning location system LP200) through forecast skill scores.

- An investigation of projected future thunderstorm activity; based on three stability indices computed from an ensemble of eight downscaled global climate models using RCA4.

- An Analysis of what causes changes in thunderstorm patterns from the stability indices.

- An Investigation of the stability indices correlation with precipitation and temperature.

From this it is concluded to what extent thunderstorms are projected to increase in a future climate with rising temperature and what causes the changes.
2 Background

This section details convection, thunderstorms and stability indices. Climate change and climate models are also described.

2.1 Convection and Thunderstorms

Convection generally develops during warm summer days when the ground is heated, creating an upward buoyant force. The colder the air above is, the more unstable is the atmosphere and the more favorable are conditions for (deep) convection. There are also other factors triggering rising air, e.g. terrain, fronts and convergence. As a warm and humid air parcel rises, the water vapour will cool down and condense into droplets. When the water vapour condenses, latent heat will be released, heating the parcel such that it might stay warmer than the surrounding air. Thus, the droplets will ascend even higher in the atmosphere, creating a large towering cumulonimbus cloud, often called a thundercloud (Lohmann et al., 2016).

In this towering cloud, the droplets will freeze as they rise, collide and accrete with other water particles and ice crystals, and in turn grow larger. When the hydrometeors are heavy enough they will fall until they are swept up again by a strong updraft, a process which allows further growth and might create hailstones. One of the reasons lightning is believed to occur is due to collision of graupel particles and ice crystals at different temperatures, where charges are generated because of the different terminal velocities of the oppositely charged hydrometeors (Lohmann et al., 2016).

About 2000 thunderstorms occur at all times around the world. Higher temperature and humidity in the tropics give rise to a larger density of thunderstorms in that area, while they are fewer closer to the poles (Isaksson & Wern, 2010). The severity of thunderstorms depends on the lifting force and the wind shear, and more importantly on the stability of the atmosphere and the available moisture. The two last factors can be described through stability indices.

2.1.1 Lightning Location Systems

Thunderstorm activity in Sweden has been recorded regularly by observers since the nineteenth century, first from telegraph stations and later at meteorological station. In 1960, the first lightning detector was put to use, and in 1979 Uppsala University, together with the military, bought the first modern lightning location system: Lightning Location and Protection System (LLP). SMHI began using the Lightning Position and Tracking System (LPATS) in 1986 (Isaksson & Wern, 2010). Since then, the system has changed several times. First in 2002 to IMPACT (IMProved Accuracy using Combined Technology) and later in 2014 to TLP (Total Lightning Processor). Differences between the systems, however, make it difficult to use them as a homogeneous data set.

2.1.2 Observed Thunder Activity in Sweden and Europe

In Sweden, thunderstorms are not as common and severe as in other places around the world, mainly due to the relatively cool climate. One of the worst thunderstorms in connection with heavy precipitation in Sweden was at Fulufjället between the 30th and 31st of August 1997. The mountain got hit by 700 lightning strikes during a few hours, with precipitation at a certain location measured up to 400 mm (Isaksson & Wern, 2010).
Isaksson & Wern (2010) showed that northern Sweden gets very few days with thunder while in southern Sweden the density is much higher. Isaksson & Wern (2010) and Andersson (2002) also found a variation between the eastern and western coasts of southern Sweden. The reason for the variation might be due to different types of thunderstorms. In south-west of Sweden, lightning from frontal passages are the most common, which is reinforced by the Swedish highlands, while in the eastern part, less moisture leads to fewer thunderstorms.

A small difference in thunderstorm patterns was found between the IMPACT data (2002-2009) and the manual observations made through 1961 to 1990. The discrepancy may be due to natural variation, but uncertainties regarding the collection of the manual data might also be a reason for the differences. The observational density and the capability of the observers to hear thunder are uncertain and can be causes for missing data, resulting in the variations (Isaksson & Wern, 2010). Isaksson & Wern (2010) also showed that lightning during the investigated period was most common at 14-15 UTC (16-17 Swedish summer time) between May to September. Lightning over land is most common in July, when the ground is heated, while in August lightning is most common over sea regions (Andersson, 2002).

Thunderstorms are more common in continental Europe than over Scandinavia. Anderson & Klugmann (2014) concluded that the mountain areas of continental Europe and the north coast of the Mediterranean Sea have the highest flash density, due to surface heating in April to September. The rest of the year, most of the thunderstorm occur over the ocean because of the warm surface water under the cool atmospheric air.

2.2 Stability Indices

The forecast models generally have coarser resolution than the size of a thunder cloud and therefore parameterisation of convection is required. This makes it very uncertain predicting thunderstorms using forecast models and instead stability indices has traditionally been used as an indicator for risk of thunder. The stability indices use components of the atmosphere, such as its stability and the available moisture, to determine the potential for convection. Most of the stability indices use radiosonde data and model data to empirically determine the potential of convection, working best at the specific place investigated (Peppler, 1988).

Although the stability indices depend upon many components, the output is only a single numerical value representing the potential for convection at a certain location. The value has a statistical threshold that differentiates between risk of thunderstorms and no risk of thunderstorms. There are many different stability indices, both specialised and integrated. The specialised indices use only information at certain levels in the atmosphere while the integrated use data at all levels from a sounding. In this study only specialised indices has been used. The stability indices are performing differently predicting atmospheric phenomena. Some are better at predicting precipitation while others are better at predicting severe thunderstorms and tornadoes (Peppler, 1988).

Many uncertainties are found related to the stability indices in their use as indicators of convection, precipitation and thunder. A central uncertainty relates to the triggering of convection. Even if conditions may be favourable for instance with upper air instability, if there is no triggering mechanism of the convection there will be no convective precipitation and thunder. As mentioned above, the indices are local and might not be optimal at other places around the world. In situations with homogeneous conditions at large scales, however, stability indices based on local data can be considered representative.
for larger areas. Indications show that the efficiency of the indices depends on the time of day, as well as season (Andersson et al., 1989). Three of the most common stability indices used in Sweden are the K-index, the KO-index and the HH-index (Sohlberg, 2007).

2.2.1 K-index

George (1960) used data that determines the stability and the available moisture in the atmosphere to measure thunderstorm potential through the K-index. The K-index considers the vertical temperature lapse rate, the moisture content of the lower atmosphere and the moisture in the upper atmosphere. This is described in the following equation

\[ K = (T_{850} - T_{500}) + Td_{850} - (T_{700} - Td_{700}) . \]  

(1)

Where T is the temperature (°C) at pressure levels 850, 700 and 500 hPa, and Td is the dew point temperature (°C) at levels 850 and 700 hPa. A high value of K indicates larger risk for convection, and therefore also thunder.

George (1960) used the K-index in relation with the probability of occurrence of a thunderstorm, Table 1. Nowadays, it is usually a measurement of the certainty of thunderstorm occurrence. The K-index was first locally computed with the help of radiosonde data from the United States and southern Canada, which might cause uncertainties using the index in Europe. The conclusion by Peppler (1988) was that the K-index is a poor indicator of severe thunderstorms, but works very well for rainfall and non-severe convection during the summer.

Other uncertainties regarding the K-index have been found as well. When there is a capping inversion at ground level that prevents convection to develop, the K-index might still indicate large potential for convection. As well, when the lower atmosphere lack moisture, the K-index may still show large potential for convection given high enough vertical temperature gradient. Studies also show that the K-index works best for flat areas.

Table 1. K-index values in relation with Thunderstorm Probability.

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<tr>
<th>K-index value</th>
<th>Thunderstorm Probability</th>
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<tr>
<td>K &lt; 20</td>
<td>No thunderstorms</td>
</tr>
<tr>
<td>20 ≤ K &lt; 26</td>
<td>isolated thunderstorms</td>
</tr>
<tr>
<td>26 ≤ K &lt; 31</td>
<td>Widely scattered thunderstorms</td>
</tr>
<tr>
<td>31 ≤ K &lt; 35</td>
<td>Scattered thunderstorms</td>
</tr>
<tr>
<td>K &gt; 35</td>
<td>Numerous thunderstorms</td>
</tr>
</tbody>
</table>

In Sweden, Sohlberg (2007) used a threshold of 21 ≤ K ≤ 26 for moderate risk thunderstorms and K > 26 for large risk of thunder when studying a couple of thunderstorms.

2.2.2 KO-index

The KO-index was first developed by the Deutcher Wetterdienst in Germany to distinguish rising air in a cold front. The KO-index uses pseudo-adiabatic equivalent potential temperatures at different pressure
levels in the atmosphere to describe the potential for convection. This is defined as follows,

\[ KO = \frac{\theta_{ae500} + \theta_{ae700} - \theta_{ae850} - \theta_{ae1000}}{2}, \]  

(2)

where \( \theta_{ae} \) is the pseudo-adiabatic equivalent potential temperature (K) at pressure levels 500, 700, 850 and 1000 hPa. The pseudo-adiabatic equivalent potential temperature can be described as the increase in potential temperature of a saturated parcel of air lifted pseudo-adiabatically until all water has been condensed and then compressed dry adiabatically to a reference pressure. This can be calculated as follows

\[ \theta_{ae} = \theta \exp \left( \frac{l_{wv} m_s}{c_{pd} T_s} \right), \]  

(3)

where \( \theta \) is the potential temperature, \( l_{wv} \) is the specific latent heat for water vapour, \( m_s \) is the saturated mixing ratio, \( c_{pd} \) is the dry specific heat and \( T_s \) is the lifted condensation temperature.

Approximations are needed to solve for the pseudo-adiabatic equivalent potential temperature. Bolton (1980) found the best approximation with an error of less than 0.3 K, given by

\[ \theta_{ae} = T \left( \frac{1000}{p} \right)^{0.2854(1-0.28\cdot10^{-3}m)} \cdot \exp \left[ \frac{3.376}{T_s} - 0.00254 \right] \cdot m(1 + 0.81 \cdot 10^{-3} m) \].  

(4)

where \( T \) is the temperature (K) at the specific pressure level \( p \) (hPa) and \( m \) is the mixing ratio (g/kg). A higher \( \theta_{ae} \) means a warm and humid atmosphere, while a lower means a colder and drier atmosphere. In other words, if \( \theta_{ae} \) is low at 500 hPa, indicating dry and cold conditions, and high at 1000 hPa, indicating humid and warm conditions, there is a larger risk for thunder to occur.

Andersson et al. (1989) used a threshold of \( KO < 4 \) to indicate thunderstorm potential in Sweden. Sohlberg (2007) used the same threshold to distinguish between thunderstorms and non-thunderstorms event but found that this gave poor result, while a lower threshold of \( K < -3 \) was better. Studies have also shown that the KO-index is not as successful regarding frontal thunder as previously claimed, but nevertheless an index often used (Nilsson, 1987).

### 2.2.3 HH-index

Håkan Hultberg, a forecast meteorologist at SMHI, produced a new stability index by combining the K- and KO-index:

\[ HH = K \cdot KO' \]  

(5)

where \( KO' = 20 - KO \) if KO is less than or equal to 20. Using this removes the negative sign from the KO-index. The HH-index (°C) was for a long time used as one of the indices at SMHI to predict thunderstorm potential in forecasts. Sohlberg (2007) found that the HH-index is better at predicting thunderstorms than both the K- and KO-index. HH-index probably performed better because the threshold and the index are empirically based on data used in Sweden, while for the K- and KO-index, old thresholds from earlier studies were used.
2.3 Climate

The climate is constantly changing, but in the last 100 years an abnormal rise in the global average temperature has been observed. The Intergovernmental Panel on Climate Change (IPCC, 2013) has concluded that humans are the main cause of the current global warming with a certainty of 95%. The main sources of climate change are the large emissions of greenhouse gases, aerosols and their precursors, and changes in the surface properties of the Earth, that in turn affects the Earth’s energy budget. Disruptions of the climate will amount to greater risks of severe and non-reversible impacts on ecosystems, which will affect humans (IPCC et al., 2014).

During the period between 1880 and 2012, the mean temperature rose by 0.85 °C (IPCC, 2013). Out of the seventeen warmest years on record, sixteen have been during the 21st century, where the warmest year so far was 2016 (NOAA, 2017), indicating that the Earth is getting warmer. The impact of higher temperatures can be seen in rising sea level, melting ice caps and glaciers, and it is projected to become worse in the future if nothing changes. To be able to project a possible future climate evolution, climate models are used.

2.3.1 Climate Models

A numerical climate model is built upon physical, mathematical and chemical principles and can be used for simulating past, current and future climate conditions. The climate system is highly complex involving a large range of processes operating on a wide variety of scales starting from the molecular level to planetary waves and from nanoseconds to centuries and millennia. The climate models are therefore simplified using empirical laws and parameterisations. Parameterisations describe the dynamics at smaller than grid scales in terms of large-scale atmospheric properties (Provenzale, 2014), e.g. convection, cloud and aerosol processes (IPCC, 2013).

The complexity of the models varies. The simplest models use the energy balance to describe changes in the atmosphere, such as variations in the solar radiation. In this study, the more advanced General Circulation Models (GCMs) are used. GCMs represent the Earth through a three-dimensional grid, where the atmosphere, ocean, cryosphere and land surfaces interact and give dynamical and physical components (Provenzale, 2014). The models can be used for making projections of future climate change as a consequence of emission of greenhouse gases and aerosol forcing, called scenarios.

Scenarios

To project a future climate, estimations of the anthropogenic and natural emissions in the atmosphere are made, using forcing factors in the climate model. The scenarios are not only dependent on the emission of greenhouse gases, such as carbon dioxide, methane and aerosols (radiative forcing), but also on the hypothesis of the globalisation, land use, economic development and industrialisation. Several scenarios are described in the Special Report on Emission Scenarios (SRES), used in IPCCs earlier assessment reports. The latest type of scenarios from the fifth assessment report (IPCC, 2013) are the Representative Concentration Pathways (RCP). The RCPs interpret the increase of greenhouse gas emissions as the radiative forcing (W/m²) of the climate system compared to pre-industrial conditions. The four scenarios assessed by the IPCC are called RCP2.6, RCP4.5, RCP6 and RCP8.5, where the number denotes the radiative forcing in the year 2100.
Regional Climate Models

The GCMs typically have a coarse resolution of around 100-200km and describe global and large-scale processes, for instance, the general circulation of both the atmosphere and the ocean. To better represent finer scales and certain geographical regions, the global climate models are downscaled by nesting the regional climate models (RCM) (Rummukainen, 2010). The grid resolution of RCM is usually 50 km or lower and the lateral boundary conditions of the RCMs are from different GCMs.

The finer resolution enhances the representation of landscape features such as mountains and lakes. The smaller scale allows probing of regional circulations and finer precipitation patterns, which also modifies the temperature and winds at the lower scale. As the scale decreases, the structure of synoptic and mesoscale systems improve as well (Rummukainen, 2010).

At the Rossby Centre at SMHI in Sweden the regional climate model Rossby Centre regional Atmospheric climate model (RCA) is developed, the latest version being RCA4 (Kjellström et al., 2016).

Coupled Model Intercomparision Projects

The number of different GCMs, RCMs and scenarios lead to an extensive data set. To evaluate all this data, an organised and well-documented collection of model simulations is essential. The Coupled Model Intercomparision Projects (CMIPs) was established by the World Climate and Research Programme (WCRP) to develop a standardised set of data and study the outputs of the GCMs (IPCC, 2013).

The CMIPs were also created to allow scientist easier access to data; validate, compare and improve the models; and assess climate change. The IPCC Assessment Report (AR) has used CMIP data sets to produce their material, both in the AR4, and in the latest AR5, using the CMIP3 and CMIP5, respectively (Meehl et al., 2007; Taylor et al., 2011).

CORDEX

Coordinated Regional Climate Downscaling Experiment (CORDEX) is a global partnership for the regional climate downscaling models. The goal is to better understand the regional climate phenomena, improve the RCMs, produce a set of coordinated regional downscaled projections worldwide and exchange knowledge with others. SMHI is a part of this international research project (CORDEX, 2017).

Ensemble

An ensemble is a set of different model simulations, that might differ in physics, forcing scenarios and boundary conditions. In climate modelling an ensemble generally differ in emission or radiative forcing scenarios, but can also differ in physical components used in the climate models. An ensemble of different global climate models gives a spread in the results, which can be associated with the uncertainties in simulating the future climate, and gives an idea about the reliability of the models (SMHI, 2017).

2.3.2 A Future Climate

For the same reasons the temperature has risen during the last 100 years, the projection shows that the global mean temperature will continue to rise over the 21st century. IPCC (2013) has reported that the global mean surface temperature is projected to rise by a value between 1.1 °C and 2.6°C (range from CMIP models) for the period 2081-2100 relative to 1986-2005 using the RCP4.5 scenario. For the RCP8.5 scenario, the temperature is projected to rise by 2.6°C to 4.8°C in the same period.
In Sweden, the largest temperature rise is projected in winter in the north. When the temperature rises, the snow and ice cover will decrease, altering the albedo, which is mostly true for the north. A change in the albedo gives rise to a positive feedback, making the climate even warmer. A warmer temperature means significantly milder winters and warmer summers in Sweden (Kjellström et al., 2011).

Precipitation, however, is not as easy to project, and does not show as strong statistical significance as the temperature. Nikulin et al. (2011) investigated precipitation patterns in Europe and concluded that a few local spots show a statistically significant change in the extreme daily precipitation at the end of the 21st century, compared to the end of the 20th century. The overall tendency for precipitation shows an increase in heavy precipitation in northern Europe and a decrease in precipitation in southern Europe. The recurrence time of heavy precipitation in the north is projected to be reduced from 20 to 10 years in the summer, while in the wintertime it may be reduced to 4 years.

The changes in temperature and precipitation patterns might not be the only factors affected. Low and high pressure systems as well as thunderstorm patterns might change as well. Thunderstorm activity in a future climate has been investigated by, e.g. Trapp et al. (2007) and Del Genio et al. (2007). The two studies show that the convective available potential energy (CAPE) is expected to increase towards the end of the 21st century in the United States. The increase in CAPE is associated with the larger amount of available moisture in the atmosphere as the temperature rises. However, the studies also show a decrease in the vertical wind shear (S06) over large areas of the United States. A reduction of the temperature differences between the equator and the poles, decreasing the thermal wind, is the reason for a decrease in the wind shear. Brooks et al. (2007) conclude that a strong CAPE and a strong S06 are the reason for severe thunderstorms. The studies claim that CAPE has a larger impact on thunderstorms than the wind shear, and therefore thunderstorms are believed to become more common in a future climate.
3 Method

3.1 Climate Data

Temperature, specific humidity and precipitation data from the regional climate model RCA4 were analysed over Europe for a grid resolution of 50x50 km. RCA4 has been downscaling eight different GCMs, seen in Table 2. The data contains both RCP 4.5 and RCP 8.5 scenarios daily at 12 UTC for the period 2011-2100, together with a historical simulation between 1971 and 2006. A reanalysis-driven simulation with RCA4, driven by ERA-interim data (Dee et al., 2011), was used between 1979-2011, when comparing the model derived stability indices with lightning observations.

The data for temperature (T) and specific humidity (q) at different pressure levels were used when calculating the stability indices. The different levels include 2 metres height, 850 hPa, 700 hPa and 500 hPa. With the specific humidity, the dew point temperature could be calculated. Precipitation during the six-hour period 12.00 to 18.00 UTC every day was also used in this study.

In this study an ensemble mean of all eight models was used for the temperature, precipitation and for number of days with thunder.

Table 2. The eight GCMs downscaled by RCA4 used in this study.

<table>
<thead>
<tr>
<th>Institute</th>
<th>Model</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CCCMA, Canada</td>
<td>CanESM2</td>
<td>Chylek et al. (2011)</td>
</tr>
<tr>
<td>2 CNRM-CERFACS, France</td>
<td>CNRM-CM5</td>
<td>Voldoire et al. (2013)</td>
</tr>
<tr>
<td>3 EC-EARTH, EU</td>
<td>EC-EARTH</td>
<td>Hazeleger et al. (2010)</td>
</tr>
<tr>
<td>4 NOAA GFDL, USA</td>
<td>GFDL-ESM2M</td>
<td>Dunne et al. (2012)</td>
</tr>
<tr>
<td>5 IPSL, France</td>
<td>IPSL-CM5A-MR</td>
<td>Dufresne et al. (2013)</td>
</tr>
<tr>
<td>6 MIROC, Tokyo</td>
<td>MIROC5</td>
<td>Watanabe et al. (2011)</td>
</tr>
<tr>
<td>7 MPI-M, Germany</td>
<td>MPI-ESM-LR</td>
<td>Popke et al. (2013)</td>
</tr>
<tr>
<td>8 NCC, Norway</td>
<td>NorESM1-M</td>
<td>Bentsen et al. (2012)</td>
</tr>
</tbody>
</table>

3.2 Lightning Observation

The lightning observation data is from the lightning location system LP2000 managed by SMHI. LP2000 counted the lightning strikes occurring in Sweden between 2003-01-01 and 2013-12-31.

The lightning data was gridded with the same coordinates as the climate models with a resolution of 50x50km. The data set contains information about the position and time of every lightning strike that was sorted into the correct gridbox each day. Finally, days were classified as days with or without thunderstorm activity for each gridbox.

The lightning observations were only analysed between 12.00 and 18.00 Swedish time, given that this study only uses model data at time 12 UTC. Isaksson & Wern (2010) investigated the same lightning observation data and found that most of the thunder in the summer months strikes during this time interval. Cloud-to-cloud lightning strikes and strikes less than 5 kA were advised by SMHI to be removed from the data set due to uncertainties in the lightning location system. SMHI also gave information about strikes wrongly registered by the system that might be due to technical problems, therefore at least 10 strikes per day was a requirement for a day with thunder. Improvements of the system were done over
the years, thus the data might not be homogeneous. Examples of this are upgrades of sensors or system configurations.

3.3 Procedure

3.3.1 Stability Indices

From the climate data three stability indices were computed, \( K \)-, \( KO \)- and \( HH \)-index. The dew point temperature \( T_d \), used in the stability indices, was calculated from pressure and specific humidity in the atmosphere (Yau & Rogers, 1996) at different levels, using the equation,

\[
T_d = \frac{5.45 \cdot 10^3[K]}{\ln\left(\frac{2.53 \cdot 10^5[kPa]}{q_p} \cdot \varepsilon\right)},
\]

where \( q \) is the specific humidity in g/g, \( \varepsilon = 0.622 \) and \( p \) is the pressure in kPa. The equivalent potential temperature (Eq. 4) was also calculated at different levels to compute the \( KO \)-index. For \( \theta_{ae1000} \) the ground temperature was used. The three different stability indices were computed from model output with the help of Climate Data Operators (CDO). The rest of the data processing was done in MATLAB.

3.3.2 Forecast Skill Score and Optimised Threshold

Thunderstorm forecasts are often divided into event/non-event called a dichotomous forecast. Dichotomous forecasts are generally verified by observations through a contingency table (see Fig. 1) For the cases when thunderstorms are observed and forecast, it is said to be a hit (A); when observed but not forecast it is a surprise event (B); when forecast but not observed it is a false alarm (C); and when neither observed nor forecast, it was a null-correct (D); where \( A + B + C + D = 1 \). This method is regularly used when evaluating this type of phenomenon in weather forecasts (Kunz, 2007). In this case it was used to evaluate the thresholds for the stability indices.

\[
\begin{array}{c|c|c}
\text{Forecast} & \text{Yes} & \text{No} \\
\hline
\text{Yes} & A \text{ Hits} & B \text{ Surprises} \\
\text{No} & C \text{ False alarm} & D \text{ Null correct} \\
\end{array}
\]

\textbf{Figure 1.} Contingency table
From the contingency table, forecast skill scores can be calculated. Five common skill scores used here are described below.

- The Probability of Detection (POD) shows the fraction of all observed events that was a correct forecast. A perfect score is equal to one. The problem with this skill score is that POD can get a high percentage just by forecasting the event often, which might not be accurate. However, when evaluating rare events, such as thunderstorms, the POD is more accurate (Donaldson et al., 1975).

\[
POD = \frac{A}{A + B} \quad (7)
\]

- The False Alarm Ratio (FAR) determines the amount of forecast events that were false alarms. The lower the FAR the better and FAR=0 implies that there were no false alarms. FAR gives a compliment to POD. A problem with FAR is that it can be low just by never predicting an event, which may not be accurate.

\[
FAR = \frac{C}{A + C} \quad (8)
\]

- True Skill Score (TSS) is a more advanced skill score. TSS determines how well the forecast separates the expected events from the unexpected non-events. A disadvantage with the TSS is that the null-correct term will dominate and approach the POD when a phenomenon with very few events is analysed (Doswell et al., 1990). A perfect score is one.

\[
TSS = \frac{A}{A+B} - \frac{C}{D+C} = \frac{(AD - BC)}{(A+B)(D+C)} \quad (9)
\]

- Critical Success Index (CSI) indicates the fraction of hits to the total number of events, except for the cases when the non-events were correctly forecast. Excluding the correctly forecast non-events avoids the problem associated with a large number of null correct situations. The disadvantage is that the effort taken to conclude that nothing will happen has no positive influence on the evaluation (Doswell et al., 1990). A perfect score is one.

\[
CSI = \frac{A}{A+B+C} \quad (10)
\]

- Heidke Skill Score (HSS) is defined as the number of correct forecasts minus the correct forecasts purely due to chance over the total number of forecasts minus the correct forecasts purely due to chance (E). E is given by \( E = \frac{(A+B)(A+C)+(B+D)(C+D)}{(A+B+C+D)} \). HSS has no problem when null correct is the dominating forecast, and therefore HSS is better suited for evaluating rare events compared to other skill scores (Doswell et al., 1990). A perfect score is one.

\[
HSS = \frac{A + D - E}{A + B + C + D - E} = \frac{2 \cdot (AD - BC)}{B^2 + C^2 + 2AD + (B + C)(A + D)} \quad (11)
\]
Since thunder is divided into yes/no-events, the stability indices are given a threshold value that should reflect the limit between when thunder occurs or not. Thresholds were optimised by comparing lightning observations to the number of days with potential thunder in the ERA-Interim-driven RCM simulation. One wants the stability indices and the lightning observations to be maximised for hits; and minimised for false alarms and surprise events. The three stability indices were compared with lightning observation for a wide range of different threshold values, using forecast score in the same way described by Haklander & Van Delden (2003) and Kunz (2007). The best optimised threshold was set to be where the skill score HSS has its maximum, appendix A.

3.3.3 Statistical Significance Test

After the optimal thresholds for the stability indices were chosen, the projected future climate change could be analysed. The null hypothesis is that there will be no change in number of days with risk of thunder in a future climate compared to the reference period 1971-2000. A statistical significance t-test was done with the help of MATLABs builtin function ttest2 to prove the null-hypothesis. A t-test compares two independent data samples with each other. The null hypothesis assumes two different expected values to be equal.

\[
t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_x^2}{n} + \frac{s_y^2}{m}}}
\]

where \( \bar{x} \) and \( \bar{y} \) are the sample means; \( s_x \) and \( s_y \) are the standard deviations of the data set; and \( n \) and \( m \) are the number of data points. If \( |t| > 1.96 \), the null hypothesis is rejected with a 95% confidence and the two data sets are said to be significantly different.

Another approach to visualise statistical significance and statistics used in this study is through box plots. In a box plot, the median of a data set is described by the horizontal line of the box, while the edges of the box indicate the 25th and 75th percentiles. The minimum and maximum values are found through the whiskers, where extreme values (outliers) are shown with red pluses. Notches in the box inform about the significance between data sets. If the notches between two boxes do not overlap, one can conclude with 95% confidence that the data sets (median) differ.
4 Result

4.1 Evaluation of Stability Indices as Indicators for Thunder

An important step before analysing the projected future climate is evaluating the models against observations. In this case, the three stability indices were first computed with data from a re-analysis driven climate model to compare and optimise the thresholds with lightning observations and investigate uncertainties in the indices. The thresholds for the stability indices were chosen such that the indices agreed optimally with lightning observations covering all of Sweden for the period 2003-2011. The approach and results can be found in Appendix A. When the observations showed a day with thunder, the thresholds for the stability indices were best fit to $K > 28$, $KO < -4$ and $HH > 620$. These thresholds were used in the rest of the study.

After the thresholds were determined, the stability indices could be investigated in more detail. The investigation was done by comparing the average annual days with risk of thunder determined from the stability indices with the actual amount of days with thunder from the lightning observations, Figure 2. Generally, all indices show less days with risk of thunder in the north, in line with observations. Further, the KO-index shows a strong land-sea contrast generally in line with the observations and the K-index estimates well in the south east. However, there are also a number of differences between observations and model estimates. The K-index overestimates the number of days with risk of thunder in the Swedish mountain area; the KO-index shows too many days with risk for thunder in south eastern Sweden and in the middle of Sweden (Svealand); while the HH-index, which is a combination of the other two indices, has issues in both of these areas. All three indices underestimate the number of thunderstorms in southwestern Sweden. A further analysis of the uncertainties can be found in chapter 4.3.

Figure 2. Total amount of days per year with thunder, averaged over the period 2003-2011 for a) observations, the ERA-interim driven data for b) K-index, c) KO-index and d) HH-index. e-g) show difference between respective stability index and observation.
The number of days with thunder per month in Sweden during the period 2003 and 2011 were also investigated, see Figure 3. The box plot shows information about the number of days with risk of thunder each month for all the grid boxes in Sweden, as an average over the investigated period. The box represents the 25th and 75th percentile while the horizontal line indicates the median. The whiskers represent maximum and minimum values. The investigation was done to get a better understanding of the spread in thunderstorms in Sweden, especially regarding the uncertainties, and at the same time study the monthly variations between the indices and observations. The lightning observations show thunder earlier in May and June compared to the KO- and the HH-index. The K-index, however, shows more days with risk of thunder between August and October compared to days with actual lightning observations. In July and August, the whiskers show that some places do not experience any thunder at all, while the stability indices always indicate days with risk for thunder. Figure 18 in appendix A shows the difference between lightning observations and the derived risk of thunder based on the stability indices for number of days per month with risk of thunder for Sweden. In certain areas of the mountainous region, the risk of thunderstorms derived from the K-index are overestimated with up to 15 days per month.

The analyses and comparisons with observations were only performed using data over Sweden. However, days with risk of thunder in the rest of Europe were also investigated. Figure 4 shows days per month with risk of thunder for the K-, KO-, and HH-index, between May and September for the period 1979-2011. The stability indices, especially the K-index, show a large amount of days with risk of thunder in the Alps and other mountain areas. Anderson & Klugmann (2014) investigated the flash density in Europe and found a higher potential for thunder in the mountain areas. Though it differs from the investigation in this study of days with risk of thunder, it might have a relation. The KO-index shows large amount of days with risk of thunder over the Mediterranean Sea in the summer. Anderson & Klugmann

![Figure 3](image-url)

**Figure 3.** Number of days with risk of thunder per month for all the grid boxes in Sweden, for data driven with ERA-interim. Blue is the K-index, pink is the KO-index, green represents the HH-index and black is the lightning observation data.
(2014) found that the flash density over the Mediterranean Sea is largest during winter time and almost non-existing during the summer, which is not in agreement with the KO-index. The HH-index does not have the extremes of the K-and KO-index as it is a blend of the two indices. The uncertainties regarding the large potential for thunder in the mountain region and over the Mediterranean Sea for the stability indices are investigated in chapter 4.3 and should be kept in mind for the rest of the results.

In the next section, an ensemble mean of eight RCM simulations has been used to project the future climate. Each GCM-driven RCA4 simulation should first be evaluated against the reanalyse-driven simulation with ERA-interim for the historical period. The evaluation gives a better idea of uncertainties for each RCA4 simulation and gives a qualified estimate on how well they work when comparing with ERA-interim and in that way also the observations. A comparison between the ERA-interim simulation, the ensemble mean and the different GCM-driven simulations can be found in Appendix B, for the three stability indices using data for the interval 1979 and 2006. The comparison shows very similar annual average days with risk of thunder for ERA-interim and the ensemble mean, indicating that the GCM-driven RCA4 simulations constitute a reasonable representation of the atmospheric conditions required for deep convection to occur.

**Figure 4.** Amount of days with risk of thunder for May to September as an mean between 1979 and 2011. The first row represents the K-index, middle represents the KO-index and the last represents the HH-index.
4.2 Thunderstorms in a Future Climate

The future projected climate, especially the rise in temperature, is found to have an impact on the thunderstorm activity in the future, as can be seen in Figure 5. The figure shows the average annual number of days with risk of thunder for the three investigated stability indices, calculated as an ensemble mean of 8 different GCMs. Data from 1971 to 2000 were compared with three different projected future periods, 2011-2040, 2041-2070 and 2071-2100 for scenario RCP 4.5.

In future projections, an increase in days with risk of thunder can be seen for all indices. In the earliest period, between 2011 and 2040, the simulated increase is approximately five days. At the end of the 21st century, around 15 more days with risk of thunder have been projected in Sweden, corresponding to an increase of about 40% in the south and an even larger increase in the north. Higher potential for thunder can be found in the mountain regions in the K-index, but should be regarded somewhat with caution as the agreement between derived days with risk of thunder in the historical climate is strongly biased compared to the days with observed lightning (see 4.1 above). The KO-index shows more days with risk of thunder in the central and eastern part of Sweden. The statistical significance test showed that the historical period is different from the future periods for RCP4.5 at 5% significance level for all simulations except one, indicating increase in thunderstorm potential. The MPI-ESM-driven simulation for the KO-index during 2011-2040 and 2041-2070 do not show as strong significance.

Figure 5. Average annual number of days with risk of thunder, for a) the K-index, e) the KO-index, and i) the HH-index during the period 1971-2000. Difference between thunder days for the period 2011-2040 and 1971-2000 (b-f-j); 2040-2071 and 1971-2000 (c-g-k); and 2071-2100 and 1971-2000, for respective index. The plots represent RCP 4.5.
In Figure 6, the projected annual average number of days with risk of thunder for RCP8.5 is shown, in the same way showing the four different periods for the K-, KO- and HH-index as in the previous figure. A higher potential for thunderstorms can be seen in all three indices for RCP8.5. At the end of the 21st century the increase in days with risk of thunder is about 20 days per year, corresponding to about 60% more days with potential for thunder in the south and an even higher potential in the north. The statistical significance test showed that the historical period is different from the future periods for RCP8.5 at 5% significance level for all models, except for KO in the early period (2011-2040) for the models GFDL-ESM2M and MPI-ESM. The large amount of projected days with risk of thunder in the mountain region in a future climate for the K- and HH-index should be examined with caution given the poor relation between these indices and the number of days with risk of thunder in the evaluation.

To get a better understanding of temporal changes, monthly averages for days with risk of thunder were investigated in Figure 7 for the KO-index. The box plot shows the mean value of days with risk of thunder for all data points in Sweden for each month during the four 30-year periods. The potential for thunderstorms is projected to increase through May to September for all four 30-year periods, and the statistical significance is visible (no overlaps in the notches) for both RCP4.5 and RCP8.5. Corresponding figures for the K- and HH-index can be found in appendix C, showing similar result. The rest of the months do not show any statistically significant changes in thunderstorm potential in the future.

Figure 6. The same as in figure 5, but for scenario RCP 8.5.
The increase in days with risk of thunderstorms can be found in the rest of Europe as well for the K-, KO- and HH-index, see Figure 8. The largest increase in thunderstorm potential is naturally for the warmer RCP8.5 scenario. The increase is generally in the order of 15 to 20 more days per year over large parts of Europe. However, regional variations occur, including a tendency for larger differences over some mountain regions and a notable increase for the Mediterranean area for the KO-index. However, the large increase over mountain and sea regions should be used with caution. The maps clearly show differences between the K- and KO-index, as a result of the different definitions of the indices. Above all, the essential conclusion is that all three indices project an increase in days with risk of thunderstorms.
Figure 8. Ensemble mean of yearly number of days with risk of thunder, first column shows the period 1971-2000, second column shows the difference between RCP 4.5 scenario for year 2071-2100 and period 1971-2000 and the third shows the difference between RCP 8.5 for 2071-2100 and the period 1971-2000, while the rows show numbers derived from the K (top), KO (middle) and HH (lower) indices at the reference period.

4.3 Causes for Changes in Thunderstorm Activity

The increase of days with risk of thunder in the 21st century is clear in the previous section. To study the cause for a higher potential for thunderstorm, each component in the stability indices was investigated (cf, eq.1, eq.2). Figure 9 shows the average annual number of days with risk of thunder, the mean value of the K-index and the three main components: the vertical temperature lapse rate \( T_{850} - T_{500} \), the available moisture in the lower atmosphere \( T_d_{850} \) and the moisture conditions in the free troposphere \( T_{700} - T_d_{700} \) for days with risk of thunder. The rows in the figure show the historical period in the first row, the difference between the projected climate at end of the century and the historical period for RCP 4.5 and RCP8.5, for the second and third row, respectively. Figure 10 is similar to Figure 9 but instead uses all data from the investigated period (and not only days with \( K > 28 \)).

To better understand changes in a future climate, the historical climate has to be analysed as well. The historical simulations for the K-index shows a larger number of days with risk of thunder in the mountain regions. In these areas, where the K-value is the highest, one can see that despite relatively dry conditions at 850 hPa (panel d), the strong lapse rate (panel c) in combination with the relatively humid surrounding atmosphere at 700 hPa (panel e) give rise to the high K-index value, seen in both Figure 9 and Figure 10. Fewer days with risk of thunderstorms are found closer to the poles and in the Mediterranean region. The lower number of days with risk of thunderstorms closer to the poles corresponds with low moisture content in the lower atmosphere (panel d), while fewer days with risk of thunderstorms over the Mediterranean Sea are due to the very dry conditions in the free troposphere (panel e) \( T_{700} - T_d_{700} \).
In a future climate, small changes in each component correspond to changes in the potential for thunderstorm. The combination of these main components leads to a higher K-index value and more days with risk of thunder, most notably over continental parts of Europe, mountainous areas, including Scandinavia, and over parts of the north Atlantic. The significant increase in moisture in the lower atmosphere ($T_{d850}$, panel i,n) leads to an increase of thunderstorm potential despite the generally weaker vertical temperature lapse rate ($T_{850} - T_{500}$, panel h,m) and the relatively drier conditions in the free atmosphere ($T_{700} - T_{d700}$, panel j,o).

The decrease in the difference between temperature and dew point temperature (drying) at 700 hPa (j-o) in the southern parts of the domain counteracts the impact of increased absolute humidity in the lower levels. As a consequence, there is only small changes in the number of days with risk of thunder over the Mediterranean Sea. In the Alps, an increase can be found for the vertical temperature lapse rate, which contributes to more days with risk of thunderstorms in that area. The increase in the vertical lapse rate in the Alps in the future might be due to changes in the snow cover. In the mountain areas in Sweden an apparent increase in days with risk of thunder can be seen, but none of the three components indicates specifically higher K-index value in that area. The cause might be the relatively high numerical values of K from the start. When K increases by only a few units, the threshold is reached more frequently and gives rise to substantially more days with risk of thunder.

Differences can be seen when using only data for $K > 28$ and all data. In Figure 10 there is a strong increase in the K-index in the north related to the increase of the low level humidity, but the relatively low K-index in the historical period makes the potential for thunderstorm still relatively small. Over the Mediterranean Sea and the Atlantic Ocean a drier and more stable free atmosphere in the future projections limit the increase in the K-index, and also limits the risk of days with thunder in the future in those areas. When only days with risk of thunder are considered, Figure 9, the K-index value shows small positive changes in Europe. The relatively uniform K-index value might indicate that the change in the severity of the thunderstorms is similar in almost the whole domain. The average of the K-index value increases with about 1-2 °C for the investigated area. This might give stronger and more severe thunderstorms in a future warmer climate in Europe according to the definition of the K-index by George (1960).
Figure 9. The annual average of a) number of days with risk of thunder based on the K-index, b) K-index value c) $t_{850} - t_{500}$, d) $td_{850}$ in °C, e) $(t - td)_{700}$ for days with risk of thunderstorms. a-e) show period 1971-2000. The difference between the period 2071-2100 and 1971-2000 for f-j) the RCP4.5 scenario and for k-o) the RCP 8.5 scenario. Blue differences correspond with decrease in days with risk of thunderstorms while red with increase.

Figure 10. Similar figure as Figure 9, but with all days for the investigated period.
Each component in the KO-index has been investigated as well. In Figure 11, only data when the KO-index value is less than \(-4\) is analysed. In other words, when it is said to be a day with risk of thunder. In Figure 12 instead all data for the investigated period is shown. The figures show days with risk of thunder, the KO-index value, the pseudo adiabatic potential temperature at 500hPa, 700hPa, 850hPa and at 2 metres for the historical period in the first row and the difference between the future projection at the end of the century for RCP 4.5 and RCP 8.5, and the historical period, respectively for row 2 and 3.

Analysing the historical period, the KO-index takes relatively low values over the Mediterranean Sea, indicating larger potential for thunderstorm in that area. The cause for larger risk of thunderstorms over the sea is due to the high value in the pseudo-adiabatic potential temperature at ground level (see panel f). In the Alps and other mountain regions in the south a larger potential for thunderstorms are found, which are due to the higher values of the pseudo adiabatic potential temperature at 850 hPa (panel e) and 1000 hPa (panel f). In the north, the potential for thunderstorms are small and in the Swedish mountains the risk of thunder is almost non-existent.

In a future warmer climate, one can conclude that the pseudo-adiabatic potential temperature increases at all levels in the atmosphere. The largest increase is found at ground level and is one reason why days with risk of thunderstorm is projected to increase in most of Europe. An increase at the 500hPa and 700 hPa levels tend to increase the KO-index and give a lower risk of thunderstorms, while an increase in 850hPa and 1000 hPa give a lower KO-index value and a larger risk of thunderstorms. A larger difference between the potential temperature for lower and upper levels in the atmosphere will be in favour of more convection. The higher potential for thunderstorm over the Mediterranean Sea can be explained in the same way as for the increase of days with risk of thunderstorms in the mountain areas for the K-index. If the value of the KO-index is close to the threshold, it will cross the threshold with merely a small change.

Differences when using only data with days with risk of thunder \((K < \ -4)\) and all the projected data can be seen for the KO-index. Over the Atlantic Ocean thunder is projected to decrease, which is connected to a larger value in the KO-index in Figure 12, which is not as clear in Figure 11. A lower value over the Alps and the Mediterranean Sea are also clearer in Figure 12 which also indicates more days with risk of thunder in the future projections.

In connection with strong convection and thunderstorms, precipitation regularly occurs. Therefore, together with the HH-index, total precipitation and temperature were analysed. Figure 13 shows the number of days with risk of thunder for the HH-index, the HH-index value, the 2m-temperature and the total precipitation for days with risk of thunderstorms for the historical period, RCP4.5 and RCP8.5 at the end of the century. Figure 14 shows the same as the previous figure but instead uses all the data.

Analysing the historical simulations shows similarities between the patterns of the HH-index and that of precipitation, especially for the mountain regions. In Figure 13, the largest amount of precipitation for days with risk of thunder is generally found where the HH-index value is the largest. When studying Sweden (appendix D), the largest amount of precipitation is seen in the Swedish highlands, where also the HH-index has the most days with risk of thunderstorms. When analysing all days, Figure 14, the precipitation maximum is instead found along the west coasts and mountainous areas in the British Isles and Scandinavia and in the western parts of the Iberian Peninsula which is not in agreement with the potential for thunder. The difference between precipitation and risk of thunder in these areas might be due to the type of weather phenomena.
Figure 11. Average annual a) number of days with risk of thunder during period 1971-2000 with KO-index, b) the KO-index value for days with risk of thunder, c) $\theta_{ae}$ at 500 hPa, d) $\theta_{ae}$ at 700 hPa e) $\theta_{ae}$ at 850 hPa f) $\theta_{ae}$ at 2m. g-l) maps the difference between 2071-2100 and 1971-2000 for RCP 4.5 scenario and m-r) for the RCP 8.5 scenario. Blue indicate less risk of potential of convection while red an increase in thunderstorm potential.
Figure 12. Similar figure as in Figure 11, but instead all data is used for the investigated period.
When analysing the projected future climate, the largest increase in precipitation and HH-index value is seen in the Alps. In areas around the Mediterranean Sea, days with risk of thunder is projected to increase, while the precipitation is projected to decrease for most parts. The reason for the differences might be the uncertainty for the HH-index around the Mediterranean Sea, which originates from the KO-index. The HH-index increases in the same areas as for the 2m-temperature, which should be somewhat consistent since the stability indices are based on the temperature.

Comparing Figures 13 and 14 reveals that the changes in precipitation on days with risk of thunder are less significantly different between northern and southern Europe compared to the overall changes. An implication is that even if precipitation is expected to decrease on average, heavy precipitation associated with thunderstorms may become more intense in the future both in the south and north of Europe.

Figure 13. Average annual a) number of days with risk of thunder for HH-index for period 1971-2000, b) HH-index value c) temperature (°C), and d) total precipitation (mm) computed for days with risk of thunder. Difference between 2071-2100 and 1971-2000 for e-h) RCP 4.5 scenario and i-l) RCP 8.5 scenario.
5 Discussion

5.1 Increase in Days with Risk of Thunder

Potential for thunderstorms is projected to become more common in a future warmer climate, concluded from the three stability indices used in this study. A higher temperature, seen in Figure 13 and Figure 14, will increase the available water vapour in the atmosphere (Trapp et al., 2007). This is the reason thunderstorm potential is projected to become more common in most of Europe, noted from Figure 9. Even if the increase in moisture makes thunderstorms more likely, other components affecting deep convection could make thunderstorms less likely (Brooks et al., 2007). This can be seen when analysing the vertical temperature lapse rate and the content of moisture at high altitudes in the atmosphere for the K-index. Even if the two factors show convective inhibition, the low level moisture seems to be the key factor for increasing the potential of convection, and therefore, the risk of thunder is projected to increase in the future warmer climate, in agreement with Trapp et al. (2007), Del Genio et al. (2007) and Van Klooster & Roebber (2009).

Analysing the K-index value for a projected future climate shows that the increase is about 1-2°C at the end of the century. Despite this seemingly relatively small increase the frequency of days passing the threshold may increase considerably in some regions thereby leading to a strong increase in the potential of thunderstorms.
The number of days with risk of thunderstorms are projected to increase the most over mountain areas. If the climate gets warmer, snow and ice will melt earlier in the spring and therefore the albedo will change. When the albedo changes, the amount of solar radiation absorbed by the ground will increase, making the ground even warmer. The changes in temperature might therefore affect the vertical temperature lapse rate due to the warmer ground compared to the atmosphere above, seen in Figure 9 over the Alps.

The problem is not only how often thunderstorms occur, but also their magnitude (Doswell et al., 1996). This is especially true for thunderstorms that through lightning, hail, flash floods and tornadoes damage material for large expenses every year. Studies, e.g. Del Genio et al. (2007) and Trapp et al. (2007), concluded that CAPE will increase at the end of the 21st century and most likely make thunderstorms become more common. However, the deep wind shear is projected to decrease which is believed to make the severe phenomenon become more unusual (Brooks, 2013). Xie et al. (2010) investigated hail and found that a higher CAPE means higher potential for larger hails to form. However, in a warmer climate, the freezing point will become more elevated, and therefore the hails will fall from higher altitudes with longer distances at melting temperatures, leading to less hail events. If this is the case, the risk of hail would be lower, but when hail does strike, they could be larger and cause more damage. In this study, the values of the stability indices increase to the end of 21st century, which might give rise to more severe thunderstorms according to George (1960).

Together with lightning and convection, heavy rain showers often occur. In Figure 13 one can see that the areas where the highest potential for thunderstorms are found are also the areas where most of the precipitation falls. This indicate that there is a correlation between the precipitation and the stability indices. In a future climate, the precipitation is projected to increase over the Alps and in the Swedish mountain areas, where also the largest increase in the number of days with risk of thunderstorms is seen. It is also clear that the precipitation increases for most of the domain on day with risk of thunder.

5.2 Consequences of Increase in Risk of Thunderstorm Activity

Changes in convective precipitation, hail and thunder might have a significant impact on society. More thunderstorms might result in more extensive damage. Figure 13 shows an increase in precipitation when there is risk for thunder in most of Europe. However, Figure 14 shows that the precipitation is projected to decrease in the south of Europe when all days are analysed, which is in agreement with Nikulin et al. (2011). If thunder and lightning become more common, dry areas might easier catch fire if lightning strikes, as a result the climate might change even more (Del Genio et al., 2007) due to change in the albedo.

Nikulin et al. (2011) also mention an increase in the extreme precipitation for a future climate, giving a larger risk for flash floods, which also might have a connection with hail. As mentioned in Chapter 5.1, even if hails seem to become less common, larger hails might fall. Flash floods and hail can damage crops as well as property. Rossati (2017) mentions the connection between climate change and human health, and concluded that extreme events and floods increase the risk of infection as well as having a negative impact on our mental health.
5.3 Analysis of the Stability Indices

One should have in mind that even though the regional climate model used in this study simulates day-to-day weather events it is not a representation of the real state of the climate system on any day or year, making it harder to evaluate against lightning observations, both in time and space. Another problem is that the stability indices are local and the threshold may vary in different places. In this study the threshold for the stability indices were optimised through skill scores calculated taking lightning observations covering all of Sweden into account (chapter 3.3.2). Therefore, the threshold used for the stability indices differ from earlier studies, e.g. Sohlberg (2007) and Andersson et al. (1989).

It was found that the stability indices have problems indicating thunderstorms correctly in different geographical areas when compared with lightning observations. The K-index overestimates the potential of thunder in the mountain areas in Sweden, while the KO-index estimates a very large and unrealistic amount of days with risk of thunder over the Mediterranean Sea. The reason the K-index estimate high number of days with risk of thunder in the mountain areas can be explained through the large temperature lapse rate ($T_{850} - T_{500}$). Over mountains, the pressure at 850 hPa is relatively close to the ground level temperature, which might make the temperature at 850 hPa similar to the surface temperature, and therefore one gets a larger lapse rate. This indicates that the K-index is not ideal for mountainous regions and that it should be used with caution there. However, in all the three indices, a large number of days with risk of thunder can be seen in the mountain areas around Europe, Figure 5, which is to some extent consistent with a large flash density in the mountain areas as seen from lightning observation, investigated by Anderson & Klugmann (2014).

The KO-index shows a very large amount of days with risk of thunder over the Mediterranean Sea. This result is not in line with observations and does not follow simple physical principles, where the warm air above the cool water in the summer will suppress the instability, which in turn would give fewer days with thunderstorms over the sea and coast (Anderson & Klugmann, 2014). The pseudo-adiabatic equivalent potential temperature at ground level was found to show very high temperatures over the Mediterranean Sea. Whether this might be due to the use of the ground temperature in the calculations, instead of the actual 1000 hPa level temperature, remains to be analysed and could be the subject of another investigation.

The uncertainties regarding the stability indices for estimating risk of thunder can be addressed by using more stability indices and doing a larger study on which index is the best fit for different parts of Sweden and Europe. An improved stability index might include other important factors for deep convection such as wind shear. It is also believed that a thunder cloud has to have top temperatures below a certain temperature for lightning to occur, if that temperature was included in the calculation the indices might give a better result when comparing with observations. The specialised stability indices often do not use ground temperature in the calculations. However, the stability indices should in reality be used together with a sounding to analyse if there really is potential for thunderstorm or if an inversion is found closer to the ground. To get a better understanding of the whole atmosphere, integrated indices could compliment the specialised ones.

The factors investigated only include the moisture and the stability of the atmosphere, more factors such as wind shear and a lifting force are not investigated in this study. Wind shear is important for the severity of the thunderstorm, and if the wind shear changes, the thunderstorms might behave differently.
5.4 Uncertainties in Climate data and lightning observation

The climate system is global, and in order to make a projection of a future climate both observations and theory are needed in climate research. The lack of climate data for thunderstorms makes it difficult to evaluate thunderstorms in climate models, as well as making analysis of changes in thunderstorm patterns in the future.

Uncertainties in the stability indices used in this study can also be due to systematic errors in the climate models regarding the temperature and specific humidity. Errors of several degrees have been found over high topography (IPCC et al., 2013). Nikulin et al. (2011) also found deviations when comparing simulations of the precipitation for RCA3 and observations, which they concluded to be due to topographical and meteorological conditions, and differences in the grids and observations. Similar problems might be the case in this study as well.

Deviations between the observations and the ERA-interim simulation were found for the different stability indices. When comparing ERA-interim with an ensemble mean of the 8 regional downscaled global climate models, the outcome shows very similar result, found in appendix B. The similarity of the ERA-interim and the ensemble mean strengthens confidence in using output from the RCM driven by different GCMs. ERA-interim might also give uncertainties regarding the nesting with the regional climate model. The boundary condition can be far away from the investigated area and therefore the RCM may produce results differing from the large-scale forcing in its interior domain.

The Lightning observations are also very coarse and have their uncertainties. During the investigated period, changes in the system were made, such as upgrades of sensors and system configuration, which might give uncertainties regarding days of thunder. It has been found that two different systems used at the same time period did not give the same observations. This was bypassed in this case by using a threshold at a minimum of 10 strikes per day.
6 Conclusion

The risk of thunderstorms in Europe is projected to become more common in a future climate with rising temperatures. The increase in days with risk of thunderstorms is seen in most of Europe, with a larger increase in the mountain areas. The results also indicate that the season with risk of thunderstorms gets longer. This implies a higher risk of thunderstorms from May through September in Sweden.

The main reason for the projected increase in the risk of thunder activity is because the atmosphere will hold more water vapour in a warmer climate, which applies particularly to the lower atmosphere. The available moisture in the atmosphere is one of the main components for the potential of convection. Other factors, such as a projected decrease in the vertical temperature gradient and drier conditions in the upper atmosphere act to inhibit the potential for convection. Even if the potential for thunderstorms is projected to increase because of rising temperatures and more moisture in the atmosphere, more information about deep convection is needed to make a more certain conclusion, especially regarding the intensity of thunder. Wind shear is one example that might change and that has large effects on the severity of thunderstorms.

The stability indices have their flaws as indicators for potential for thunder. The indices show deviations from the lightning observation in Sweden, especially regarding overestimation in the mountain areas and an underestimation on the west coast. Further studies would need to include more indices to see which one works best for Europe and Sweden at different areas such as mountain areas, sea and over land mass. Further studies may also include convective precipitation in addition to thunder potential and make a larger study investigating daily and monthly changes.
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References


Appendix A  Optimising the Threshold for the Stability Indices

The optimised thresholds for the three stability indices, the K-, KO- and HH-index were found through a dichotomous scheme compared with observations at every grid point of 50x50 km resolution for the period 2003 to 2011, where it either was a day with thunder or not. In figure 15(a) the K-index is compared with the observation showing the numbers of (A) hits, (B) surprises, (C) false alarm and (D) correct null, for a set of different threshold values, evaluating all data points over Sweden. One can see a large amount of null correct during the whole period, the hits (A) decreases with rising threshold, surprises (B) increases with rising threshold while false alarms (C) decreases.

Figure 15(b) show the five different verification scores for different thresholds. The figure shows that FAR is high, indicating poor performance for almost all thresholds values. To go from this figure to decide a threshold that can be used for this study, it seems reasonable to take a value that is close to the max value of Heidke and CSI due to the large amount of null correct. Therefore, the best threshold is taken to be K>28. Figure 16 and figure 17 show similar graphs but for the KO- and HH-index, respectively, where KO<-4 and HH>620.

![Graphs](image)

**Figure 15.** Validation of K-index through a) Contingency values of 30 different threshold compared with observation and b) Skill score for the different threshold
Figure 16. Validation of KO-index through a) Contingency values of 30 different threshold compared with observation and b) Skill score for the different threshold

Figure 17. Validation of HH-index through a) Contingency values of 30 different threshold compared with observation and b) Skill score for the different threshold
Figure 18. Average of total days of thunder per month during period 2003-2011, for months between April and October for a-g) observation, h-n) difference between K-index and observation, o-u) difference between KO-index and observation, and v-ö) difference between HH-index and observation for ERA-interim driven run.
Appendix B  Validation of the Model Mean

**Figure 19.** Annual average days with risk of thunder for the K-index driven by RCA4 for a) ERA-interim period 1979-2011, b) mean of 8 downscaled GCMs during period 1971-2000, and c)-j) show each model 1-8 described in Table 2

**Figure 20.** Annual average days with risk of thunder for the KO-index driven by RCA4 for a) ERA-interim period 1979-2011, b) mean of 8 downscaled GCMs during period 1971-2000, and c)-j) show each model 1-8 described in Table 2
Figure 21. Annual average days with risk of thunder for the HH-index driven by RCA4 for a) ERA-interim period 1979-2011, b) mean of 8 downscaled GCMs during period 1971-2000, and c)-j) show each model 1-8 described in Table 2
Appendix C  Monthly Changes in Thunderstorms in a Future Climate

**Figure 22.** Boxplot over the average monthly days with risk of thunder for the K-index, where blue correspond to 1971-2000, red to 2011-2040, green to 2041-2070 and black to 2071-2100 for a) RCP 4.5 and b) RCP 8.5. The numbers represent the average value over Sweden for an ensemble based on the 8 RCM simulations.

**Figure 23.** Same as in fig. 22 for the HH-index.
Appendix D  Cause for Change in Thunderstorm Activity in Sweden

Figure 24. Similar as in fig. 9 for Sweden.

Figure 25. Similar as in fig. 10 for Sweden.
Figure 26. Similar as in fig. 11 for Sweden.

Figure 27. Similar as in fig. 12 for Sweden.
Figure 28. Similar as in fig. 13 for Sweden.

Figure 29. Similar as in fig. 14 for Sweden.