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# Comparison of Data from a Lightning Location System and Atmospheric Parameters from a Numerical Weather Prediction Model

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**Abstract:** This study presents a comparison between the occurrence of thunderstorms in Iceland as identified by lightning location systems and the properties of the atmosphere as analysed and predicted by a short range numerical meteorological forecast model. The purpose of the comparison is to identify thunderstorm prediction indices, suitable for Iceland. The numerical meteorological forecast model of Météo-France, Arpège, was used for this study. On the basis of output from the Arpège, the key atmospheric variables were defined in a grid. The lightning locations of the ATD sferics system of the UK Met Office and the LLP-based lightning location system of the Icelandic Meteorological Office, were used for this study. Several thunderstorm indices based on the temperature and humidity profile of the atmospheric column of each element of the forecast model were calculated. The indices that best predicted occurrences of lightnings were then used in a statistical similarity model that estimates thunderstorm probabilities. These were adjusted for annual variations and diurnal variations in the summer. The results enable the construction of probabilistic local thunderstorm forecasts for Iceland, based on output from an operational numerical weather prediction model.

**Keywords:** Thunderstorm prediction, Numerical weather prediction model, Thunderstorm index, ATD sferics, Iceland

## 1. Introduction

The ability to accurately predict thunderstorms a few days in advance is enormously important. This ability can both save lives and in some instances also prevent damage to property.

In the 1940's and 50's some fairly simple atmospheric stability indices were developed. They were designed to estimate chances of thunderstorms from a single radiosonde profile. One of the oldest indices, still in use, is the Showalter stability index, published in 1953 [1].

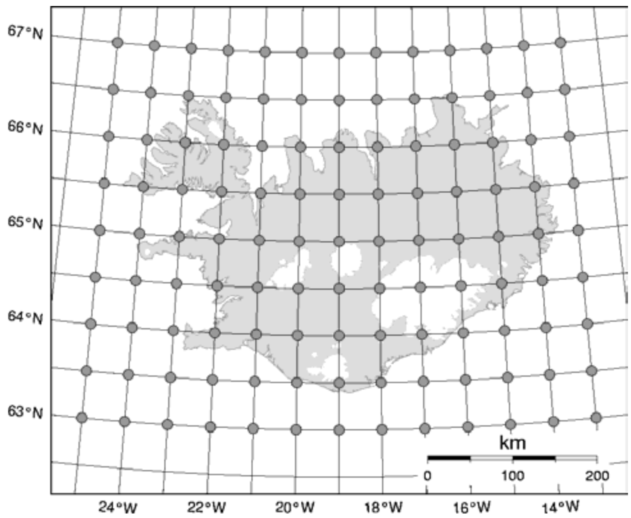


**Figure 1: The grid-points of the Arpège weather prediction model over Iceland.**

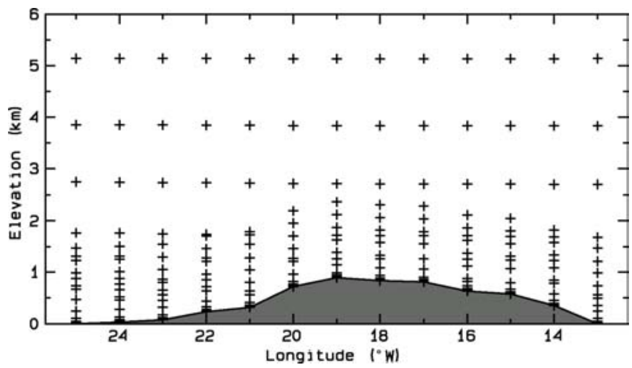


**Figure 2: A sample vertical cross section at 65°N showing typical distribution of the Arpège grid-points. The three pressure levels at the highest elevation are the 500, 600 and 700 hPa isobars.**

Many of the indices were developed in the pre- or early-computer era. Now, forecasters have access to powerful computers and numerical weather prediction models. Significant advances are being made in incorporating atmospheric convection into the numerical models. However, one of the fundamental problems is that the horizontal grid size of the weather prediction models is almost an order of magnitude larger than the convection cells.

In this study we have compared several atmospheric stability indices to lightning location data in a statistical way to predict thunderstorms. Our hope is to be able to predict thunderstorms beyond what currently operational numerical weather prediction models can. One of the advances of using this statistical point of view is that several underlying, known as well as unknown, processes, properties and local phenomena will be taken into account.

In this article we outline a prototype of a statistical similarity model that seems to accurately predict thunderstorms in Iceland. Next steps will include assessing the accuracy of the predictions and making the model operational.

## 2. Weather prediction model

One of the operational models used at the Icelandic Meteorological Office is the output of a numerical weather prediction model, Arpège, made by Météo-France [2]. The parameters given by the Arpège output at each grid point are elevation of an air parcel above sea level, air pressure, air temperature, relative humidity, wind speed and wind direction. Output from the Arpège is received twice daily with analysis for 00:00 and 12:00 UTC. The forecast range is 0, 6, 12, 18, 24, 30, 36, 42, 48, and 54 hours.

For this study, the analysis output of Arpège was used to determine the state of the atmosphere at 00:00 and 12:00 UTC. The 6 hour forecasts at 00:00 and 12:00 were used to determine the state of the atmosphere at 06:00 and 18:00 UTC.

The horizontal spacing of the grid on which the Arpège is projected spans 1° of longitude and 0.5° of latitude. The domain of the study extends from 63°N to 67°N and 13°W to 25°W, see Figure 1. Each of these 117 horizontal elements of the study area is therefore about 47 × 55 km. For each areal element, the Arpège model output predicts the state of the atmosphere in 11-19 vertical layers below the 500 hPa pressure level, which is about 5 km above sea level. A sample cross section showing the vertical distribution of the Arpège grid is shown in Figure 2.

Models output at 00, 06, 12, and 18 UTC for the four years 2000-2003 are represented by 5844 time points. Two of the outputs were damaged and not used for this study. For every time point we have 117 areal elements, above which the properties of the atmospheric column are defined. Therefore, by using the Arpège model output we have an estimate of the properties of 683514 atmospheric columns above an areal element.

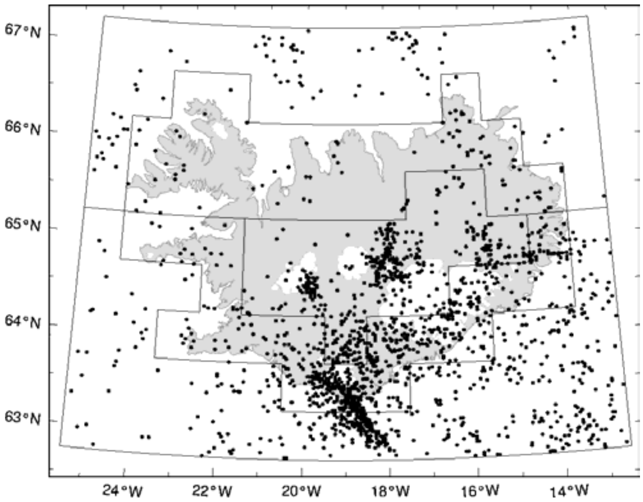


**Figure 3: The study area was split into five distinct geographical regions, shown on this map along with the located lightnings 2000-2003.**

## 3. Lightning location data

For this study we have used lightning locations for the four years 2000-2003 from the Icelandic lightning location system [3, 4, 5] and data from the ATD sferics system of the UK Met Office [6]. The lightning data were used to determine times and places of thunderstorms.

For comparison purposes the lightning location data were gridded in space and time in the same way as the Arpège model output, i.e. the same 117 areal elements and 6 hour time intervals. Thunderstorms occurring between 03:00 and 09:00 were set at time 06:00 UTC.

Figure 3 shows all the located lightnings during these four years 2000-2003. Volcanogenic lightnings [7] from the Hekla 2000 eruption were omitted.

## 4. Temporal and spatial variation

There is considerable temporal variation in the occurrence of thunderstorms in Iceland, both as an annual variation and diurnal variation during the summer. Figure 4 shows the annual variation in thunder reports from manned observations during the fifty year period 1951-2000. The figure shows the number of reported thunder days for each day of the year. Note that the graph shows a higher number than thunder days, since for example five manned stations reporting the same thunderstorm will count as five reports.

During these fifty years there has been considerable change in the number of manned stations. However, those changes should not affect the shape of the graph since there is not a seasonal variation in the number of stations.

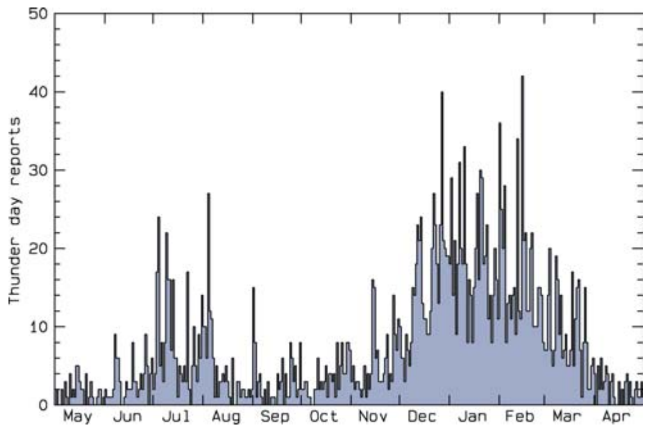


**Figure 4: The number of thunder day reports for each day of the year, as determined by manned observations 1951-2000.**

Clearly, Figure 4 shows the two distinct thunder seasons in Iceland. First, there is a thunder season during the summer, centered in July. Second, the main thunder season in Iceland is during the winter, from November to March. There is considerably lower activity during spring and fall.

Furthermore, previous studies have shown that there is significant difference between these two thunder seasons, both in spatial distribution, thunderstorm duration and in the lightning polarities and observed peak current [3, 4, 5].

During summer there is a strong diurnal variation in the occurrence of thunderstorms. Figure 5 shows the number of lightnings in the study area versus time of day. For this figure the data were split into the winter half (October-March) and summer half (April-September). One thunderstorm with over 200 lightnings on 2002-06-08 was omitted for this figure. During the summer there is a significant increase in lightning activity in the afternoon. In Figure 5, time of day represents UTC time, and local noon in Iceland is at 13:00 – 13:30 UTC.

Due to the temporal variations we split the data into 9 temporal groups for our calculations as shown in Table 1.

**Table 1. Summary of temporal groups**

| *No* | *Months* | *Time of day* |
|---|---|---|
| 1 | November through March | 00, 06, 12, 18 |
| 2 | April and May | 00, 06 |
| 3 | April and May | 12, 18 |
| 4 | June, July and August | 00 |
| 5 | June, July and August | 06 |
| 6 | June, July and August | 12 |
| 7 | June, July and August | 18 |
| 8 | September and October | 00, 06 |
| 9 | September and October | 12, 18 |

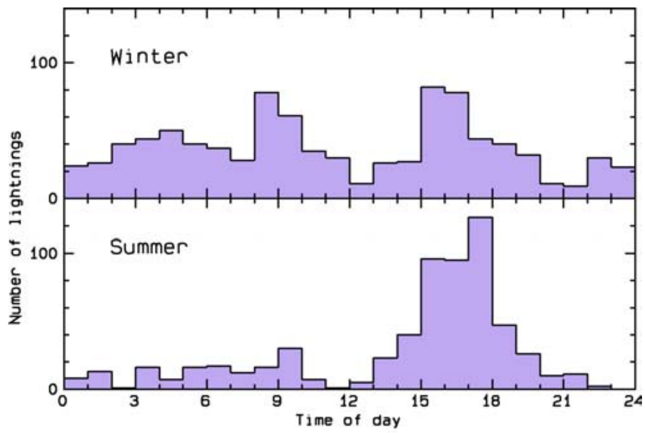


**Figure 5: The diurnal variation in the occurrence of lightnings in the study area for 2000-2003. The top panel shows the winter half of the year, while the lower panel shows the diurnal variation during the summer half of the year.**

Previous studies have shown significant spatial variation in thunderstorm occurrence. The frequency appears highest over the ocean south of Iceland and at the Southern coast. We split the data into five geographical regions based on thunderstorm distributions [5, 8]. These are: 1–Southern ocean; 2–Southern coast; 3–Central highlands; 4–Northern coast; 5–Northern ocean. The boundaries between the five geographical regions are shown in Figure 3.

## 5. Thunderstorm indices

A variety of thermodynamic and kinematic parameters have been used to indicate potential instability of the atmosphere [9].

As an example of a very simple index, the Vertical Totals Index is defined as the temperature difference between the air at 850 hPa and 500 hPa pressure levels. Some indices take into account the moisture content of the air. Some measure the temperature difference of the ambient air and the final temperature of an air parcel lifted pseudo-adiabatically from some lower level. Most of the indices only compare properties at a few distinct pressure levels.

The Convective Available Potential Energy (CAPE) index utilizes all of the temperature and moisture profile, by integrating the energy released during an ascent of an air parcel up through the atmosphere. Conventionally, CAPE is only calculated when energy is released. We have also calculated negative terms of CAPE, i.e. the total energy released or required to lift an air parcel from the surface to the 500 hPa level.

In Table 2 we have summarized the indices that we have considered for the current study. In the table the subscripts 500, 700, 850 and 1000 indicate pressure levels in hPa. Subscript s indicates conditions at the surface and subscript 0.5 indicates average state in the lowest 0.5 km of the atmosphere. The symbol $T$ stands for temperature, $Td$ for dew point, $p$ for pressure, $u$ and $v$ are wind speeds, $Z$ and $z$ indicate elevation, $g$ is the acceleration of gravity and $\rho_v$ is the density of water vapor in air. $T^*_{a \rightarrow b}$ is the terminal temperature of a moist air parcel that is lifted pseudo-adiabatically from level a to level b. $\theta w$ and $\theta s$ are the wet bulb potential temperature and the saturated potential temperature, respectively.

**Table 2. Summary of indices considered for this study**

| *No* | *Index* | *Definition* |
|---|---|---|
| 1 | Air temperature at surface | $T_s$ |
| 2 | Air temperature at 700 hPa | $T_{700}$ |
| 3 | Air pressure at sea level | $p$ |
| 4 | Westerly winds at 700 hPa | $u_{700}$ |
| 5 | Southerly wind at 700 hPa | $v_{700}$ |
| 6 | Elevation of the 500 hPa level | $Z_{500}$ |
| 7 | Adedokun 1 Index | $\theta w_{850} - \theta s_{500}$ |
| 8 | Adedokun 2 Index | $\theta w_s - \theta s_{500}$ |
| 9 | Boyden Index | $0.1(Z_{700} - Z_{1000}) - T_{700} - 200$ |
| 10 | Bradbury Index | $\theta w_{500} - \theta w_{850}$ |
| 11 | Negative Convective Available Potential Energy (all terms) | $g \int (T^*_{0.5 \rightarrow z} - T)/T\, dz$ |
| 12 | CAPE (only positive terms) | $g \int (T^*_{0.5 \rightarrow z} - T)/T\, dz$ |
| 13 | Cross Totals Index (CT) | $Td_{850} - T_{500}$ |
| 14 | Deep Convective Index | $T_{850} + Td_{850} - \mathrm{LI}_s$ |
| 15 | Jefferson Index | $1.6\theta w_{850} - T_{500} - (T_{700} - Td_{700})/2 - 8$ |
| 16 | K Index (KI) | $T_{850} - T_{500} + Td_{850} - T_{700} + Td_{700}$ |
| 17 | Lifted Index (from surface) ($\mathrm{LI}_s$) | $T_{500} - T^*_{s \rightarrow 500}$ |
| 18 | Lifted Index (0.5km) ($\mathrm{LI}_{0.5}$) | $T_{500} - T^*_{0.5 \rightarrow 500}$ |
| 19 | Showalter Stability Index | $T_{500} - T^*_{850 \rightarrow 500}$ |
| 20 | S Index | $\mathrm{TT} - (T_{700} - Td_{700}) - A$ |
| 21 | Thompson Index | $\mathrm{KI} - \mathrm{LI}_{0.5}$ |
| 22 | Total Totals Index (TT) | CT + VT |
| 23 | Vertical Totals Index (VT) | $T_{850} - T_{500}$ |
| 24 | Integrated Water Content | $\int \rho_v\, dz$ |

## 6. Statistical similarity analysis

In order to estimate thunderstorm probabilities for a given place in space and time, we chose to compare the state of the atmospheric column to previous states at similar times and places. Once we have identified an adequate number of previous occurrences that are similar, we calculate the frequency of thunderstorms in our data set.

In order to assess similarity of two states of the atmosphere we calculate the distance between the 24-dimensional thunderstorm index vectors in 24-dimensional space. If two states are identified by the subscripts $n$ an $m$, then we measure the distance of the $i$-th stability index by

$$d_{i\,n\,m} = w_i\,(x_{i\,n} - x_{i\,m}) / \sigma_i \qquad [1]$$

where $x_{i\,n}$ and $x_{i\,m}$ are the value of the $i$-th stability index for state $n$ and $m$, respectively, $\sigma_i$ is the standard deviation of index $x_i$, and $w_i$ is an empirically chosen weight for the $i$-th index.

The distance between two states, $n$ and $m$, in the 24-dimensional space is $D_{n\,m}$

$$D_{n\,m}^{\;2} = d_{1\,n\,m}^{\;2} + d_{2\,n\,m}^{\;2} + d_{3\,n\,m}^{\;2} + \ldots + d_{24\,n\,m}^{\;2} \qquad [2]$$

For a given situation, $n$, we calculate $D_{n\,m}$ for all previous situations, $m$, for the time group and region of $n$. The lowest distances in the 24-dimensional space $D_{n\,m}$ represent similar situations. Then we select a sufficient number, $N$, of similar situations and estimate the frequency of thunderstorms in our selection. We have estimated the thunderstorm frequency as the highest frequency for $N$ in the range 200-300.

Our current choice of weights for the 24 indices in Table 2 for the similarity calculations are $w$ = [0.1 0.1 0.2 0.1 0.2 0.1 0.7 0.7 0.2 0.2 1.0 0.5 0.5 0.1 1.0 0.5 0.5 1.0 1.0 0.5 0.1 0.5 0.2 0.1]. The highest weights are assigned to Negative CAPE, Jefferson index, $\mathrm{LI}_{0.5}$, and Showalter index. The standard deviations of the 24 indices in Table 2 were estimated from the whole data set and are $\sigma$ = [5.4 6.1 13.8 8.5 8.5 178 2.9 3.7 2.1 2.9 0.65 48.0 6.8 11.1 7.4 14.1 6.1 5.7 4.8 16.9 11.8 10.1 4.2 5.3].

As an example of the results of our calculations we show, in Figure 6, a contour plot of the predicted thunderstorm probabilities on 20 February 2003 at 06:00 UTC. The similarity calculations indicate increased chances of thunderstorms on the SE-coast. The highest probability in a single element in this case is 2.5%.

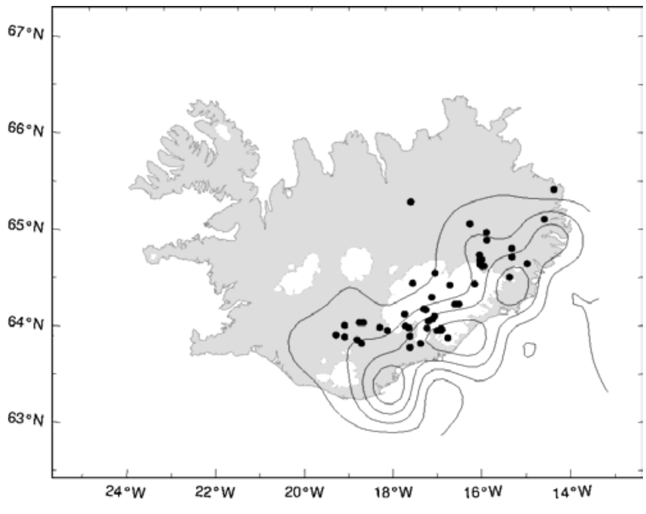


**Figure 6: Estimated thunderstorm probability on 2003-02-20 at 06:00 UTC. Contour interval is 0.5%. The dots show located lightnings at the same time.**

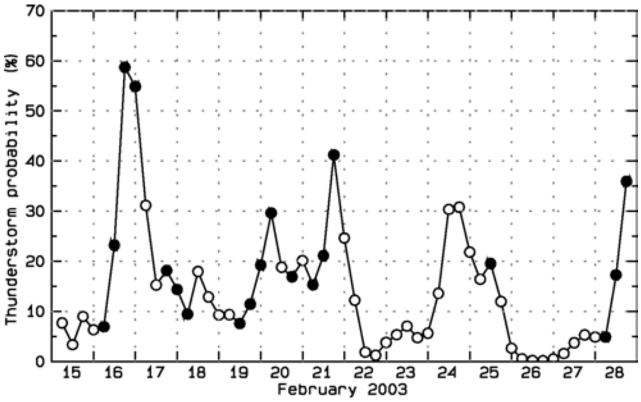


**Figure 7: Estimated thunderstorm probability for 6 hour time steps for the latter half of February 2003. Filled dots indicate times with located lightnings in the study area.**

Combining all the 117 elements in Figure 6, we can calculate the thunderstorm probabilities for the whole domain for the 6 hours

$$P = 1 - \prod (1 - p_j) \qquad [3]$$

In the case shown in Figure 6 the probability of a thunderstorm anywhere in Iceland is estimated 30%.

Figure 7 shows this total probability, $P$, as a function of time for a half month in February 2003, when winter-thunderstorms were quite frequent. The filled circles indicate that the lightning location systems measured some lightnings during the time period, and open circles where no lightnings were registered. Most of the high peaks are associated with observed thunderstorms, although on 24 February no lightnings were registered even though chances seem to be high.

## 7. Further developments

The current model is a prototype for feasibility study of the method. A systematic survey of false alarms and surprise events needs to be undertaken. Furthermore, the accuracy needs to be better quantified and any shortcomings of the method identified.

The empirical weights used in calculating similarity in the 24-dimensional space need to be further tuned. It is believed that by doing so we may significantly advance our predictions.

There are plans to make the model operational and the thunderstorm forecasts available on our web page. As time passes we will systematically add more lightning and atmospheric data into the statistical base, which will make the predictions more reliable.

This model has been developed for Iceland. The methods described can easily be applied to other places.

## 8. Acknowledgements

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