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Radar Indices for Thunderstorms in Southern Sweden

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Abstract

A radar index for detecting summertime thunderstorms has been developed. Such a index is useful because the synoptic network is not dense enough and has a too low time resolution for the monitoring of thunderstorms in now-casting. Even if lightning location systems are available a radar index is useful since it may show the forecaster that there is a risk of discharges before they have actually occurred and hence give him/her some lead time. The aim of the index is not only to be a 'yes or no', but also to give an indication of the thunder activity, expressed as the frequency of ground strokes given by a lightning location system or the frequency of thunder reports from synoptic stations. For this purpose, as well as for selecting the 'best' predictor, forward step-wise regression has been used. The index developed gives a probability of detecting thunder of about 90%. The regression analysis shows that the index 'explains' about 70% of the observed variance of 'thunder activity' during afternoon. The index is much less efficient during night, indicating that different lightning-producing processes may be operating in night and day-time thunderstorms.

1. *Introduction*

Several methods for identifying thunderstorms from radar echos have been proposed, see for instance *Donaldson* (1965). Some of these are subjective, dealing with the shape of the echos (horizontal and vertical) and hence directly observable on the radar screen, others are quantitative, as the reflectivity of the echos, their top height or the height where the maximum reflectivity is attained. Since the number of digital weather radars is increasing, a quantitative index may easily be computed. Hence, if a proper index can be found, it could be displayed to the forecaster in real time thus being an aid in the weather monitoring. There exist, however, no generally accepted radar criteria for thunder. Moreover, it is questionable if a criteria valid in all climates can be found. Since there is until now only one work available treating the conditions in Scandinavia (*King*, 1980) this work is justified.

Since most quantitative radar indices for thunder, as well as for 'severe weather'(hail, windstorms and tornadoes) contain a reflectivity threshold and/or a minimum echo top height it is reasonable to design a parameter containing such quantities. This work has been made in two steps.

1) studies of a few individual Cumulonimbus clusters using data from radar and lightning location systems to find possible radar thunder indices
2) applying them on a larger data set.

For (1) radar and lightning location system data from mainly three thunder days during the summer of 1985 were available. For (2) radar data were collected during May 27 to Aug 18 1987, but then no lightning location data were available to us. Due to problems with the automatic collection system, malfunction of the radar etc., radar data are available for only 55 days.

2. *Case studies using lightning location system data as ground truth*

3-dimensional radar and detailed lightning location system data were available for the larger part of three days (June 16 and 24, July 15) in the summer of 1985. Besides, only radar data were available for some thunder-free days with Cumulonimbus. An Ericsson C-band radar system described by *Andersson et al.* (1984) was used.

The following data types from the non-doppler mode were extracted. a) pseudo-CAPPIs of reflectivity for 500 m height every 15th minute. A 500 m pseudo-CAPPI is a horisontal mapping of the 500 m altitude as far out from the radar as possible due to the curvature of the earth (with the lowest antenna elevation used by us, 0.5^o, this is about 40 km) and further out following the lowest beam. The radius of the area covered by the radar was 240 km, the horisontal resolution 2x2 km^2 and the resolution in the equivalent radar reflectivity factor 0.4 dB.

b) Data volumes containing reflectivities for 12 CAPPI levels (0.5, 1.5, 2.5,...., 11.5 km) for the same area and with the same resolutions as in (a).
This data collection was made by manually recording of the data on tape.

The lightning location data were received from the Lightning Location and Protection (LLP) system (*Krider et al.*, 1980) in Sweden managed by the Institute of High Voltage Research, University of Uppsala. For our purpose the positions of Cloud to Ground discharges (CG) were collected for 15-minutes' intervals, centered around the times of the radar observations. The system accepts only discharges between cloud and ground, and identifies negative and positive ones.

In order to get a reasonable resolution in height, we confined our investigation to a north-south orientated area of 240x240 km^2 centered over the radar, see Fig. 1.

The radar data were condensed into height-reflectivity tables according to Fig. 4, giving the relative areas with reflectivity exceeding threshold values. Also the vertical integrated liquid water content (*Greene et al.*,1972) was computed.

$$M = 0.00334 \cdot Z^{4/7} \tag{1}$$

M = liquid water content, g/m^3
Z = radar reflectivity factor, $(mm)^6/m^3$

Summing from the lowest level to the highest and over whole the area gives the total vertical integrated liquid water content (*VIL*), which we have expressed in dB with respect to 1 ton.

Cumulonimbus clusters, which were possible to follow for some hours, were identified on the pseudo-CAPPIs and height-reflectivity tables were prepared for rectangular areas surrounding the clusters. A typical size of those areas was 2000 km^2. Fig. 2 gives an example of Cumulonimbus clusters and associated CG. This figure also illustrates one difficulty, namely that the CG positions do not always coincide with the echos. This is probably due to errors in the direction-finders of the lightning location system (*Pisler and Schütte,* 1985). The error in our area is expected to be within ±20 km. There is, however, no reason to believe that the CG occur outside the echo areas. Therefore a CG in an echo-free area but up to about 20 km from an echo has been ascribed to that echo. The number of CG of each cluster, that is within each cluster area, was then counted and will be called the CG frequency, which thus is the number of CG per 15 minutes. Some parameters from the height-reflectivity tables were then plotted against the CG frequency in order to find the most promising predictor. The top of the echo contour for a suitable reflectivity, for instance 20 dBz, was a fairly good predictor. Some care must however be exercised when using the echo top. This is due to the fact that there are side-lobes, which may depict a strong echo, see Fig. 3. For our radar the first side-lobe is about 2^o from the center of the main lobe and about 23 dB below it. This means that if we for instance have an echo of 45 dBz at a height of 4 km and a distance of 100 km, the first side lobe will depict this echo with a reflectivity of 45 - 23=22 dBz at an elevation of $4 + 100 \cdot \sin 2^o = 7.5$ km. This is an underestimate of the possible height error, since there are somewhat weaker side lobes outside the first one, which also may depict the echo. Therefore, if the echo tops are used as predictors, the tops for fairly high reflectivity thresholds should be chosen, so that the echos from the sidelobes fall below it. The echo top should however not be dismissed as a predictor since.

a) there is much evidence in the literature for it's use
b) our results prove it's value
c) even if side lobe give a too high echo top, which may be bad enough in several applications, it shows that there are high reflectivities, which is favourable for thunder.

As noted by *King* (1980) some combination of reflectivity and echo top heights may be expected to be a good thunder predictor. We formed a possible predictor (*RT*) as an area on the reflectivity-height table as

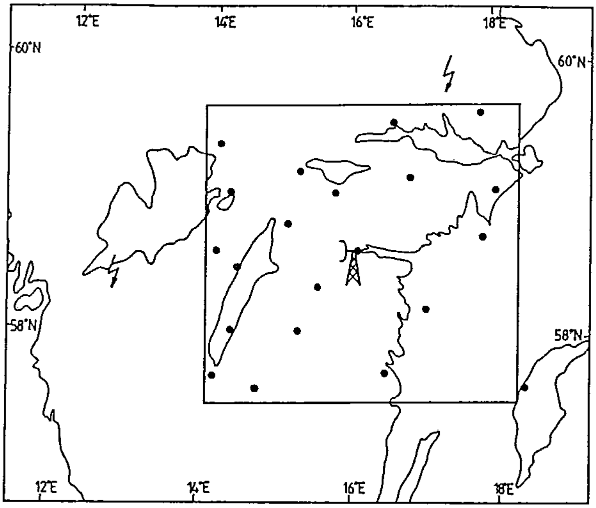


Fig. 1. The investigation area and positions of the radar, the lightning direction finders and the synoptic stations. A direction finder at Vitemölla (55° 42'N, 14°12'E) was situated south of the map.

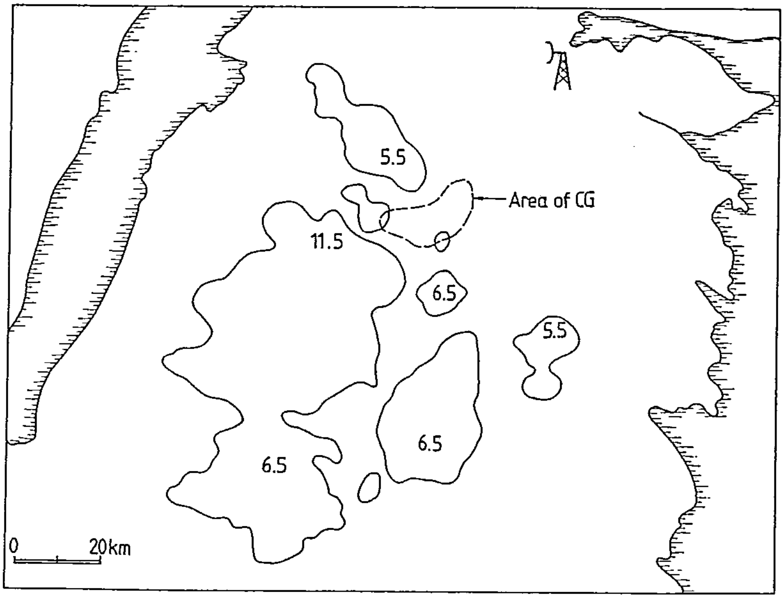


Fig. 2. Echo top map, June 24, 1985, 12:31 UTC. Echo contours are solid lines and tops above 4.5 km written. The area of cloud to ground discharges (12 from 12:23 to 12:38 UTC) is shown by a broken line.

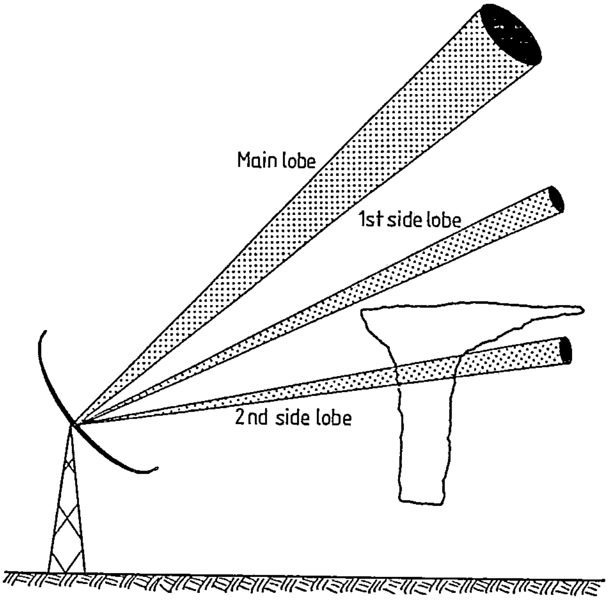
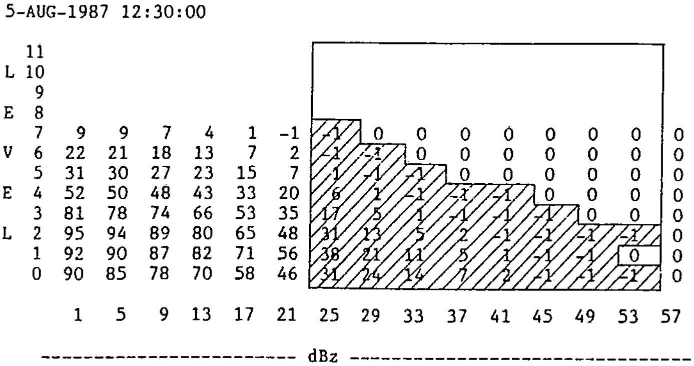


Fig. 3. Side-lobe depicting a strong echo and giving a false (too high) echo top.



5-AUG-1987 12:30:00

		1	5	9	13	17	21	25	29	33	37	41	45	49	53	57
	11															
L	10															
	9															
E	8															
	7	9	9	7	4	1	-1	-1	0	0	0	0	0	0	0	0
V	6	22	21	18	13	7	2	-1	-1	0	0	0	0	0	0	0
	5	31	30	27	23	15	7	1	-1	-1	0	0	0	0	0	0
E	4	52	50	48	43	33	20	6	1	-1	-1	-1	0	0	0	0
	3	81	78	74	66	53	35	17	5	1	-1	-1	-1	0	0	0
L	2	95	94	89	80	65	48	31	13	5	2	-1	-1	-1	-1	0
	1	92	90	87	82	71	56	38	21	11	5	1	-1	-1	0	0
	0	90	85	78	70	58	46	31	24	14	7	2	-1	-1	-1	0

------------------------ dBz ------------------------------

Fig. 4. Height-reflectivity diagram and definition of the index *RT*. The x-axis gives thresholds in dBz and the y-axis numbers of height levels (height in km - 0.5). The figures give the relative area, in parts per thousands, of echos exceeding the thresholds given on the x-axis, -1 denoting echos but relative area less than 1. The reflectivity classification for each level was only written if the total relative area at that level was at least 5. The area tabulated here is the total investigation area, a square with sides of 240 km, centered over the radar. *RT* = 100·(the hatched area/the rectangle's area)

$$RT = 100 \cdot \sum_{L=0}^{11} \sum_{dBz=25}^{57} A(L,Z)/[\text{nr of } L \text{ classes}) \cdot (\text{nr of dBz classes})] \quad (2)$$

where $A(L, Z) = 1$ if the relative area in $(L,Z) > 0$ and $A(L, Z) = 0$ if the relative area in $(L,Z) = 0$; see Fig. 4. In this Figure the number of L classes (CAPPI levels) is equal to 12 and the number of dBz classes is equal to 8 (class width = 4dBz). The area with echos, i e $A(L,Z) = 1$, is hatched, and the total area, i e the denominator of the index, delineated by heavy lines. The performance of this index is shown by Figs. 5 and 6. They indicate a correlation between the index and the frequency of CG and a threshold of the index below which CGs are not probable.

3. *Study using synoptic observations as ground truth*

During the summer of 1987 an automatic routine was used to collect 3-dimensional radar data in the form shown by Fig. 4. The radar generally made scans every 15th minute. Since no lightning location system data were available to us we used the ordinary 3-hourly synoptic stations to estimate the thunder frequency. Observations from about 20 synoptic stations within the investigation area were used. The number of available observations was not constant since some stations only make observations during part of the day. Since we wanted an index expressing the thunder frequency during each 3-hour period the code figures ww and W1 in the present SYNOP code (*WMO*,1984) were used. The thunder index (*TH*) then reads

$$TH = 100 \cdot (\text{number of thunder observations})/(\text{total number of observations}). \quad (3)$$

A 'thunder observation' was defined as.

- Thunder should have been observed during the last hour (ww=29, 91, 92, 93, 94 according to the present SYNOP code of WMO) or during the observation period (ww=17, 95, 96, 97, 98, 99)
- Thunder should have been observed during the last 3 hours preceding the observation (W1=9).

If both conditions are fulfilled the observation gives a contribution of 2 to the nominator of *TH*. Hence the maximum possible value of *TH* is equal to 200. Some ambiguity arises here because W1 describes the weather since the last main observation period (00, 06, 12, 18 UTC), not since the last one. Consequently, some old thunder observations may linger, for instance thunder observed at 13.30 UTC gives a contribution to *TH* for 18 UTC.

The following radar parameters (refer to Fig. 4) were chosen as possible predictors.

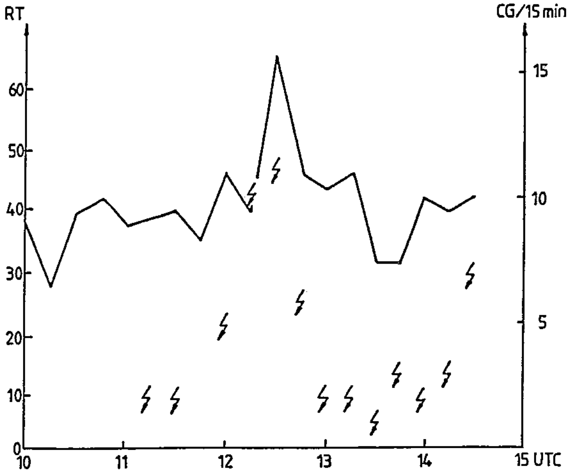


Fig. 5. Time development of the index RT (solid line) and frequency of cloud to ground discharges for the Cumulonimbus cluster in Fig 2. June 24, 1985, 10:00-14:30 UTC.

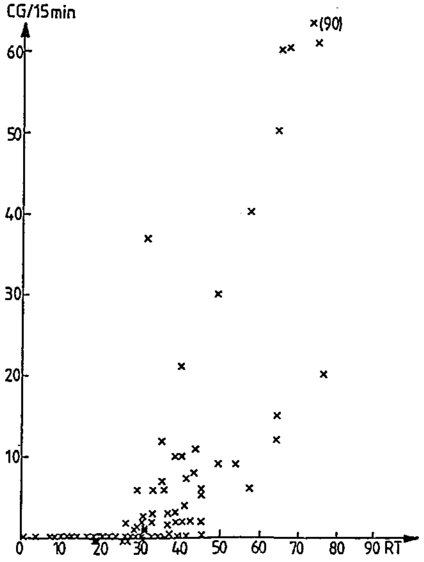


Fig. 6. Frequencies of CG/15 minutes versus *RT*. The 1985 data.

Table 1. Contingency table of diagnosed and observed occurrences

		Diagnosis	
		yes	no
O	yes	X_{11}	X_{12}
B			
S	no	X_{21}	X_{22}

Table 2. Verification scores for radar indices versus thunder ($TH > 0$). See text for explanation. Norrköping area, 27 May - 18 Aug, 1987.

Time	Index	Threshold	pd	pf	ps	yi	pei
00-24	A_{45}	1	91	76	23	38	64
00-24	Z_o	2.5	88	68	30	46	70
00-24	RT	28	86	48	47	62	78
09-18	RT	28	92	33	63	73	84

Table 3. Verification scores for *King*'s logical index versus thunder ($TH > 0$). Norrköping area, May 27 to Aug 17, 1987.

Time UTC	Threshold	pd	pf	ps	yi	pei
00-24	$h_o = 4.5$ and $Z_o = 25$	97	86	13	23	42
00-24	$h_o = 2.5$ and $Z_o = 45$	88	66	32	48	72
09-18	$h_o = 2.5$ and $Z_o = 45$	96	57	41	54	76

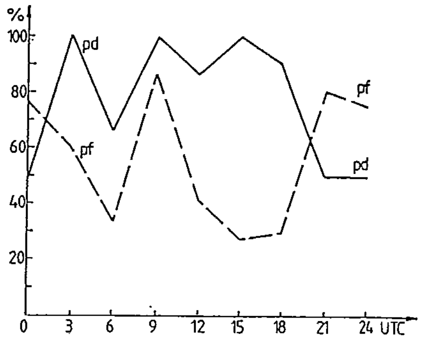


Fig. 7. Diurnal variation of the performance of *RT* as thunder indicator.

A_{25} = relative area with reflectivity above 25 dBz at level 1 (1.5 km)
A_{45} = ———— " ———— 45 dBz at level 1 (1.5 km)
H_{25} = top height for the reflectivity of 25 dBz
H_{45} = ———— " ———— 45 dBz
RT = the index described by Fig. 4.

The reason for not choosing level 0 (0.5 km height) is that due to the curvature of the earth it is not possible to map the conditions at 0.5 km out to the borders of our area.

For each 3-hour period (00-03, 03-06,...., 21-24 UTC) the maximum value of each parameter was extracted, and ascribed to the last time, i.e. the values between 00 and 03 UTC were assigned to 03 UTC.

It must be noted that these data do not apply to single cells or cell clusters, but to the whole investigation area. Usually however the extreme values of parameters as reflectivity and echo heights belong to one single cell.

Since the lowest CAPPI level used was 500 m and the radar furthermore has an algorithm for removing ground clutter, 'normal' ground echos do not interfere. Anomalous ground echos may however appear in the non-Doppler mode we used. As to the nocturnal ones there were few and they did not affect RT very much, since it takes account of the 3-dimensional echo distribution and in the ranges used the anomalous ground echos only appear at low levels. Anomalous ground echos after showers may have passed unnoticed, but are rare. Radar parameters, as the relative areas of high reflectivity may have been more seriously affected by anomalous ground echos.

3.1 *Analyses of occurrence and non-occurrence*

For these analyses we have used contingency tables according to Table 1.
The following quantities have been used:

$$pd = 100\cdot X_{11}/(X_{11} + X_{21}) = \text{'probability of detection'} \qquad (4)$$

$$pf = 100\cdot X_{11}/(X_{11} + X_{21}) = \text{'probability of false alarm'} \qquad (5)$$

$$ps = 100\cdot X_{11}/(X_{11} + X_{12} + X_{21}) = \text{'threat score'} \qquad (6)$$

$$yi = 100\cdot V \qquad (7)$$

$$V = (X_{11}\cdot X_{22} - X_{12}\cdot X_{21})/[(X_{11} + X_{12})\cdot(X_{21} + X_{22})\cdot (X_{11} + X_{21})\cdot(X_{12} + X_{22})]^{1/2} \qquad (8)$$

$$pei = 100\cdot[X_{11}/(X_{11} + X_{12}) + X_{22}/(X_{21} + X_{22})] - 100, \qquad (9)$$

where X_{11} = number of cases when the event is diagnosed and observed
X_{12} = ———————— " ———————— not diagnosed but observed
X_{21} = ———————— " ———————— diagnosed but not observed
X_{22} = ———————— " ———————— not diagnosed and not observed.

-Above V is the Yule's index (*Meteorological Office*, 1975) and *pei* the Peirce's index.

For perfect diagnoses $X_{12} = X_{21} = 0$, $pd = ps = yi = pei = 100$ and $pf = 0$, i.e. all occurrences of the event are detected and no false alarms are given. For totally wrong diagnoses $X_{11} = X_{22} = 0$, $pd = ps = 0$, $pf = 100$ and $pei = yi = -100$.

The indices *pd*, *pf* and *ps* only give measures of the efficiency of the method when the event occurs and/or is diagnosed, but pays no attention to correct diagnosed non-occurrences. The indices yi and pei also consider the latter, and are hence better measures if non-occurrenses are important. If 'occurrence' is denoted by 1 and 'non-occurrence' by 0 Yule's index is the correlation between diagnosed and observed events. For a thorough discussion of verification parameters the reader is referred to *Daan* (1984) or *Ivarsson* (1982).

Of the chosen radar parameters A_{45}, H_{25} and *RT* gave the best scores, with *RT* as the superiour one, Table 2. This is hardly surprising since *RT* is a measure of both the echos' reflectivity and vertical extent. The probability of detection is nearly 90% and the probability of false alarms about 50%. However some caution must be exercised when interpreting these figures, since we have used several observations for each day and the observations within a day can hardly be considered independent. As to the thresholds used, the one for *RT* (28) is suggested by the 1985 study. For the other parameters we choosed reasonable thresholds, not necessarily those giving the best scores on this small sample. The indices performed best during the afternoon, Table 2 and Fig. 7, and most of the false alarms as well as most of the not detected thunderstorms occurred during night. This indicates a dependence on the time of the day that is not explained by our indices

In a study of Florida thunderstorms *Lopez et al.* (1986) noted that no-lightning, high-reflectivity echos tended to occur preferentially in the morning and night hours. Hence, there must be one or several factors causing thunder that either operates during day but not during night or whose efficiency depends upon the time of the day. These factors may contribute to the pronounced afternoon maximum of inland summer thunderstorms.

Thunderstorm indices developed by *King* (1980) are interesting for us, since they were developed with radar data from Rovaniemi in northern Finland, in a climate similar to ours. *King*'s relation reads:

$$(h_{crit} - h_o) \cdot (Z_{crit} - Z_o) > 4.5, \qquad (10)$$

where h_{crit} is the cell top height in km
h_o is a threshold height (4.5 km according to *King*)

Z_{crit} is the cell's maximum intensity in dBz

Z_o is a threshold intensity (25 dBz according to *King*)

On a height-reflectivity diagram the product to the left is a rectangle, bounded by h_o, Z_o and the extremes of reflectivity and echo heights. Hence, *King*'s index is more sensitive to a few extreme values than *RT*.

The parameters h_{crit} and Z_{crit} were deduced from vertical reflectivity profiles from Cumulonimbus cells. Those profiles are not available for our 1987 data. *King* however noted that the logical relation

$h > h_o$ and $Z > Z_o$,

where h and Z are any cell's height and intensity, would work almost as well. This relation is possible to test on our data. If we assume that the cell top is the top of the 25 dBz contour (H_{25}) the result is given by Table 3. The high false alarm probability there suggests higher threshold values. Repeating the tests with higher thresholds, i.e.$Z_o = 45$ dBz and $h_o = 2.5$ km, where h_0 denotes the top of the 45 dBz contour, gave much better results. Also this index is more efficient during day-time.

An advantage of indices as *King*'s is that they can be directly observed on the screen of a radar with suitable displays, see Fig. 8. A index as our *RT* needs computations, which however are easy to make on a digitized radar.

Some hail studies are also interesting. A hail criterium by *Waldvogel et al.* (1979) reads:

$$H_{45} > H_o + 1.4, \qquad (11)$$

where H_{45} = height of the 45 dBz contour, km

H_o = height of the 0 °C isotherm.

This criterium is claimed to have detected all hail cells early in their life, but about 50% of the cells identified did not produce hail at the the ground, i.e. $pd = 100$, $pf = 50$ and $ps = 50$. Similar criteria have been successfully used in other parts of the world (*Joss et al.*, 1987).

Donaldson et al. (1975) have made a survey of verification scores for severe hail criteria. The best results were obtained with criteria demanding high reflectivities at upper levels, though the verification scores showed a large scatter, the probabilities of detection varying between 46 and 90, and those of false alarms between 45 and 13. Other criteria, as high reflectivities, heights of echo tops and echo shapes might also give high probabilities of detection, but also very high ones of false alarm.

Summing up, it seems clear that relevant radar criteria detect hail and thunder with a high degree of probability, but the probability of false alarms is also fairly high. Besides, the efficiency of radar criteria have a diurnal variation worthy of more attention.

3.2 *Analyses of lightning frequency*

The analyses of 'occurrences and non-occurrences' are useful for probability estimates. However, the frequency of lightnings is also important. A radar index should be able to give an acceptable estimate of the thunder activity as expressed by lightning location data or an index as *TH*, which can be regarded as a crude measure of the lightning frequency within an area. We have used forward step-wise regression (the routine *RLSEP* in the *IMSL Library*, 1984) to select the best predictors and estimate *TH*.

According to Chp. 3.1 the most promising of our radar indices is *RT*, which however has a distribution quite different from that of *TH*. The distribution of *TH* is positively skew. To transform *RT* to a positively skew distribution we made the transformation $\exp[(RT - tt)/tt]$, where *tt* is a value to be chosen. In Chp. 3.1 we used $RT = 28$ as a threshold for thunder, but some thunder cases were then not detected. The transformed distribution of *RT* should be such that to the left of the value tt it is constant or grows very slowly, but to the right fast, without attaining unreasonably high values for possible RT ones. The maximum possible *RT* is equal to 100, and the maximum possible *TH* is equal to 200. Choosing $tt = 20$ gives a maximum $TH = 54$, which may be reasonable.

Of the other radar indices, the distributions of A_{45} and H_{25} are positively skew. A_{25} and H_{25} did not seem very promising from the analysis of the 1985 cases. The vertical integrated liquid water content when applied on single cells seemed a good predictor. When used for a large volume as here it is however somewhat ambiguous since high values may be attained by a few large water-rich Cumulonimbus clusters as well as by wide-spread precipitation not attaining high reflectivities or giving thunder.

The step-wise forward regression using $A_{25}, H_{25}, A_{45}, H_{45}$, the transformed *RT* and *VIL* as independent variables and *TH* as dependent at the 0.01, 0.01 significance levels (for entrance and deletion resp) gave for the whole day (00-24 UTC) the regression equation

$$TH = -2.3 + 4.0\cdot\exp[(RT - 20)/20)] \qquad (12)$$

with an explained variance of 51%.

We have tried some other values of *tt* (beside $tt = 20$ as in the equation above) but the results do not differ much in the sense of explained variance. For some values other parameters, namely A_{25} and *VIL*, entered the regression equation. Due to the facts that our sample is quite small and our observations not quite independent we will not discuss this any further. We noted, however, earlier that the index worked best in the afternoon. Making the regression on the 15 UTC data gives

$$TH = -3.88 + 1.76\cdot A_{45} + 4.08\cdot\exp[(RT - 20)/20)] \qquad (13)$$

with an explained variance of 71%. It should be noted that in this test the observations are independent. That the thunder activity should depend upon the relative area of strong echos, A_{45}, and the echos' intensities and heights as expressed by the index RT is an attractive idea and suggests the parameters $\exp[(RT - 20)/20]$ and A_{45} for estimating the thunder activity, though further tests on new data are desireable to establish their value.

The index RT may be considered a simple index for the convective and thunderstorm activity. Fig. 9 shows the time development of RT, A_{45} and the lightning frequency, TH, during a thunderstorm day. *Schultz et al.* (1984) suggest a convective index as the square of the reflectivity (in dBz) at each pixel, summed over the entire image (512x512 pixels). They also found a simple positive correlation between this index and the precipitable water. However, no quantitative data (correlations etc.) are given in their paper, and we feel that a radar convective index ought to contain some measure of the 3-dimensional echo structure.

Lopez et al. (1986) noted a correlation coefficient of 0.29 between hourly lightning counts and area-weighted hourly low-level reflectivities for an area of 14800 km^2 in Florida. Somewhat better correlation coefficients were obtained between lightning counts and areas of high reflectivities (35 to 40 and 40 to 50 dBz).

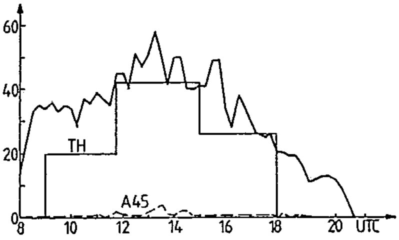


Fig. 9. Time development of the indices RT, A_{45} and the lightning frequency, TH. Aug. 6, 1987.

4. *Conclusions*

The radar index for thunderstorms developed not only gives a 'yes/no' answer but also an indication of the frequency of ground strokes. It must however be noted that the index is formed from only two summers' data over one area. Tests over other areas and other seasons are needed in order to establish it's validity. During winter for instance the conditions for thunderstorms are quite different from those during summer. There are clear indications that the efficency of the index is best during afternoon. During the summer of 1987 it's probability of detection was about 90% with a probability of false alarms of about 30%. The index then also 'explained' about 70% of the variations in our measure of the lightning frequency.

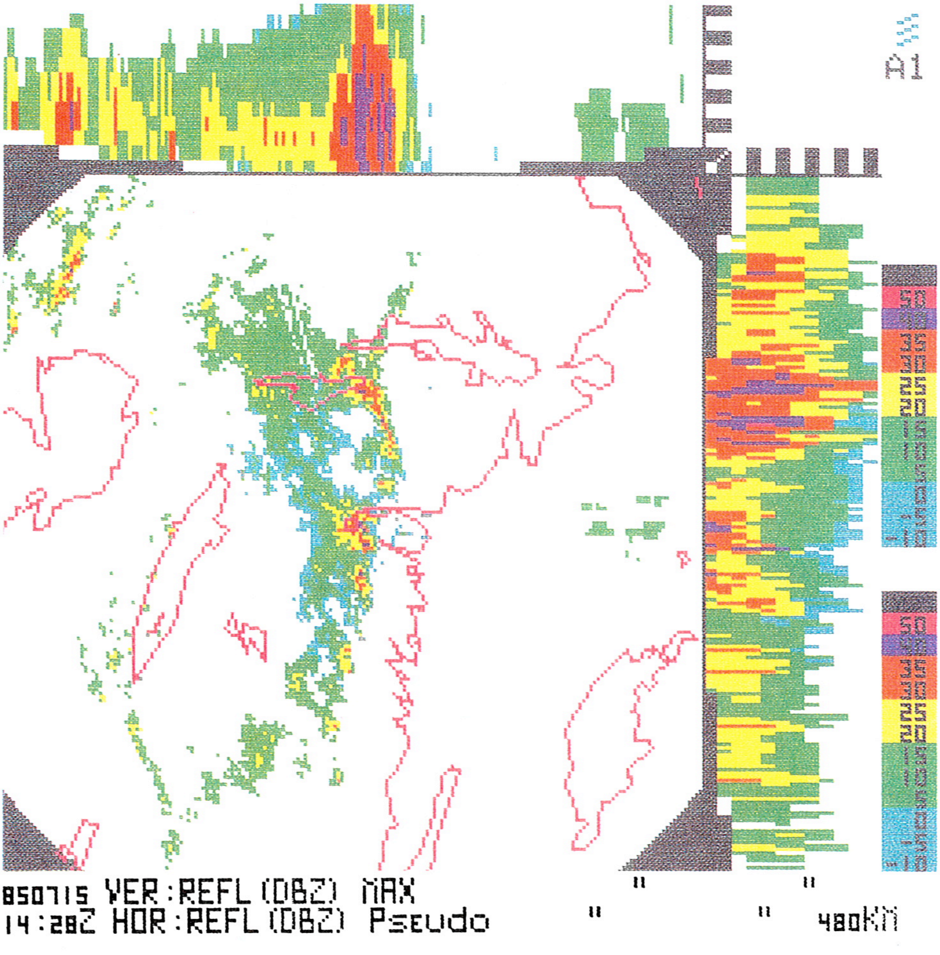


Fig. 8. *a*). Pseudo-CAPPI for 500 m altitude and max projection vertical cross sections. The maximum reflectivities have been projected horizontally on the cross sections. The height scale goes up to 11.5 km with a resolution of 1 km. The Ericsson radar in Norrköping. 15 July, 1985, 14:28 UTC, range 240 km.

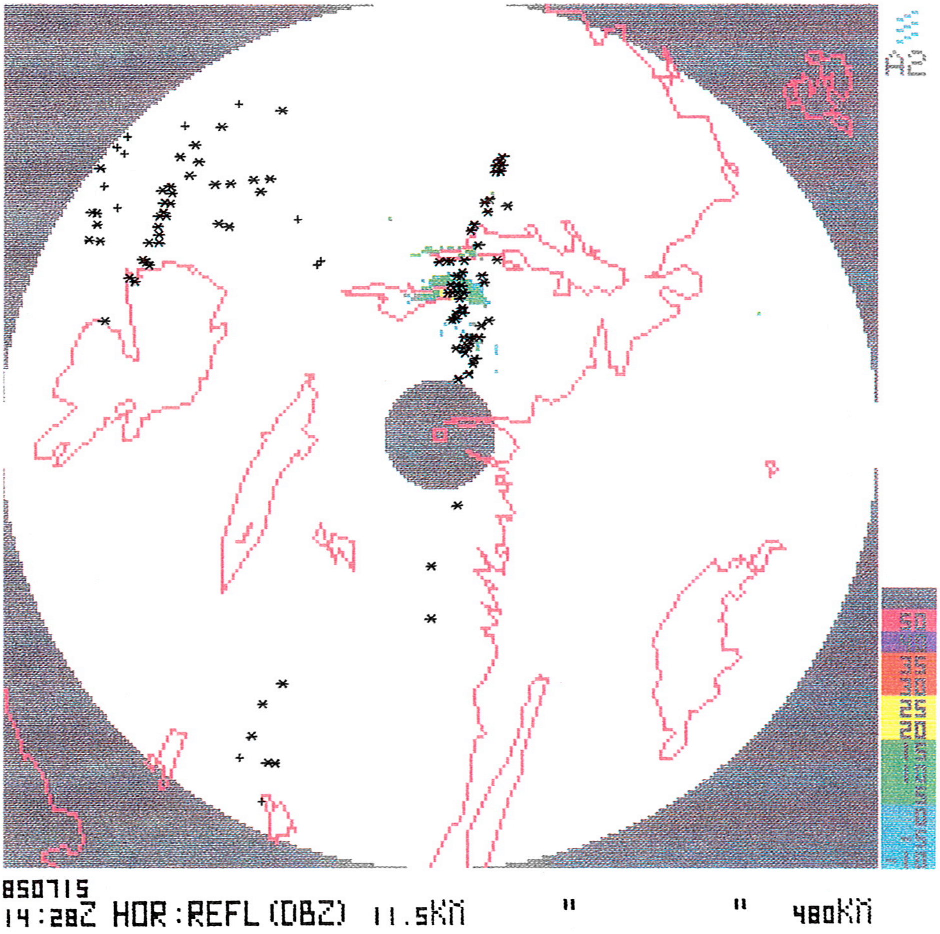


Fig. 8. *b*). Positions of cloud to ground discharges (14:20 - 14:35 UTC) corresponding to the radar picture, and radar echos at 11.5 km
* negative discharge
\+ positive discharge
Lightning data from the Institute of High Voltage Research, University of Uppsala, Sweden.

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