ISSN 0169-1708

KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT

TECHNISCHE RAPPORTEN

T.R. - 54

S.Kruizinga

Development of guidance forecasts at KNMI
3. Probability of thunderstorm activity

De Bilt, 1985

Publikatienummer: K.N.M.I. T.R. 54 (DM)

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ISSN: 0169-1708

Introduction

Thunderstorm activity is a significant element in weather typing. In The Netherlands warm periods in summer often end with thunderstorm activity. Therefore the probability of thunderstorms (POT) is a relevant element in the general public weather forecast. In this paper we will describe the development of an objective forecast scheme, based on the Model Output Statistics (MOS) approach for the probability of thunderstorms in the Dutch area. This scheme results in MOS-equations with which these forecast probabilities can be computed from the output of the numerical model of the European Centre for Medium range Weather Forecasts (ECMWF). We will focus on lead times ranging from 48 hours up to 144 hours, mainly to support the further outlook in the public weather forecast. The other important aspect of thunderstorm activity, short term warnings for light aircraft and so on, is neglected in this study. Earlier work at our Institute mainly focused on short term forecasting (Hanssen, 1965), or on special types of thunderstorms (Roodenburg, 1973).

2. Definition of predictand and predictand climatology

The predictand we will study is the occurrence of thunderstorm activity within a certain time period and area. Because we are only interested, at the moment, in lead times larger than, say, 36 hours the chosen time period is rather large. It covers 24 hours starting at 00 GMT; the area chosen covers the whole Dutch area. For the detection of the occurrence of thunderstorm activity we used the data assembled by our Climatological Branch. Observers are expected to report thunderstorm activity in hourly reports when thunder has been heard. At least one hour with such report a defines a local thunderstorm day. The definition of an areal thunderstorm day was based on ten key stations in the Dutch area (Figure 1). If one of the stations reports thunderstorm activity that day was called an areal thunderstorm day.

Table 1.

Monthly mean probabilities of a local and of an areal thunderstorm day.

station / month	1	2	3	4	5	6	7	8	9	10	AREA
1	2	1	1	2	2	1	0	1	2	1	6
2	2	3	0	2	3	1	1	1	2	1	6
3	1	1	0	2	4	3	1	2	4	1	10
4	0	2	3	3	5	4	3	2	5	3	15
5	5	10	17	11	17	13	10	12	17	13	33
6	12	12	16	12	17	18	16	15	21	17	40
7	9	10	11	11	11	12	13	10	19	13	31
8	8	12	14	15	17	16	18	13	19	13	38
9	13	9	8	14	9	7	7	11	11	6	31
10	7	3	3	7	3	2	2	4	4	2	17
11	12	8	5	11	6	5	3	6	6	2	23
12	6	2	2	4	6	2	0	2	5	1	14

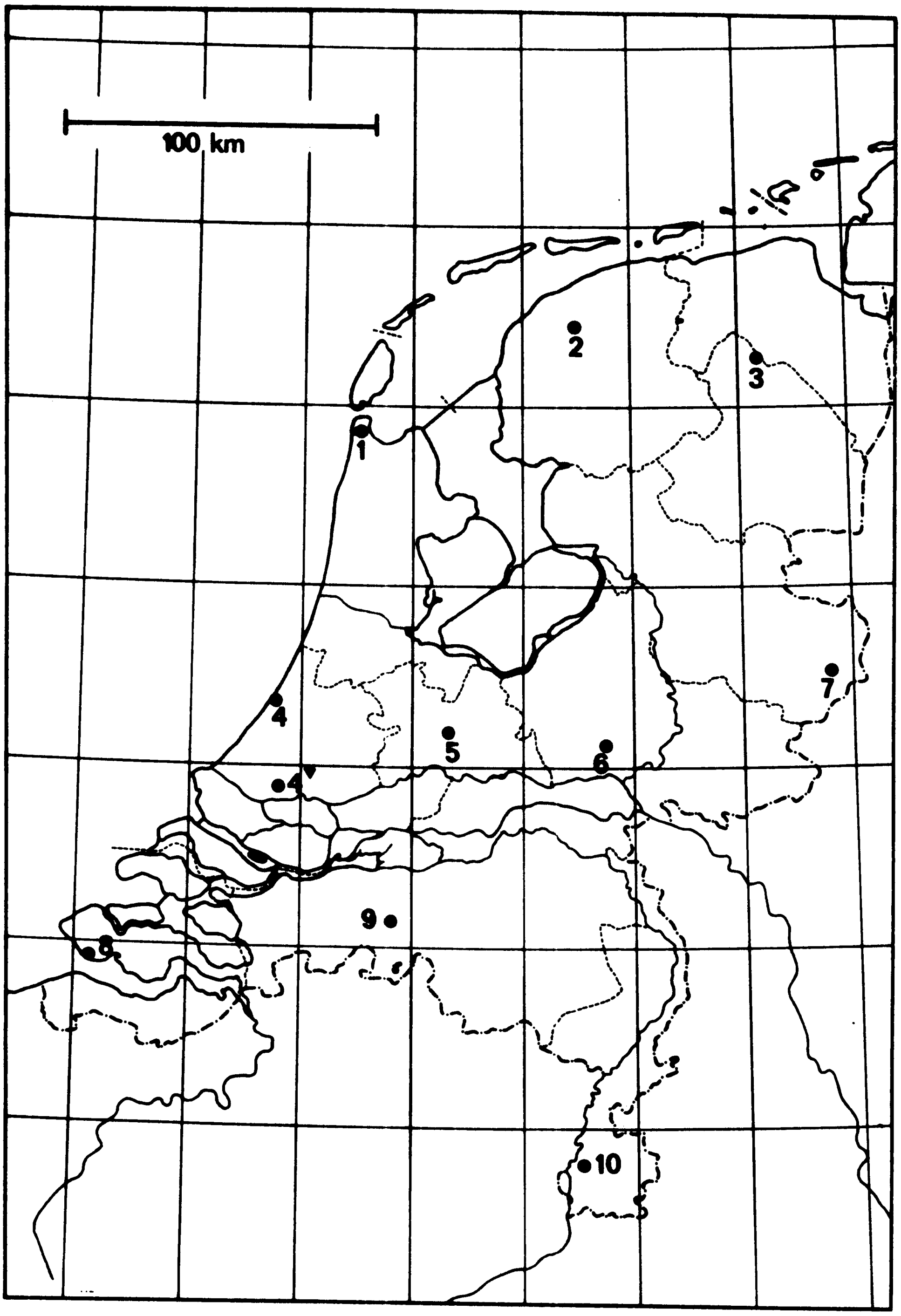
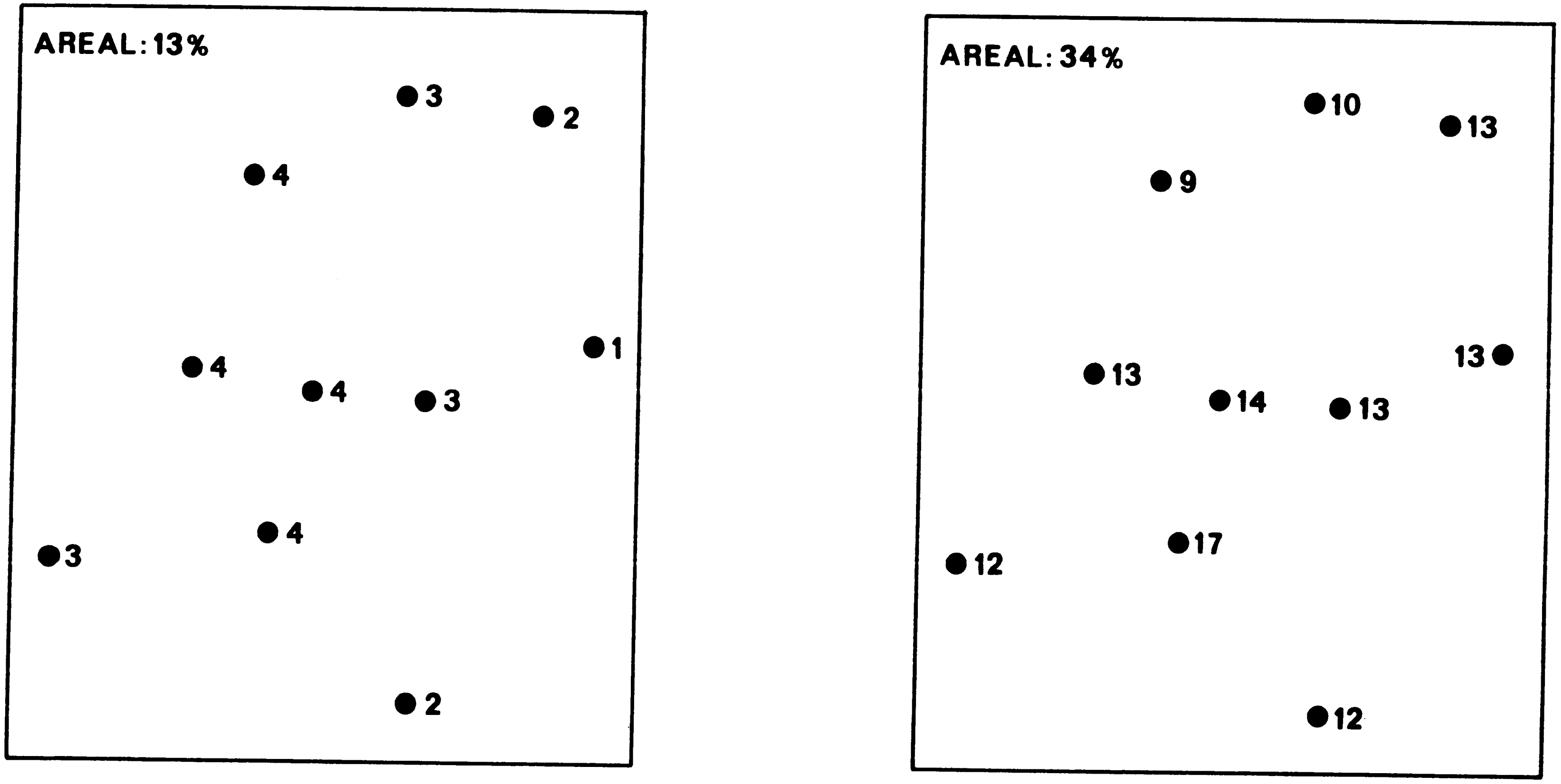


Figure 1 Position of the ten key stations (station 4 was later on replace by 4').

In table 1 the probability of occurrence of a thunderstorm day by month and station are given. These probabilities are derived from the period 1-1-1972 upto 31-12-1979 inclusive. The probabilities of an areal thunderstorm day are given also. As is seen there is a marked difference between the period May to September inclusive (warm season) and the other months. Thunderstorm activity is usually of interest during the warm season only therefore we limited our study to these months. In Figure 2 the average probabilities over both distinct periods are given for each station separately and for the area.



Cold season

Warm season

Figure 2 Average probabilities of a local or areal thunderstorm day during cold and warm season respectively.

3. Preliminary Perfect Prog study

Before the MOS equations were developed a preliminary study based on the Perfect Prog approach was performed. In this study the occurrence of thunderstorm was related with geopotential height patterns at 500, 850 and 1000 mb. These height patterns were extracted from the analyses of National Meteorological Center of the United States of America. The gridded fields were transformed to the grid depicted in Figure 3.

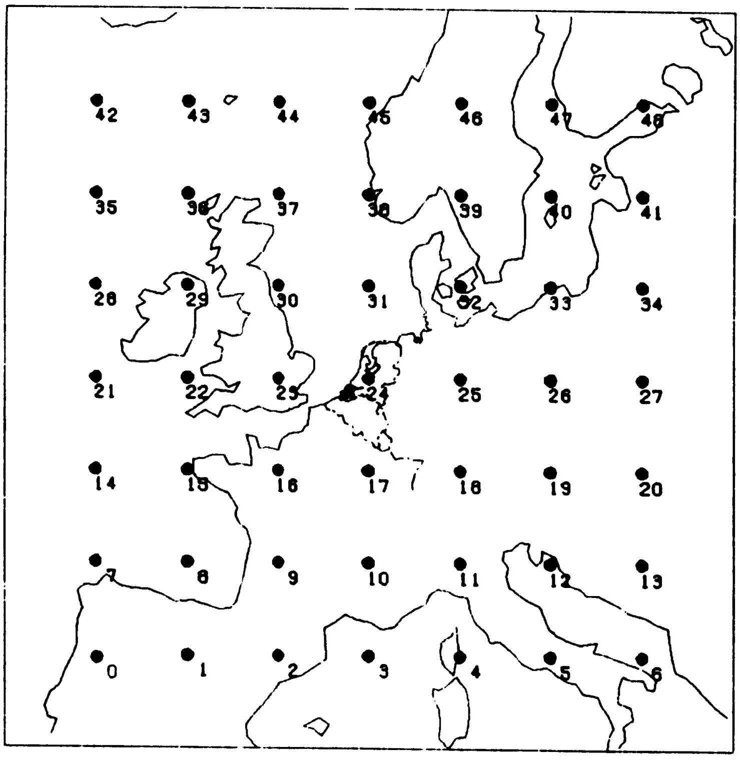


Figure 3 Stereographic grid used for computing geostrophic wind and vorticity (grid spacing = 400 km).

On this grid the local height at De Bilt, the geostrophic wind and the geostrophic vorticity were defined (see Lemcke and Kruizinga (1984)). These data covered the same period 1972-1979 as the data set with thunderstorm observations. It is well known that some sort of stability index is usually a good predictor for thunderstorm activity. There exists a large number of stability indices (Pickup, 1982). Most of these, however, could not be used by us due to the limitations of our data set. Hanssen (1965) however, used a very simple index which depends on the local heights only:

$$\Delta D = (Z_{700} - Z_{1000}) - (Z_{500} - Z_{700})$$

where Z_i is the geopotential height at De Bilt at level i mb. Our data set contained 1000, 850 and 500 mb data so an alternative but similar index was developed:

$$\begin{aligned} DDH = 3.39 - 5.31E{-}3 * (Z_{500}{-}5200) + 2.12E{-}2 * (Z_{850}{-}1400) \\ - 1.82E{-}2 * Z_{1000} \end{aligned}$$

with the geopotential heights denoted in meters. This index was developed by multiple linear regression from the heights on the zero/one variable related to the occurrence of thunderstorms. In Figure 4 the dependence of the thunderstorm probability on this index DDH is shown. This figure was constructed by subdividing the data set into 20 groups with different DDH ranges and determining the relative frequency of thunderstorm days in each group. In Figure 4 this relative frequency is plotted versus the average DDH within a group. The relative explained variance on the dependent data was 31%.

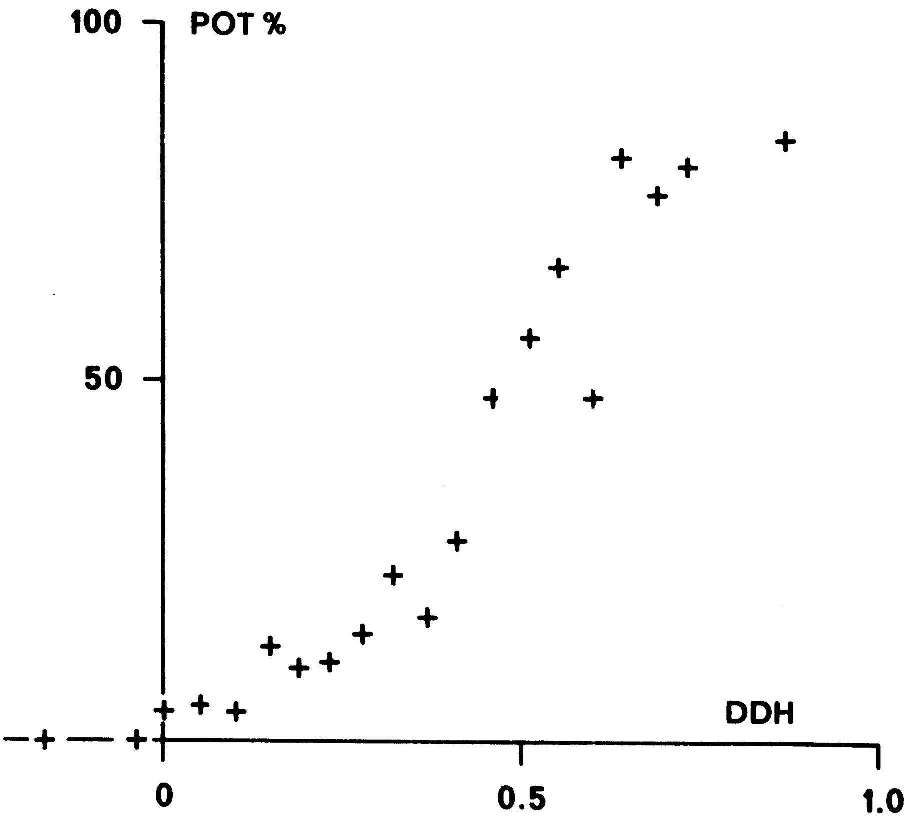


Figure 4 Probability on thunderstorm activity versus DDH (differential thickness).

Subsequently some more complex regression equations containing five predictors were developed. This was done by month as well as for the whole season. However, no significant differences were found between the monthly (and seasonal) equations so it was decided to use one interpretation equation valid throughout the period from May upto September inclusive. The final Perfect Prog interpretation equation was based on the logit model (Brelsford and Jones, 1967; Glahn and Bocchiery, 1975). With this model the probability P of a thunderstorm day is given by

$$P = 100/(1 + e^{FX})$$

with

$$FX = a_o + a_1x_1 + a_2x_2 + \dots a_5x_5$$

where x_n are the predictors and a_n the coefficients which were estimated with an iterative maximum likelyhood procedure. The predictors which were selected separately with a stepwise regression scheme, were DDH, geostrophic vorticity at 850 mb and North South components of geostrophic winds at 1000, 850 and 500 mb. With the resulting equation a Brier skill score (relative explained variance) of 38% was obtained on the dependent data. The results on independent data and forecast data will be discussed in the next paragraph.

4. The MOS-equations

The development of the MOS-equations is based on 3 seasons of forecast fields. These forecasts were obtained from the output of the numerical model of the European Centre for Medium range Weather Forecasts (ECMWF). This data set was assembled in the years 1981, 1982 and 1983. First MOS-equations were developed on the first two years and tested on data from 1983. The final equations were developed on the three season data set.

4.1 Predictor selection

Usually the predictors used in the equations are selected on the same data set used with the estimating of the coefficients. However our data set was so small that we judged this a dangerous procedure. Therefore we decided to use the same predictors as in the PP-equations and to adapt the coefficients through the MOS-approach. At least at short lead times this ought to be a valid method and for longer lead times more stable equations are expected. This is illustrated in table 2 where the Brier score of the MOS-equations with prescribed predictors and with new selected predictors are given for the dependent data set (years 81 + 82, 300 days) as well as for the independent data set (83, 150 days).

Table 2 Brier scores of MOS-equations with prescribed predictors (A) and selected predictors (B) for dependent (81/82) as well as independent (83) data for seven lead times.

	81/82		83	
	A	B	A	B
0	.1136	.1122	.1433	.1397
24	.1313	.1212	.1393	.1488
48	.1406	.1293	.1455	.1579
72	.1514	.1473	.1564	.1609
96	.1752	.1678	.1644	.1665
120	.1842	.1831	.1759	.1686
144	.1988	.1963	.1967	.1996

The Brier score of climatology is .2280 so, as is seen, the equations improve on climatology for each lead time. Furthermore the equations with newly selected predictors clearly improve the equations with prescribed predictors on the dependent data set. But on the independent data these last equations beat the first on average and in five out of seven cases. So we decided to use preselected predictors.

In table 3 the linear correlation coefficients between the selected predictors and the occurrence of thunderstorms are given for the PP-data set

(1200 days) as well as the MOS-data set (for seven lead times).

Table 3 Linear correlation (times 100) coefficient of preselected predictors with thunderstorm occurrence.

		MOS-data ('81 + '82), Lead time in hours						
	72/79	0	24	48	72	96	120	144
DDH	53	59	58	52	48	38	33	24
VORT85	41	40	35	37	31	25	19	23
VNZ50	37	45	45	45	46	44	41	33
VNZ99	11	16	13	14	9	18	18	14
VNZ85	25	31	27	26	23	30	29	23

This table shows that the correlation of DDH starts at a high level but deteriorates markedly with increasing lead time whereas the correlation of VNZ_{50} is much more stable. This implies that the MOS-equations will assign relatively more weight to this last predictor with increasing lead time. Moreover it will be clear that if we compare the correlation coefficient of DDH at +24 hours (.58) with the correlation coefficients given by Reap and Foster (1979) for the K-index (.41) or the Total Totals index (.33), DDH is a very suitable predictor. It is conspicuous that four out of five predictors show a better correlation in the period '81 + '82 (ECMWF analysis) than in the period 72/79 (NMC analysis). Studies with other predictands have shown that this effect is probably realistic and possibly due to the improved analysis techniques.

As said before the final MOS-equations were developed on the basis of the three year data set. Of course there is no independent data set available to test these final equations. However the use of these final equations is justified by the results of the experiment (MOS-E) equations scored on their independent data set (1983). In table 4 the test results of the final MOS-equations (MOS-F) are given for each year separately together with the results obtained with the PP-equations and the experimental MOS equations (MOS-E). All equations contain the same set of predictors. In this table the results are expressed as a Brier Skill Score or the improvement in Brier score over the Brier score obtained with climatology used as forecast on the same days. For the climatological forecast a constant probability of 34.5% was used throughout the warm season.

Table 4 Yearly Brier Skill Scores of PP-equations, experimental MOS-equations (MOS-E) and final MOS-equations (MOS-F).

Lead time in hours

1981	0	24	48	72	96	120	144
PP	41	27	26	22	-8	-16	-38
MOS E	46	34	34	34	18	15	6
MOS F	43	33	31	34	17	16	5

1982	0	24	48	72	96	120	144
PP	51	45	34	29	19	14	-3
MOS E	53	49	42	35	29	25	20
MOS F	49	46	42	35	29	23	21

1983	0	24	48	72	96	120	144
PP	32	33	29	20	16	6	-6
MOS E	37	38	36	32	28	22	13
MOS F	43	44	43	32	29	25	14

This table demonstrates that MOS clearly improves on PP at short ranges, due to the improved quality of the analysis, and at longer ranges, due to the better handling of the information.

In table 5 the bias (average forecast probability - frequency of occurrence) obtained with the three different equations in 1983 is given. The PP-equations show a clear bias, ascending with forecast time, indicating an overestimation of thunderstorm probability at longer ranges. The MOS-equations perform much better.

Table 5 Observed bias (%) in 1983 for the three types of equations PP, MOS-E and MOS-F.

	0	24	48	72	96	120	144
PP	6	5	8	9	11	12	14
MOS-E	1	0	1	2	1	1	-1
MOS-F	1	0	1	1	1	0	-1

The foregoing verification strongly focused on the direct verification of the probabilities, however with categorical variables contingency tables are often used for verification. To perform such a verification it is necessary to transform the probability forecasts into a categorical forecast. We decided to forecast thunderstorm activity if the forecast probability exceeds 34.5%. In table 6 the contingency tables obtained in 1983 for two lead times (48 and 96 hours) and the three types of equations are given. With each table the associated Hanssen-Kuipers Index I (Hanssen and Kuipers, 1965) is given. According to Woodcock (1976) this score is preferable for the evaluation of yes/no forecasts. The results found here are fairly high when compared with the results obtained by Hanssen

(I = .48) or Pickup (I = .52). It must be emphasized however that our verification results are based on one warm season only and that the predictands in the refered papers are not identical to our predictand.

Table 6 Contingency tables of yes/no forecasts obtained in 1983.

PP +48		FORC		
		NO	YES	
OBS	NO	63	34	97
	YES	8	45	53
		71	79	150

$$I = \frac{63}{97} + \frac{45}{53} - 1 = .50$$

PP +96		FORC		
		NO	YES	
OBS	NO	51	46	97
	YES	9	44	53
		60	90	150

$$I = \frac{51}{97} + \frac{44}{53} - 1 = .36$$

MOS-E +48		FORC		
		NO	YES	
OBS	NO	73	24	97
	YES	7	46	53
		80	70	150

$$I = \frac{73}{97} + \frac{46}{53} - 1 = .58$$

MOS-E +96		FORC		
		NO	YES	
OBS	NO	69	28	97
	YES	12	41	53
		81	69	150

$$I = \frac{69}{97} + \frac{41}{53} - 1 = .48$$

MOS-F +48		FORC		
		NO	YES	
OBS	NO	73	24	97
	YES	7	46	53
		80	70	150

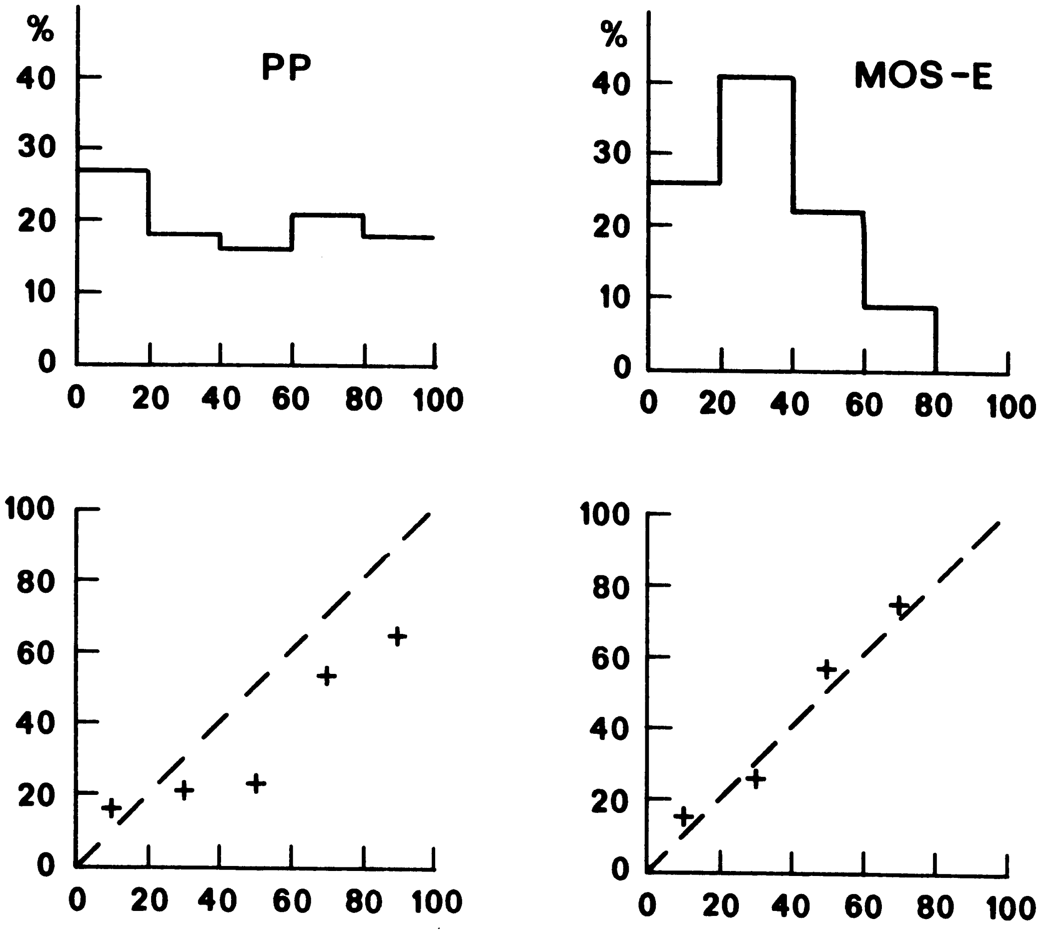
$$I = \frac{73}{97} + \frac{46}{53} - 1 = .58$$

MOS-F +96		FORC		
		NO	YES	
OBS	NO	70	27	97
	YES	11	42	53
		81	69	150

$$I = \frac{70}{97} + \frac{42}{53} - 1 = .51$$

Apart from the skill the reliability of probability is an important characteristic. Reliability means that a set of p% forecasts is followed by thunderstorm in p% of all such forecasts. Reliability is usually illustrated by means of a reliability diagram. To construct such diagrams we grouped the forecasts of the independent data set of MOS-E and PP according to their forecast value in groups 0-20, 20-40 and so on. The relative frequency with thunderstorms observed is plotted versus the midpoints of the groups. The plots are expected on a 45° diagonal from 0,0 tot 100, 100. In figure 5 the average diagrams of the +120 and +144 forecast are given for PP and MOS-E from 1983 forecasts. It should be kept in mind that satisfactory reliability diagrams need a large amount of data and smaller groups than used in this diagrams. The diagrams given here only serve to illustrate that the MOS-approach has the desired effect of making the forecasts more reliable. The PP-diagram indicates clearly that especially in the high ranges the thunderstorm probability is overestimated by the equations.

Fig. 5 Reliability diagrams for PP and MOS-E. Verification period, warm season 1983. The results of +120 and +144 hour forecasts are averaged. The upper histograms give the relative distributions of the forecasts over the groups.



5. Summary and conclusions

In this report the forecasting of thunderstorm probabilities was studied. First the PP-approach was used and this resulted in an equation based mainly on a stability index with minor contributions from some other predictors. The stability was based on local heights of some isobaric planes only. In a second stage a set of MOS-equations based on the same predictors was developed. It was clearly shown that these MOS-equations perform better than the PP-equations especially at longer lead times. The MOS-equations proved to be skillful and reliable out to the +144 hour forecast.

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