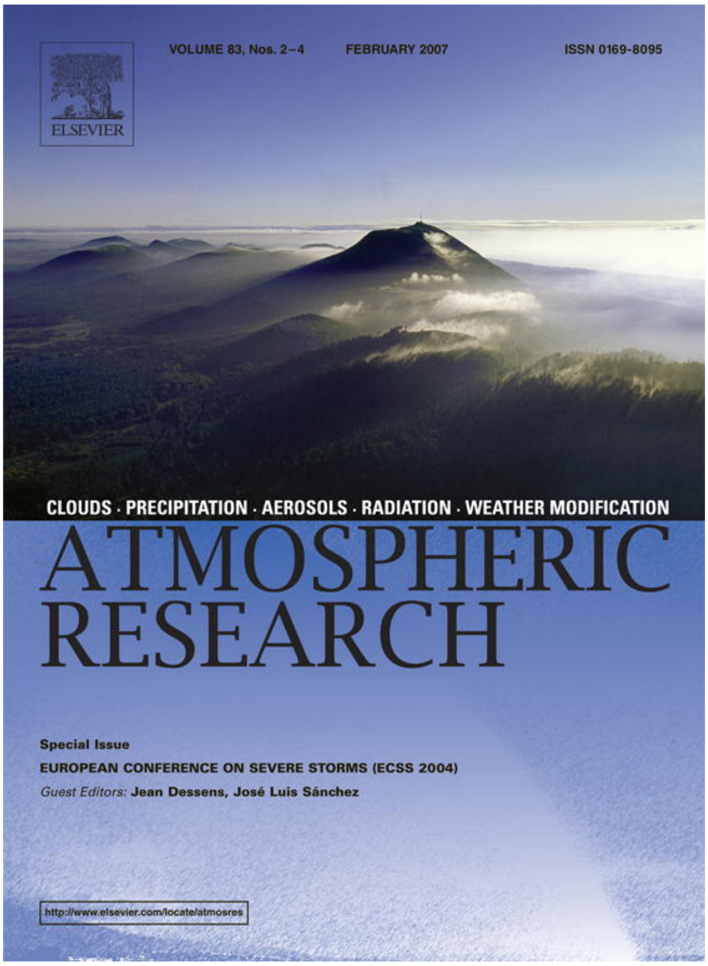
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Vertically integrated moisture flux convergence as a predictor of thunderstorms

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Abstract

Vertically Integrated Moisture Flux Convergence (VIMFC) alone and in combination with the lifted stability index of the most unstable layer (SMUL) is evaluated as a thunderstorm predictor. By using six-hourly standard pressure weather analysis data from the European Centre for Medium-range Weather Forecasts (ECMWF) during 30 days in the summers of 1992 and 1994 containing several severe weather events along with quiescent events in northwestern Europe 17,206 events are obtained. The location and time of a lightning discharge are obtained from the Arrival Time Difference (ATD) sferics lightning location system from the UK Meteorological Office. Using the Heidke Skill Score (HEIDKE) to determine the best threshold we conclude that VIMFC alone, does not perform well as a dichotomous thunderstorm predictor compared to the stability index. However, the Thundery Case Probability (TCP) tested as function of VIMFC results in a high correlation with thunderstorms. By combining SMUL and VIMFC the surplus value as a thunderstorm predictor of VIMFC was established. TCP percentages up to 95% were found in an unstable environment with high positive values of VIMFC. In a marginally unstable environment with a high positive VIMFC the thunderstorm probability is higher than in a very unstable environment with no or negative VIMFC. These results are illustrated with a study of the case of the disastrous flash flood at Vaison-La-Romaine (southeastern France) on September 22, 1992. Although latent instability was present in a large area surrounding Vaison-La-Romaine, nearly all and especially the most severe thunderstorm activity occurred within the smaller area with positive VIMFC *and* latent instability.

Keywords: Thunderstorm; Lightning; Moisture flux convergence; Weather prediction

1. Introduction

Long lived thunderstorms usually only arise when there is forced lifting of potentially unstable moist air and when the low level moisture is replenished continuously due to the action of synoptic scale disturbances (Bechtold et al., 2003). Nevertheless, almost all thunderstorm predictors represent only the potential or latent instability of a layer in the atmosphere and do not take into account the forced lifting and moisture supply. Haklander and van Delden (2003) compared the performance of 32 such thunderstorm predictors that have been proposed over the past 50 years. Thunderstorm predictors based upon near surface latent instability, such as the Lifted Index (Galway, 1956) were found to be the best predictors, better than e.g. CAPE (Convective Available Potential Energy). As a continuation of the research done by Haklander and van Delden (2003) we here present the

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results of an investigation of the performance of a parameter representing the effect of forced lifting and moisture supply. The parameter in question is the "Vertically Integrated Moisture Flux Convergence" (VIMFC) in the lowest 3 km of the atmosphere. VIMFC consists of two terms: a term proportional to the convergence of the horizontal wind vector and a second term that is proportional to moisture advection, sometimes referred to as "moisture pooling." The first term is often the largest term. This term is associated with forced lifting. By combining the influence of forced lifting and moisture pooling in one parameter, VIMFC incorporates the ingredients necessary for convection that are not taken into account in traditional thunderstorm indicators.

The main question to be addressed is the following. Can knowledge of the value of VIMFC together with knowledge of the value of the lifted index contribute to an improved estimate of the probability of thunderstorm occurrence and also be an aid in better pinpointing the location of future thunderstorms?

The usefulness of horizontal Moisture Flux Convergence *at or near the earth's surface* (MFC) as a thunderstorm predictor has been recognized throughout various studies (e.g. Waldstreicher, 1989; Nierow, 1989; Beckman, 1990). However, surprisingly little research has been done regarding VIMFC as a thunderstorm predictor. The only study related to this subject that we know of is that by Hudson (1971) who used VIMFC to determine the convective cloud cover produced in the lowest 10,000 ft in nine severe weather episodes.

MFC is presumably preferred over VIMFC because data is available from surface stations at a relatively high resolution. Unfortunately, surface data is not always representative for the deeper atmosphere. There have been several studies aimed at finding a relation between MFC and severe weather (tornado, hail ≥ 2.0 cm and/or wind gusts ≥ 50 kn), e.g. Waldstreicher (1989) and Nierow (1989). Nierow (1989) found that well-defined MFC was generally associated with intense convection, and that MFC tended to increase rapidly prior to severe convective development. In the severe weather and heavy rainfall case in southern New England on the 22nd and 23rd June of 1989 studied by Waldstreicher (1989), MFC delineated an area of severe weather, while other conventional fields from the Nested Grid Model failed to provide detailed information about the potential threat. Beckman (1993) states that certain MFC patterns and larger MFC centre values gave confidence in the prediction of severe weather events. Large values ($\geq 100 \times 10^{-5}$ g kg^{-1} s^{-1}) of MFC, forecasted 12 h in advance at 0000 UTC by the Nested Grid Model, are often associated with the occurrence of numerous severe weather reports (Beckman, 1990). Rogash and Smith (2000) investigated the synoptic and mesoscale characteristics of the environment just prior to and during tornado and flash flood events. It was concluded that moisture, convective instability, vertical wind shear and lifting mechanisms all contributed to those events. The quantity of precipitation falling over a given area can be at least partially related to the magnitude of the lower-tropospheric moisture convergence (Rogash and Smith, 2000). By examining the (wind) divergence–lightning relationship (not taking moisture into account) near the Kennedy Space Center, Florida, Watson et al. (1990) found that lightning began near the time of the strongest wind convergence, that the peak in lightning activity typically occurred when airflow was undergoing a transition from predominantly convergent to predominantly divergent and that cloud to ground lightning ended shortly after peak wind divergence. In the case of no wind convergence, there is unlikely to be lightning. Similar results were found by Calas et al. (1998, 2000).

Waldstreicher (1989) found two types of convergent field patterns in MFC, that are similar to the types found by Hirt (1982) in dew point convergence. The first type is a convergent monopole, the most common of both and is associated with non-severe convection. However if the convergent monopole is stationary, areas of excessive rainfall and/or severe weather are possible (Waldstreicher, 1989). The second type is associated with severe weather and consists of a maximum convergence area coupled to a maximum divergence area. The favoured area of convection was found to be located in the gradient between these centres.

Calas et al. (1998) introduced a new parameter by multiplying MFC and CAPE. This parameter shows potential, despite of its lack of physical meaning. Another convective index was introduced by McGinley et al. (1991) as $\log_{10}(-\mathrm{LI} \times w)$, called LLIW. Here w is the vertical velocity (in cm s^{-1}) and LI is the Lifted Index (in °C). To isolate only the areas of the strongest forcing, LLIW is set to 0 if $(-\mathrm{LI} \times w) < 1$ or $w < 0$ or $\mathrm{LI} > 0$. Although this parameter is associated with a large false alarm rate, it is also associated with a high probability of detection. Unfortunately, the performance strongly deteriorates over the slightest orography.

The structure of this article is as follows. In Section 2 the data used and area of interest are discussed, in Sections 3 and 4 VIMFC and the stability indices respectively are defined. The statistical methods and the definition of a so-called "thundery case" are presented in Section 5. The results along with an illustrative case study of the severe weather event that occurred in

Vaison-La-Romaine on 22 September 1992 are presented in Section 6. Finally, the conclusions are given in Section 7 and additional details are given in the Appendix.

2. Data and area of interest

Lifted indices and VIMFC are calculated from the European Centre for Medium-range Weather Forecasts (ECMWF) analysis on standard pressure levels. The analysis domain runs from −6° to 12°E and 39°N to 54°N and has a resolution of 1° in both longitude and latitude. The standard pressure levels we use are 1000, 925, 850, 700 and 500 hPa. The variables available for each level are geopotential height, temperature, wind velocity (*u* and *v*) and humidity. When deriving statistics from this data set, we exclude areas where the earth's surface is higher than 1000 m above sea level.

The data set used contains 119 interesting moments (00, 06, 12 and 18 UTC) of the summers of 1992 and 1994, when several severe weather events occurred including the severe weather of July 20 and 21, 1992 affecting much of western Europe (Haase-Straub et al., 1997; Van Delden, 2001), of August 8, 1992 affecting southern Iberia to northern France (Van Delden, 1998), of August 20, 1992 affecting western Germany (Kurz, 1993), of September 22, 1992, affecting southeastern France and in particular the town of Vaison-la-Romaine (Sénési et al., 1996) and of July 24 and August 3–4, 1994 affecting the United Kingdom (Galvin et al., 1995). The choice of this data set was determined partly by the convenience of being directly available. It was used by the second author of this paper in several case studies. Of course it is of great interest to have these intensely studied cases within a data set that is used to evaluate the performance of thunderstorm predictors. It is also interesting to note that July 1994 was the warmest month ever recorded at many locations within the area (France, England, Benelux and Germany) of interest in this study.

Next to mountainous areas, we also exclude the Mediterranean areas from the statistics (Fig. 1). By doing so we avoid having two separate domains with different climates. We thus derive statistics from a dataset of 17,374 events. Excluding 168 events with suspicious moisture data leaves a substantial dataset of 17,206 useful events.

Following Haklander and van Delden (2003) we use data from the Arrival Time Difference (ATD) sferics lightning location system from the UK Meteorological Office to fix the time and location of thunderstorms.

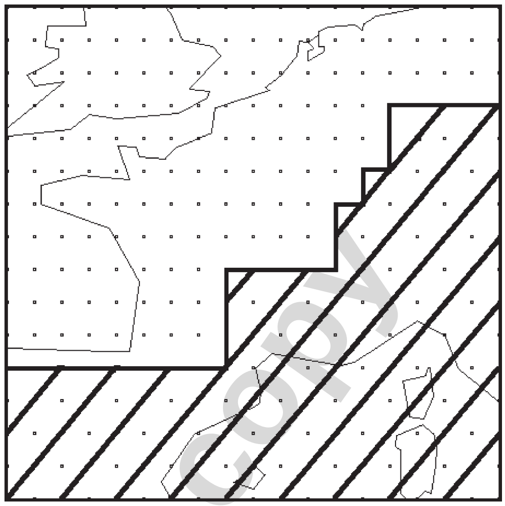

Fig. 1. Domain ranging from −6° to 12°E and from 39° to 54°N with a resolution of 1° in both longitude and latitude (every gridpoint is indicated by a dot). The area indicated by hatching was excluded from the statistics. This gives 146 gridpoints, covering the Bay of Biscay, most of France, Southern UK, the English Channel, Benelux, and northern Germany.

Therefore, we assume that thunderstorm occurrence is synonymous to lightning occurrence. Within the region in question, the ATD system fixes the location of lightning with an accuracy of about 5–10 km in space (Lee, 1986, 1990) and 6 min in time (Holt et al., 2001).

There are, however, a few limitations to the ATD system dataset used. It detects a maximum of about 400 strikes an hour. The ATD detection efficiency depends upon the strength of the received sferic i.e. weak thunderstorms with weak sferics may go undetected by the ATD system. The accuracy of the location of a lightning discharge is reduced when some ATD stations do not function. When less than 4 stations are operational the system will not work at all. Fortunately this is a rare occasion and did not occur at the times of interest in this study. Furthermore the ATD system primarily detects the so-called cloud-to-ground lightning discharges. The overall detection rate is estimated to be around 20% in the UK but still it is reasonable to assume that this is representative for the total electrical storm activity (Holt et al., 2001). In our case the 20% detection rate is not a problem since we are only interested in answering the question whether a thunderstorm did occur and not in the severity or intensity of the storm. As explained in Haklander and van Delden (2003) it is very difficult to determine the exact amount of false detections of the ATD sferics lightning location system that result in false thundery cases. In our case, no particularly strange values of the Lifted Index and/or VIMFC were found to be associated with a thundery case. Therefore it is judged extremely unlikely that false detections interfere with the results.

3. Computation of vertically integrated moisture flux convergence

Because we want a parameter that is a measure of the lower tropospheric forced lifting and because most water vapor exists below 700 hPa, VIMFC is defined in this study as the horizontal moisture flux convergence integrated between 1000 hPa and 700 hPa, i.e.

$$\mathrm{VIMFC} = -\frac{1}{g}\int_{700\ \mathrm{hPa}}^{1000\ \mathrm{hPa}} \left(\frac{\partial uq}{\partial x} + \frac{\partial vq}{\partial y}\right)\mathrm{d}p \quad (1)$$

In this equation q is the specific humidity, u and v are the x- and y-components of the wind velocity, respectively, p is the pressure and g is the acceleration due to gravity. VIMFC is calculated by summation of the horizontal moisture flux convergence over the intervals 1000–925, 925–850 and 850–700 hPa using finite centred differences on a lat/lon grid to approximate the term between brackets in Eq. (1). In the following we will express values of VIMFC in units of 10^{-5} kg m^{-2} s^{-1}.

4. Stability

We introduce four stability indices, which we refer to as S1000, S925, S850 and S700 respectively. These indices are determined similarly to the Lifted Index (Galway, 1956) and the Showalter Index (Showalter, 1953). S850 actually is the Showalter Index, but to remain consistent with the names used in this study we will refer to it as S850. Stated more specifically, the indices are defined as the temperature of the environment at 500 hPa (T_{500}) minus the temperature of a parcel with the characteristics (moisture amount, temperature and pressure) of its level of origin lifted pseudoadiabatically to 500 hPa, i.e.

$$S_p = T_{500} - T_{p\rightarrow 500} \quad (2)$$

Here p represents the pressure of the level of origin of the air parcel, i.e. 1000, 925, 850 or 700 hPa, $T_{p\rightarrow 500}$ is the temperature of a parcel lifted pseudoadiabatically from level p to 500 hPa and T_{500} is the environmental temperature at 500 hPa. The stability of the most unstable level (SMUL) at a particular time and place is defined as the minimum value of S1000, S925, S850 and S700 at that particular time and place.

During the night the pressure levels 925, 850 and especially 700 hPa are quite often the most unstable level. By using the most unstable level in the atmosphere as a gauge for the potential of thunderstorms, it is less likely that nocturnal thunderstorms are overlooked.

High amounts of latent instability i.e. low values of SMUL occur in areas where the temperature and moisture amount is high in the lower parts of the atmosphere along with low temperatures at 500 hPa. High amounts of moisture in the lower parts of the atmosphere can be responsible for low values of SMUL as well as high values of VIMFC. High values of VIMFC and low values of SMUL are therefore not entirely independent of each other.

5. Methods

To evaluate the performance of a thunderstorm predictor, several skill scores have been defined based upon a dichotomous scheme with two simple questions (Doswell et al., 1990). Is the event observed? Is the event forecasted? Based upon this scheme an optimum threshold can be derived using the Heidke Skill Score (HEIDKE), as explained in Haklander and van Delden (2003). In this study the Probability Of Detection (POD) and the False Alarm Ratio (FAR) are also determined merely to interpret HEIDKE. In various studies the True Skill Statistics (TSS) is used as well to determine the optimum threshold. However, since Doswell et al. (1990) concluded that TSS has a problem with a relatively large amount of quiescent events, we choose HEIDKE instead of TSS. For those who are not familiar with these concepts, we refer to the above-mentioned publications for the exact definitions.

We use two different sets of criteria to fix a “thundery case.” The first set of criteria are identical to those used by Haklander and van Delden (2003). We define a thundery case as follows. *At least one sferic is fixed by the ATD system at less than 100 km from a grid point during the six hours after the time for which the value of the parameter is determined*. In the second case, the set of criteria for a thundery case are made more strict. In this case we define a thundery case as follows. *At least three sferics are fixed by the ATD system at less than 50 km from a grid point during the three hours after the time for which the value of the parameter is determined*. With this set of criteria the effect of thunderstorm advection is reduced and thus we hope to be more certain that a thundery case can be associated with the values of the thunderstorm predictors corresponding to a particular time and a particular grid point. Since we intend to test the usefulness of parameters as thunderstorm *predictors*, we have chosen six- and three-hour intervals, respectively, *after* the time of the analysis on which the calculation of the parameters is based.

The first set of criteria is referred to as “TC-6 hrs” while the second set of criteria is referred to as “TC-3 hrs.” Thundery cases with “TC-6 hrs” occur in 26.19% of the 17,206 cases while thundery cases with “TC-3 hrs” occur in 7.24% of all cases.

6. Results

6.1. Skill scores

In the following section we present the results for the “TC-6 hrs” criteria. The results for the “TC-3 hrs” criteria are described in the Appendix. Fig. 2 shows the three skill scores for VIMFC as a function of threshold value. The optimum threshold is determined by the highest HEIDKE score. The optimum threshold is attained at 11.4 units with a score of 23.2%. At this threshold POD = 36.7% and FAR = 53.7%. These scores are not very good.

The maximum HEIDKE score for the stability indices ranges from 36.5% to 43.2% (Table 1). The Showalter Index (S850) performs best in this study with a HEIDKE of 43.2% at 1.7 °C. These scores are similar to those obtained by Haklander and van Delden (2003) for the lifted index. Therefore, compared to the stability indices, VIMFC performs rather poorly.

6.2. Thundery case probability

The Thundery Case Probability (TCP) is calculated following the procedure described in Haklander and van Delden (2003). By making an ordered list of high to low parameter values and taking the 1st to the 200th events in that ordered list and calculating the percentage of thundery events for these 200 events, we obtain the TCP corresponding to the average parameter value for these 200 events. This procedure is repeated for the 2nd to 201st event in the ordered list and so on until the 17,007th to the 17,206th event.

Table 1
Highest Heidke skill scores for “TC-6 hrs” criteria with corresponding threshold values and corresponding values of POD and FAR for all parameters

Index	Threshold	HEIDKE	POD	FAR
S1000 (°C)	≤ −0.2	38.7%	65.9%	49.9%
S925 (°C)	≤ 1.4	43.0%	70.1%	47.5%
S850 (°C)	≤ 1.7	43.2%	63.0%	44.5%
S700 (°C)	≤ 3.4	36.5%	65.1%	51.6%
SMUL (°C)	≤ −0.3	42.3%	74.3%	49.3%
VIMFC (10^{-5} kg m^{-2} s^{-1})	≥ 11.4	23.2%	36.7%	53.7%

The TCP as a function of VIMFC is plotted in Fig. 3 for both “TC-6 hrs” criteria and “TC-3 hrs” criteria. With “TC-6 hrs” criteria VIMFC scores a TCP maximum of 73.0% at 75.2 ± 14.2 units. Unlike the TCP of the stability indices, the TCP of VIMFC does not go to 0% at any value. After reaching a minimum value of 8.5% at −10.7 ± 0.2 units, the TCP increases again to 31.5% at −52.9 ± 6.4 units. This effect is associated with thunderstorm advection and the fact that high positive values of VIMFC often occur close to negative VIMFC, as is illustrated in Fig. 4. As expected, with “TC-3 hrs” criteria much lower TCP-values are found. The maximum TCP score is 38.0% at 77.8 ± 16.7 units (see also Table A2). However, in this case the TCP does not increase at negative VIMFC values.

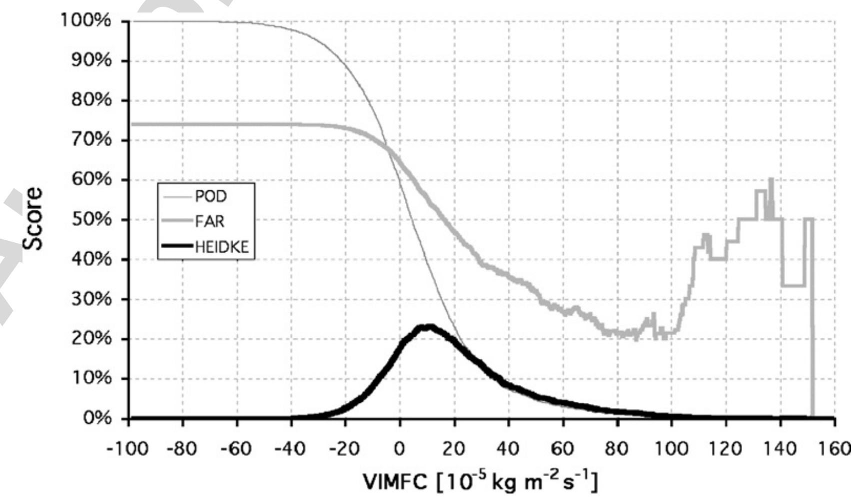

Fig. 2. Overview of skill scores (HEIDKE, POD and FAR) for VIMFC as a function of threshold value using the criteria corresponding to “TC-6 hrs.”

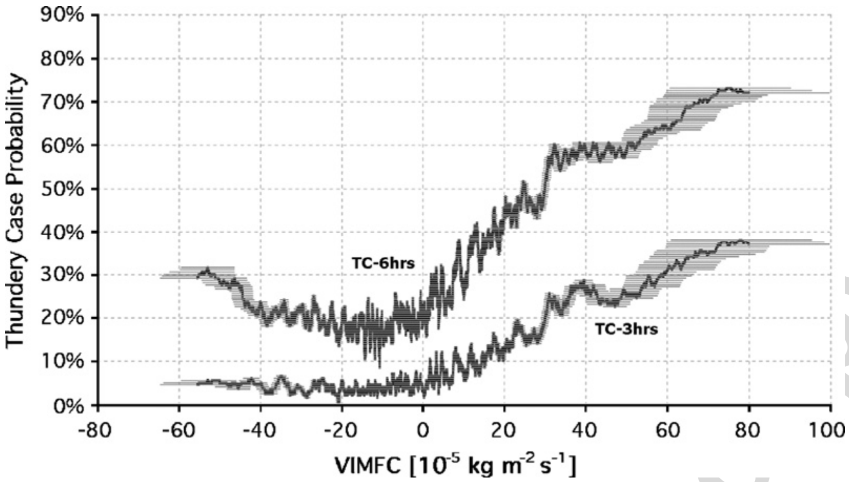

Fig. 3. TCP as a function of VIMFC and corresponding standard deviations (indicated by horizontal grey lines) following the criteria "TC-6 hrs" (upper curve) and "TC-3 hrs" (lower curve).

The maximum TCP values (with "TC-6 hrs") for the stability indices range from 73.5% to 78.5% (Table 2). Therefore, in terms of TCP, the performance of VIMFC as a thunderstorm predictor is similar to the performance of the stability indices.

6.3. VIMFC in combination with SMUL

We now make an attempt to combine VIMFC and SMUL by constructing a two-dimensional TCP plot. In our dataset VIMFC varies by 260 units while SMUL varies by 28 °C. The 17,206 events are divided into 182 bins of 20 units of VIMFC and 2 °C of SMUL. Fig. 5 shows the distribution of events. The bin with the most events (1547) has values between −20 and 0 units of VIMFC and SMUL ranging from 0 to 2 °C. We assume that a good indication of the TCP value can be given if 25 or more events occur within a bin. In that case we determine the thundery case probability by computing the percentage of thundery cases within the particular bin. This results in a two-dimensional thundery case probability diagram (Fig. 6).

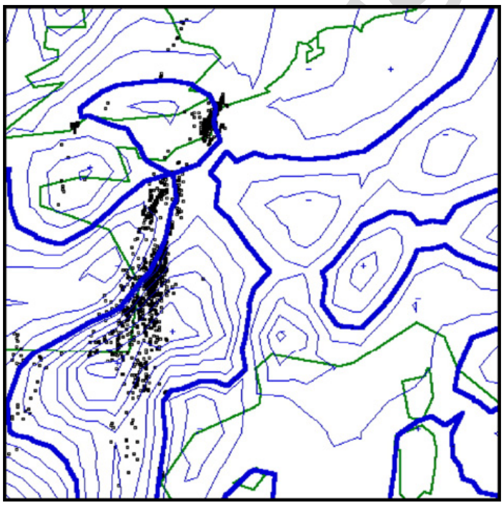

Fig. 4. Distribution of VIMFC (blue) (zero-contour: thick; contour interval 10 units) on August 8, 1992, 12 UTC, and the location of lightning discharges (black dots) between 12 and 18 UTC fixed by the ATD lightning location system.

From this diagram it is clear that high positive VIMFC along with negative values of SMUL correlate strongly with the occurrence of thunderstorms. For instance, using the "TC-6 hrs" criteria, the probability of a thundery case is 89% with SMUL ranging between −4 and −6 °C along with VIMFC ranging between 40 and 60 units. Separately, VIMFC and SMUL reach a maximum TCP of 73% at 75.2 units and 74% at −5.2 °C respectively. In an area where the VIMFC is 75.2 units and SMUL is −5.2 °C the thundery case probability reaches 95%! It is clear from this that by combining the two parameters the usefulness of these parameters as thunderstorm predictors is increased.

Table 2
Highest TCP for "TC-6 hrs" criteria for all parameters with corresponding values and standard deviations

Index	TCP (TC-6 hrs)	Value	Std dev
S1000 (°C)	73.5%	−5.2	0.1
S925 (°C)	77.5%	−5.6	0.5
S850 (°C)	78.5%	−3.7	0.3
S700 (°C)	75.5%	−1.1	0.6
SMUL (°C)	74.0%	−5.1	0.1
VIMFC (10^{-5} kg m^{-2} s^{-1})	73.0%	75.2	14.2

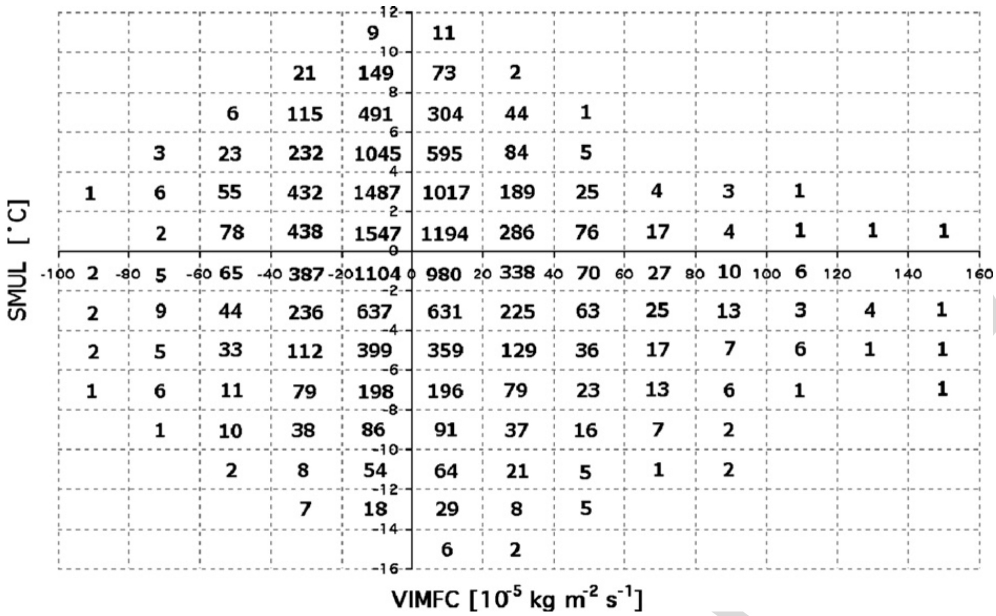

Fig. 5. Distribution of the 17,206 cases in parameter (VIMFC and SMUL) space.

6.4. Case study

On 22 September 22, 1992 a devastating flash flood occurred in the town of Vaison-La-Romaine in southeastern France with dozens of fatalities and huge property damage. The destructive flash flood of the river Ouvèze was caused by several slow moving Mesoscale Convective Systems producing extreme amounts of rain (220 mm within 3 h) in the morning and early afternoon in the area of the Ouvèze river and its side streams. All this water converged into Vaison-La-Romaine, which is very vulnerable for flash floods due to local topographic features (Sénési et al., 1996).

Although this case is excluded from the statistics of the previous sections, because of the uneven topography

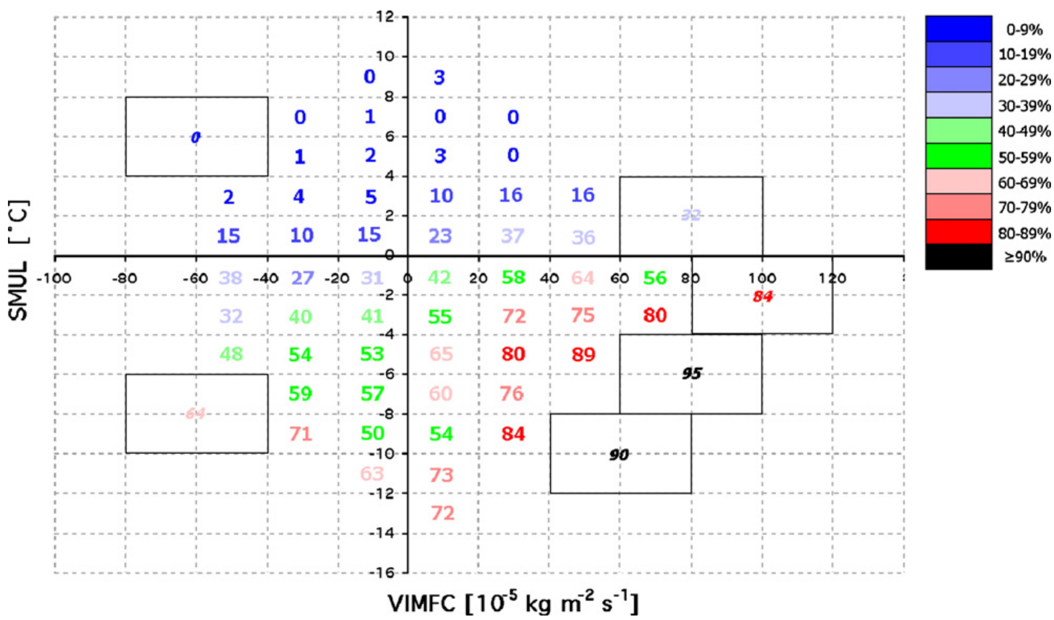

Fig. 6. TCP using "TC-6 hrs"-criteria as a function of SMUL and VIMFC. TCP per bin (20 units VIMFC and 2° SMUL) is given if there are 25 or more cases (Fig. 5). An indication of the thundery case probability in the more rare and extreme cases is given in italic by combining four bins if they contain a total of 25 or more cases.

in the area around Vaison-La-Romaine, we are nevertheless curious to see how well VIMFC and SMUL perform as thunderstorm predictors in this case. According to our calculations the VIMFC has a maximum value of 219.6 units near Vaison-La-Romaine at 12 UTC on September 22, 1992. VIMFC values over 75 units are observed in a large area surrounding Vaison-La-Romaine (Fig. 7a). According to our statistics using the "TCP-6 hrs" criteria and not taking into account the value of SMUL, this would imply a 73% probability of thunderstorms. However, when we take into account the low values of SMUL at 12 UTC (Fig. 7b), the TCP in the area around Vaison-La-Romaine may be estimated at approximately 95%. Although this estimate is not very accurate because the statistics in this extreme parameter range is based on relatively few cases (Fig. 5), Fig. 7d nevertheless clearly illustrates the usefulness of the combination of SMUL and VIMFC in predicting the

Table A1
Highest Heidke skill scores for "TC-3 hrs" criteria with corresponding threshold values and corresponding values of POD and FAR for all parameters

Index	Threshold	HEIDKE	POD	FAR
S1000 (°C)	≤−3.6	20.9%	41.4%	78.3%
S925 (°C)	≤−1.3	22.9%	41.8%	76.5%
S850 (°C)	≤0.2	24.3%	52.2%	77.1%
S700 (°C)	≤1.5	21.3%	37.6%	77.2%
SMUL (°C)	≤−3.7	21.6%	43.4%	78.1%
VIMFC (10^{-5} kg m^{-2} s^{-1})	≥22.0	19.5%	30.7%	77.2%

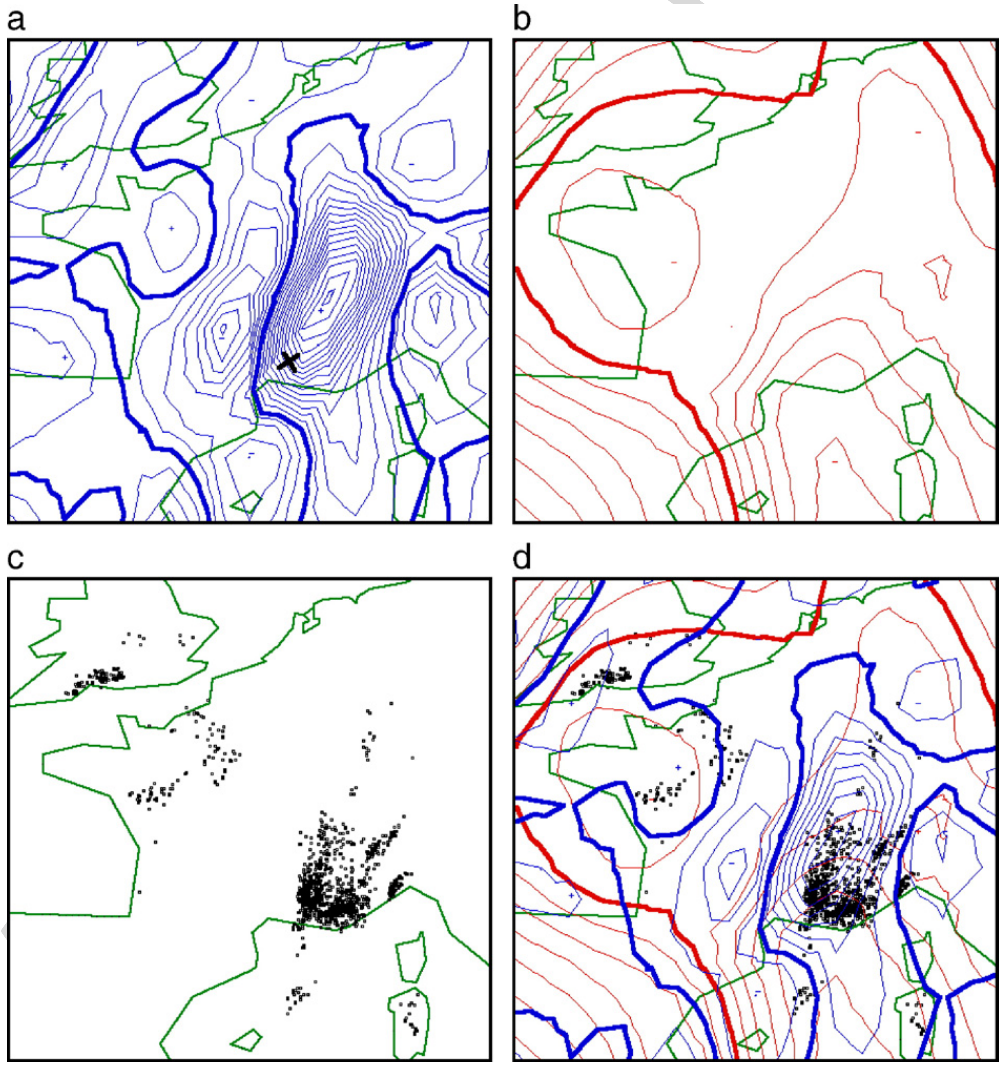

Fig. 7. (a) Distribution of VIMFC over Europe on September 22, 1992, 12 UTC (zero-contour: thick; contour interval is 10 units; lines are smoothed). The cross indicates the approximate location of Vaison-La-Romaine. (b) Distribution of SMUL over Europe on September 22, 1992, 12 UTC (zero-contour: thick; contour interval: 2 °C; lines are smoothed). (c) Lightning discharges (black dots) on September 22, 1992, between 12 and 18 UTC fixed by the ATD lightning detection system. (d) Distributions of VIMFC, SMUL on September 22, 1992, 12 UTC together with the locations of lightning discharges (black dots) between 12 UTC and 18 UTC.

Table A2
Highest TCP for "TC-3 hrs" criteria for all parameters with corresponding values and standard deviations

Index	TCP (TC-3 hrs)	Value	Std dev
S1000 (°C)	30.5%	−5.2	0.1
S925 (°C)	31.5%	−4.4	0.2
S850 (°C)	33.0%	−3.2	0.3
S700 (°C)	37.5%	−1.1	0.6
SMUL (°C)	30.0%	−5.2	0.1
VIMFC (10^{-5} kg m^{-2} s^{-1})	38.0%	77.8	16.7

occurrence of severe thunderstorms. Intense lightning activity was indeed observed in the area with both high VIMFC and low SMUL.

7. Conclusion and recommendation

We can now answer the main question posed in the introduction positively. Although VIMFC is a relatively bad dichotomous predictor of thunderstorm occurrence, together with the lifted index of the most unstable level (SMUL), it can certainly be very useful as an indicator of the *probability* of thunderstorm occurrence and it can also be an aid in better pinpointing the location of a possible future thunderstorm. It is important to remember that VIMFC is calculated by taking a mathematical derivative, and thus highly dependent on the spatial resolution of the analysis from which it is calculated. A data set with a better spatial resolution would much better resolve the extreme values of VIMFC. This would undoubtedly increase the performance of VIMFC as a thunderstorm predictor.

Table A3
Schematic 2 by 2 contingency table

		Event observed?		
		Yes	No	
Event forecast?	Yes	h	f	EF=h+f
	No	s	q	NEF=s+q
		E=h+s	NE=f+q	SS=h+s+f+q

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Appendix A. Results using the criteria of "TC-3 hrs"

With the criteria of "TC-3 hrs" it is more difficult to find a threshold value (Table A1). Maximum HEIDKE scores in this case are relatively low. All thresholds are found at lower values of SMUL and higher values of VIMFC. VIMFC still does not perform as well as the

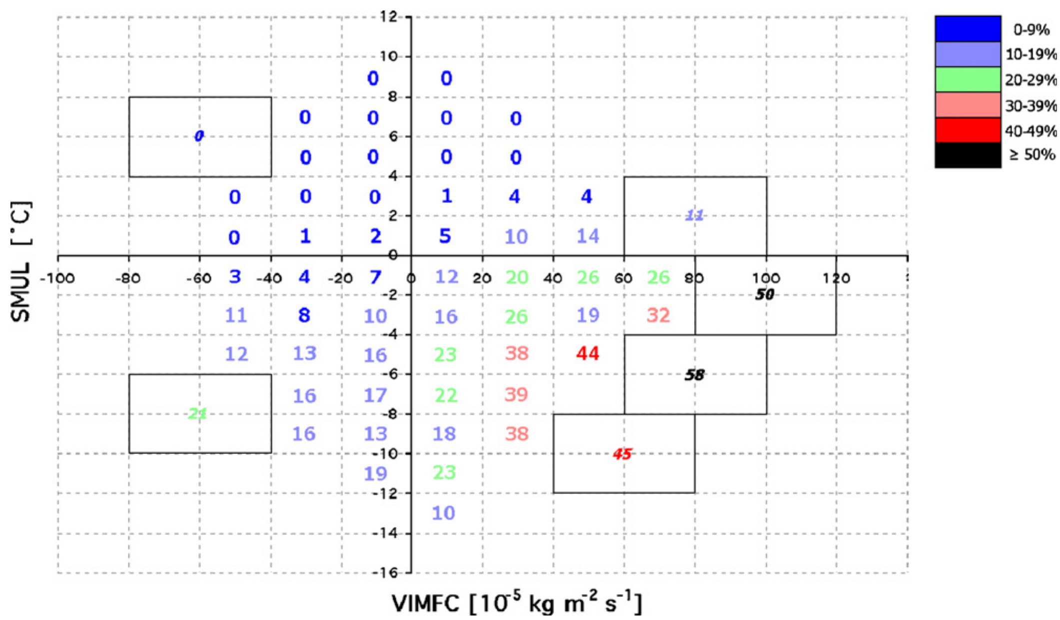

Fig. A1. TCP using "TC-3 hrs"-criteria as a function of SMUL and VIMFC. TCP per bin (20 units VIMFC and 2° SMUL) is given if there are 25 or more cases (Fig. 5). An indication of the thundery case probability in the more rare and extreme cases is given in italic by combining four bins if they contain a total of 25 or more cases.

stability indices but the performance of VIMFC is less affected by the more strict criteria. VIMFC has relatively strong gradients at small spatial scales. The spatial scale and the time scale of "TC-6 hrs" (100 km and 6 h, respectively) are probably too large compared to the time scale and spatial scale of the variations of VIMFC.

As far as the thundery case probability is concerned, the tightening of criteria again has more effect on the performance of the stability indices than on the performance of the VIMFC (compare Table A2 with Table 2).

The two-dimensional TCP-diagram corresponding to the "TC-3 hrs" criteria is displayed in Fig. A1 (compare this figure with Fig. 6). As expected, the TCP values are significantly lower with more strict criteria. Nevertheless, Fig. A1 again illustrates the value of combining SMUL and VIMFC when estimating the thunderstorm probability.

Appendix B. The 2 by 2 contingency table and verification parameters

Dichotomous (event/non-event) forecasts are often verified by using a 2 by 2 contingency table (Table A3). The letters h, s, f and q denote the number of correct event forecasts (hits), surprise events, false alarms and correct non-event forecasts ('quiescent' cases), respectively. In the most right column and lowest row of Table A3, the number of event forecasts (EF), non-event forecasts (NEF), events (E), and non-events (NE) are given, as well as the sample size (SS).

Different skill scores can be derived from the four independent entries in Table A3. Doswell et al. (1990) discuss eight ways in which ratios can be formed, involving each of these four entries with their associated marginal sums. Here we use only four (Table A4): the Probability of Detection (POD) and the False Alarm Ratio (FAR), True Skill Statistic (TSS) and the Heidke skill score (HEIDKE).

The POD gives the percentage of all events that are forecast. However, it is possible to create an artificially high POD by forecasting the event (too) often. For instance, if the meteorologist always forecasts the event ($E = h$), the POD will be 100%. To put things in the right perspective, the False Alarm Ratio (FAR) can then be used.

The True Skill Statistic, the TSS, takes the quiescent cases into account. Its definition is quite simple, namely the probability that an event is indeed forecast (POD) minus the probability that a non-event occurs unexpectedly (POFD).

Table A4
Skill scores and their interpretations

Skill score		Percentage of...	Definition
POD	Probability of detection	Expected events	h/E
FAR	False alarm ratio	False event forecasts	f/EF
TSS	True skill statistic	Expected events minus unexpected non-events	$h/E - f/\mathrm{NE}$
HEIDKE	Heidke skill score	Correct forecasts not due to chance	See text for definition

The Heidke Skill Score gives credit for all correct forecasts that were not merely due to chance. This yields a computation method with HEIDKE = (CF − CFC)/(SS − CFC), where the number of correct forecasts is denoted by CF and the expected number of correct forecasts due to chance by CFC. Obviously, CF = $h + q$. The expected number of correct forecasts due to chance (CFC) is the number of event forecasts times the event frequency plus the number of non-event forecasts times the non-event frequency. In symbolic notation: CFC = EF(E/SS) + NEF(NE/SS). With these definitions made, writing out the results and rearranging terms, the Heidke Skill Score can be written as

$$\mathrm{HEIDKE} = \frac{(h+s)(q-f)+(h-s)(q+f)}{(h+s)(s+q)+(h+f)(q+f)} = \frac{(E)(q-f)+(\mathrm{NE})(h-s)}{(E)(\mathrm{NEF})+(\mathrm{NE})(\mathrm{EF})}.$$

We see that all correct forecasts (h and q) are rewarded whereas all incorrect forecasts (s and f) are penalized, but everything in a controlled way. A perfect forecast, $s = 0$ and $f = 0$, would imply HEIDKE = 1. For a totally random forecast, $q = f$ and $h = s$, and HEIDKE = 0.

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