Supplementary material

S1. FSS statistic

The fractions skill score (FSS; Roberts and Lean, 2008) statistic is defined for each rainfall threshold (q) using a binary field (I) that equals 1 wherever pixel values are $\geq q$, and 0 elsewhere. Thus, the fraction of radar-derived (observed) pixels for a given rainfall threshold over a given neighborhood length n (i.e. spatial averaging) termed O_n and the similar modelled fraction derived from the WRF model (M_n) is used to calculate the MSE as follows:

(Eq. S1) $MSE_n \equiv \overline{(O_n - M_n)^2}$

where overbar denotes averaging. The MSE is then used to calculate the FSS:

(Eq. S2) $FSS_n \equiv \frac{MSE_n - MSE_{(n)ref}}{MSE_{(n)perfect} - MSE_{(n)ref}} = 1 - \frac{MSE_n}{MSE_{(n)ref}}$,

where $MSE_{(n)perfect} \equiv 0$ is the MSE of a perfect forecast, and $MSE_{(n)ref} \equiv \overline{O_n^2} + \overline{M_n^2}$.
The uniform FSS is defined as half of the way between a random forecast and a perfect skill forecast:

(Eq. S3) $FSS_{(n)uniform} \equiv \frac{1+f_{(n)O}}{2}$,

where f_O is the observed frequency. I.e. the fraction of observed pixels exceeding the threshold over the entire domain using a neighborhood length of size n.

S2. SAL analysis

The structure-amplitude-location analysis (SAL; Wernli et al., 2008) shown in the text also requires setting up a rainfall threshold (f) that enables a distinction between precipitation objects that are greater than this threshold. Following is a summary of the calculation of each of the three components of SAL:

A-component (amplitude):

(Eq. S4) $A = \frac{\overline{R_M} - \overline{R_O}}{\frac{1}{2}(\overline{R_M} + \overline{R_O})}$,

Where R is the rainfall accumulation field and M and O denote modelled (WRF) and observed (radar) rain, respectively, and $A \in [-2,2]$.

The L-component (location) is a sum of two components. The first one (L_1) is a normalised measure of the distance between the center of mass of the modeled and observed rain fields, and the second (L_2)

considers the average distance between the center of mass of the total precipitation fields and individual precipitation objects within them, as follows:

(Eq. S5) $L_1 = \frac{|x_M - x_O|}{d}$,

where x denotes the center of mass of a rain field and d is the largest possible geographic distance along the considered domain.

The second location component (L_2) wheights each precipitation object using its total amount of rain (R_n) using a weighted average distance:

(Eq. S6) $r = \frac{\sum_{n=1}^{M} R_n |x - x_n|}{\sum_{n=1}^{M} R_n}$,

where n is an index of precipitation objects ranging from 1 to the number of objects existing (M). L_2 is computed through the difference between the modelled distance (r_M) and the observed one (r_O), calculated according to eq. A7, for the modelled and observed precipitation objects, respectively.

(Eq. S7) $L_2 = 2(\frac{|r_M - r_O|}{d})$

Finally, the L-component is simply the sum of L_1 and L_2:

(Eq. S8) $L = L_1 + L_2$

where $L \in [0,2]$.

The S-component (structure) is calculated through a scaled volume of each precipitation object (V_n):

(Eq. S9) $V_n = \frac{R_n}{R_n^{max}}$,

where R_n^{max} is the maximum rainfall value of the precipitation object n. The weighted mean of scaled volume is calculted through:

(Eq. S10) $V = \frac{\sum_{n=1}^{M} R_n V_n}{\sum_{n=1}^{M} R_n}$,

Which is then used to calculate the S-component:

(Eq. S11) $S = \frac{V_M - V_O}{\frac{1}{2}(V_M + V_O)}$,

where V_M and V_O represent the scaled volume calculated using the modelled and observed rain fields, respectively, and $S \in [-2,2]$.

S3. HPEs identified and analysed

Table S1 – HPEs identified and analysed in this study

HPE #	Start time*	End time*	Synoptic classification[#]	HPE duration [h]						
				1	3	6	12	24	48	72
1	2-11-1991 9:00	5-11-1991 9:00	MC	X	X	X	X	X	X	X
2	22-2-1992 8:00	27-2-1992 21:00	MC						X	X
3	23-11-1992 9:00	26-11-1992 7:00	MC	X	X	X	X			
4	12-12-1992 14:00	18-12-1992 13:00	MC	X	X	X	X	X	X	X
5	31-3-1993 9:00	2-4-1993 2:00	ARST			X				
6	21-12-1993 12:00	23-12-1993 15:00	ARST						X	
7	21-2-1994 19:00	25-2-1994 0:00	MC		X	X	X			
8	1-11-1994 15:00	7-11-1994 13:00	ARST	X	X	X	X	X	X	X
9	14-11-1994 1:00	18-11-1994 5:00	MC	X	X	X	X	X	X	X
10	15-12-1994 12:00	20-12-1994 21:00	MC	X	X			X	X	X
11	28-12-1994 10:00	31-12-1994 23:00	MC			X				
12	4-2-1995 8:00	9-2-1995 10:00	MC					X	X	X
13	1-11-1995 11:00	3-11-1995 14:00	MC	X	X					
14	7-11-1995 10:00	10-11-1995 17:00	MC							X
15	6-3-1996 13:00	8-3-1996 4:00	MC		X	X	X	X	X	
16	11-12-1996 14:00	14-12-1996 15:00	ARST	X	X	X	X	X	X	X
17	13-1-1997 11:00	17-1-1997 7:00	MC	X	X	X	X	X	X	X
18	3-3-1997 6:00	4-3-1997 16:00	MC	X	X	X	X			
19	19-10-1997 11:00	20-10-1997 10:00	MC		X	X	X			
20	25-11-1997 10:00	27-11-1997 9:00	ARST		X	X	X	X		
21	4-4-1998 4:00	4-4-1998 17:00	MC			X	X			
22	28-12-1998 6:00	31-12-1998 21:00	MC							
23	13-12-1999 6:00	15-12-1999 8:00	MC	X	X	X	X			
24	18-1-2000 6:00	24-1-2000 2:00	MC		X	X	X	X	X	X
25	25-1-2000 15:00	28-1-2000 20:00	MC	X	X	X	X	X	X	X
26	12-2-2000 22:00	16-2-2000 16:00	MC	X	X	X	X	X	X	X
27	29-11-2000 0:00	1-12-2000 10:00	MC				X	X	X	X
28	19-12-2000 6:00	21-12-2000 17:00	MC	X	X					
29	30-4-2001 9:00	2-5-2001 17:00	MC	X	X	X	X	X	X	X
30	9-12-2002 6:00	12-12-2002 6:00	MC		X	X	X	X	X	X
31	2-1-2003 16:00	4-1-2003 12:00	MC		X	X				
32	27-1-2003 10:00	30-1-2003 13:00	MC	X	X	X	X	X		X
33	3-2-2003 0:00	5-2-2003 16:00	MC				X	X	X	
34	17-2-2003 19:00	22-2-2003 23:00	MC						X	X
35	24-2-2003 1:00	28-2-2003 2:00	MC				X	X	X	X

36	1-12-2003 14:00	5-12-2003 20:00	ARST	X	X	X	X	X	X	X
37	14-12-2003 16:00	15-12-2003 10:00	MC	X	X	X	X	X		
38	15-12-2005 15:00	18-12-2005 9:00	MC		X	X	X			
39	18-12-2007 14:00	21-12-2007 8:00	MC			X	X	X	X	
40	2-1-2008 3:00	5-1-2008 19:00	MC		X	X	X	X	X	X
41	17-1-2010 16:00	22-1-2010 6:00	MC	X	X	X	X	X	X	X

*Local winter time (UTC+2).

[#]Simplified synoptic classification (Sect. 3.4).