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Supplement of

Radar-based characterisation of heavy precipitation in the eastern Mediterranean and its representation in a convection-permitting model

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Supplementary material

S1. Fractions Skill Score (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 neighbourhood length n (i.e., spatial averaging), termed O_n, and the similar modelled fraction derived from the Weather Research and Forecasting (WRF) model (M_n), are used to calculate the mean square error (MSE) as follows:

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

where the 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 halfway 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 neighbourhood length of size n.

S2. Structure–amplitude–location (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 distinguishing 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 the sum of two components. The first one (L_1) is a normalised measure of the distance between the centre of mass of the modelled and observed rain fields, and the second (L_2)

considers the average distance between the centre 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 centre of mass of a rain field and d is the largest possible geographical distance along the considered domain.

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

(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. S7, 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 the scaled volume is calculated 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. Heavy precipitation events (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	X	X	X	X	X		
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), presented as day-month-year and hour.

#Simplified synoptic classification (Sect. 3.4 in the main text).

S4. WRF namelist.input file example

```
&time_control
 run_days                 = 0,
 run_hours                = 138,
 run_minutes              = 0,
 run_seconds              = 0,
 start_year               = 2010, 2010, 2010,
 start_month              = 01,   01,   01,
 start_day                = 16,   16,   16,
 start_hour               = 12,   12,   12,
 start_minute             = 00,   00,   00,
 start_second             = 00,   00,   00,
 end_year                 = 2010, 2010, 2010,
 end_month                = 01,   01,   01,
 end_day                  = 22,   22,   22,
 end_hour                 = 06,   06,   06,
 end_minute               = 00,   00,   00,
 end_second               = 00,   00,   00,
 interval_seconds         = 21600
 input_from_file          = .true.,.true.,.true.,
 history_interval         = 360,  180,   10,
 frames_per_outfile       = 1, 1, 1,
 restart                  = .false.,
 restart_interval         = 1440,
 io_form_history          = 2,
```

```
 io_form_restart                 = 2,
 io_form_input                   = 2,
 io_form_boundary                = 2,
 debug_level                     = 0,
iofields_filename = “varsNot2Use_d01.txt”, “varsNot2Use_d02.txt”, "varsNot2Use_d03.txt",
ignore_iofields_warning = .true.,
 /
 &domains
 time_step                       = 8,
 time_step_fract_num             = 0,
 time_step_fract_den             = 1,
use_adaptive_time_step           = .true.,
 step_to_output_time             = .true.,
 target_cfl                      = 1.2, 1.2,1.2,
 target_hcfl                     = .84, .84,0.84,
 max_step_increase_pct           = 5, 51,51,
 starting_time_step              = -1, -1,-1,
 max_time_step                   = -1, -1,-1,
 min_time_step                   = -1, -1,-1,
 adaptation_domain               = 1,
 max_dom                         = 3,
 e_we           =  100, 221, 551,
 e_sn           =  100,  221, 551,
 e_vert                          = 68,    68,    68,
 p_top_requested                 = 2500,
 num_metgrid_levels              = 61,
 num_metgrid_soil_levels         = 4,
 dx                              = 25000, 5000,  1000,
 dy                              = 25000, 5000,  1000,
 grid_id                         = 1,     2,     3,
 parent_id                       = 0,     1,     2,
 i_parent_start   =   1,  28, 55,
```

```
j_parent_start    =   1,  28, 55,
parent_grid_ratio                = 1,     5,     5,
parent_time_step_ratio           = 1,     5,     5,
feedback                         = 1,
smooth_option                    = 0,
/

&physics
mp_physics                                 = 8, 8, 8,
cu_physics                                 = 6, 6, 0,
ra_lw_physics                              = 4, 4, 4,
ra_sw_physics                              = 4, 4, 4,
bl_pbl_physics                             = 2, 2, 2,
sf_sfclay_physics                          = 2, 2, 2,
sf_surface_physics                         = 2, 2, 2,
radt                        = 15,    15,    15,
bldt                        = 0,     0,     0,
cudt                        = 2,     2,     2,
icloud                      = 1,
isfflx                                     = 1,
ifsnow                                     = 1,
num_soil_layers                  = 4,
num_land_cat                     = 21,
sf_urban_physics                 = 0,     0,     0,
surface_input_source                       = 1,
/

&fdda
/

&dynamics
w_damping                        = 1,
```

```
diff_opt                        = 1,      1,      1,
km_opt                          = 4,      4,      4,
diff_6th_opt                    = 0,      0,      0,
diff_6th_factor                 = 0.12,   0.12,   0.12,
base_temp                       = 290.
damp_opt                        = 3,
zdamp                           = 5000.,  5000.,  5000.,
dampcoef                        = 0.2,    0.2,    0.2
khdif                           = 0,      0,      0,
kvdif                           = 0,      0,      0,
epssm                           = 0.2,    0.2,    0.2,
non_hydrostatic                 = .true., .true., .true.,
moist_adv_opt                   = 1,      1,      1,
scalar_adv_opt                  = 1,      1,      1,
gwd_opt                         = 1,
/

&bdy_control
spec_bdy_width                  = 5,
spec_zone                       = 1,
relax_zone                      = 4,
specified                       = .true., .false.,.false.,
nested                          = .false., .true., .true.,
/

&grib2
/

&namelist_quilt
nio_tasks_per_group = 0,
nio_groups = 1,
/
```

S5. Figures

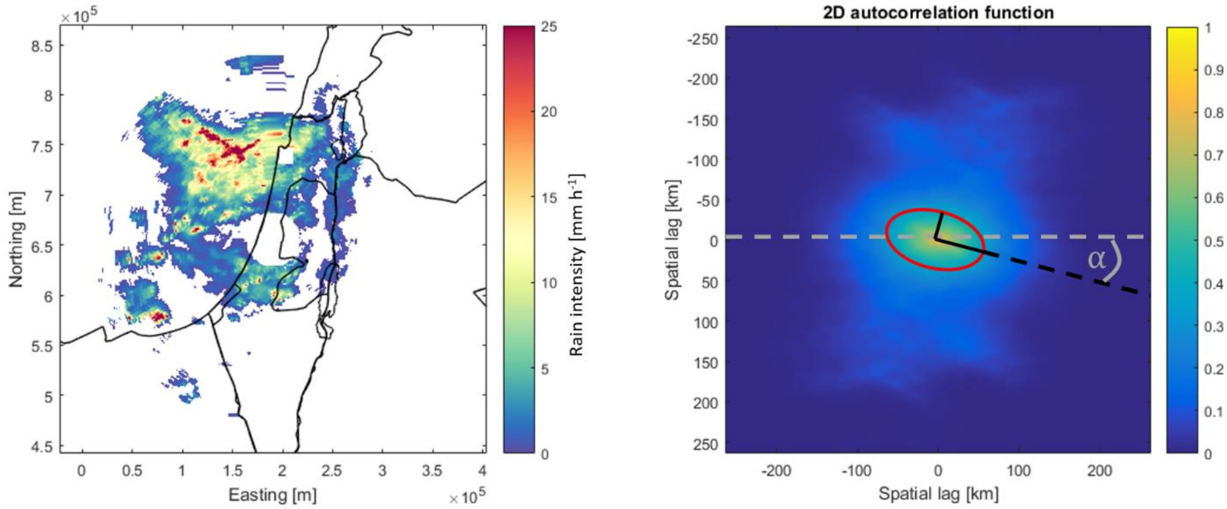

Figure S1: An example of the spatial autocorrelation analysis (Sects. 3.5.4, 4.4.2 in the main text). The left panel shows a 10-min rainfall map based on radar data from HPE #1. The right panel shows the 2-D autocorrelation field of the same map. The red ellipse represents the approximate e^{-1} correlation region and its axes are in black. Deviation of the major axes from the east-west axis (grey) is denoted α. The short-to-long axis ratio defines the ellipticity of the autocorrelation field.

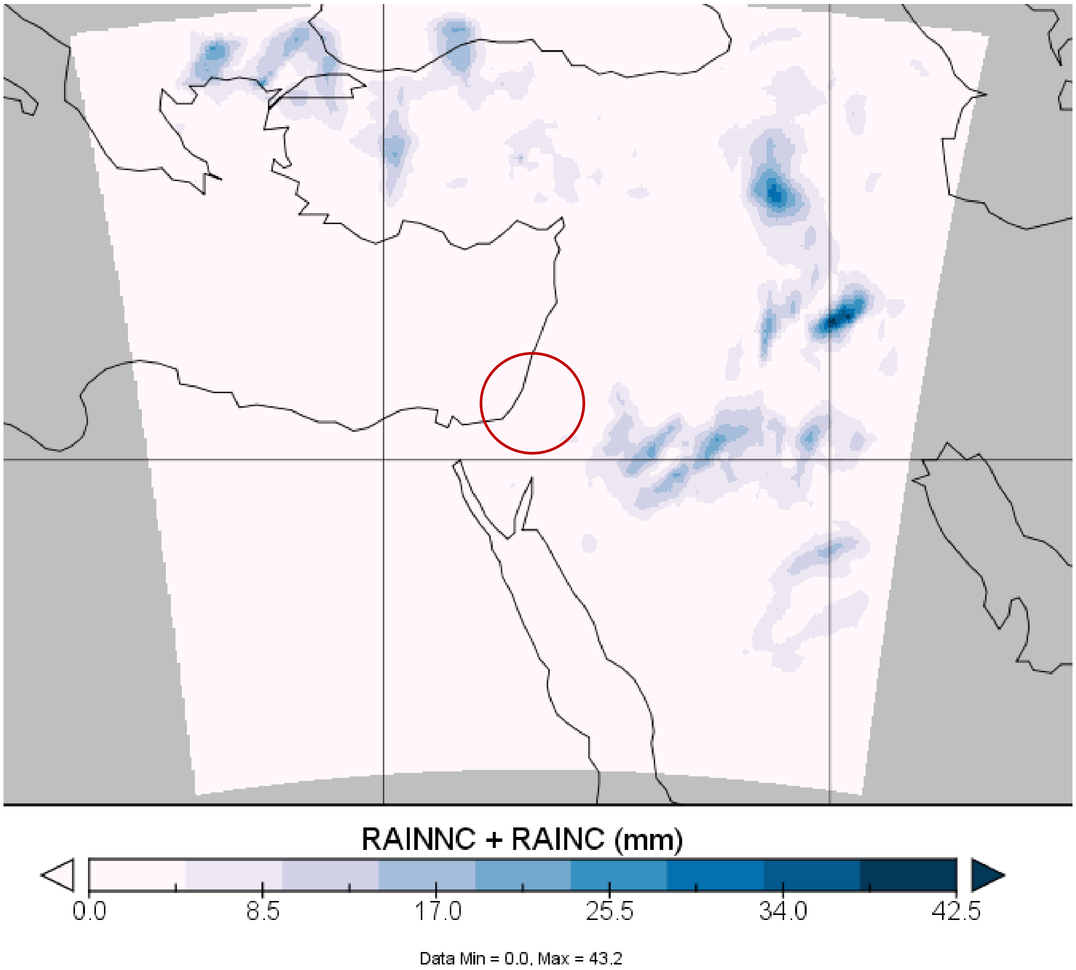

Figure S2: Accumulated precipitation (convective [RAINC] + non-convective [RAINNC] rainfall) in the coarsest WRF domain during HPE #5 (Table S1) and the approximate range of the Shacham radar (Fig. 1 in the main text). Notice the absence of rainfall within the radar range, as opposed to the radar QPE (Fig. 8a in the main text).