Extreme precipitation projections by a convective-permitting regional climate model — T2-04

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Abstract

Southern UK extreme precipitation projections for the end-of-21st-century are simulated by the GCM-driven Met Office 1.5-km very-high-resolution convective permitting ("explicit convection") limited-area regional climate model. Such explicit convection models avoid known physical issues that are caused by convective parameterisation [7]. Furthermore, these simulations are continuous over multiple years (i.e. not seasonal slices), so that land-surface feedbacks are reasonably captured.

Air temperatures for extreme wet days are projected to increase by approximately $4-5$K. Summer (JJA) extreme precipitation intensities are projected to increase by about 30%, and are consistent with the expectations from the Clausius - Clapeyron (CC) relation [$\approx 6.5\% \cdot \mathrm{K}^{-1}$; 15]. We note that the higher temperature days in the future climate simulation have suppressed precipitation intensities, and this phenomenon is actually noted in observations in the warmer regions [5]. These high temperature days are not simulated in the control climate simulation.

The occurrence of precipitation in summer is projected to decline substantially (by as much as 50%) in the future climate, and this leads to a smaller but still significant ($\approx$ 10%) increase in future summer return levels. The large event frequency decline is also found with coarser RCMs which give different intensities and return level projections [8]. Hence, the summer model guidance can be summarised as "less frequent precipitation, but more intense if it does".

A much larger increase ($50+$%) of winter (DJF) return levels are projected by the future climate simulation. Unlike the summer, no significant changes in precipitation frequencies are found. A similar CC scaling relationship is found for the winter increases.

The 1.5-km limited-area model

The 1.5-km southern-UK limited-area "convective permitting" (explicit convection) model is based on the Met Office operational UKV NWP model. Despite the model having positive precipitation biases, it has a more realistic representation for diurnal variability, precipitation duration, and extreme events [7, 1].

Lateral boundary conditions are provided by 12-km European regional simulations, which are driven by:

- ERA-Interim reanalysis [3]
- HadGEM3 GA3 present-climate simulation [17]
- HadGEM3 GA3 RCP8.5 end-of-C21 simulation [12]

It is hoped that the 1.5-km model to have more realistic extremes and temperature scaling relationships. Analysis here is carried out at the 12-km resolution.

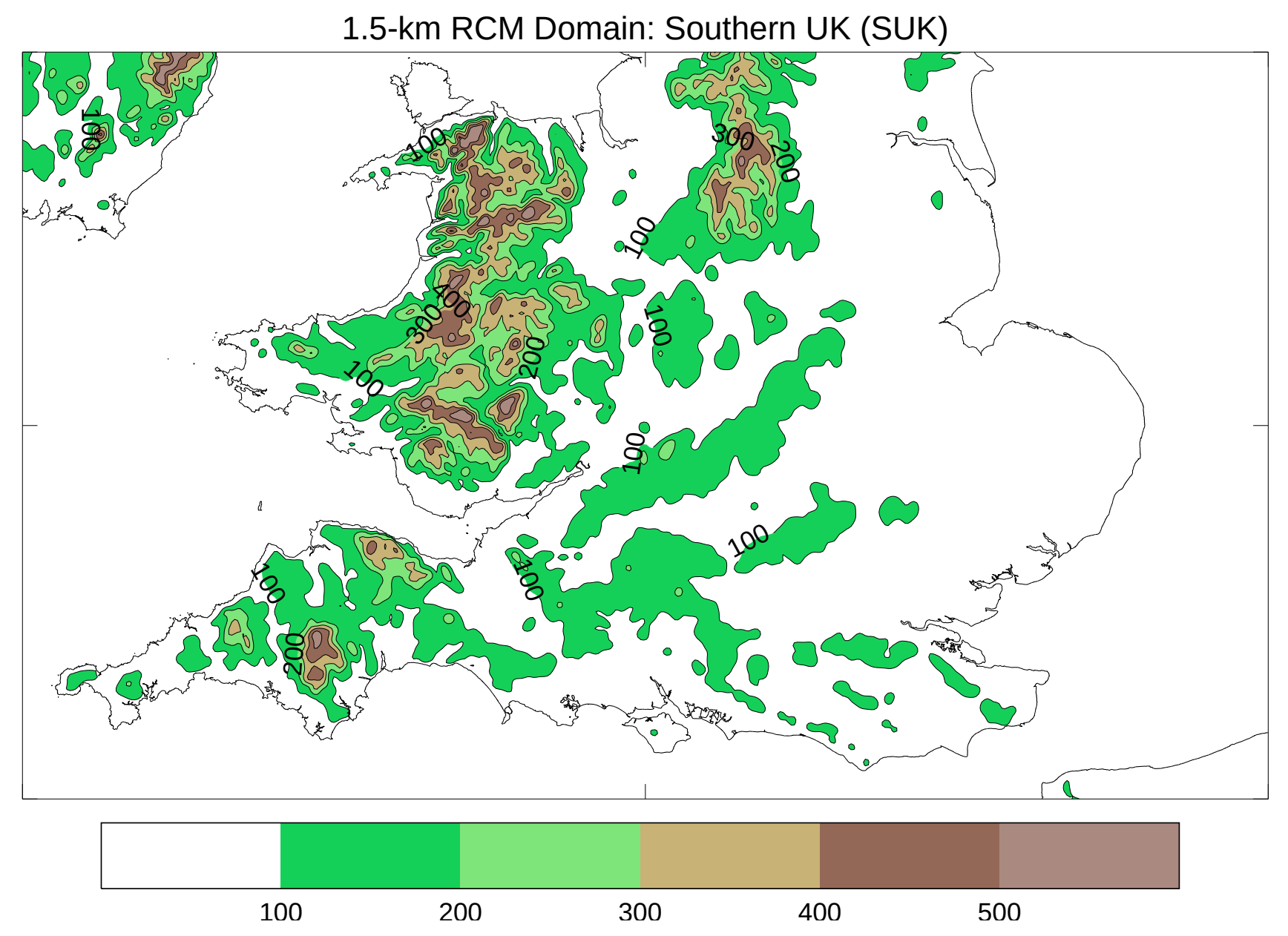


Figure 1: Inner domain of the 1.5-km model with orography

Extremes in the 1.5-km limited-area model

Extremes are estimated by fitting the generalised Pareto distribution to hourly and daily totals that exceed the 95th percentile (q_{95}) with a minimum "wet value" threshold of 0.1mm [Peaks-over-threshold; 2, 11]. Data samples are declustered to account for autoregressive nature of precipitation [4].

We compare our model estimates with radar-estimated return levels. Radar precipitation has been proven to be reasonable enough for extreme analysis [13].

$$z\left(n|t,\sigma,\xi\right)=\begin{cases} t+\frac{\sigma}{\xi}\left[\left(\lambda n\right)^{\xi}-1\right] & \xi\neq 0 \\ t+\sigma\ln\left[\lambda n\right] & \xi=0\end{cases} \qquad (1)$$

- n = Return period (yr)
- z = Return level (mm/...)
- t = q_{95} extreme threshold (mm/...)
- σ = Scale parameter (akin to standard deviation; mm/...)
- ξ = Shape parameter (akin to skewness; dimensionless)
- λ = Event frequency (yr^{-1})

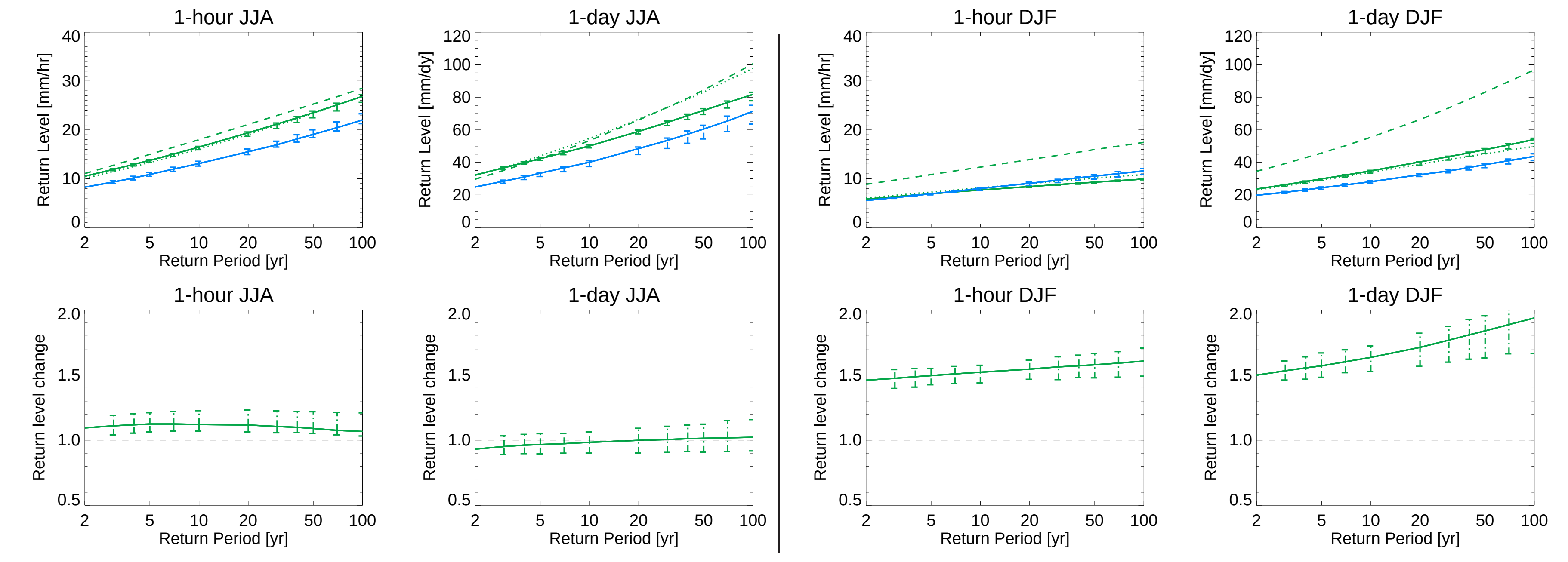


Figure 2: Upper panels: southern UK spatial median return levels for 1-hr ($\frac{\mathrm{mm}}{\mathrm{hr}}$) and 1-day ($\frac{\mathrm{mm}}{\mathrm{day}}$) precipitation; green for the 1.5-km RCM, and blue for radar observations; solid line for reanalysis downscaling simulations, and short/long dashes for present/future-climate simulations. Bottom panels: the change (Future/Present) for the spatial median between the G-P and G-F simulation. CIs estimated by year jackknives.

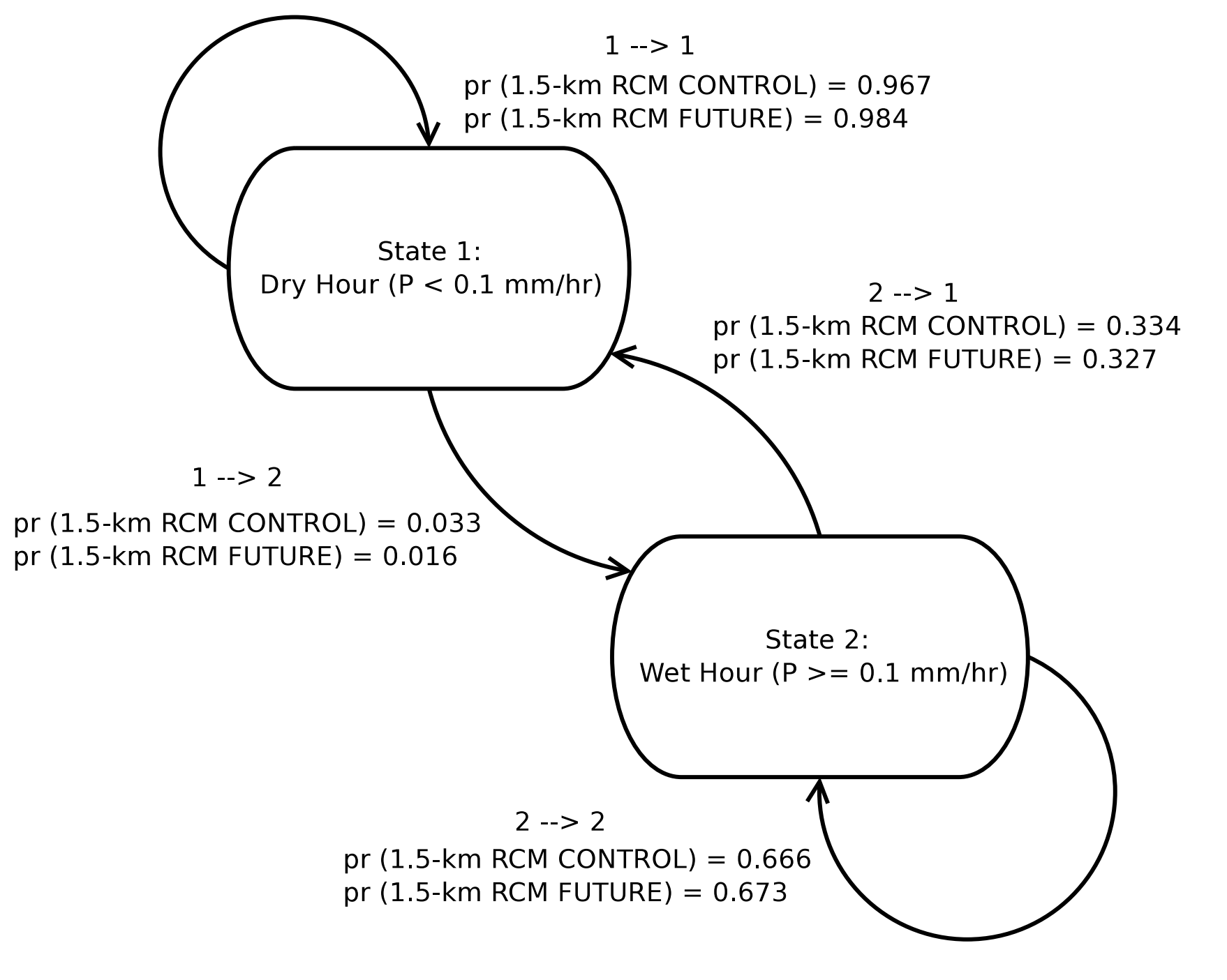
JJA

- Consistent overestimate of intensity in the reanalysis and present-climate simulation relative to radar
- Consistent $\approx$ 10% increase of 1-hr return levels
- Negligible change for 1-day return levels

DJF

- Overestimation of 1-day return levels in the present-climate/reanalysis simulations
- $50+$% increase in both daily and hourly totals
- Projected DJF 1-day return levels as large as JJA

Frequency of precipitation in the 1.5-km model


1 --> 1
pr (1.5-km RCM CONTROL) = 0.967
pr (1.5-km RCM FUTURE) = 0.984

State 1:
Dry Hour (P < 0.1 mm/hr)

2 --> 1
pr (1.5-km RCM CONTROL) = 0.334
pr (1.5-km RCM FUTURE) = 0.327

1 --> 2
pr (1.5-km RCM CONTROL) = 0.033
pr (1.5-km RCM FUTURE) = 0.016

State 2:
Wet Hour (P >= 0.1 mm/hr)

2 --> 2
pr (1.5-km RCM CONTROL) = 0.666
pr (1.5-km RCM FUTURE) = 0.673

Figure 3: The 1.5-km-model-simulated JJA Markov stochastic matrix between "dry" (state 1) and "wet" hours (state 2).

	1.5G-P	1.5G-F	1.5G-P	1.5G-F
JJA	1-hr		1-day	
$\lambda[\mathrm{yr}^{-1}]$	4.82	2.27	1.96	1.07
DJF	1-hr		1-day	
$\lambda[\mathrm{yr}^{-1}]$	6.44	6.09	2.50	2.40

Table 1: JJA/DJF 1-hr/1-day frequency of events (λ) exceeding q_{95} for the GCM downscaling simulation (G-P: present-, G-F: future-)

- Large JJA declines in λ and precipitation initiation probability (1-1 in Figure 3)
- Consistent with JJA RH declines in the future simulation ($\approx$ 8%) [not shown]
- JJA intense precipitation intensifies by $30+$% [8], but return level increases are moderated by λ reductions
- JJA - Longer dry spells, heavier precipitation
- Much smaller λ change projected for DJF

The C-C scaling relationship

C-C scaling hypothesis [15]: If relative humidities during wet periods are constant, precipitation intensities should follow a climate sensitivity relationship with temperature as given by the thermodynamic C-C equation:

$$\frac{\Delta P}{P}\approx\frac{\Delta e_s}{es},\quad \frac{1}{e_s}\frac{\partial e_s}{\partial \mathrm{T}}=\frac{L}{R_v\mathrm{T}^2}\Rightarrow\frac{\Delta P}{P}\approx\frac{\Delta e_s}{es}\approx\gamma\Delta\mathrm{T},\quad \gamma=\frac{L}{R_v\overline{\mathrm{T}}^2}\approx 0.05-0.07\mathrm{K}^{-1}\text{for }\frac{\Delta \mathrm{T}}{\overline{\mathrm{T}}}\ll 1$$

For $\overline{\mathrm{T}}\approx 13^{\circ}$C, $\gamma\approx 6.5\%\cdot\mathrm{K}^{-1}$.

Surface air temperature scalings as high as 2γ ("super-scaling") have been observed in the Netherlands and Hong Kong [9, 10]. However, negative scalings for hourly precipitation have been observed at warm temperatures in northern Australia and Japan [$25+^{\circ}$ C; 5, 16].

The hourly scaling relationships are usually diagnosed by picking the maximum hourly intensities from each wet day ($P_{\text{max,1-hr}}$), and comparing them with the daily mean near-surface air temperature: $\mathrm{T}_{\text{avg}}=\frac{\mathrm{T}_{\text{max}}+\mathrm{T}_{\text{min}}}{2}$. $P_{\text{max,1-hr}}$s are binned according to T_{avg}, and n-th quantile (q_n) of each bin is estimated. Here we do the same with gridded model and UK observational data, and pool values from neighbouring grid points (3-by-3 moving boxes).

Intensity dependency on temperature for observations and the 1.5-km limited-area model

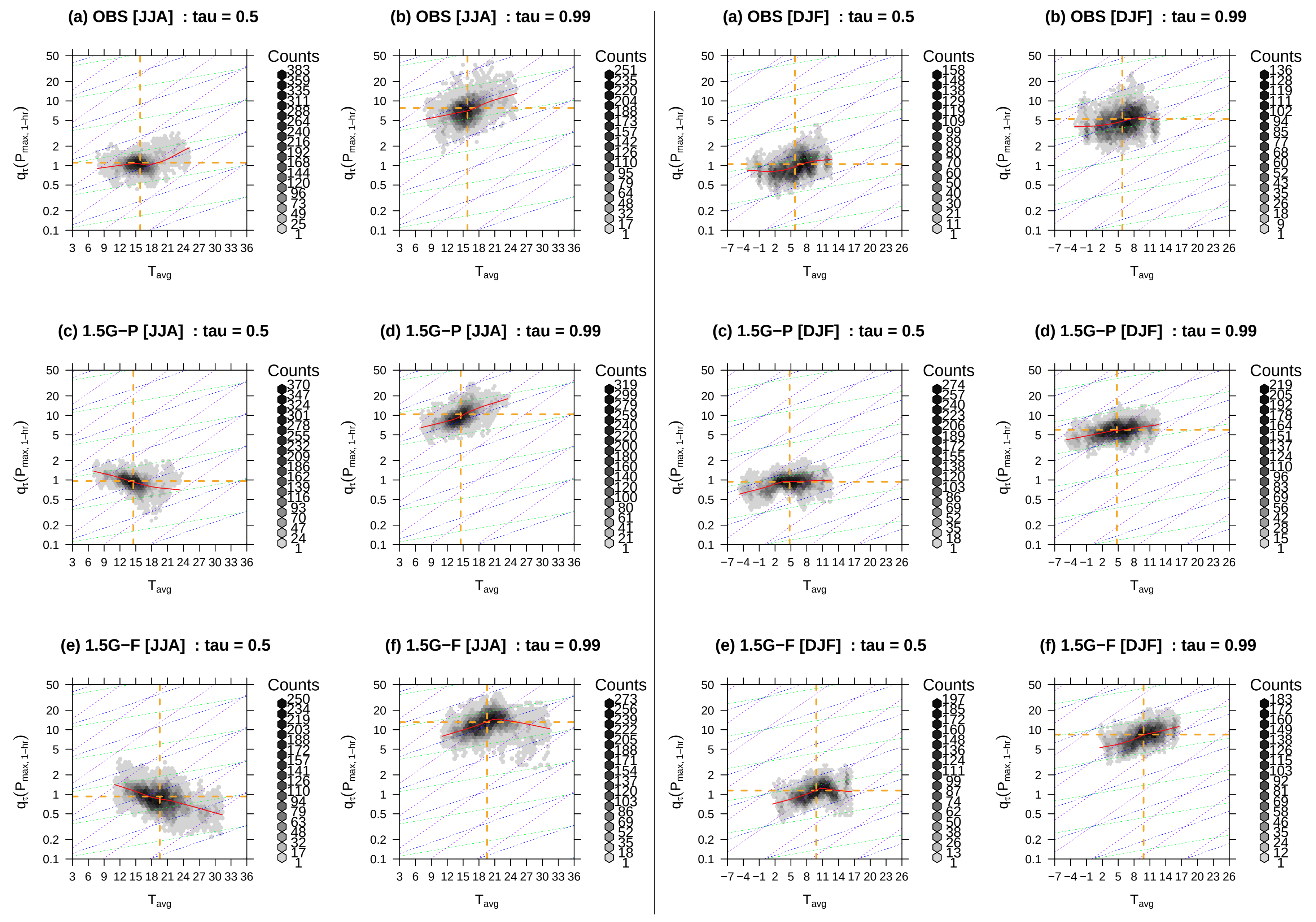


Figure 4: The locally-estimated JJA (left) & DJF (right) T_{avg} bins and $q_{\tau}(P_{\text{max,1-hr}})$ pairs are spatially pooled, and visualized with hexagon x-y scatter density plots. The x- and y-axis represent the T_{avg} bins and $q_{\tau}(P_{\text{max,1-hr}})$ respectively. The observed, 1.5-km present- (G-P) and future-climate (G-F) simulation are in the upper, middle, and lower rows respectively. Solid-red lines indicate the LOESS-estimated relationship between $log_{10}(q_{\tau}(P_{max,1-hr})$ and $\mathrm{T}_{avg})$, and the orange dashes indicate the mean quantile value ($E(q_{\tau}(P_{\text{max,1-hr}}))$) and temperature ($E(\mathrm{T}_{\text{avg}})$). The dashed green, blue, and purple lines indicate $\frac{1}{2}\gamma$, γ, and 2γ respectively. q_{50} and q_{99} are examined.

UK observations

- Data: Met Office radar and surface temperature observations [6, 14]
- Scalings for JJA q_{50} are generally sub-γ and non-negative
- JJA q_{99} are on the order of γ
- DJF q_{99} scalings do not appear to differ substantially from q_{50}
- High temperature turning points (found in the future simulation) are observed in lower latitudes [5, 16]

Model - JJA

- q_{50}: Precipitation intensities decrease with T_{avg} in all simulations
- q_{99}, present: Increases at γ
- q_{99}, future: Increases at γ till $\mathrm{T}_{\text{avg}}\approx 20^{\circ}$C, then turn negative
- $q_{75}+$ T_{avg} in the future simulation sees 15% RH suppression [not shown]
- Average q_{99} are up $\approx$ 25% as T_{avg} are up $\approx 5^{\circ}$C

Model - DJF

- Present-climate simulation scaling consistent with observations
- q_{50}: Steeper rate for lower temperatures, generally sub-γ scaling
- q_{99}: Sub- or at-γ scaling
- In winter, temperature aloft is possibly a better indicator for the air mass temperature
- Mean T_{avg} change gives γ scalings

Future Work

- Alternatives to surface air temperature - upper-air data, temperature-humidity combined measures
- Sub-hourly precipitation scaling - difficult to test in observations, but easy in models
- Circulation regimes and occurrence of extreme precipitation relative to low pressure systems
- Effects of aerosol coupling

Conclusions

- The 1.5-km model is generally able to simulate the UK present-climate scaling relationship and extreme event PDFs.
- Extreme events are projected to intensify - DJF intensification larger than JJA
- The 1.5-km model finds a decline in high precipitation intensities at high UK air temperatures
- Longer dry spells, more intense extremes
- Summer return level changes more moderate than intensity change due to precipitation frequency declines
- Future warm days may see precipitation suppression

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