Clausius-Clapeyron temperature-precipitation scaling over the UK in high-resolution climate models

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Abstract

The temperature dependencies for UK hourly precipitation intensity are diagnosed from observations and Met Office high-resolution (1.5km) explicit-convection multi-year present- and future-climate simulations. The observed relationships have been diagnosed elsewhere [7, 8, 4, 14], but not for the UK nor with such high-resolution (future-climate) model simulations. In the present climate simulations, precipitation intensities are found to increase according to the Clausius-Clapeyron relationship [13]. In the future climate simulations, the intensities of heavy precipitation increase as temperatures increase. However for the hottest days, there is a drop-off in precipitation intensity; indicating present relationship may not apply for the future.

The Clausius-Clapeyron scaling relationship

Hypothesis[13]: if the relative humidity during wet periods are to stay constant, precipitation intensities should follow a climate sensitivity relationship with temperature that are given by the Clausius-Clapeyron equation as long as the temperature perturbations are small:

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

$L \approx 2.47 \times 10^6 \mathrm{J} \cdot \mathrm{kg}^{-1}$: enthalpy of vaporisation; $R_v \approx 461.5 \mathrm{J} \cdot \mathrm{K}^{-1} \cdot \mathrm{kg}^{-1}$: $H_2O_{(g)}$ gas constant. γ is mean temperature-dependent $(\overline{T})$ Clausius-Clapeyron precipitation increase rate. For $\overline{T} \approx 13°\mathrm{C}$, $\gamma \approx 6.5\% \cdot \mathrm{K}^{-1}$.

Station observations for some parts of the world have been shown to have surface air temperature dependencies that are as high as 2γ ["super-scaling"; 7, 8]. Such "super-scaling" relationships are believed to be caused by convective feedbacks and reduction of stratiform precipitation [2]. However, observations from Australia and Japan have shown that such high scalings do not apply for hourly precipitation at high surface air temperatures [25 +° C; 4, 14]; but "super-scaling" may still hold for sub-hourly precipitation [14]. Prior to this study, UK scaling relationships have not been examined, but there have been studies for places that have climates similar to the UK [US Pacific North-west; 9]. Another open question is the applicability of present relationship for the future, in which one must rely on model projections for the future.

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: $T_{\text{avg}} = \frac{T_{\text{max}} + T_{\text{min}}}{2}$. $P_{\text{max,1-hr}}$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). The analysis here uses a "wet-day" threshold of 0.1mm/hr.

The 1.5-km limited-area model

The 1.5-km southern-UK limited-area "convective permitting" (explicit convection) model is based on the 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 [6, 3].

Lateral boundary conditions are provided by 12-km limited-area simulations, which are driven by:

- HadGEM3 GA3 present-climate simulation [15]
- HadGEM3 GA3 future RCP8.5 end-of-21st century simulation [10]

Especially for 1.5-km grid cells, convection is not fully resolved, but we expect larger mesoscale systems to be better simulated than by lower-resolution models that use convection parameterisation. Hence, one hopes the 1.5-km model to have more realistic temperature - precipitation relationships.

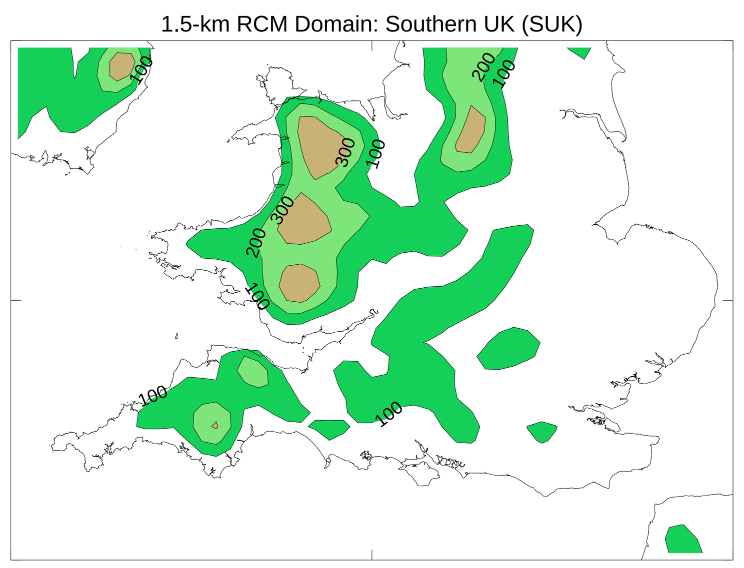

Figure 1: The inner domain of the 1.5-km model with surface height (at 12-km resolution)

Convective parameterisations are not intended to work properly at "grey-zone" ($\approx 2 - 50$ km) resolutions [11, 1] as the division between parameterised and resolved convection is blurred.

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

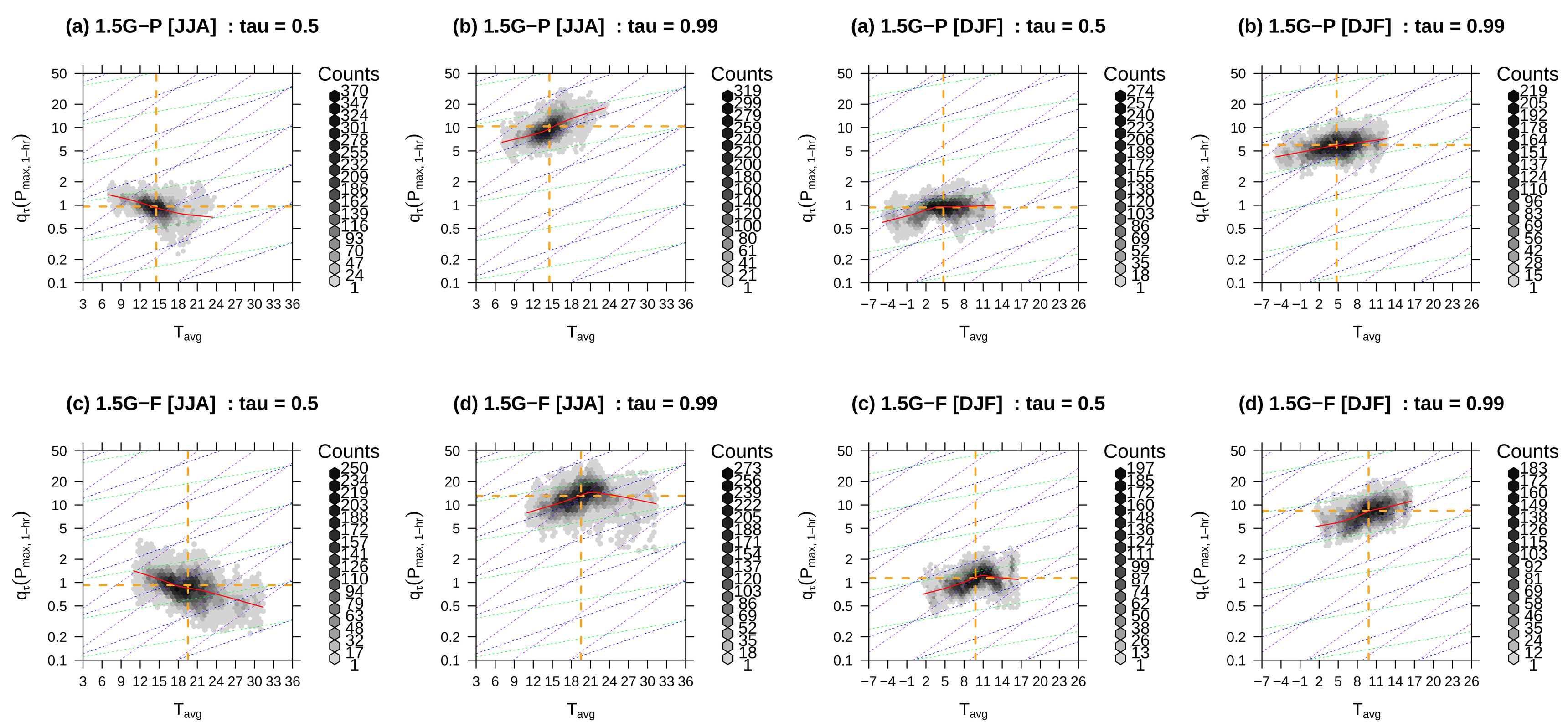

Figure 2: The locally-estimated JJA (left) & DJF (right) T_{avg} bins and $q_\tau(P_{\text{max,1-hr}})$ pairs are spatially pooled, and visualized with hexagon x-y scatter density plots. The x- and y-axis represent the T_{avg} bins and $q_\tau(P_{\text{max,1-hr}})$ respectively. The 1.5-km present- and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

JJA

- Most wet day temperatures are concentrated in a small temperature range
- q_{50}: Precipitation intensities decrease with temperature in both the present- and future-climate simulation
- q_{99}, present: Intensities increase with temperature at the rate of γ
- q_{99}, future: Increase at γ till $T_{\text{avg}} \approx 20°\mathrm{C}$, then turn negative at higher temperatures
- Average intensities for q_{99} are increased by $\approx 25\%$ as T_{avg} increased by $\approx 5°\mathrm{C}$

DJF

- q_{50}: Increase at steeper rate for lower temperatures, but are generally sub-γ scaling
- q_{99}: Dependencies on T_{avg} are below or at γ
- In winter, temperature aloft (say 850-hPa) is possibly a better indicator for the air mass temperature as air mass may be from somewhere else with stronger advection aloft; summer lower troposphere is more well mixed
- Mean shifts of temperature and intensity between present and future simulation do indicate γ scalings

Results - Observed estimates of the relationship

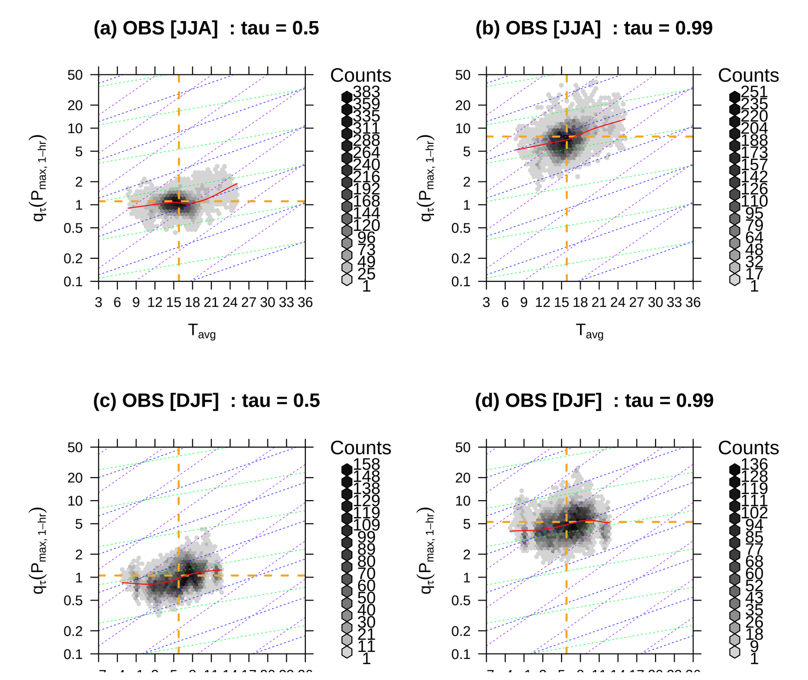

Figure 3: Same as in Figure 2, but for gridded JJA (upper) and DJF (lower) radar precipitation and daily station air temperatures

UK observations

- Results are here estimated by Met Office radar and surface temperature observations [5, 12]
- Scalings for JJA q_{50} are generally sub-γ and non-negative; in contrast with the 1.5-km simulations which generally give negative scalings for JJA q_{50}
- Observed scalings for JJA q_{99} are on the order of γ, comparable for the 1.5-km present-climate simulations
- DJF q_{99} scalings do not appear to differ substantially from q_{50}, the flattening out of the scaling at higher temperature are found in both observations and the 1.5-km model
- No turning point found at higher temperature for JJA q_{99} - this is only detected in the future climate simulation which samples higher temperatures

Results - Model-simulated temperature changes from the top 5% wettest days

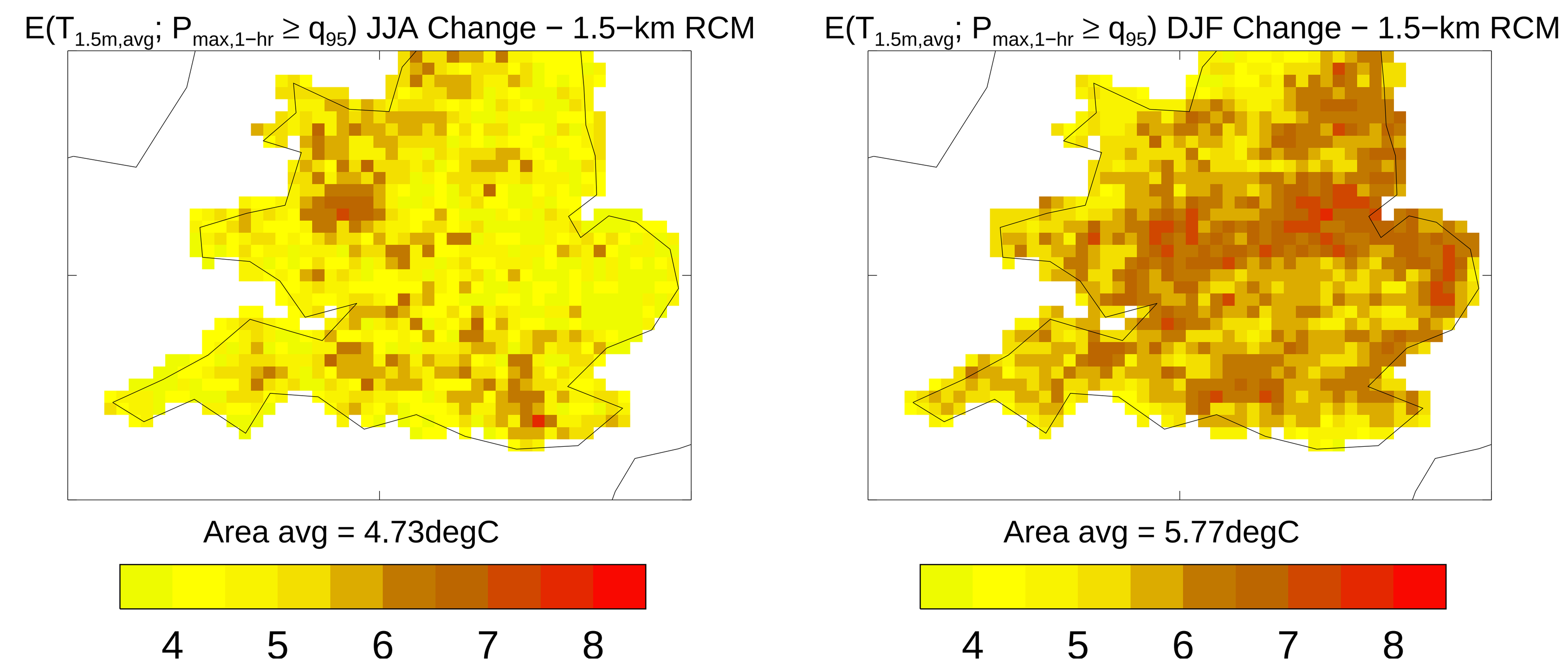

Figure 4: Change of JJA & DJF T_{avg} (in °C) between present- and future-climate simulation whenever precipitation exceeds q_{95}

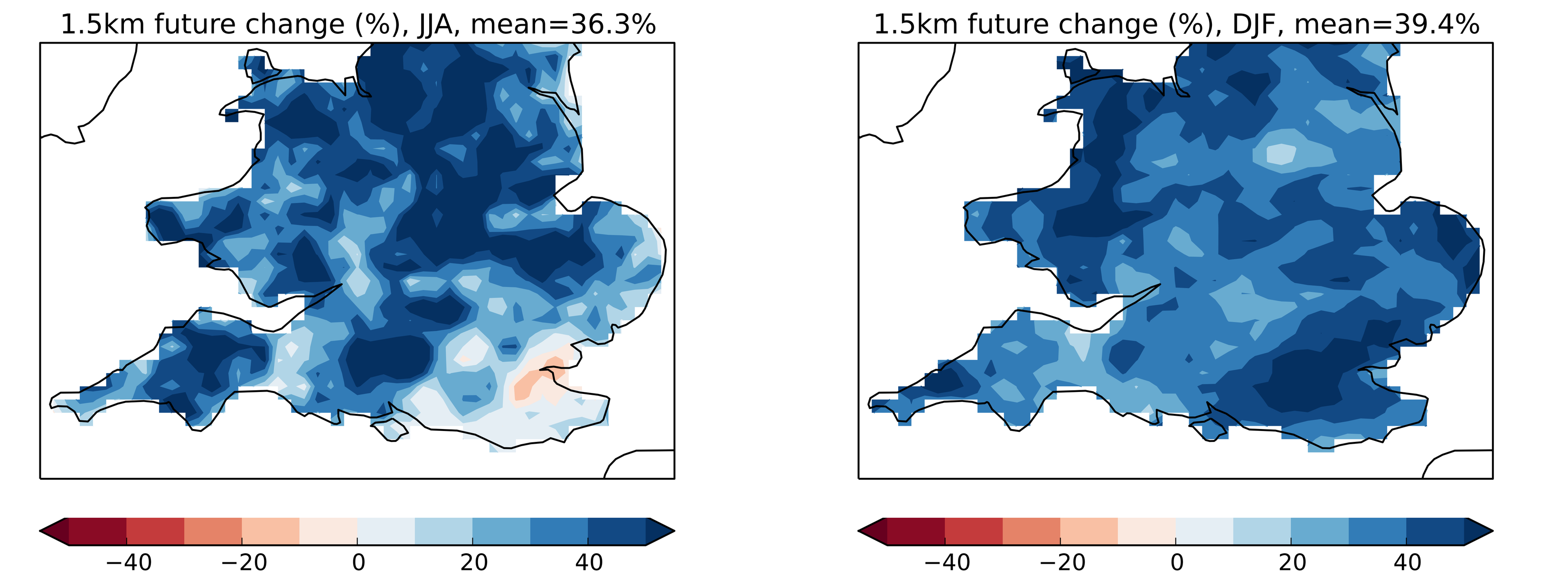

Figure 5: % change of JJA & DJF hourly intensities that exceeds q_{95} between present- and future-climate simulation

- $\gamma \approx 6.5\%$; JJA: $\Delta T \approx 4.7°\mathrm{C} \rightarrow \gamma\Delta T \approx \Delta P_{\text{JJA,cc}} \approx 30\%$; DJF: $\Delta T \approx 5.8°\mathrm{C} \rightarrow \gamma\Delta T \approx \Delta P_{\text{JJA,cc}} \approx 38\%$
- For the model top 5% of the JJA and DJF events, the simulated increases at γ (or slightly higher than γ)

Conclusions

- The 1.5-km model is generally able to simulate the UK present-climate scaling relationship
- For q_{99}, precipitation intensities approximately scale with the Clausius-Clapeyron relationship in the present climate, and the mean future climate change shift also appears to follow the scaling
- The 1.5-km model finds a decline in high precipitation intensities at high UK air temperatures; decline occurs in the future climate simulation at a temperature range not well-sampled by present-climate simulation

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