Fine-Scale Climate Projections: What Additional Fixed Spatial Detail is Provided by a Convection-Permitting Model?

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1. Motivation and Key Questions

Inter-disciplinary discussions reveal different perspectives on the value of high-resolution convection-permitting (CP) climate model experiments: climate scientists often emphasise the importance of an improved representation of convection, whereas impacts scientists often emphasise the importance of the unprecedented spatial scale of climate projection data.

This raises the question: **What is the best spatial scale on which to provide climate change information from CP models?** More specifically, for sub-25km scales and 10-year simulations, we ask:

1) How widespread is robust fine-scale projection detail?
2) Over what kind of terrain is it most prevalent?
3) Is it large enough to make a real differences to users?
4) In regions where fine-scale projection detail is limited, to what extent does spatial aggregation reduce uncertainty?

2. CP4A Simulations and Methods

Experiments: Two pan-Africa climate simulations of the Met Office CP model (CP4A), run at 4.5km resolution:

- Control: 10 years with lateral boundary forcing from a global simulation with observed 1997-2006 SST forcing
- Future: 10 years lateral boundary forcing from a global simulation with observed SSTs + coupled model projected SST anomalies for *circa*-2100 and RCP8.5 2100 CO_2 concentrations

Stratton et al. (2018)
Kendon et al. (2019)
Senior et al. (2020)

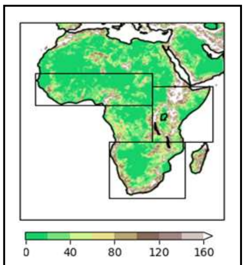

Fig.1: Model domain and standard deviation of topographic height (m) over a rolling window of 5x5 grid-boxes. Also shows the pooling regions used in Figs.3,4,5.

Variables: Seasonal mean rainfall (Pseas) and intensity of daily rainfall extremes (P99; 99th all-days percentile for each season)

Spatial Scale: For Figs.2&3, data is smoothed to a 3-grid-length scale (see paper for grid-scale analysis)

Metric of fine-scale projection detail: Δ_R = Future / Control, then compare Δ_R for each 3x3 (13km) box with Δ_R at 8 neighbours

Null Hypothesis (H_0): Neighbouring Δ_R are from same population

Significance testing: Paired-difference t-test for seasonal means, bootstrapping for extremes (Chan et al. 2020; 1000 resamples of the 10 years with replacement)

3. How Widespread is Robust Fine-Scale Projection Detail?

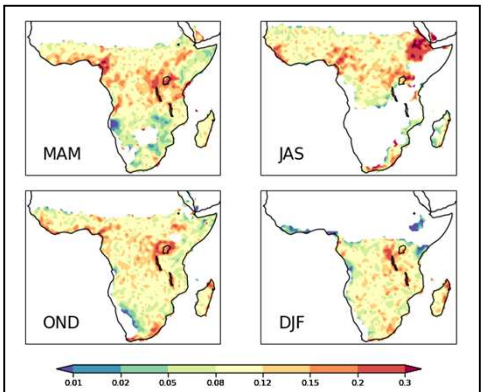

Fig.2: Fraction of statistically significant fine-scale projection detail, at the 10% level, for seasonal mean rainfall. White mask is arid regions (Pclim < 1mm/day) vulnerable to significance bias.

- Weakly field significant sub-25km scale projection detail
- Local significance constrained by short 10-year simulation period
- Some areas of enhanced significance, e.g. East Africa
- Less significance for daily rainfall extremes (see paper)

4. To What Extent is Robust Fine-Scale Projection Detail More Prevalent in Mountainous Regions?

Method: Bin grid-boxes across a large region (Fig.1) by local topographic variability (Fig.1). Compute percentage of pairs of points with statistically significant local differences of Δ_R = Fut / Ctl.

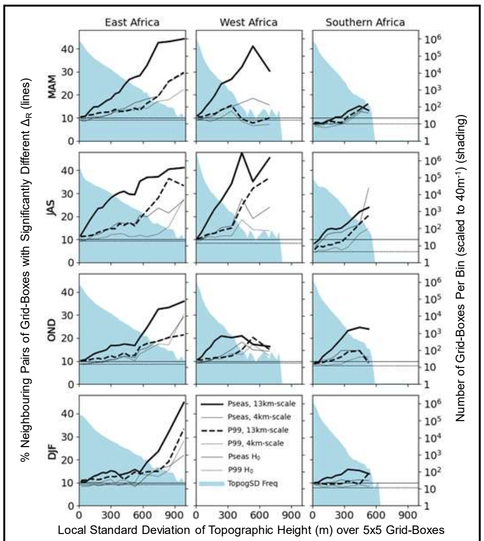

Fig.3: Impact of local topographic variability on fractional statistical significance of fine-scale projection detail (10% level), for 2 spatial scales. H_0 = null hypothesis (horiz lines). DJF W.Africa is too arid.

Flat Regions (low topographic variability) (most points):
- Little or no significant fine-scale detail in the projection (~10% fractional significance as expected by chance)

Mountainous Regions (high topographic variability) (few points):
- Fine-scale projection detail is statistically significant for 30-45% of locales for seasonal means at 3-grid-length scale in East Africa (all seasons) and West Africa (MAM, JAS), but less in Southern Africa.
- Less significance on scale of native grid (more chaotic variability)
- Less impact on extreme rain events (perhaps lower test power)

5. How Large is the Fine-Scale Projection Detail?

Fine-scale projection detail is statistically significant in mountain regions, but is it large enough to be useful?

Method: Compute SD of %(Fut/Ctl) over 25 (5x5) neighbouring grid-boxes if ≥2/8 neighbours are significantly different (10% level), and exclude arid points (Pclim < 1mm/day).

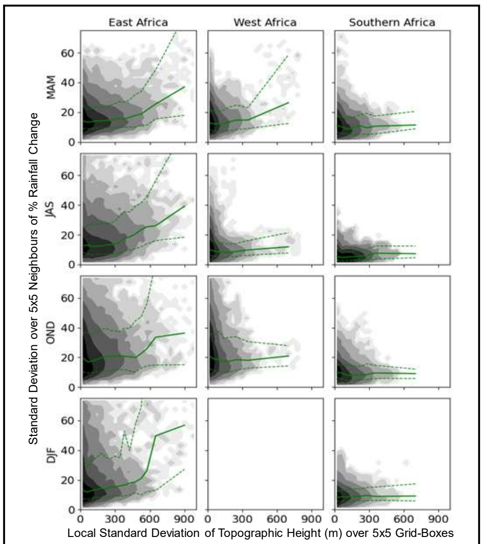

Fig.4: 2D histogram of the impact of local topographic variability on the amplitude of fine-scale projection detail relative to climatology (defined above), shown by shading on a log scale. For seasonal mean rainfall. Green lines are median, 10th & 90th percentiles within topographic variability bins. DJF W.Africa is too arid to analyse.

- Tendency for larger fine-scale projection detail in mountainous regions due to heterogeneous interactions between climate change processes and local topography (altitude, shape and orientation) (large spread along y-axis is due to random weather and climate variations)
- East Africa: Increase in local spatial SD in mountainous regions is typically 20-40% for seasonal means, so increase in local spatial range is ~4 x ~30%, so approx. 100%, so local spatial range of sub-25km projection detail can be similar to the local climatology
- West Africa: Similar, but pre-monsoon season only (MAM)
- Southern Africa: Minimal topographic impact on amplitude of fine-scale projection detail
- Rainfall extremes: Maybe larger topographic impact on amplitude of fine-scale projection detail (not shown; see paper)

6. How Much Does Aggregation to a 25km Scale Reduce Sampling Uncertainty?

Method: Consider locales with no fine-scale projection detail (<2/8 neighbours significantly different), *ie.* low topographic variability away from lake coasts, and exclude arid points (Pclim < 1mm/day). Sampling uncertainty is calculated as variance of anomalies across 1000 bootstrap resamples at grid-scale and 25km-scale.

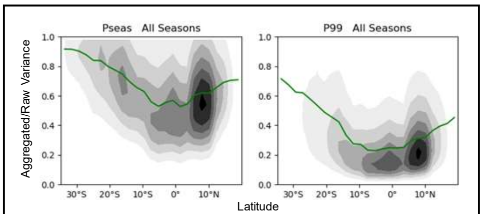

Fig.5: 2D histograms of the impact of spatial aggregation on sampling uncertainty (ratio of aggregated-to-raw variance) as a function of latitude for sub-Saharan Africa (south of 20°N), shown by shading on a linear scale. Green line is the median variance ratio at each latitude.

- Aggregation to 25km reduces uncertainties due to chaotic weather variability by up to 50% for seasonal mean rainfall
- Reductions are larger for the intensity of extreme events, up to 80%, due to smaller data samples contributing to their calculation
- Uncertainty reductions are larger in equatorial regions, perhaps due to larger fractions of small-scale convective rainfall
- Sampling uncertainties are of similar magnitude to the projection anomalies (see paper), so aggregation is potentially useful

7. Conclusions

The spatial detail we analyse is geolocated, so relevant to users

Locales with significant sub-25km-scale projection detail:
- This is most frequent in regions of high topographic variability
- Found for seasonal means and daily extremes (more the former)
- Most prominent in East Africa (all seasons) and West Africa (pre-monsoon and monsoon seasons), less over Southern Africa
- Lake coastal features also create significant fine-scale projection detail, but less frequently (not shown; see paper)
- The amplitude of this projection detail can be similar to that of the local climatology in mountainous regions
- So potentially beneficial for improved local future climate info

Locales *without* significant sub-25km-scale projection detail:
- Flat regions away from lake shores, *ie.* most of Africa in this study
- Includes ocean coastlines and urban conurbations which have little detectable fine-scale projection detail (not shown; see paper)
- So spatial heterogeneity in these regions is mostly due to chaotic weather variability
- So the signal-to-noise ratio of local future climate information can be substantially enhanced by spatial aggregation to at least 25km scales, especially for daily extremes and equatorial regions

The balance between these choices depends on simulation length, ensemble size, lead-time and RCP scenario

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