Changes in precipitation extremes for Ireland: Theoretical basis and future outlook

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Abstract
Understanding the changing nature of extreme events is critical for implementing effective and robust responses to climate change, particularly with respect to mitigation of risk and design of long life infrastructure. To this end we examine the likely response of rainfall extremes to climate forcing in an Irish context. Firstly we discuss the theoretical basis which links changes in local precipitation to larger scale atmospheric processes under a warming climate. We then highlight recent research exploring observed trends in precipitation extremes. Finally we examine projected changes in rainfall for the Island of Ireland (IoI) derived from the pan European EURO-CORDEX domain - which to date constitutes one of the largest high-resolution (~12 km) multi-model experiments undertaken. The ensemble consists of 19 dynamically downscaled GCM (Global Climate Models) simulations provided by different European agencies. With respect to a series of indices (e.g. rainfall intensity, percentiles, wet/dry spell persistence) relating to moderate extremes we discuss the performance of individual ensemble members in reproducing the Island’s baseline climatology. Following this we outline projected changes in seasonal extremes under different emission scenarios (RCP 4.5; 8.5) and time horizons (2040-2069; 2070-2099). Results underpin the theoretical and observed basis for increases in rainfall intensity. However, whilst we can have confidence in the likely direction of change, the ensemble highlights large uncertainties associated with the exact magnitude, spatial pattern and timing of such changes. We highlight key questions for developing robust responses to changing extremes in a hydrological context and outline the importance of addressing current research gaps.

1. INTRODUCTION
Since the beginning of the industrial era human activity has had a detectable influence on the Global climate system. While this is most conspicuously experienced through increases in global temperature, the fingerprint of anthropogenic climate change is also present through shifts in the duration, frequency, timing and spatial extent of extreme precipitation and associated events including fluvial flooding and hydrological drought (Blöschl et al., 2017; Habeeb et al., 2015; Min et al., 2011; Trenberth et al., 2003). Extreme precipitation has widespread implications for a diversity of sectors including agriculture, transport, catchment management and water services. While prolonged shortages can impact supply and reduce water quality thus impairing aquatic ecosystems, short duration high intense events lead to
inundation of flood risk property and agricultural land. Given the significant human, environmental and financial costs involved, understanding future changes in extremes and enacting adaptation measures which are robust across a range of impacts is critical for reducing future risk to vulnerable populations and infrastructure (Nissen and Ulbrich, 2017). On this basis much attention in the climate community has been given to investigating the drivers of precipitation extremes and their likely response to further increases in atmospheric warming. The current study uses climate simulations from a nineteen member MME developed within the CORDEX experiment. The ensemble considers thirteen highly resolved RCMs run at 0.11° resolution and forced using lateral boundary conditions from one or more of six different CMIP5 GCMs (Taylor et al., 2012). The performance of climate models in accurately simulating future changes highlights their applicability to climate impact and analyses. Therefore a series of indices which quantify moderate extremes are employed to examine model performance for the IoI with respect to the baseline climatology. Following this projected future changes are investigated. The study focuses on winter (DJF) and summer (JJA) seasons respectively.

2. THEORETICAL AND EMPIRICAL BACKGROUND

While differences exist regarding the exact rate, temporal scale (e.g. daily, sub-hourly) and spatial extent (e.g. wet versus dry areas, ocean versus land) for which changes are experienced, evidence gathered both from observational records and climate model experiments indicate an ongoing intensification of the global hydrological cycle. Changes are manifest through increases in the intensity and frequency of tropical storms, floods and drought; accompanied by which is an amplification of atmospheric warming through water vapour feedback (Alexander et al., 2006; Asadieh and Krakauer, 2015; Donat et al., 2016; Westra et al., 2013; Wu et al., 2013). Trends found to occur globally are reflected by changes in precipitation extremes at continental and regional scales (Blöschl et al., 2017; van den Besselaar et al., 2012; Vautard et al., 2014; Wagner et al., 2013). Similarly trends relating to increases in daily intensities are mirrored at higher temporal sub-daily/hourly scales and across a variety of indices (Chan et al., 2016). Identifying trends in observed records is critical for attribution of the human contribution and for outlying the possible future trajectory of extremes as temperatures continue to increase globally (Easterling et al., 2000).

The theoretical basis for understanding increases in intensity with warming atmospheric conditions is the Clausius–Clapeyron (CC) relation. This indicates that specific humidity and hence atmospheric moisture increases approximately exponentially with temperature (6.5%K⁻¹) (Boer, 1993). While a number of factors complicate this relation when translating it into increases in intensity locally (e.g. geographic region, temperature, moisture availability), it provides a physical grounding for understanding the changing patterns found in observed (Groisman et al., 2005; Prein et al., 2016; Shiu et al., 2012) and model simulated data (Groisman et al., 2005; Sun et al., 2006). Several studies indicate that under particular atmospheric conditions CC scaling may be conservative, with research highlighting a doubling of the rate in extreme hourly intensities (Bao et al., 2017; Blenkinsop et al., 2015; Lenderink
et al., 2017; Lenderink and van Meijgaard, 2008). Previous analysis also point to the influence which rainfall type (convective versus stratiform) and synoptic scale circulation have on the relationship between temperature and atmospheric moisture (Berg et al., 2009). This underlines the complex character of extremes and the uncertainty associated with using temperature as a proxy to infer changes in rainfall intensity using CC scaling alone. Alongside analysis of long term records climate model experiments constitute a significant line of inquiry for investigating future extremes. Experiments such as CMIP5 (Climate Model Intercomparison Project Phase 5 (Taylor et al., 2012) - which underpin findings set out in the latest Intergovernmental Panel on Climate Change (IPCC; AR5) report – in conjunction with observational data help us to understand the physical processes which drive extremes. Furthermore, by providing an insight to future behaviour their predictions inform much of the adaption planning necessary to mitigate future climate risk (Frei et al., 2006a; Nissen and Ulbrich, 2017; Russo et al., 2014; Vautard et al., 2014).

3. CLIMATE MODEL PROJECTIONS

This paper investigates changes in precipitation extremes for the IoI using Regional Climate Model (RCM) simulations from the CORDEX project (Coordinated Regional Climate Downscaling Experiment, (Giorgi et al., 2009; Jacob et al., 2014). GCMs are the primary tool used to investigate future changes in the Earth’s climate. However, due to computational limitations they are run at a relatively coarse spatial resolution. RCMs operate over a smaller spatial domain but at a higher resolution. As a result they are better able to resolve the smaller scale features (e.g. orography, land-sea interactions) and finer scale atmospheric processes (e.g. convection, cloud formation (Vaittinada Ayar et al., 2016; Wilby and Wigley, 1997) which influence local weather and climate. When used in combination RCMs provide a bridge to downscale GCM simulations to the higher spatiotemporal scales associated with extremes. However, despite significant advances model projections remain subject to much uncertainty. This is attributed to several factors including model limitations (parametrization of system processes, coarse scale), the inherent variability of the climate system, and the unknowable pathway of future greenhouse gas (GHG) emissions. Addressing this uncertainty requires using multiple but equally valid realizations of future climate derived from Perturbed Physics and/or Multi-Model ensembles (MMEs). In the case of the former, successive simulations using the same model are produced however, between model runs adjustments are made to its parameters or structural components thus eliciting a different but equally valid response. For MMEs the output from different model structures are used. Both approaches provide a sample from a range of uncertainty but plausible climate models. Hence the accessibility and application of ensemble projections is essential from a planning perspective where underestimation of model uncertainty, by using a single or limited number of simulations, may result in over confidence in a certain climate outcomes potentially leading to ineffective and costly adaptation measures.
4. DATA

Performance of the CORDEX ensemble in simulating historical conditions for the IoI is examined using a 1×1 km gridded data of daily precipitation developed by Met Éireann (Walsh, 2012). The study considers daily precipitation from nineteen different GCM-RCM combinations which comprise the CORDEX ensemble (Table 1). To develop this, eight different participant agencies deployed their RCMs at a 0.11° (~12.5 km) at a horizontal grid resolution for a European wide domain taking boundary conditions from one of five different GCMs. The ensemble used here includes historical GCM simulations (1976-2005) alongside future projections representing two different Representative Concentration Pathways (RCPs; +4.5 and +8.5 W/m²). Each RCP relates to the range of radiative forcing by the year 2100 relative to preindustrial levels and is indicative of atmospheric GHG concentrations. RCP4.5 is more conservative than RCP8.5; it represents a mid-century peaking and stabilization of GHG concentrations. In contrast RCP8.5 is characterised by a continual upward trend in emissions and is associated with greater increases in global temperature. For additional information on the RCMs used and their configuration refer to Jacob et al. (2014). For the purposes of model evaluation and ensemble averaging gridded model output and observed data are interpolated to a common a 0.125°×0.125° resolution latitude-longitude grid. For this the indices are firstly estimated for each grid point on their native grid. Values are then linearly interpolated to the same grid format.

5. INDICES OF EXTREMES

Sixteen different statistical measures (Table 2) are used to quantify precipitation extremes. This includes a number of internationally agreed indices supported by the STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions; https://crudata.uea.ac.uk/projects/stardex/) project and the ETCCDI (Expert Team on Climate Change Detection and Indices; http://www.wcrp-climate.org/etccdi/) (Klein Tank, AMG. et al., 2009). Eight measures relate to the mean and intensity of daily precipitation. Also adopted are four duration based measures alongside four which describe extreme precipitation according to exceedance of a fixed threshold. For percentile values indices are estimated both using the full series (all-days; RA975p) and wet-days (>1 mm; RW95p) only. Both measures are employed as changes in the overall statistical distribution of daily precipitation may be more appropriate for impact and adaptation assessment (Schär et al., 2016). Conversely wet day rainfall intensity is useful interrogation of model performance. It is highlighted that, due to model and data limitations the indices used here relate to moderate rather than rare or unusual extreme events. The relatively short series length (30 years) used limits extreme distribution fitting and confident extrapolation of exceptional events. Similarly the degradation of information associated with spatial interpolation means that gridded observations will not capture extremes with the level of detail as point scale observations. Furthermore, given their current limitations (e.g. spatial resolution, parameterization of convective precipitation) such events are likely to exceed the reliable predictive capability of RCMs used in CORDEX (Diaconescu et al., 2015).
Table 1: Ensemble members of the CORDEX project study. Daily precipitation is downscaled using RCMs run at a 0.11° resolution. Asterisk (*) identifies ensemble member without a corresponding RCP4.5 simulation.

<table>
<thead>
<tr>
<th>Modelling group</th>
<th>GCM</th>
<th>GCM Ensemble Member</th>
<th>RCM</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Modelling (CLMcom)</td>
<td>CNRM-CERFACS-CNRM-CM5</td>
<td>r1i1p1</td>
<td>CLMcom-CCLM4-8-17</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>ICHEC-EC-EARTH</td>
<td>r12i1p1</td>
<td>CLMcom-CCLM4-8-17</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MOHC-HadGEM2-ES</td>
<td>r1i1p1</td>
<td>CLMcom-CCLM4-8-17</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MPI-M-MPI-ESM-LR</td>
<td>r1i1p1</td>
<td>CLMcom-CCLM4-8-17</td>
<td>v1</td>
</tr>
<tr>
<td>Centre National de Recherches Météorologiques (CNRM)</td>
<td>CNRM-CERFACS-CNRM-CM5</td>
<td>r1i1p1</td>
<td>ALADIN53</td>
<td>v1</td>
</tr>
<tr>
<td>Danish Meteorological Institute (DMI)</td>
<td>ICHEC-EC-EARTH</td>
<td>r3i1p1</td>
<td>DMI-HIRHAM5</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>NCC-CanESM1-M</td>
<td>r1i1p1</td>
<td>DMI-HIRHAM5</td>
<td>v2</td>
</tr>
<tr>
<td>Institut Pierre-Simon Laplace (IPSL- INERIS)</td>
<td>IPSL-IPSL-CM5A-MR</td>
<td>r1i1p1</td>
<td>IPSL-INERIS-WRF311F</td>
<td>v1</td>
</tr>
<tr>
<td>Koninklijk Nederlands Meteorologisch Instituut (KNMI)</td>
<td>ICHEC-EC-EARTH</td>
<td>r12i1p1*</td>
<td>KNMI-RACMO22E</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MOHC-HadGEM2-ES</td>
<td>r1i1p1</td>
<td>KNMI-RACMO22E</td>
<td>v2</td>
</tr>
<tr>
<td></td>
<td>ICHEC-EC-EARTH</td>
<td>r1i1p1</td>
<td>KNMI-RACMO22E</td>
<td>v1</td>
</tr>
<tr>
<td>Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology (MPI-CSC)</td>
<td>MPI-M-MPI-ESM-LR</td>
<td>r1i1p1</td>
<td>MPI-CSC-REMO2009</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MPI-M-MPI-ESM-LR</td>
<td>r2i1p1</td>
<td>MPI-CSC-REMO2009</td>
<td>v1</td>
</tr>
<tr>
<td>Royal Meteorological Institute of Belgium and Ghent University (RMMB-Ugent)</td>
<td>CNRM-CERFACS-CNRM-CM5</td>
<td>r1i1p1</td>
<td>RMIB-UGent-ALARO-0</td>
<td>v1</td>
</tr>
<tr>
<td>Swedish Meteorological and Hydrological Institute, Rossby Centre (SMHI)</td>
<td>CNRM-CERFACS-CNRM-CM5</td>
<td>r1i1p1</td>
<td>SMHI-RCA4</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>ICHEC-EC-EARTH</td>
<td>r12i1p1</td>
<td>SMHI-RCA4</td>
<td>v1</td>
</tr>
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<td></td>
<td>IPSL-IPSL-CM5A-MR</td>
<td>r1i1p1</td>
<td>SMHI-RCA4</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MOHC-HadGEM2-ES</td>
<td>r1i1p1</td>
<td>SMHI-RCA4</td>
<td>v1</td>
</tr>
<tr>
<td></td>
<td>MPI-M-MPI-ESM-LR</td>
<td>r1i1p1</td>
<td>SMHI-RCA4</td>
<td>v1a</td>
</tr>
</tbody>
</table>

Table 2: Sixteen indices used to examined observed and simulated precipitation extremes for the IoI. In estimating relative future changes those indicators marked with an asterisk (*) use the 1976-2005 percentile as the threshold value.

<table>
<thead>
<tr>
<th>Indices</th>
<th>ID</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean and Intensity indices</td>
<td>Ave</td>
<td>Daily average precipitation</td>
<td>mm/day</td>
</tr>
<tr>
<td>Precipitation intensity</td>
<td>SDI</td>
<td>Average precipitation on wet days (&gt; 1 mm)</td>
<td>mm/day</td>
</tr>
<tr>
<td>Wet day percentile</td>
<td>RW95p</td>
<td>The 95th percentile of precipitation on wet days (&gt; 1 mm)</td>
<td>mm/day</td>
</tr>
<tr>
<td>All day percentile</td>
<td>RA975p</td>
<td>The 97.5th percentile of precipitation on all days</td>
<td>mm/day</td>
</tr>
<tr>
<td>Quotient of heavy precipitation: Wet day threshold</td>
<td>PFLW95</td>
<td>Fraction of total precipitation occurring on days &gt; RW95p threshold</td>
<td>%</td>
</tr>
<tr>
<td>Quotient of heavy precipitation: All day threshold</td>
<td>PFLA975</td>
<td>Fraction of total precipitation occurring on days &gt; RA975p threshold</td>
<td>%</td>
</tr>
<tr>
<td>Heavy precipitation amount: Wet day threshold*</td>
<td>PTLW95</td>
<td>Total precipitation from events occurring on days &gt; RW95p threshold – reported as a seasonal average</td>
<td>mm</td>
</tr>
<tr>
<td>Heavy precipitation amount: All day threshold*</td>
<td>PTLA975</td>
<td>Total precipitation from events occurring on days &gt; RA975p threshold – reported as a seasonal average</td>
<td>mm</td>
</tr>
<tr>
<td>Duration indices</td>
<td>PWAV3</td>
<td>Average wet spell length - defined as a spell with minimum 3 day duration (&gt;1 mm)</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>PDASV3</td>
<td>Average dry spell length - defined as a spell with minimum 3 day duration (&lt;1 mm)</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>PWEXT3</td>
<td>The 95th percentile of wet spell length - defined as a spell with minimum 3 day duration (&gt;1 mm)</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>PDEXT3</td>
<td>The 95th percentile of dry spell length - defined as a spell with minimum 3 day duration (&lt;1 mm)</td>
<td>days</td>
</tr>
<tr>
<td>Frequency indices</td>
<td>R1mm</td>
<td>Frequency occurrence of wet days (&gt;1 mm) - reported as a percentage of the series length</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>R20mm</td>
<td>Frequency occurrence of heavy rainfall days (&gt;20 mm) - reported as a percentage of the series length</td>
<td>%</td>
</tr>
<tr>
<td>Count of heavy precipitation days: Wet day threshold*</td>
<td>PNLW95</td>
<td>Count of heavy rain days (&gt; RW95p) – reported as the seasonal average of occurrence</td>
<td>days</td>
</tr>
<tr>
<td>Count of heavy precipitation days: All day threshold*</td>
<td>PNLW975</td>
<td>Count of heavy rain days (&gt; RA975p) – reported as the seasonal average of occurrence</td>
<td>days</td>
</tr>
</tbody>
</table>
Seasonal (DJF and JJA) indices are analysed for two 30 year future time slices (2050s: 2040-2069 and 2080s: 2070-2099) and RCP scenarios (4.5 and 8.5) respectively. Differences are quantified relative to the 1976-2005 baseline period which provides a benchmark for projected climate conditions. For all indices the percentage change (Pdiff) between the baseline and each future period is quantified according to equation 1.

\[ P_{diff} = \frac{(future - baseline)}{baseline} \times 100 \]  

(1)

6. MODEL PERFORMANCE AND ESTIMATION OF UNCERTAINTY

Model performance is investigated by comparing indices estimated from the simulated and observed data. Three measures including: (i) the domain area mean, (ii) standard deviation, and (iii) spatial correlation coefficient (Pearson’s r) are employed. In the case of the mean and standard deviation the percent differences between observed and simulated data (1976-2005) is examined. Values which deviate from zero indicate a lack of concordance; with respect to correlation, values closer to one suggest that the model is better able to capture the observed spatial pattern.

In determining the significance of change signals the unforced (natural) variability of the climate system as a source of uncertainty must be considered. To address this a non-parametric bootstrap technique is employed (Frei et al., 2006b; Rajczak et al., 2013). For this 50 time series are generated by resampling (with replacement) 30 individual years from the original grid point time series. The procedure is applied to the observed and model simulated data for each season, RCP and 30 year time slice respectively. The median - considered the most likely estimate - and confidence bounds are calculated from the resampled data. Significance in the strength of projected changes are investigated by comparing all combinations of the 50 thirty year bootstrapped historical and future samples using equation 1 (i.e. applied 1225 times). In accordance with (Frei et al., 2006b) changes are deemed significant if the majority - either 90% or 95% dependent on significance level - of comparisons are greater or less than 0% (indicating no difference relative to 1976-2005). This benchmark hence requires that the projected climate is sufficiently beyond the bounds of natural variability over the baseline period as to signify a clear shift in the precipitation regime.

7. RESULTS

7.1 Model validation

Figure 1 shows results from the seasonal assessment of each ensemble member for all indices. As they are the least correlated with other measures and are important for impacts assessment, three indices are investigated in closer detail using Figure 2. This includes precipitation intensity (SDII), wet day occurrence (R1mm) and the quotient of heavy precipitation (PFLW95). Results highlight the extent to which no single ensemble member outperforms
others for all indices, seasons and model diagnostics. Models both over and underestimate (particularly C1-C4; Climate Limited-area Modelling Community) winter precipitation (Ave), but typically tend only to overestimate average summer receipts (particularly S5; Swedish Meteorological and Hydrological Institute). Most ensemble members underestimate the length of dry and wet spells during winter; however they tend only to underestimate summer dry spells. Furthermore, all exhibit poor skill ($r \sim 0$) in capturing spatial patterns in the length of winter dry spells. In the case of SDII differences in spatial correlations are most notable for ensemble members developed by the Max Planck Institute (M1 and M2); this is a pattern common to both seasons. Similarly, in contrast to other members M1 and M2 overestimate the standard deviation associated with all indices in winter except PDEXT3. Ensemble members from the Danish Meteorological Institute (DMI) are notable for overestimating (with the exception of spell length) most indices particularly during winter.

**Figure 1**: Ensemble member performance with respect to differences (%) in the domain area average (a-b) and standard deviation (c-d). Also shown is the spatial correlation (e-f). Plots are developed using the median of the bootstrapped samples from the observed and model simulated datasets. Columns relate to winter (DJF; a, c, e) and summer (JJA; b, d, f) respectively.
However DMI simulations show high spatial correlations with the observed data. Based on Figure 2 all ensemble members underestimate the standard deviation of summer intensity and

**Figure 2:** Taylor plots showing correspondence between the gridded observed and model simulated fields. Proximity of each point to the red line (observed) shows ensemble member performance in simulating the spatial variability (standard deviation). Blue lines show values for the correlation coefficient (Pearson’s r). Values further/closer to 0/1 are indicative of lesser/greater skill in reproducing the observed spatial pattern. Aptitude in capturing the IoI average value (mean % bias) is depicted using colour shading of individual points (see colour bar). Model evaluation is based on the median estimate from the bootstrapped samples. Taylor plots are constructed for the mean winter/summer wet day occurrence (1 day length; R1mm), precipitation intensity (SDII), and the quotient of heavy precipitation (PFLW95).
the proportion of rainfall from heavy events. The same pattern is not present in winter. Results indicate that the models perform better in simulating indices relating to average and intensity as opposed to duration based metrics. In cases where GCM-RCM combinations differ only in the GCM realization used (M1 M3; K1 and K3), the downscaled simulations tend to exhibit the same biases highlighting the importance of the parent model.

7.2 Model Projections: Domain area Average

Figure 3 and 4 show the projected changes in sixteen indices of extremes for the IoI estimated on a seasonal basis (DJF; JJA) by each CORDEX ensemble member; also shown is the ensemble (arithmetic) average. Projections relate to two future horizons (2040-2069; 2070-2099) and RCP scenarios respectively. Results are shown as the percent difference calculated relative to the 1976-2005 baseline. Both figures relate to changes averaged across the IoI. Changes identified as significant at the 90% and 95% level are highlighted.

Figure 3: Projected changes in winter (DJF) precipitation from the CORDEX ensemble investigated using sixteen indices of extremes (Table 2). Percent changes (equation 1) are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040-2069; 2070-2099) relative to the 1976-2005 baseline. Black circles and dots denote changes which are significant at the 95% and 90% level respectively. For plotting values >100% are highlighted with a cross. The suffix rel identifies indices calculated using the baseline threshold. Also shown is the ensemble average (Ave).
The majority of ensemble members show an increase/decrease in average winter/summer precipitation indicating an increasingly seasonal annual cycle. For winter projections suggest a clear increase in precipitation intensity. This pattern becomes more pronounced as the century progresses and under the more GHG intensive 8.5 RCP. In this case the ensemble average indicates a 16% increase in intensity. However, the range in ensemble projections varies between ~7 and 25%. All simulations differ. The majority of ensemble members show an increase/decrease in average winter/summer precipitation indicating an increasingly seasonal annual cycle. For winter projections suggest a clear increase in precipitation intensity. This pattern becomes more pronounced as the century progresses and under the more GHG intensive 8.5 RCP. In this case the ensemble average indicates a 16% increase in intensity. However, the range in ensemble projections varies between ~7 and 25%. All simulations differ significantly from the baseline climate indicating a clear change with respect to natural variability.

**Figure 4:** Projected changes in summer (JJA) precipitation from the CORDEX ensemble investigated using sixteen indices of extremes (Table 2). Percent changes (equation 1) are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040-2069; 2070-2099) relative to the 1976-2005 baseline. Black circles and dots denote changes which are significant at the 95% and 90% level respectively. For plotting values >100% are highlighted with a cross. The suffix rel identifies indices calculated using the baseline threshold. Also shown is the ensemble average (Ave).
Increases across the ensemble are also evident in the magnitude of events relating to heavy precipitation events (all (RA975p) and wet day percentiles (RW95p)). In addition, by the 2080s all members indicate an increase in the frequency of heavy events (PNLA95rel and PN LW975rel). Based on the ensemble average there is a projected doubling in the number of days with rainfall $>20$ mm by the 2080s (RCP85). In addition the total amount (PTLA95rel and PTLW975rel) as well as the proportion (PFLA95rel and PFLW975rel) of precipitation from heavy events is projected to increase significantly. Similar to SDII changes in threshold based indices are most pronounced for the 2080s and under RCP8.5. Changes in the intensity indices are contrary to those relating to spell duration. In this case some projections show little difference, however where a change is registered disagreements exist in both magnitude and direction. Overall the ensemble mean suggests an increase in the number of wet days (R1mm; 5.5%; 2080s; RCP8.5). However, by the same measure the mean duration of wet and dry spells (minimum 3-day consecutive) is shown to decrease. Based on the ensemble mean the greatest difference in duration measures is associated with a decrease in the extended wet spell ($\sim 15\%$; RCP8.5, 2080s).

Relative to winter, summer projections are affected by greater uncertainty, characterised by larger differences between ensemble members regarding the strength, magnitude and in some cases direction of change. Despite this, for most simulations a general increase in rainfall intensity is projected. For SDII the ensemble average suggests increases of between 5% (RCP4.5; 2050s) and 10% (RCP8.5; 2080s). Additionally increases are projected in the frequency of days with $>20$ mm precipitation. This is reflected by increases in the amount of total rainfall which is contributed by heavy rainfall days. In addition to intensity, simulations show an increase in the magnitude of events associated with the upper percentiles. For this an increase of 15% in the 95th percentile is associated with the ensemble mean (2080s; RCP8.5). In contrast to winter, there is a greater degree of concordance between simulations in relation to spell length. However projected changes are generally not significant. In most cases the length of dry/wet spells is projected to increase/decrease. Similar trends are registered for the extended dry spell (95th percentile of spell length). Additionally the number of wet summer days is projected to decrease. In accordance with winter, trends are most pronounced for the 2080s under RCP8.5. Findings for summer highlight the degree to which individual ensemble members can diverge on the direction of change. For example K1 (KNMI) indicates a $\sim 10\%$ decrease in days with rainfall $>20$ mm, however for the same period and simulation S1 (SMHI) returns a $\sim 50\%$ increase.

### 7.3 Model Projections: Spatially Discrete

Figure 5 and 6 show boxplots of the model simulated changes in four indices (intensity, quotient of heavy precipitation, wet day occurrence, and extended dry/wet spells). Plots are constructed based on the difference (%) between the baseline and future period for each grid point using the median from the bootstrapped samples; also shown is the ensemble average.

Results illustrate the degree to which projections vary across the IoI. Winter precipitation intensity is shown to increase almost uniformly, with an up to $\sim 25\%$ (RCP85; 2080s) increase projected by some members. As it smooths more pronounced changes the ensemble average presents a more conservative estimate, despite this an increase in winter intensity of $\sim 15\%$ is projected. A comparable picture is shown for RA975p. For both indices the signal is more pronounced for the 2080s according to RCP8.5. With respect to wet day occurrence and spell length much greater inter-model uncertainty is evident. For CN1 there are significant increases in the percentage of wet days ($\sim 20\%$). However several
Figure 5: Boxplots showing the percent difference between CORDEX simulated baseline and future conditions estimated on a grid point basis for winter (DJF). Changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040-2069; 2070-2099) relative to the 1976-2005 baseline. Also shown is the ensemble average (Ave). Boxplot whiskers extend to the 5th and 95th percentiles. Also shown are the median, 25th and 75th percentiles respectively.
projections register progressive declines in this indicator, most markedly C3. Similar patterns are shown for the extended wet spell; however the signal is weaker and there is less confidence in the exact direction of change. As illustrated by the ensemble spread in Figure 6 changes in summer intensity (as opposed to winter) are less spatially uniform. A comparable pattern of change is shown for the 95th percentile (RA975p). In the case of summer wet day occurrence the majority of ensemble members register declines across the island. The stronger spatial signal for this indicator is mirrored in the ensemble mean. In this case an up to 20% reduction in summer wet days is suggested by the 2080s (RCP85).

8. CONCLUSION

To investigate changes in precipitation extremes for the IoI an ensemble of 19 climate simulations developed within the CORDEX project are analysed. Ensemble members were developed by eight participant agencies which ran their RCMs at a resolution of 0.11° for a European wide domain using lateral forcing from one or more of six different CMIP5 GCMs. Simulations relate to historical and future simulations for two different RCPs (+4.5 and +8.5 W/m²). A suite of sixteen different indices relating to moderate extremes are adopted to assess precipitation simulations for winter (DJF) and summer (JJA) respectively. Included are measures which quantify the duration, frequency and intensity of events. The paper firstly evaluates the performance of ensemble members in simulating a 30 year baseline period (1976-2005). Subsequently future projections are assessed for each indicator. Key findings are summarised below.

- No one ensemble member outperforms all others, with diversity in performance across seasons, indices and evaluation measures evident.
- The IoI is likely to experience an increasingly seasonal precipitation regime.
- Accompanied by which is an increase in rainfall intensity during winter and summer.
- A larger proportion of total precipitation will likely be from heavy events (>95th percentile).
- Heavy rainfall days (>20 mm) are likely to increase - some suggesting a doubling.
- Winter wet-spell lengths are projected to increase.
- Summer dry and extended dry-spells are likely to increase.
- Conditional on the ensemble used there is more confidence in increased winter and summer intensities as opposed to changes in spell duration.
- Trends are more pronounced towards the end of the century and under the more GHG intense 8.5 scenario.
- Generally models agree as to the direction of change – particularly for rainfall intensities. However, differences in the timing and magnitude of changes highlight the importance of using MMEs for climate impact and adaption planning.
Figure 6: Boxplots showing the percent difference between CORDEX simulated baseline and future conditions estimated on a grid point basis for summer (JJA). Changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040-2069; 2070-2099) relative to the 1976-2005 baseline. Also shown is the ensemble average (Ave). Boxplot whiskers extend to the 5th and 95th percentiles. Also shown are the median.
Despite model differences most are in agreement that the IoI’s rainfall regime will likely undergo significant changes - characterised by an increase in the intensity, duration and frequency of extreme precipitation. Hence results mirror climate signals already evident in observed data and support evidence for an ongoing intensification of the hydrological cycle at global and regional scales. As indicated by the extent of model uncertainties the projections from CORDEX should be interpreted with caution. Decisions made should be informed with other lines of investigation including using evidence of changing patterns found in observational datasets alongside ongoing and past model experiments (Nolan et al., 2017). In assuming knowledge of future climate the current limitations of regional models (e.g. resolution, non-convective permitting) should be considered. Similarly given the impact of extremes occurring on finer temporal scales (e.g. sub-daily, sub-hourly), in utilizing the CORDEX ensemble consideration must be given to its relatively coarse temporal resolution. In this context the likely superseding of CORDEX by improved RCMs should be monitored by practitioners to ensure the best and most recent available climate information is used for climate assessment.

On the basis of supporting decision making in the face of such uncertainties the importance of maintaining high resolution observational networks and recovering historical records is underlined. Similarly the further development of model capabilities and support for international projects such as CORDEX, which share workload and allow development of valuable MMEs is essential for informing robust and cost effective adaption plans. Finally given the extent of uncertainties special attention must be given to how conventional decision making processes can adapt to best utilize uncertain information.

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10. REFERENCES


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