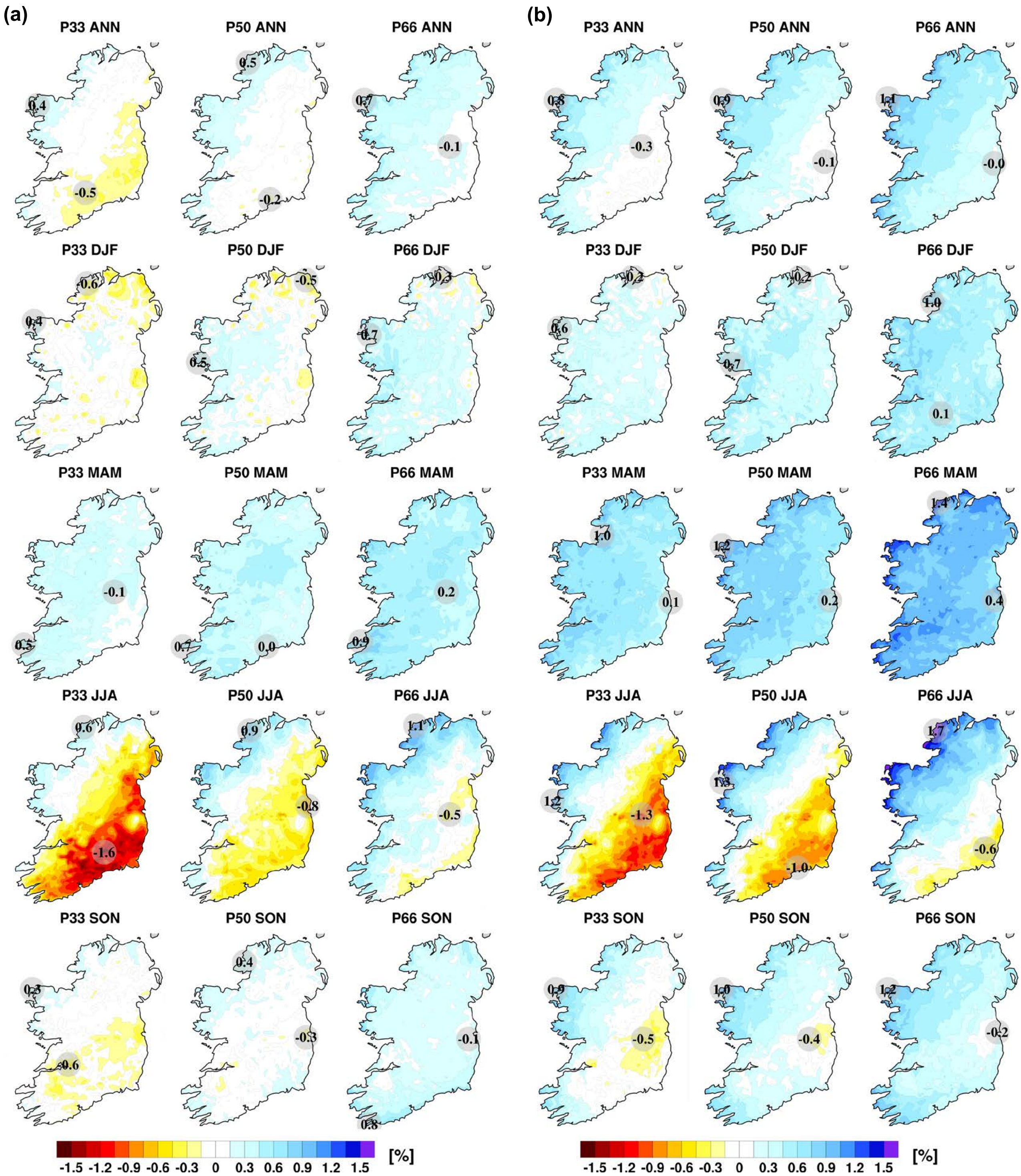


Figure 3.37. The 33rd, 50th and 66th percentiles of annual and seasonal relative humidity projections (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. ANN, annual; DJF, December, January, February; JJA, June, July, August; MAM, March, April, May; SON, September, October, November.

(see Figure 9 of Sloth *et al.*, 2012). The authors found that the regions where large changes in relative humidity are projected generally correspond to those with large projected increases in mean temperature (relative humidity decreases) or large projected increases in precipitation (relative humidity increases).

The projections of the current study, of small projected increases in relative humidity for all seasons except summer, may be partly attributed to the large influence of the North Atlantic Ocean on the Irish climate. The relative humidity projections for summer (decreases in the south-east and increases in the north-west) may be partly attributed to the temperature projections for summer; note that Figure 3.2 shows a similar south-east to north-west gradient in projected temperature increases, with enhanced warming in the south-east. However, further investigation of these factors is necessary to attribute causation to the relative humidity projections of the current study.

Relative humidity is an important climate field that has a direct impact on many sectors, including public health, agriculture and the built environment. For example, the link between low relative (and specific) humidity and greater influenza mortality is well established (e.g. Noti *et al*., 2013). The incidences of Lyme borreliosis (Lyme disease), a vector-borne illness caused by the bacterium *Borrelia* and spread by ticks, increase with high relative humidity; ticks require a minimum 80% humidity to avoid drying out during the early stages of life (Cullen, 2010) and air temperatures greater than 6°C during host questing (Süss *et al*., 2008). Potato crop failures in Ireland can result when high relative humidity and temperature combine to provide the warm, wet conditions in which the *Phytophthora infestans* fungi (potato blight) thrive (Cucak *et al*., 2019). Changes in relative humidity will have an impact on the built and archaeological heritage of Ireland, affecting deterioration mechanisms such as salt weathering, mould growth and corrosion (Daly, 2019). Relative humidity is also an important field for derived variables, such as fire risk indexes; the risk of wildfire decreases with increasing relative humidity (e.g. Dowdy *et al*., 2010).

3.16 Mean Sea Level Pressure Projections

Figure 3.38 shows that annual average mean sea level pressure (MSLP) is projected to increase by the middle of the century for both the RCP4.5 (mean value 1.4 hPa) and RCP8.5 scenarios (mean value 1.2 hPa). There exists a clear south-east to north-west gradient in the projections, with the largest increases in the north.

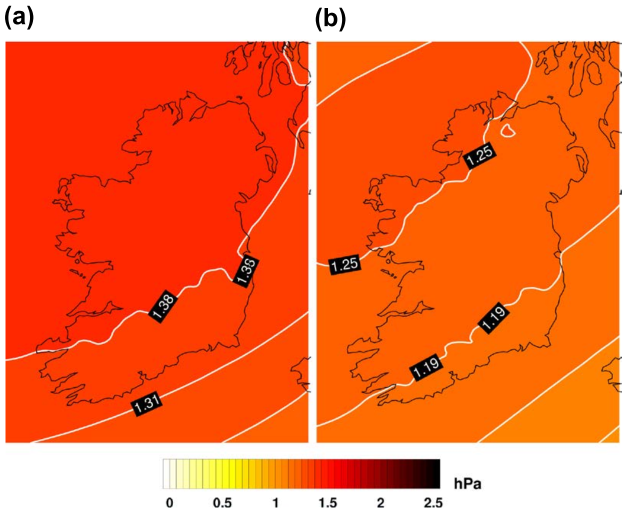


Figure 3.38. Ensemble mean of mid-century MSLP (hPa) projections for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

Figure 3.39 presents the projected mean seasonal change (hPa) in MSLP for the RCP4.5 and RCP8.5 scenarios. All seasons show a large projected increase in MSLP. Figure 3.40 shows a small variation between the 33rd, 50th and 66th projection percentiles for all seasons and both RCP scenarios. This result demonstrates good agreement (small spread) between ensemble members and adds a high level of confidence to the MSLP projections. Averaged over the whole country, the "likely" projected increases in the mid-century average MSLP are 1.2 hPa (annual RCP4.5), 0.9 hPa (annual RCP8.5), 0.6 hPa (winter RCP4.5), 0.2 hPa (winter RCP8.5), 0.8 hPa (spring RCP4.5), 0.6 hPa (spring RCP8.5), 0.6 hPa (summer RCP4.5), 1.3 hPa (summer RCP8.5), 1.6 hPa (autumn RCP4.5) and 1 hPa (autumn RCP8.5).

The projected increases in MSLP are some of many possible factors that could contribute to the projections of decreases in wind speed (section 3.13) and wind power (section 3.18), and increases in dry periods (section 3.11) and heatwave (section 3.3) events.

The projected increase in MSLP may be attributed to the projected decrease in the number of overall cyclones (section 3.17). A discussion on possible mechanisms for a reduction in the number of

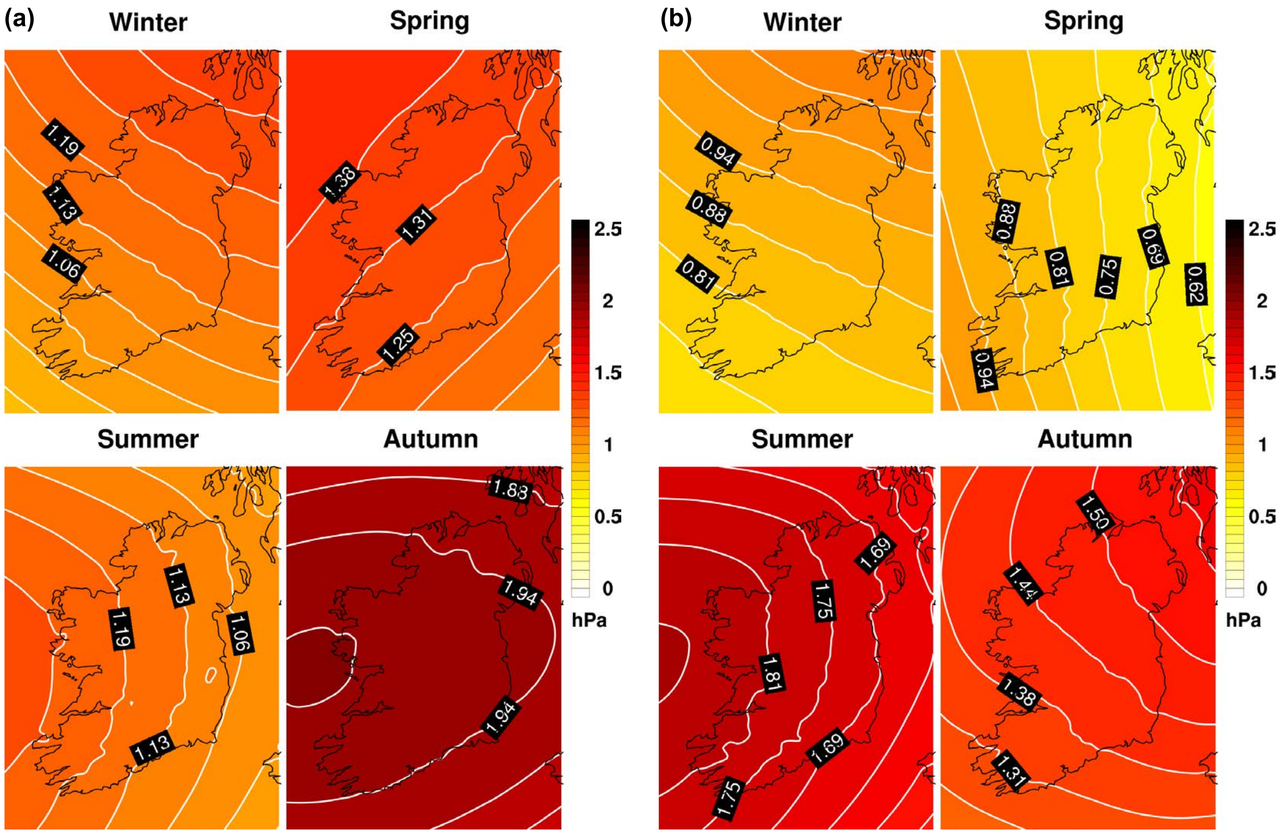


Figure 3.39. Mid-century seasonal projections of MSLP (hPa) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

mid-latitude storms in a warming world is provided in section 3.17. However, further investigation is necessary to attribute causation to the MSLP projections of the current study. Future work will attempt to address this issue by analysing a substantially larger RCM ensemble of downscaled CMIP6 data. Furthermore, the impact of changes in both the frequency and intensity of low pressure systems on MSLP will be quantified.

3.17 Storm Track Projections

Given the large societal impacts of extreme storms, there is considerable interest in the potential impact of climate change on extreme cyclonic activity in the North Atlantic. Windstorms and associated high wind speeds are a major source of natural hazard risk for Ireland and many countries across Europe. For example, Ireland and the UK were severely affected by an exceptional run of storms during the winter of 2013/2014, culminating in serious coastal damage and widespread, persistent flooding. Reports issued by the meteorological agencies of Ireland and the UK have confirmed that records for precipitation totals and extreme wind speeds were set during this period (Met Éireann, 2014; Kendon *et al.,* 2015). Matthews *et al*. (2014) found that the UK/Ireland winter of 2013/2014 was the stormiest for at least 143 years when storm frequency and intensity are considered together. In addition to the potential widespread flooding and structural damage associated with intense storms, the wind energy supply can be negatively affected, as wind turbines are shut down during periods of high wind speeds to prevent damage.

Feser *et al*. (2014) conducted a review of studies of storms over the North Atlantic and north-western Europe to identify potential long-term trends. Storm trends derived from reanalyses data and climate model data for the past were mostly limited to the last four to six decades. They found that “the majority of these studies find increasing storm activity north of about 55–60°N over the North Atlantic with a negative tendency southward” (Feser *et al*., 2014). Furthermore, “future scenarios until about the year 2100 indicate mostly an increase in winter storm intensity over the

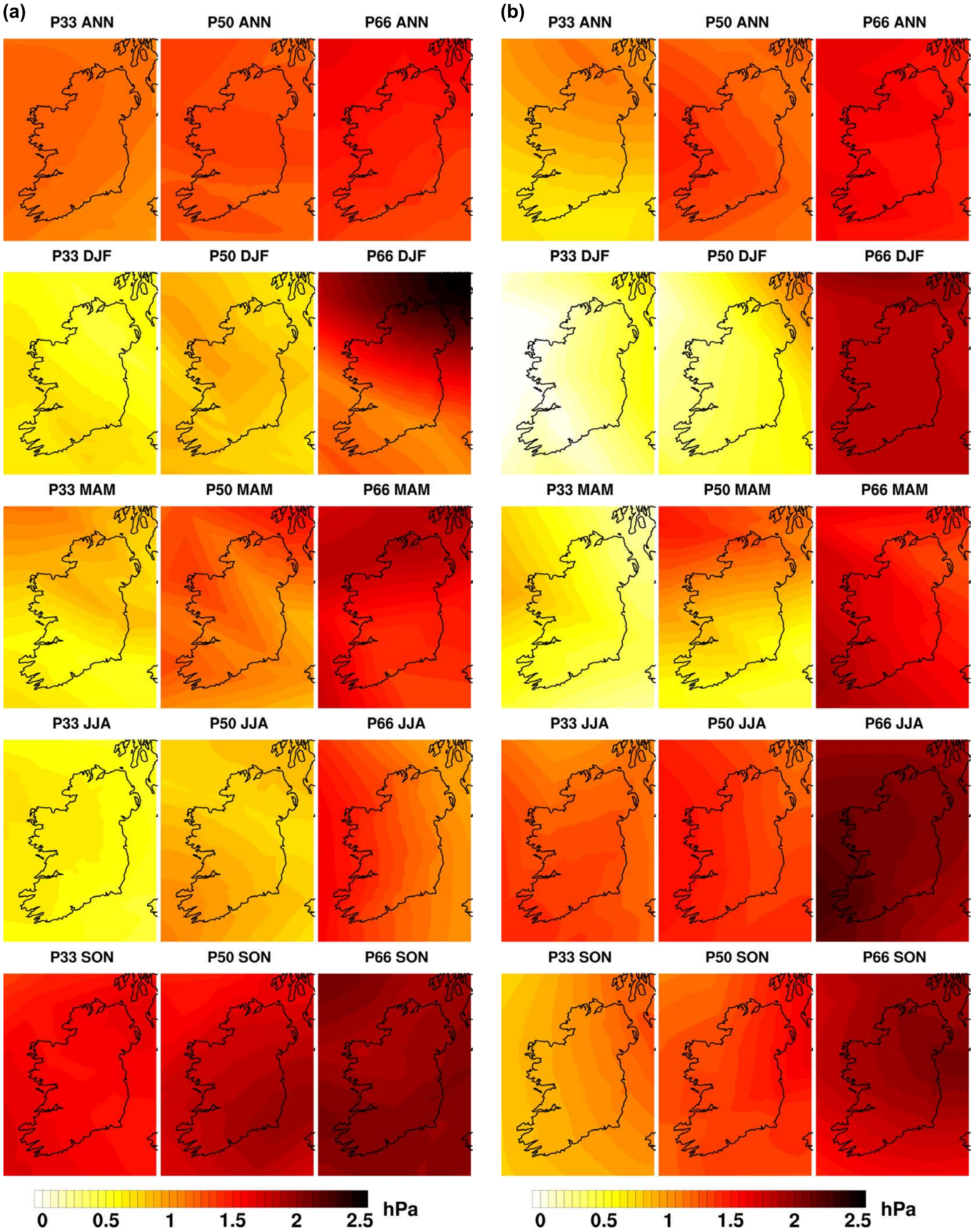


Figure 3.40. The 33rd, 50th and 66th percentiles of annual and seasonal MSLP projections (hPa) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. ANN, annual; DJF, December, January, February; JJA, June, July, August; MAM, March, April, May; SON, September, October, November.

North Atlantic and western Europe. However, future trends in total storm numbers are quite heterogeneous and depend on the model generation used" (Feser *et al*., 2014). Matthews *et al*. (2016) analysed cyclone trends in the British and Irish Isles (BI) by assessing a 142-year (1871–2012) record of cyclone frequency, intensity and "storminess" derived from the 20th-century Reanalysis V2 (20CR) dataset. They found an "upward trend in cyclone intensity for the BI region, which is strongest in winter and consistent with model projections" (Matthews *et al*., 2016). Zappa *et al*. (2013) analysed a CMIP5 ensemble of 19 GCMs and found a small, but significant, increase in the number and intensity of winter cyclones associated with strong wind speeds over the UK by the end of the century. A 2013 study with a very high-resolution version of the EC-Earth model (Haarsma *et al*., 2013) suggests an increase in the frequency of extreme wind storms affecting Western Europe in future autumn seasons as a result of climate change.

As part of the current study, an algorithm was developed to identify and track cyclones. The algorithm was applied to an ensemble subset of EURO-CORDEX 12-km downscaled CMIP5 data. Results show a reduction of ≈10% in the numbers of less intense storms affecting Ireland and suggest an eastward extension of the more severe wind storms over Ireland and the UK from the middle of the century.[13] Figure 3.41 presents intense storm tracks as simulated by the European Coordinated Regional climate Downscaling Experiment (EURO-CORDEX) ensemble. Previous studies that analysed RCM projections of future extreme storm events over Ireland are in broad agreement with these results (Semmler *et al*., 2008a,b; Nolan, 2015; McGrath and Nolan, 2017). It should be noted that extreme storms, as presented in Figure 3.41, are rare events. Therefore, the storm projections should be considered with a high level of caution. Future work will focus on analysing a larger ensemble of downscaled CMIP6 data, thus allowing a robust statistical analysis of extreme storm track projections.

The warming of the climate system on account of greenhouse gas forcing is expected to change the thermal structure of the lower atmosphere; the enhanced warming of the poles, particularly in the Arctic, will reduce the equator-to-pole temperature gradient and this effect is often appealed to as a mechanism for a reduction in the number of mid-latitude storms in a warming world. For example, Geng and Sugi (2003) and Semmler *et al*. (2008b) proposed that a decreased meridional temperature gradient and the associated reduced baroclinicity in the future climate could be responsible for the decrease of the total number of cyclones. Furthermore, the higher moisture supply as a result of a generally higher sea surface temperature and the related increase in latent heat fluxes could trigger strong-intensity cyclones (Hall *et al*., 1994; Semmler *et al*., 2008b). Further work, analysing a large ensemble of downscaled CMIP6 datasets, is required to fully investigate these issues.

3.18 120-m Wind Power Projections

There is considerable interest among policymakers and the energy industry in renewable energy resources as a means of reducing carbon dioxide emissions to minimise climate change (Solomon *et al*., 2007). Within this context, the current section assesses the impacts of climate change on the future wind energy resource of Ireland. Because the energy content of the wind is proportional to the cube of the wind speed, we focus on projections of the mean cube of the wind speed.[14] Furthermore, wind energy projections at 120 m above the surface were analysed, so the results provide information at a typical turbine height.[15]

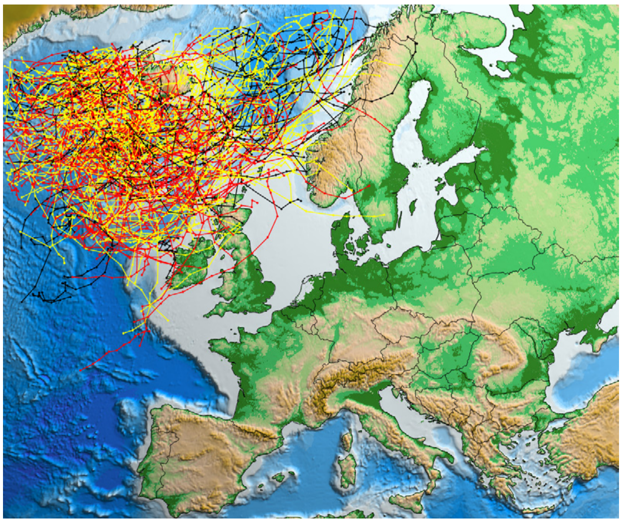
Figure 3.42 presents the mean annual percentage change in 120-m wind power for the RCP4.5 and RCP8.5 scenarios. For the purpose of onshore and offshore wind energy applications, the analyses of wind power cover all land points and a small portion of the surrounding sea. The projections show a slight reduction in the 120-m wind power of 3.1–5.8%

13 Note that because extreme storms are very rare events, a slight increase has no noticeable effect on the mean wind speed statistics presented in section 3.13. The projected decrease in less intense (very common) storms has a substantially greater effect on decreasing the frequency of higher wind speeds than the increase in very rare intense storms.

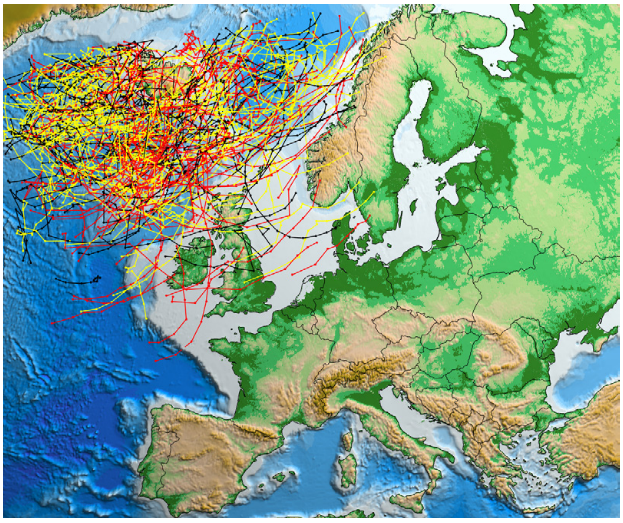
14 A more accurate measure of wind power is given by wind power = 0.5 × air density × (wind speed)^3. Because air density was not archived for all RCM ensemble members, we focus on the cube of the wind speed as a measure of wind power.

15 https://www.windawareireland.com/overview/ (accessed 31 May 2020).

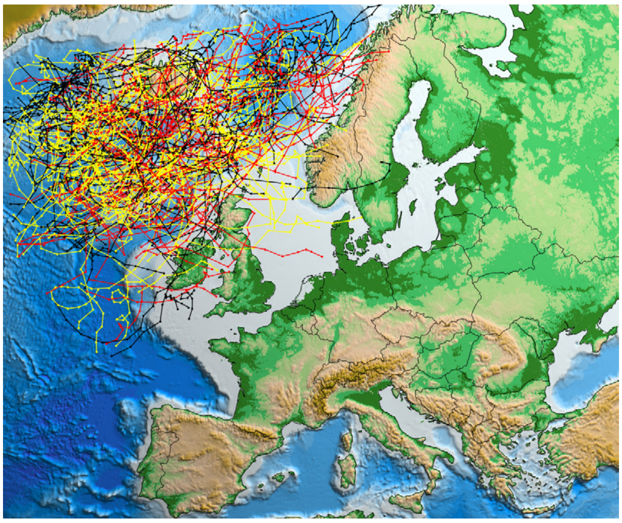
(a) EURO-CORDEX, 1976–2005



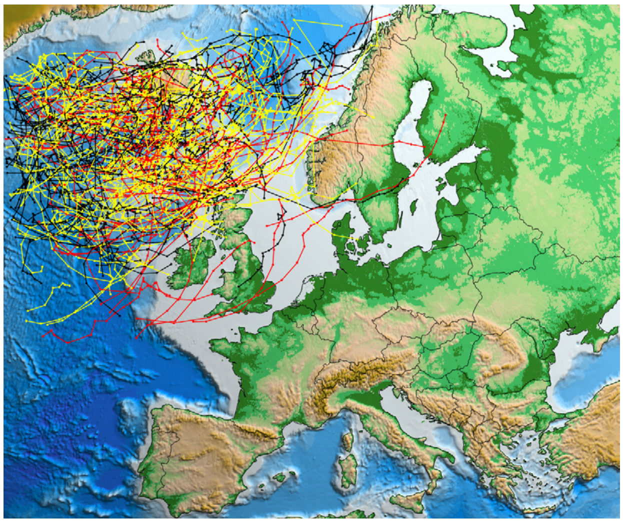
(b) EURO-CORDEX RCP4.5, 2040–2069



(c) EURO-CORDEX RCP8.5, 2040–2069



(d) EURO-CORDEX RCP4.5, 2070–2099



(e) EURO-CORDEX RCP8.5, 2070–2099

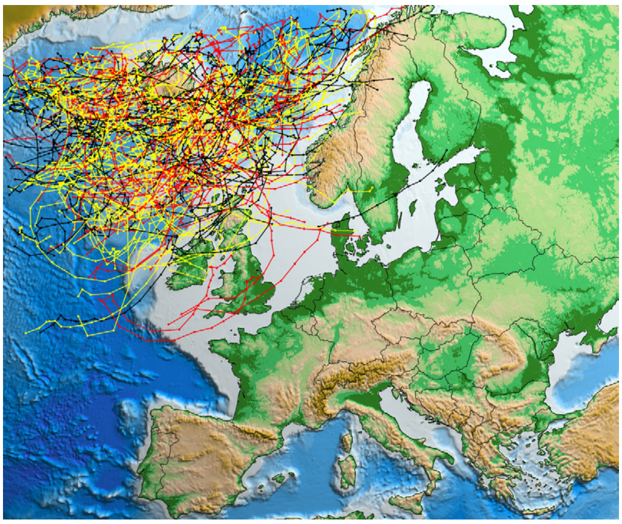


Figure 3.41. Tracks of intense storms as simulated by an ensemble of EURO-CODEX model runs. Tracks are plotted for storms with core MSLPs less than 950 hPa and that exist for at least 24 hours. In addition, storms are only considered if the maximum 10-m wind speed within 250 km of the storm centre (radius of maximum wind; denoted w_r) is greater than 24.5 m s^{-1}. Tracks are coloured black if $24.5 < w_r \leq 28.5$ m s^{-1}, yellow if $28.5 < w_r \leq 32.7$ m s^{-1} and red if $w_r > 32.7$ m s^{-1}. (a) Past simulations (1976–2005), (b) RCP4.5 (2040–2069), (c) RCP8.5 (2040–2069), (d) RCP4.5 (2070–2099) and (e) RCP8.5 (2070–2099).

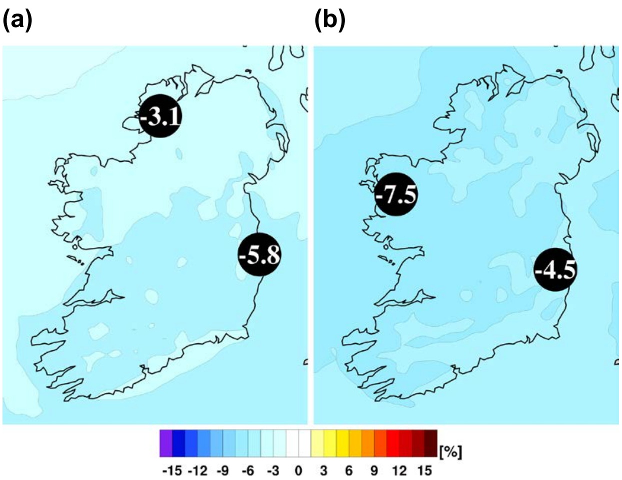


Figure 3.42. Ensemble mean of mid-century 120-m wind power projections (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

(mean value 4.5%) for the RCP4.5 scenario and 4.5–7.5% (mean value 6%) for the RCP8.5 scenario. Figure 3.43a presents the seasonal change (%) in 120-m wind power for the RCP4.5 scenario; the corresponding plots for RCP8.5 are presented in Figure 3.43b. All seasons show a projected decrease in mean 120-m wind power. The decreases are largest for summer under the RCP8.5 scenario. The summer reductions range from 2.8% to 8.7% for the RCP4.5 scenario and from 6.5% to 14.1% for the RCP8.5 scenario.

With the exception of spring and autumn under the RCP4.5 scenario, Figure 3.44 shows a small variation between the 33rd, 50th and 66th 120-m wind power projection percentiles. This agreement adds a level of confidence to the projected reductions in wind power during summer (both RCPs), winter (both RCPs), spring (RCP8.5), autumn (RCP8.5) and over the full year (both RCPs).

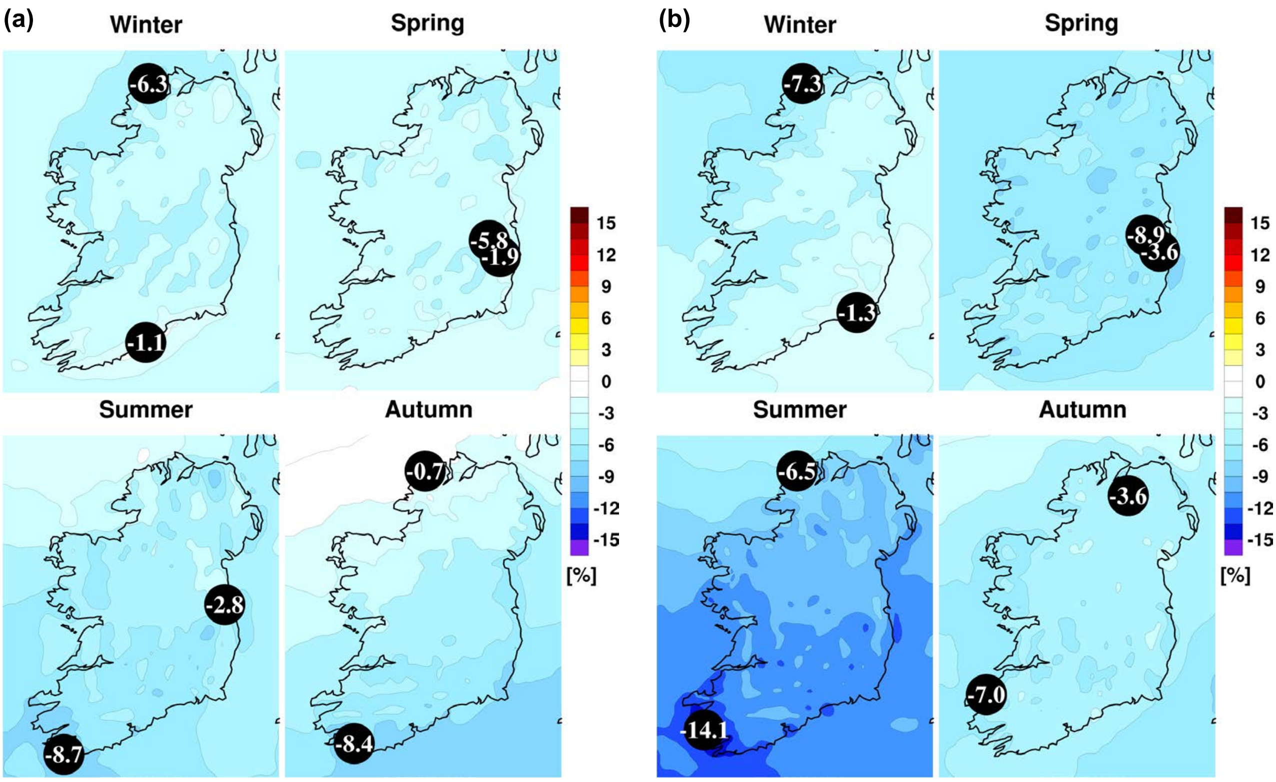


Figure 3.43. Mid-century seasonal projections of mean 120-m wind power (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

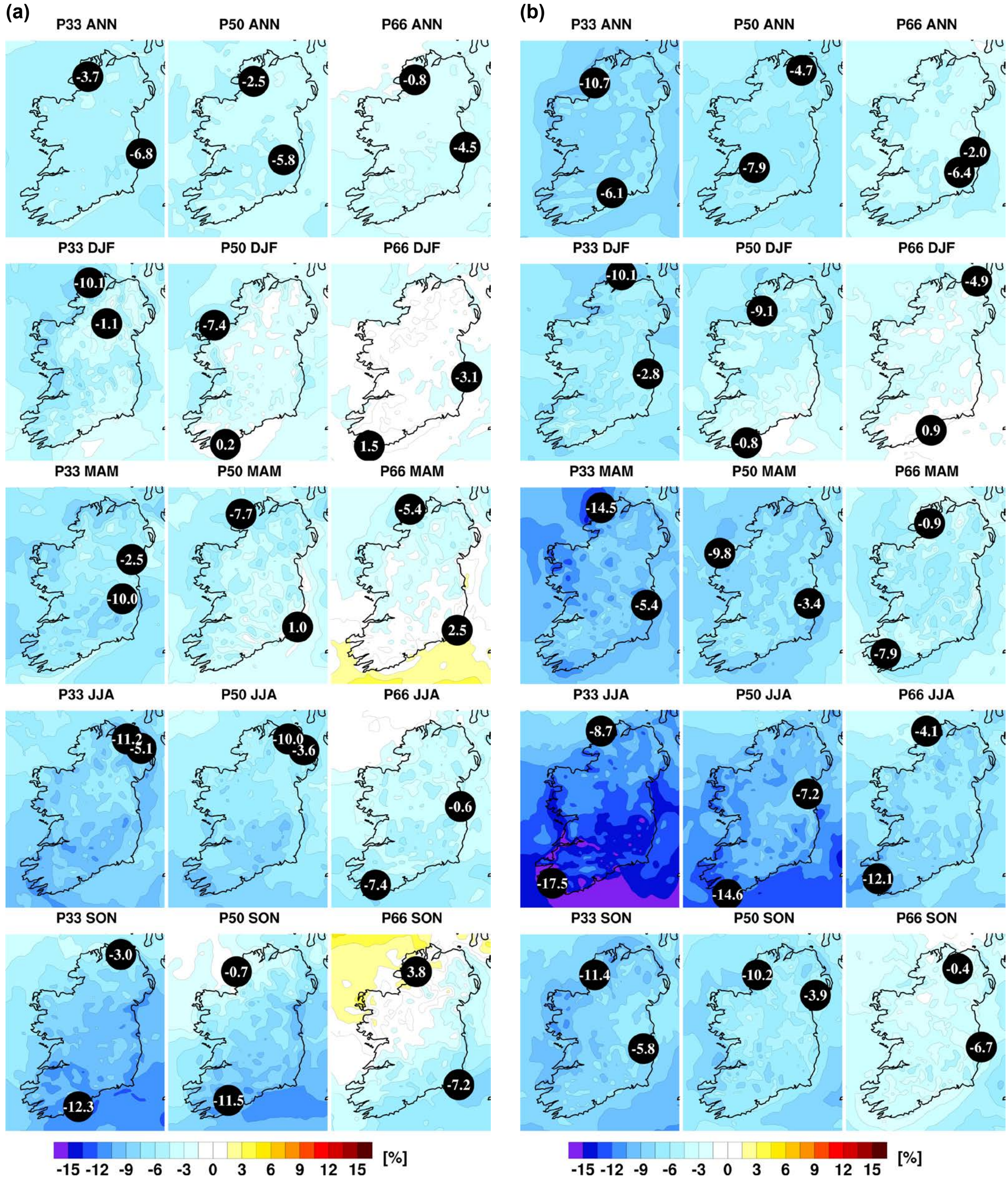


Figure 3.44. The 33rd, 50th and 66th percentiles of annual and seasonal mean 120-m wind power projections (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. ANN, annual; DJF, December, January, February; JJA, June, July, August; MAM, March, April, May; SON, September, October, November.

The annual change in the standard deviation of 120-m wind power (Figure 3.45) shows small changes of between ≈−5.5% and −0.6% for both the RCP4.5 and RCP8.5 scenarios. All seasons – except winter and autumn (RCP4.5), when small (≈0%) changes are noted – show reductions, with the largest decreases noted during summer (Figure 3.46). A reduction in 120-m wind power, coupled with a decrease in

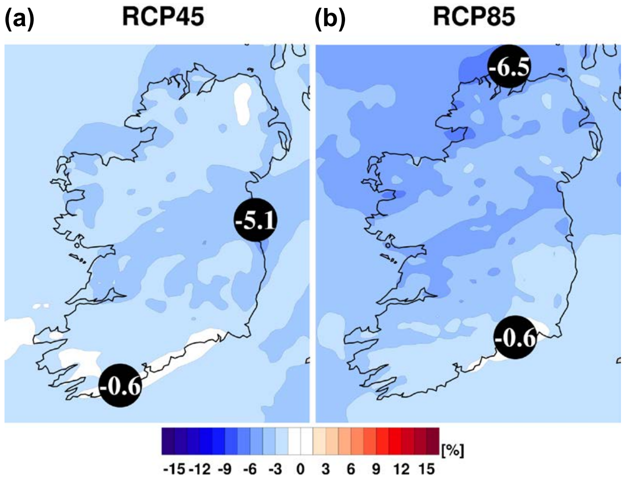


Figure 3.45. Annual projected change in the standard deviation of 120-m wind power (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

standard deviation, implies a shift to the left of the wind power distribution and an enhanced decrease in wind power in the more energetically useful range.

The projected changes in wind power are in line with previous RCM studies for Ireland, which showed projected decreases in wind power by the middle of the century during summer, spring and over the full year (e.g. Nolan *et al*., 2014; Nolan, 2015).

3.19 Surface Shortwave Radiation and Solar Photovoltaic Power

Figure 3.47a, the projected change in mean annual surface shortwave radiation, shows ≈0% or small decreases by the middle of the century. Small projected decreases are also noted for winter and spring, whereas summer and autumn show small increases, particularly in the south (not shown). However, the projected changes are small and so will have minimal effect on solar energy, agricultural and health impacts (e.g. skin cancer and vitamin D deficiency).

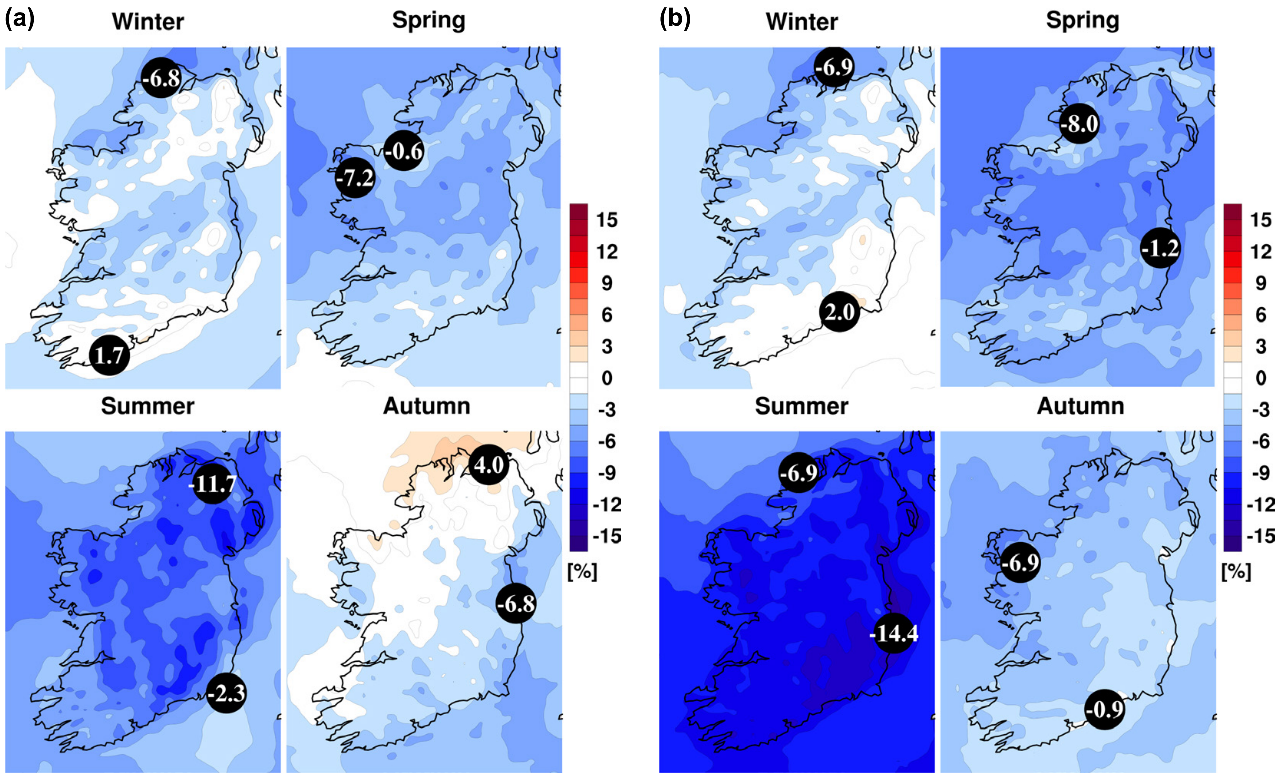


Figure 3.46. Seasonal projected change in the standard deviation of 120-m wind power (%) for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

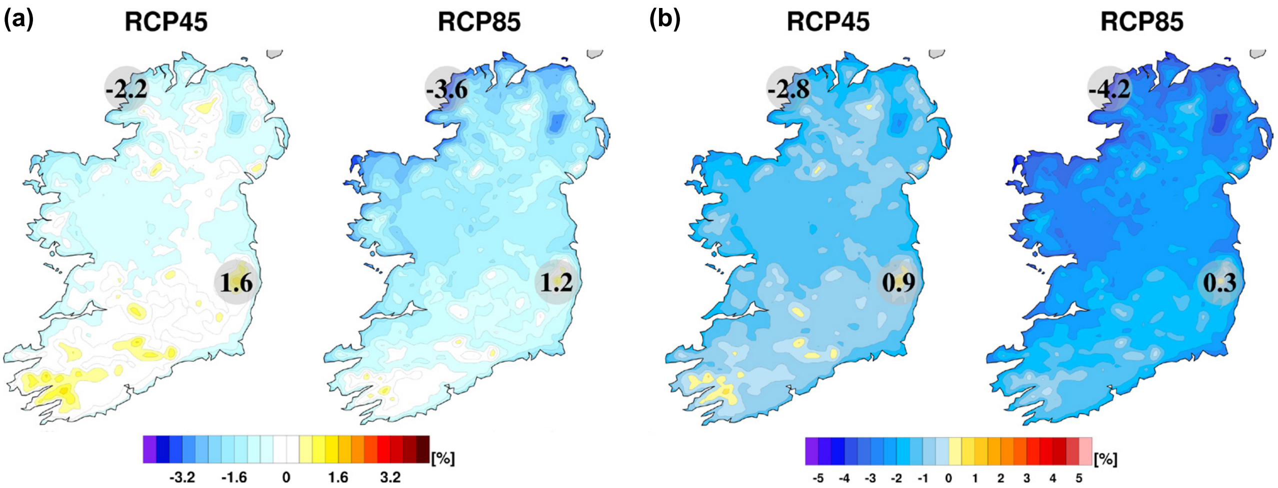


Figure 3.47. Mid-century projected changes (%) in mean annual (a) surface shortwave radiation and (b) solar PV power.

The radiation projections are in line with similar European studies. Jerez *et al*. (2015) analysed an ensemble of EURO-CORDEX RCM projections and found the ensemble mean pattern of change for mean surface-downwelling shortwave radiation (2070–2099 vs 1970–1999 climatologies under RCP8.5) shows "positive signals (about 5 $W\,m^{-2}$) in Southern Mediterranean regions" and "negative signals northwards (about −10 $W\,m^{-2}$, down to −20 $W\,m^{-2}$ in the northernmost areas)". Bartók *et al*. (2017) also analysed a EURO-CORDEX RCP85 ensemble and found that "the multi-model mean of RCMs indicates a decrease in surface solar radiation of −0.60 $W\,m^{-2}$ per decade over Europe" for the period 2006–2100. The authors proposed that the reduction of surface solar radiation in the RCMs "can be attributed to increasing atmospheric absorption in line with the increase of water vapor content" (Bartók *et al*., 2017).

A more comprehensive analysis of the impacts of climate change on solar photovoltaic (PV) power in Ireland was evaluated using the following method outlined in Jerez *et al*. (2015) and Mavromatakis *et al*. (2010):

$$PV(t) = P_R(t)\frac{SW(t)}{SW_S} \qquad (3.7)$$

where *SW* refers to surface-downwelling shortwave radiation ($W\,m^{-2}$) and SW_S refers to surface-downwelling shortwave radiation at standard test conditions ($SW_S = 1000\,W\,m^{-2}$), for which the nominal capacity of a PV device is determined as its measured power output. P_R is the "performance ratio", formulated to account for changes of the PV cells, efficiency as a result of changes in their temperature as:

$$P_R(t) = 1 + \gamma\left(T_{cell}(t) - T_s\right) \qquad (3.8)$$

where T_{cell} is the PV cell temperature, $T_s = 25°C$ (standard test conditions) and $\gamma = -0.005°C^{-1}$, considering the typical response of monocrystalline silicon solar panels (Tonui *et al*., 2008). T_{cell} is modelled considering the effects of surface temperature, *T* (°C), *SW* ($W\,m^{-2}$) and wind speed, *W* ($m\,s^{-1}$), on it as:

$$T_{cell}(t) = c_1 + c_2T + c_3SW + c_4W \qquad (3.9)$$

with $c_1 = 4.3°C$, $c_2 = 0.943$, $c_3 = 0.028°C\,m^2\,W^{-1}$ and $c_4 = -1.528°C\,s\,m^{-1}$, as recommended by Jerez *et al*. (2015) and Tonui *et al*. (2008).

The projected change in PV, presented in Figure 3.47b, shows a small expected decrease in PV by the middle of the century, ranging from ≈0 to 4%. The largest decreases are noted in the north of the country and for the RCP8.5 scenario. The results are consistent with Jerez *et al*. (2015), who analysed the effects of climate change on PV in Europe using an ensemble of Euro-CORDEX datasets.

3.20 Heating Degree Days

A degree day, an estimate of accumulated heat, is defined as the deviation (°C) from a base temperature value (Fraisse *et al*., 2010; Kalogirou, 2013; Project Team ECA&D, 2013; Kendon *et al*., 2015). Heating degree days (HDDs) are used by power companies and consumers to estimate the amount of energy required for residential or commercial space heating during the cold season. Conversely, cooling degree days (CDDs) are used to estimate the amount of air conditioning usage during the warm season.

The HDD was computed using a base temperature of 15.5°C (i.e. a temperate below which heating is required) and the daily mean temperature (T_M), as described by Spinoni *et al*. (2015) and Project Team ECA&D (2013):

$$HDD_{daily} = \max\{(15.5°C - T_M), 0\} \quad (3.10)$$

$$HDD = \Sigma HDD_{daily} \quad (3.11)$$

Conversely, CDD was computed using a base temperature of 22°C (i.e. a temperate above which air conditioning is required) and the daily mean temperature (T_M):

$$CDD_{daily} = \max\{(T_M - 22°C), 0\} \quad (3.12)$$

$$CDD = \Sigma CDD_{daily} \quad (3.13)$$

Figure 3.48, the projected change in HDDs, shows that by the middle of the century there will be a greatly reduced requirement for heating in Ireland, with HDDs projected to decrease by 12–17% and 15–21% for the RCP4.5 and RCP8.5 scenarios, respectively. A clear north-to-south gradient is evident for both

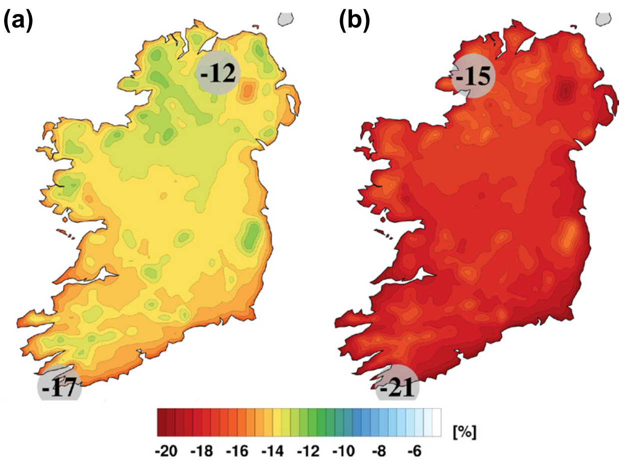


Figure 3.48. Mid-century projected changes (%) in HDDs for the (a) RCP4.5 and (b) RCP8.5 scenarios.

RCP scenarios. Averaged over the whole country, the expected decreases in HDDs are 14% and 18% for the RCP4.5 and RCP8.5 scenarios, respectively. The projections show that CDDs are projected to slightly increase (not shown), particularly over the east and midlands, suggesting a very small increase in air conditioning requirements by the middle of the century. However, the amounts are small compared with HDD and therefore have a negligible effect on the projected changes in the total energy demand (EDD = HDD + CDD).

The projected changes in heating and cooling energy demand are in line with previous RCM studies for Ireland. Semmler *et al*. (2010) found that the mid-century (2021–2060) heating demand is projected to decrease by ≈10% for the A1B and A2 emissions scenarios. The authors found a small projected increase in summer CDDs, which may intensify a weak demand for air conditioning towards the end of the century (Semmler *et al*., 2010). However, the "main influence of a warming climate will be reflected in a decrease in energy requirements for commercial and domestic heating in Ireland" (Semmler *et al*., 2010).

3.21 Driving Rain

The "driving rain" metric ($m^2 s^{-1} year^{-1}$) can be approximated from the following equation (Collins and Cummins, 1996; Met Éireann, 2010):

$$DR = W \cdot R \quad (3.14)$$

where W is the mean annual 10-m wind speed ($m s^{-1}$) and R is the mean annual rainfall ($m year^{-1}$).

The driving rain metric is a useful parameter for agriculture, construction and transport applications.

Figure 3.49a shows that by the middle of the century, "driving rain" is projected to decrease by 1–7% and 0–8% for the RCP4.5 (mean decrease 4.5%) and RCP8.5 (mean decrease 4%) scenarios, respectively. Decreases are projected for all seasons (except winter under the RCP8.5 scenario). The largest decreases are noted for summer, with overall mean decreases of 7% (RCP4.5) and 12% (RCP8.5). Increases in driving rain are projected for winter under the RCP8.5 scenario, with the largest increases noted near the south and east coastlines (see Figure 3.49b).

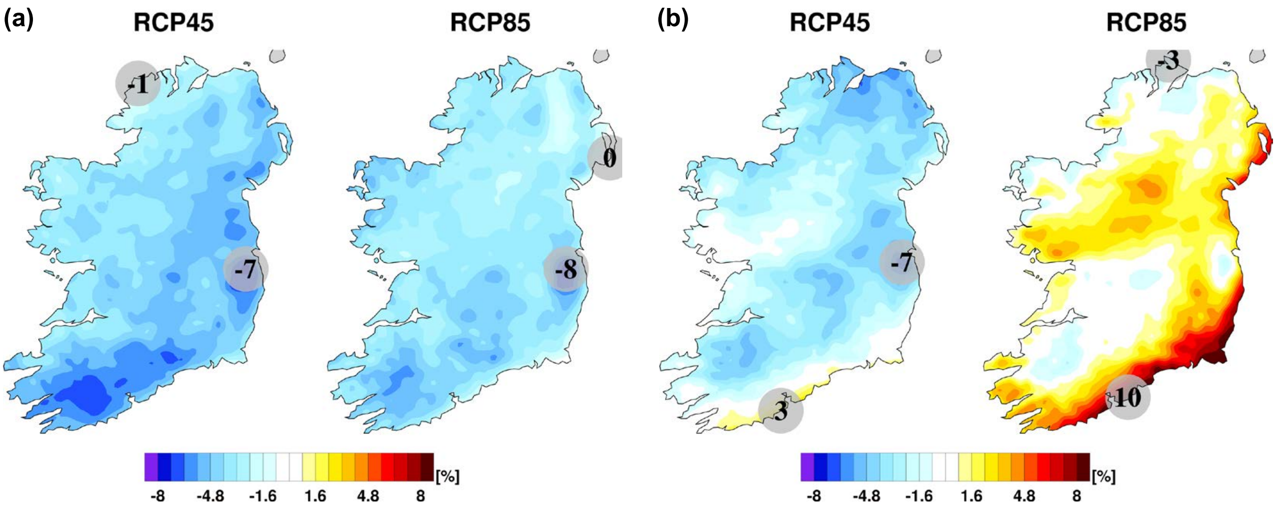


Figure 3.49. Projected changes (%) in mid-century "driving rain" (a) annually and (b) in winter. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

3.22 Evapotranspiration

Projections of evapotranspiration are presented in Figure 3.50a. The projections show that by the middle of the century, evapotranspiration is projected to increase by 2.3–7% and 1.8–8% for the RCP4.5 and RCP8.5 scenarios, respectively. The largest increases are noted in the east. All seasons show increases in evapotranspiration by the middle of the century, with the largest increases noted for summer and autumn. The projected increase in evapotranspiration may offset flooding events arising from the expected increases in heavy rainfall events (see section 3.10). For reference, "observed" annual evapotranspiration ($mm\,day^{-1}$), derived from a high-resolution (1.5-km) downscaled ERA-Interim climate simulation, is presented in Figure 3.50b. Please refer to Werner *et al*. (2019) for validations and additional maps and information.[16]

Evapotranspiration was calculated using the output of RCMs (see Table 1.1). The Penman–Monteith FAO-56 method of Zotarelli *et al*. (2010) was followed. A mathematical description is provided below.

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (3.15)$$

- ET_{sz} is the reference evaporation, $mm\,day^{-1}$;
- R_n is the net surface radiation, $MJ\,m^{-2}\,day^{-1}$ (see equation 3.16);
- G is the surface sensible heat flux, $MJ\,m^{-2}\,day^{-1}$ (see equation 3.17);
- T_{mean} is the mean daily 2-m temperature,°C;
- u_2 is the mean daily 2-m wind speed, $m\,s^{-1}$ (see equation 3.18);
- e_s is the saturation vapour pressure (daily average), kPa (see equation 3.19);
- e_a is the actual vapour pressure (daily average), kPa (see equation 3.20);
- Δ is the slope of the vapour pressure curve, kPa°C^{-1} (see equation 3.21);
- γ is the psychrometric constant, kPa°C^{-1} (see equation 3.22);
- C_n is the reference crop type constant numerator;
- C_d is the reference crop type constant denominator.

For the calculation above, $C_n = 900$ and $C_d = 0.34$ were used.

$$R_n = 0.0864(R_{ns} - R_{nl}) \qquad (3.16)$$

R_{ns} and R_{nl} are the mean daily surface shortwave and longwave net radiation in units of $W\,m^{-2}$

16 In summary, Werner *et al*. (2019) compared modelled evapotranspiration with observational data at 22 stations spanning Ireland and found that the COSMO-CLM RCM resolved evapotranspiration to "within 10% of values calculated from station measurements for all stations analysed".

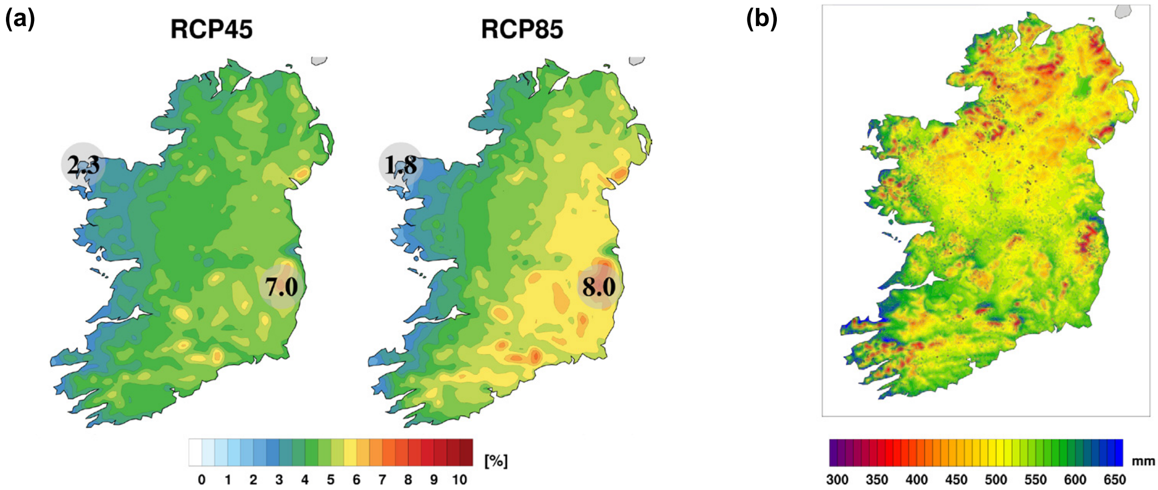


Figure 3.50. (a) Mid-century projected changes (%) in evapotranspiration. (b) "Observed" annual evapotranspiration FAO-56, 1981–2015

$$G = 0.0864\,SH \tag{3.17}$$

SH is the mean daily surface sensible heat flux in units of $W\,m^{-2}$

$$u_2 = u_{10}\frac{4.87}{\ln\left(67.8\times 10 - 5.42\right)} \tag{3.18}$$

u_{10} is the 10-m wind speed, $m\,s^{-1}$

$$e_s = 0.6108e^{\left(\frac{17.27T}{T+237.3}\right)} \tag{3.19}$$

T is the 2-m temperature,°C

$$e_a = 0.6108e^{\left(\frac{17.27T_d}{T_d+237.3}\right)} \tag{3.20}$$

T_d is the 2-m dew point temperature,°C

$$\Delta = \frac{4098.2e_s}{\left(T_{mean} + 237.3\right)^2} \tag{3.21}$$

$$\gamma = 0.000000665\,P \tag{3.22}$$

where *P* is the mean daily surface pressure, Pa.

4 Recommendations

There is higher confidence in the temperature (and derived variables related to temperature) projections than in the rainfall projections. This is reflected in a rather large spread, particularly at a regional level, in the rainfall projections between the individual RCM ensemble members. Current RCM research aims to reduce climate change projection uncertainty and provide sharper estimates of expected climate change in the decades ahead. This is being achieved by running a large ensemble of high-resolution downscaled simulations using the most up-to-date RCMs (both standard and coupled atmosphere–ocean–wave), additional CMIP5 GCM datasets including the RCP2.6 and RCP6.0 scenarios and recently completed CMIP6 GCM simulations (e.g. Nolan and McKinstry, 2020) under the full range of ScenarioMIP "tier 1" SSPs: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Riahi *et al*., 2017). Additionally, the accuracy and usefulness of the model predictions will be enhanced by increasing the model resolution (≈3 km) and using fully coupled atmosphere–ocean–wave RCMs. Preliminary RCM projection results are in line with previous work showing, for example, enhanced temperature rises by

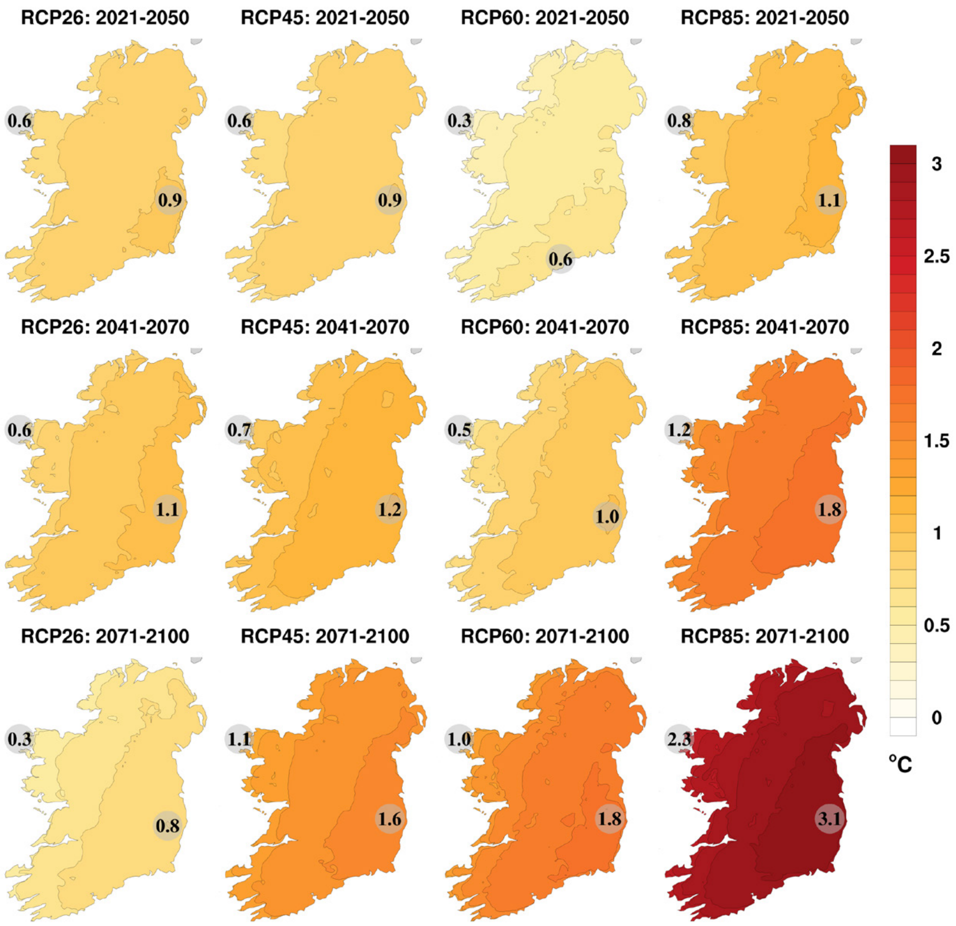


Figure 4.1. Updated RCM ensemble projections of mean annual 2-m temperature. All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1976–2005. The relatively low RCP6.0 temperature increase for early to mid-century can be attributed to a difference in RCP ensemble size. The preliminary results shown were obtained from analysing four RCP2.6, six RCP4.5, two RCP6.0 and six RCP8.5 RCM simulations. Current work is focusing on greatly increasing the ensemble size.

the end of the century (Figure 4.1), wetter winters with a clear north-west to south-east gradient (Figure 4.2) and a general decrease in wind speeds during summer. The preliminary results shown in Figures 4.1 and 4.2 were obtained by extending the COSMO5-CLM and WRF simulations outlined in Table 1.2 to cover the period 1975–2100 and inclusion of the RCP2.6 and RCP6.0 scenarios in the simulation of the future climate.

It is also important to stress that the likelihood values presented in the current study are derived from the most up-to-date evidence available. Therefore, the "likelihood" values only apply to the specific sets of high-resolution models and experimental design of the current study. It is expected that future improvements in modelling will alter the projections, as uncertainty is expected to be gradually reduced.

As extreme storm events are rare, the storm-tracking research needs to be extended. Future work will focus on analysing a larger ensemble, thus allowing a robust statistical analysis of extreme storm track projections.

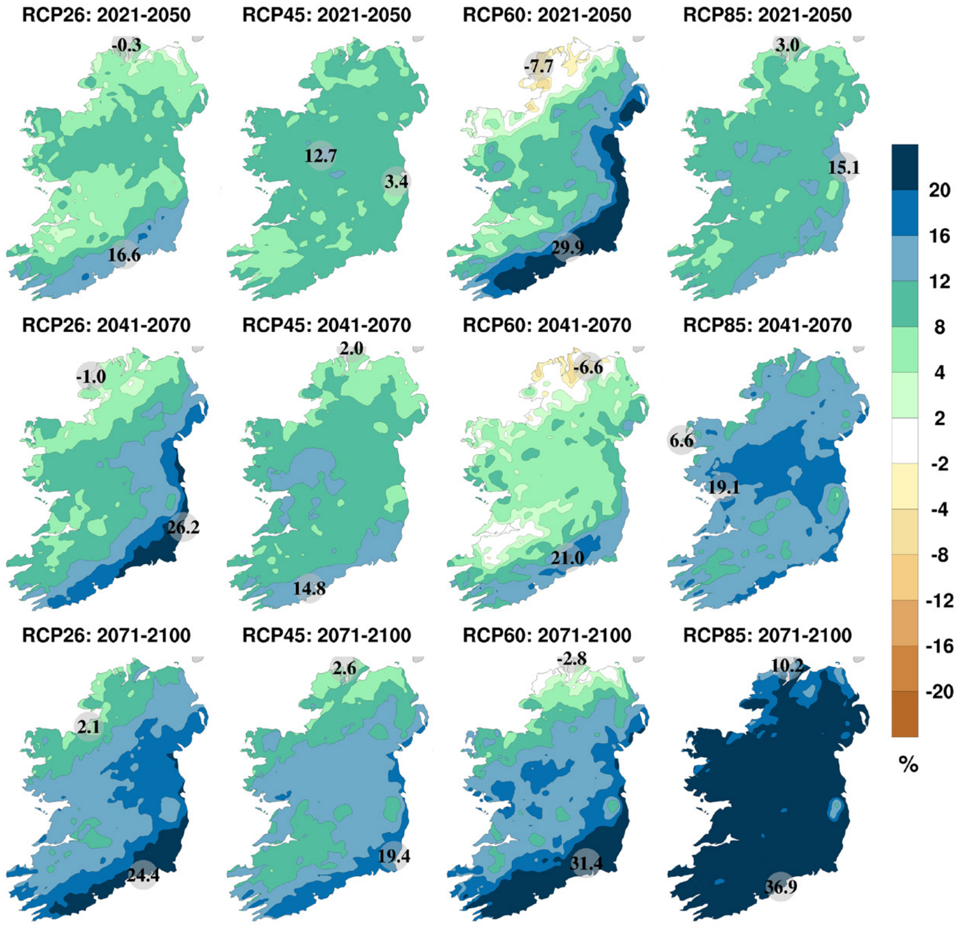


Figure 4.2. Updated RCM ensemble projections of mean winter precipitation (%). All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period, 1976–2005.

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Abbreviations

BI	British and Irish Isles
CDD	Cooling degree day
CHU	Crop heat unit
CLM	Climate Limited-area Modelling
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional climate Downscaling Experiment
COSMO	Consortium for Small-scale Modeling
ECMWF	European Centre for Medium-Range Weather Forecast
ERA-Interim	ECMWF global atmospheric reanalysis
GCM	Global climate model (or alternatively, “General Circulation Model”)
GDD	Growing degree day
HadGEM2-ES	Hadley Centre Global Environment Model version 2 Earth System
HDD	Heating degree day
ICHEC	Irish Centre for High-End Computing
IPCC	Intergovernmental Panel on Climate Change
MAE	Mean absolute error
MIROC	Model for Interdisciplinary Research on Climate
MSLP	Mean sea level pressure
OCHU	Ontario Crop Heat Unit
pdf	Probability density function
PV	Photovoltaic
RCM	Regional climate model
RCP	Representative Concentration Pathway
RMSE	Root mean square error
ScenarioMIP	Scenario Model Intercomparison Project
SSP	Shared Socioeconomic Pathway
WRF	Weather Research and Forecasting

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

High-resolution Climate Projections for Ireland – A Multi-model Ensemble Approach

Authors: Paul Nolan and Jason Flanagan

Regional climate models (RCMs) take the outputs from global climate models (GCMs) to produce more refined projections of the potential local and regional impacts of climate change. The current study used RCMs to simulate the mid-21st-century climate of Ireland. The projections were run at high spatial resolution (4 km), allowing a more realistic representation of important physical processes and enabling a more accurate evaluation of the local impacts. To address the uncertainty inherent in climate model projections, different RCMs were used to downscale outputs from a number of different CMIP5 (Coupled Model Intercomparison Project – Phase 5) GCMs. A statistical analysis of the resulting multi-model ensemble of downscaled datasets was completed allowing for the uncertainty in the projections to be partially quantified. To address the uncertainty in future emissions and changing land use, and how the world will come together to response to the challenge of climate change, the future climate was simulated under both Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 scenarios. The climate projections of the current report are in broad agreement with previous research, which adds a measure of confidence to the projections.

Identifying Pressures

Ireland's climate is changing, resulting in higher temperatures, changing precipitation patterns and increases in the frequency and intensity of extreme events, with these changes expected to continue and intensify into the future. Ongoing and projected climate change impacts pose significant risks to all aspects of Ireland's economy, society and environment. Accurate climate projections, produced by high-resolution RCMs, can assist national policymakers to plan for, and adapt to, the adverse effects of climate change.

Informing Policy

This research will inform national climate policy and further the understanding of the potential impacts of climate change in Ireland. Furthermore, the research will inform the climate change adaptation action that various governmental departments and local authorities are mandated to undertake under the National Adaptation Framework. Selected findings from this study indicate that by the middle of this century (2041–2060):

- temperatures are projected to increase by 1–1.6°C compared with the baseline period (1981–2000), with the largest increases in the east;
- warming will be enhanced at the extremes (i.e. hot days and cold nights), with summer daytime and winter night-time temperatures projected to increase by 1–2.4°C;
- substantial decreases of approximately 50% are projected in the number of frost and ice days;
- summer heatwave events are expected to occur more frequently, with the largest increases in the south;
- precipitation is expected to become more variable, with substantial projected increases in the occurrence of both dry periods and heavy precipitation events.

The research presents projections of additional climate fields and derived variables that are of importance to sectors including agriculture, health, energy, biodiversity and transport.

Developing Solutions

The research provides Ireland with a data resource to explore Ireland's future climate and enables the assessment of the scale of impacts across sectors, at regional and local scales. This report provides an outline of the regional climate modelling undertaken to assess the impacts of climate change in Ireland, based on a number of possible future scenarios, and highlights the key findings. The project has also provided a large database that can be interrogated for various meteorological parameters, essential for detailed analysis across a diverse range of sectoral concerns.

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