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Published Version

Harvey, B. ORCID: https://orcid.org/0000-0002-6510-8181, Hawkins, E. ORCID: https://orcid.org/0000-0001-9477-3677 and Sutton, R. ORCID: https://orcid.org/0000-0001-8345-8583 (2023) Storylines for future changes of the North Atlantic jet and associated impacts on the UK. International Journal of Climatology, 43 (10). pp. 4424-4441. ISSN 1097-0088 doi: 10.1002/joc.8095 Available at https://centaur.reading.ac.uk/111785/

To link to this article DOI: http://dx.doi.org/10.1002/joc.8095

Publisher: Wiley

Received: 20 December 2022 | Revised: 19 April 2023 | Accepted: 22 April 2023
DOI: 10.1002/joc.8095

RESEARCH ARTICLE

International Journal of Climatology RMetS

Storylines for future changes of the North Atlantic jet and associated impacts on the UK

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Funding information
Natural Environment Research Council; UK National Centre for Atmospheric Science

Abstract

Climate projections for the UK exhibit substantial uncertainty, and this uncertainty is a hindrance to robust and timely decision making on both adaptation and mitigation policy issues. A large part of the uncertainty is associated with dynamical changes of the regional atmospheric circulation rather than thermodynamic changes which are better constrained by model simulations. Of particular importance for the UK is the extent to which the North Atlantic jet will change over coming decades and the impact this will have on weather and climate in the region. In this article, we propose the use of jet-based storylines for assessing and communicating uncertainty in climate projections for the UK, wherein changes in each impact are explicitly conditioned on changes in the North Atlantic jet. This approach provides a framework for evaluating the impacts associated with a range of plausible future climate outcomes for the UK, including outcomes that may not be well represented in the current generation of climate models, and for communicating these potential outcomes. We construct a simple yet useful set of future jet storylines for both summer and winter and for 2°C and 4°C global warming levels and illustrate the utility of the approach by evaluating the impact of each jet storyline on future changes in UK precipitation. In doing so, we demonstrate that the relationships between the jet and UK precipitation are consistent between observed interannual variability and projected changes. This finding increases our confidence in projecting changes in UK precipitation associated with each storyline.

KEYWORDS

atmospheric circulation, climate change, climate variability, global warming levels, jet shift, precipitation

1 | INTRODUCTION

The weather and climate of the UK are strongly influenced by variability of the North Atlantic jet stream (Woollings et al., 2010). The North Atlantic jet, characterised by the band of lower-tropospheric westerly winds extending across the North Atlantic, exhibits variability on timescales from days to decades and consisting of changes in both the position and the intensity of the strongest winds. On daily timescales, jet variations are intimately linked to the development and evolution of weather systems that impact the UK. On longer timescales, the time-mean jet is highly correlated with UK weather impacts. For example, a northward-shifted jet in summer is associated with warmer, drier conditions in the UK whereas a stronger wintertime jet is associated with wetter, stormier winters (e.g., Hall & Hanna, 2018).

It has long been recognised that climate change in Northwest (NW) Europe, and especially the UK, is particularly uncertain due to the role played by regional changes in atmospheric and oceanic circulation (Shepherd, 2014; Woollings et al., 2010). To a large extent, these changes are manifested as changes in the jet stream winds. Recent assessments have shown some robust patterns emerging regarding future changes in the North Atlantic jet, notably a northward shift in summer and intensification over NW Europe in winter (Harvey et al., 2020; Lee et al., 2021). However, there is a wide range of drivers that may influence the North Atlantic jet (Figure 1) and there remains substantial uncertainty in the magnitude of the projected jet changes, in part due to uncertainty in how each driver will respond to climate change, and in part due to how the balance between them will play out. While there is currently no robust evidence that the North Atlantic jet has already changed because of anthropogenic influences, projections of its future behaviour remain poorly understood and yet have the potential to profoundly impact the UK.

One further area of concern is the growing appreciation that the current generation of climate models may fail to faithfully simulate the response to some of the drivers of jet variability and change. For example, recent work has shown that climate models exhibit North Atlantic decadal variability that is weaker than observed (Blackport & Fyfe, 2022; Bracegirdle et al., 2018; Simpson et al., 2019). Perhaps relatedly, the so-called 'signal-to-noise paradox' (Scaife & Smith, 2018) suggests that the forced response of the North Atlantic jet to certain drivers is systematically too weak in weather and climate model simulations. Likewise, there is evidence that for the specific but important case of the response of the atmospheric circulation to sea ice loss, many climate models underestimate shifts in the mid-latitude jets compared to an observationally constrained estimate (Screen et al., 2022). Finally, there is evidence that the highest resolution climate models, which can be expected to have the most faithful representation of the atmospheric processes involved, do indeed show larger future changes in North Atlantic circulation (Baker et al., 2019; Grist et al., 2021; Moreno-Chamarro et al., 2021; Roberts et al., 2020). Taken together, it is quite plausible that future changes in the North Atlantic jet could be larger (or smaller) than current model projections suggest. It is important to consider such possibilities in impact risk assessments (e.g., Sutton, 2019).

We therefore argue that there is a need for an assessment of future climate in the UK considering explicitly the role played by the North Atlantic jet, and indeed allows for the possibility of future jet changes being larger (or smaller) than climate model simulations currently project. Such an assessment should recognise: (i) the multiple and uncertain drivers of changes of the North Atlantic jet, and (ii) the multivariate and spatial co-variances present in projection uncertainties. The natural approach for such an assessment is provided by storylines, or 'physically self-consistent plausible future events or pathways' (Shepherd, 2019). In this framework, a set of plausible but divergent future outcomes for a particular link in the chain of causality is proposed, allowing for the impacts of each outcome to be assessed. In this article, we advocate explicitly conditioning UK climate change projections on plausible future changes in the North Atlantic jet, thus, providing a physically motivated self-consistent set of projections for the UK.

The storyline approach has been considered in the context of the North Atlantic before. Zappa and Shepherd (2017) consider storylines for changes in the wintertime North Atlantic jet. In that study, the ranges of simulated changes in the jet are conditioned on plausible changes in the drivers responsible. This approach provides physical insight into the causes of model spread in projections of the North Atlantic jet (e.g., identifying the drivers responsible for the most uncertainty in model projections), but is not explicitly linked to impacts. The causality chain linking a potential driver of jet change with a specific UK impact is arguably too long to be practically useful. In the present study, we condition changes in specific UK impacts on plausible future changes of the jet, thus, cutting the 'chain of causality' closer to the impact in question, without attempting to quantify the likelihood or cause of each jet outcome. We contend that the resulting framework will be useful for impact and risk assessments and informing adaptation policies for near- and long-term decision making.

To construct storylines for future changes to the jet in summer (JJA [June, July, August]) and winter (DJF [December, January, February]), we consider (i) the response of the tropospheric winds to anthropogenic forcing and (ii) the nature of present-day variability. These vary throughout the year but share common features in both summer and winter. We also follow the approach of the recent Sixth Assessment Report of the International Panel on Climate Change (IPCC, 2021) by conditioning future changes on global warming level (GWL); that is, by constructing jet storylines for the time when the global mean annual mean surface temperature time series first crosses a set of threshold values, specifically 2°C and 4°C above pre-industrial values. The aim is to avoid

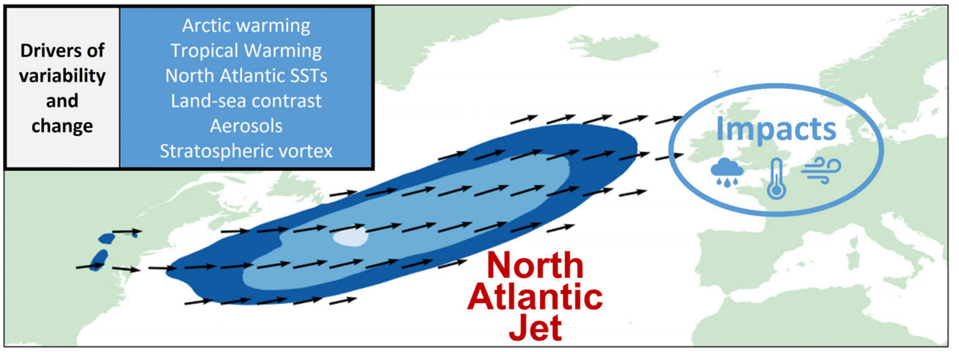

FIGURE 1 Schematic illustration of the North Atlantic jet (shading and arrows), its wide range of drivers (left box) and associated impacts in North–West Europe (right). [Colour figure can be viewed at wileyonlinelibrary.com]

uncertainty associated with the range of climate sensitivities present in different climate models, and uncertainty in future emission pathways.

The article is organised as follows. After outlining the data and methods used in Section 2, the choice of jet indices employed is motivated in Section 3. Section 4 sets out our set of plausible storylines for the North Atlantic jet, and in Section 5 the impacts of each storyline are assessed. The focus of this study is restricted to a few impact variables to illustrate the concept, notably seasonal mean precipitation because it is strongly correlated with jet variability. Section 6 summarises the main conclusions.

2 | DATA AND METHODS

2.1 | Precipitation observations

For the UK, the HadUK-Grid dataset (Hollis et al., 2019) provides monthly precipitation observations for the period 1836 to present. The data are derived from the network of UK land surface observations and are available at a range of resolutions. We utilise the data averaged over river catchment areas. For Europe, the E-OBS dataset (Cornes et al., 2018) provides gridded rainfall estimates for the period 1950 to present on a 0.25° grid. We use different time periods from these datasets depending on what is being compared and analysed below.

2.2 | Atmospheric reanalyses

The reanalysis datasets used in this study are monthly mean zonal winds on pressure levels and monthly mean precipitation from the state-of-the-art climate reanalysis of the European Centre for Medium-Range Weather Forecast (ERA5; Hersbach et al., 2019) and Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3; Compo et al., 2011, Slivinski et al., 2021). The European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) data used covers the period 1950–2021 and is retrieved on a 0.25° grid. The 20CRv3 data cover the period 1836–2015 and is available on a 512 × 256 Gaussian grid, with 80 ensemble members providing an estimate of uncertainty. In both cases, seasonal mean values are computed for each variable (and each ensemble member for 20CRv3) prior to performing the analyses presented below.

2.3 | Climate model simulations

This study also uses the output from the sixth coupled model intercomparison project (CMIP6; Eyring et al., 2016). Monthly mean zonal winds on pressure levels and monthly mean precipitation are taken from the historical and SSP5-85 simulations from 38 models. The number of climate models used is limited by the availability of suitable output. The precise model runs used in each case are described in Table S1 in the supporting information. For each model, we consider a single ensemble member for which we concatenate a matching pair of historical and future simulations to produce a single continuous realisation from 1850 to 2100, as indicated in the table. For all gridded datasets (both reanalyses and the climate model output) we define UK mean precipitation as the average over the box 0–5 W and 50–58 N.

2.4 | Global warming level calculations

To construct jet storylines relative to global warming levels, output from the CMIP6 simulations is sampled at global warming levels following a similar approach to that of the Sixth Assessment Report of the International Panel on Climate Change (Lee et al., 2021). First, we define the set of GWLs of interest as each half-degree interval from 0.5°C to 5.0°C. Next, for each model realisation, we compute 20-year running mean global mean surface temperature anomalies relative to a quasi-preindustrial value as defined below. Third, we define the GWL threshold years as the first year that the 20-year running mean anomalies exceed each GWL for each model, and, finally, we compute the 20-year mean values of each variable of interest centred on the GWL threshold years. Following a similar approach to the IPCC AR6 methodology, the quasi-preindustrial value for surface temperature is defined for each model realisation as the 50-year mean from the period 1965–2014 minus a fixed offset equal to 0.59°C. This offset is equal to the observed anthropogenic global warming up to the 1965–2014 period computed from the HadCRUT5 dataset. In the absence of precise observed changes since pre-industrial in the other atmospheric variables used here, all other anomalies are defined simply as the difference to the 1850–1900 mean values for each model.

3 | THE NORTH ATLANTIC JET AND ITS IMPORTANCE FOR UK PRECIPITATION

3.1 | Selection of jet indices for summer and winter

Variations in atmospheric circulation in the North Atlantic region are commonly characterised either in terms of large-scale pressure patterns, for example, using an index of the North Atlantic Oscillation (NAO) (Hurrell et al., 2003), or more directly in terms of the latitude and strength of the eddy-driven jet (Woollings et al., 2010). These measures are related, with a positive NAO typically corresponding to a poleward-shifted and intensified jet. However, the relationship is non-trivial due to the complex nature of the North Atlantic circulation and its variations in space and time (Madonna et al., 2017).

In this study, we focus on the jet index approach for the following reasons. First, the North Atlantic eddy-driven jet is simply and robustly defined throughout the seasonal cycle, avoiding complications inherent in defining a seasonally varying NAO index (e.g., using clustering or EOF procedures; Breton et al., 2022). Second, the definition of the indices can be tailored to capture prominent relationships of interest to a particular region.

To motivate a particular choice of jet indices for UK impacts, we consider the observed interannual relationship between seasonal mean lower tropospheric winds (zonal wind component at 850 hPa; hereafter U850) and seasonal mean UK mean precipitation, for both summer and winter (Figure 2a,b). The maps reveal that wet UK summers are typically associated with an equatorward-shifted jet whereas wet winters are characterised by an eastward extension of the jet towards Europe. To capture these circulation features the following two UK-focussed jet indices are chosen:

1. A jet latitude index for summer (*JJA jet latitude*), computed between 0 and 20 W and 30–70 N (box in Figure 2a,c), and
2. A jet speed index for winter (*DJF jet speed*), computed over the region from 20 E–20 W and 40–60 N (box in Figure 2b,d).

In more detail, for summer, we follow the approach of Ceppi et al. (2014) by defining a jet latitude index as a zonal wind-weighted average of the latitudes of mean westerly wind, here defined as

$$\phi_{jet} = \frac{\int_{30}^{70} \phi\, u(\phi)^2\, I[u>0]\, d\phi}{\int_{30}^{70} u(\phi)^2\, I[U>0]\, d\phi}$$

where ϕ is latitude, $u(\phi)$ is season mean zonal wind at 850 hPa averaged over 0–20 W and $I[u>0]$ indicates that the integrals are taken over latitudes where u is positive. Using this definition provides a smoother evolution in time compared to the latitude of peak winds which can be subject to outliers associated with relatively weak wind anomalies at high latitudes. For winter, we characterise the jet intensity over NW Europe simply as the season mean zonal wind at 850 hPa averaged over the region indicated.

These indices are calculated for 1950–2021 from ERA5, and for 1836–2015 from 20CRv3 (Figure 3). The indices from the two reanalyses agree very well during the overlapping period. For 20CRv3, the 80-member ensemble gives an indication of uncertainty. During the overlapping period, the ensemble spread is very small; it is larger further back in time, consistent with the reduced availability of observations, but the spread remains remarkably small even back to 1836. This may be in part because of the geographical location of the jet indices, which are proximate to early surface pressure observations used to constrain the reanalysis in Western Europe.

Observed trends and variability of the North Atlantic circulation are discussed in detail elsewhere (e.g., Pinto & Raible, 2012, for winter, Folland et al., 2009, for summer, and Woollings et al., 2014, focussing on jet variability). Here, we note the following features of our two UK-focussed jet indices. The DJF jet speed exhibits marked decadal variability, with peaks around 1920 and 1990 and a minimum around 1960, which is in phase with Atlantic multidecadal variability (Sutton et al., 2018). In addition, there is a hint of an intensification of the jet over recent decades with the 11-year running mean (dashed line in Figure 3a) reaching its largest value in the 150-year record at the

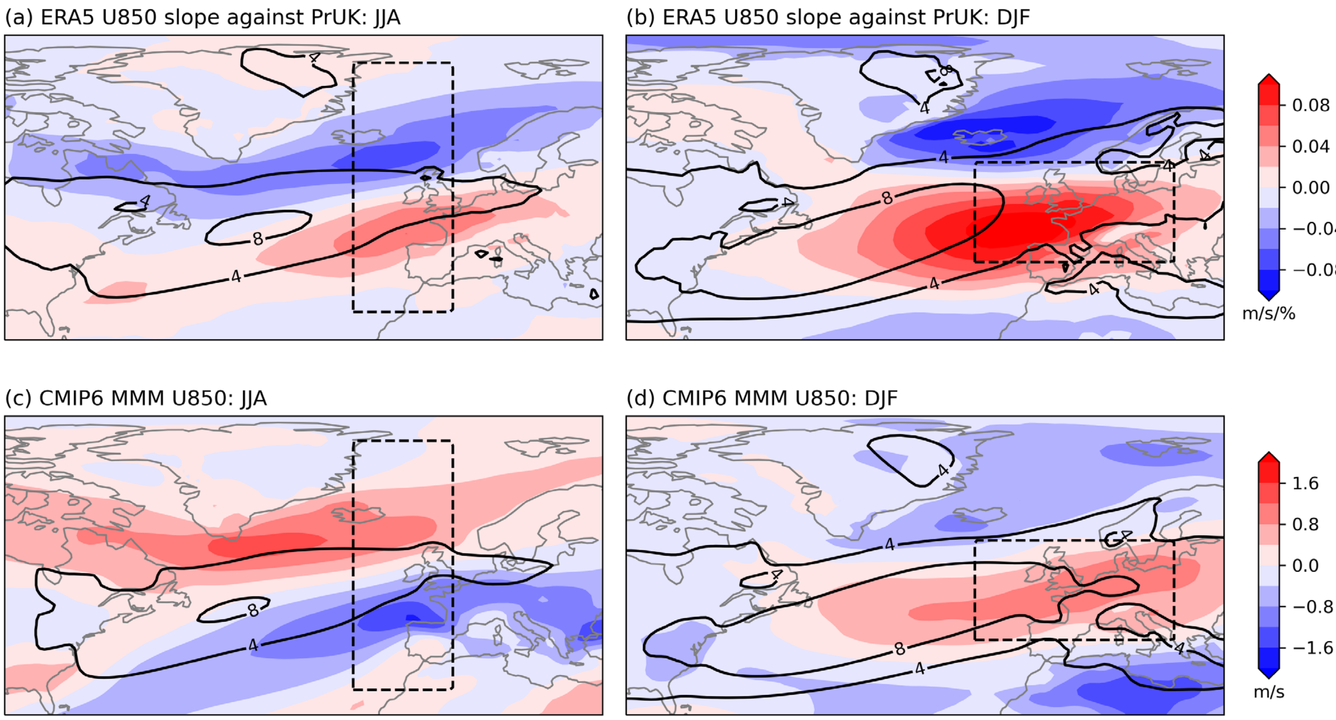

FIGURE 2 (Top row) Interannual regression slopes between (a) June, July, August (JJA) and (b) December, January, February (DJF) mean U850 and UK precipitation (50–58 N, 0–5 W) from European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) (1950–2021) (shading; units of m·s^{-1} per % change in UK precipitation) with the seasonal mean U850 over the same period (black contours; units of m·s^{-1}); (bottom row) Multi-model mean U850 response for (c) June, July, August (JJA) and (d) DJF from the 38 sixth coupled model intercomparison project (CMIP6) models used in this study (2060–2100 − 1960–2000 under SSP5-85) with the multi-model seasonal mean U850 from 1960 to 2000 (black contours; units of m·s^{-1}). The boxes indicate the areas used for the jet indices as described in Section 3.1. [Colour figure can be viewed at wileyonlinelibrary.com]

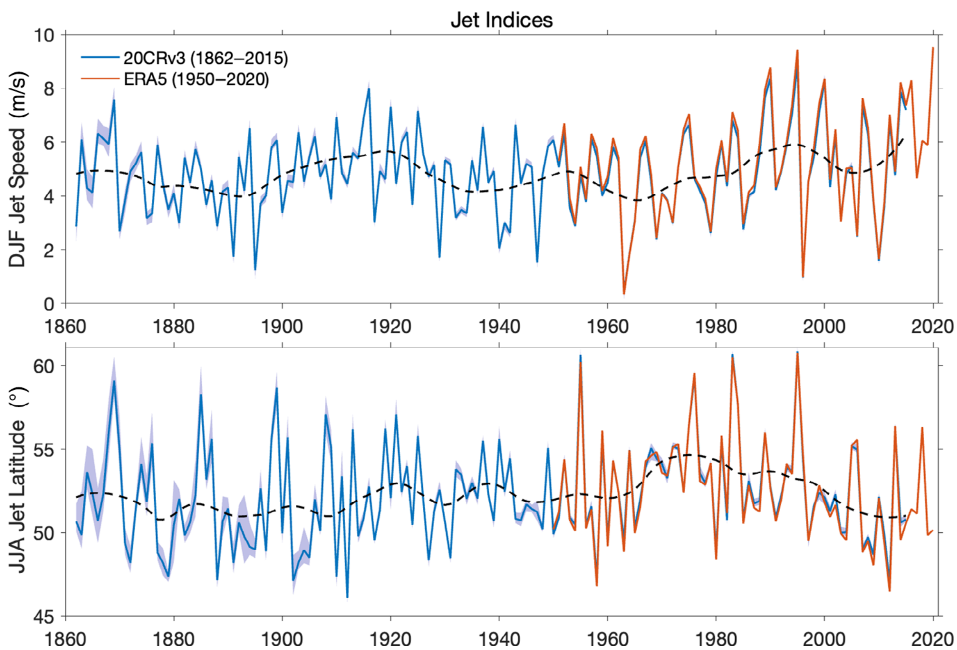

FIGURE 3 The (top) December, January, February (DJF) jet speed and (bottom) June, July, August (JJA) jet latitude indices in European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) (1950–2021) and Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3) (1836–2015). For Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3), the shading is the 5%–95% range from the 80 ensemble members, the solid line is the ensemble mean value and the dashed line is an 11-year rolling average. [Colour figure can be viewed at wileyonlinelibrary.com]

end of the dataset. In contrast, the JJA jet latitude index exhibits a substantial equatorward trend in the period 1970–2010 and is now at its lowest values.

Before considering the observed relationship between the two jet indices and UK precipitation in more detail, we briefly consider the projected future changes of U850. Figure 2c,d shows the CMIP6 multi-model mean (MMM) change in U850 by the late 21st century. The spatial structures of the projected changes share remarkable similarities to the observed interannual U850-precipitation regression slope in each season (Figure 2a,b), suggesting that the climate change circulation response may be particularly relevant for projections of UK precipitation. Indeed, the projected JJA U850 change exhibits a poleward shift of the summer jet (Figure 2c), which is consistent with the expected future drying of southern UK summers over the 21st century (REF). Similarly, the projected DJF U850 change exhibits an eastward extension of the winter jet towards Europe (Figure 2d), which is consistent with the expected future wetting of UK winters (REF). The choice of jet indices defined above is, therefore, well suited for quantifying both future changes as well as present-day variability.

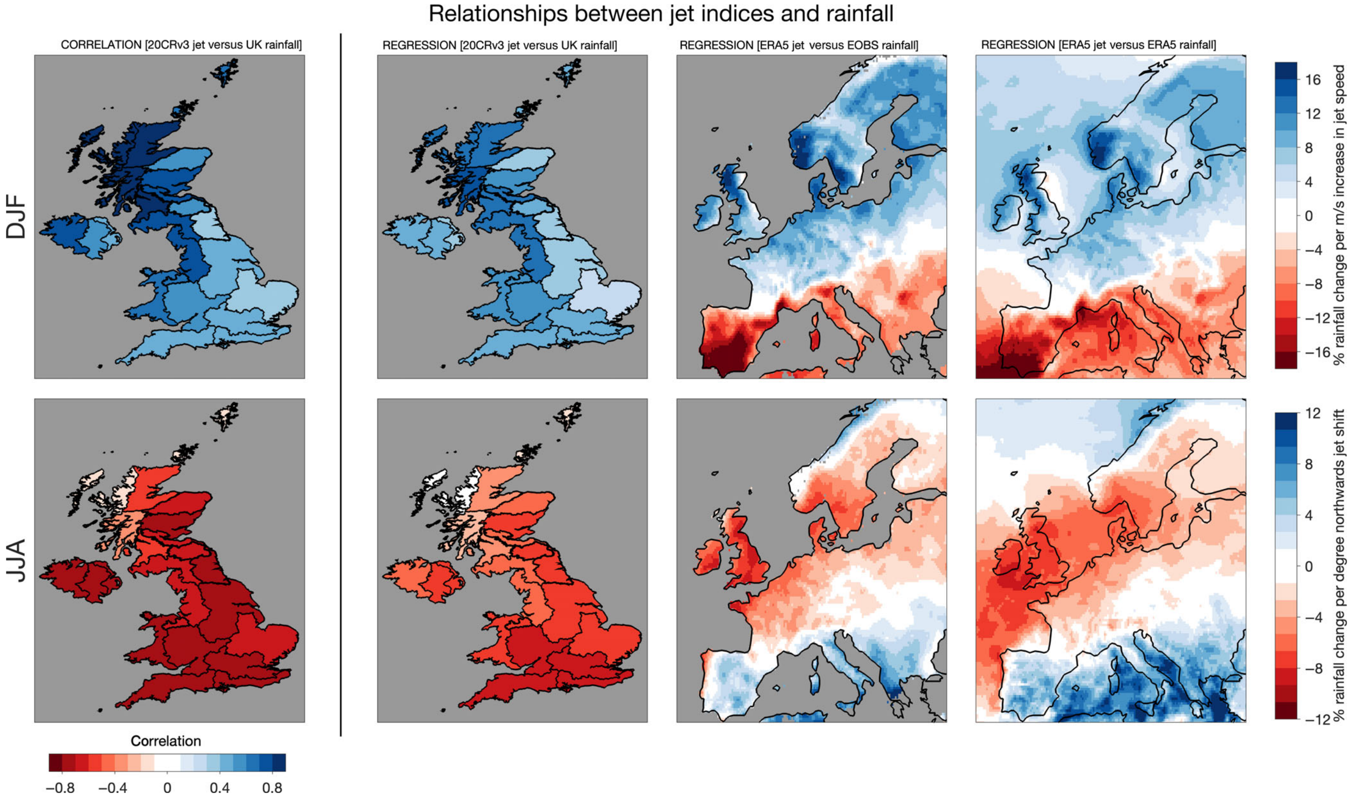

FIGURE 4 The relationship between seasonal mean rainfall and the jet indices in observations and reanalyses for (top row) December, January, February (DJF) and (bottom row) June, July, August (JJA): (far left) interannual correlation between HadUK-Grid catchment precipitation and Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3) jet indices for 1836–2015, (centre left) the corresponding regression slopes, (centre right) the regression slope between E-OBS gridded precipitation and European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) jet indices for 1950–2021, and (far right) the regression slope between ERA5 precipitation and ERA5 jet indices. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Observed interannual regression slopes between UK mean precipitation and the jet indices.

	HadUK-Grid precipitation and 20CRv3 jet (1836–2015)	HadUK-Grid precipitation and ERA5 jet (1950–2021)	ERA5 precipitation [mean over UK box] and ERA5 jet (1950–2021)
JJA [%/degree]	−6.1 ($r = 0.77$)	−6.9 ($r = 0.86$)	−6.9 ($r = -0.87$)
DJF [%/(m·s^{-1})]	10.6 ($r = 0.77$)	10.0 ($r = 0.81$)	6.7 ($r = 0.57$)

Abbreviations: DJF, December, January, February; ERA5, European Centre for Medium-Range Weather Forecasts Reanalysis v5; JJA, June, July, August; 20CRv3, Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis.

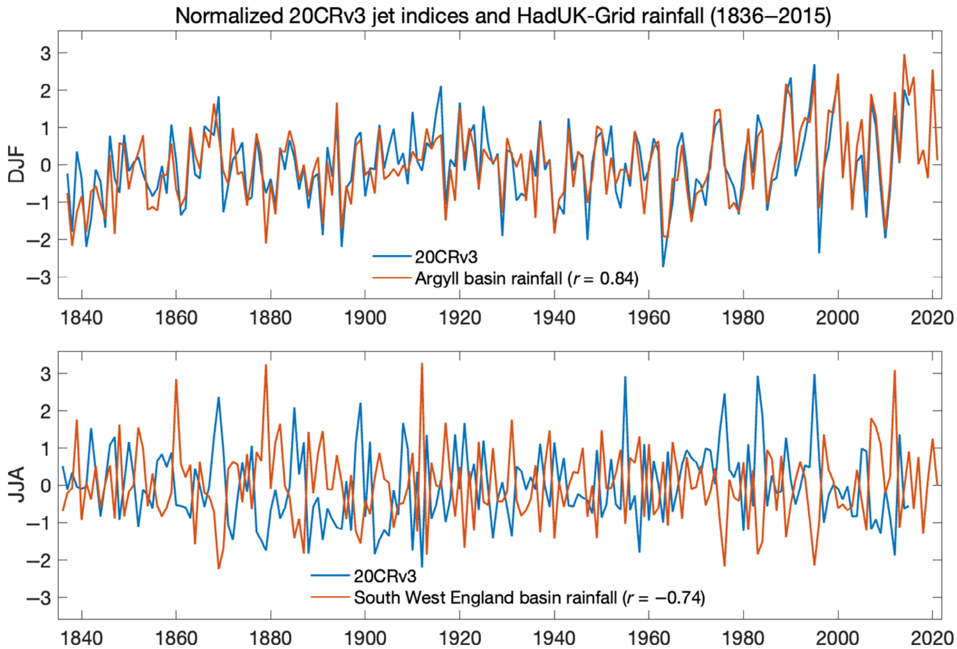

FIGURE 5 Normalised time series of (top) December, January, February (DJF) jet speed and Argyll catchment precipitation and (bottom) June, July, August (JJA) jet latitude and SW England catchment precipitation. The jet indices are the Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3) ensemble means (1836–2015) and the rainfall observations are from HadUK-Grid (1836–2021). [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Effects of jet variations on seasonal mean precipitation

Having defined jet indices for summer and winter, we now evaluate their observed associations with impacts. Figure 4 summarises the observed relationships between the jet indices and seasonal mean rainfall over the UK and Europe computed using the longest available observational datasets for each region: HadUK-Grid and E-OBS. Over Europe, both seasons show a strong latitudinal gradient (panels c and g). Winters with a strong jet are associated with relatively high precipitation across northern Europe and relatively low precipitation across southern Europe. Summers with a poleward-shifted jet are associated with the opposite pattern.

Over the UK, the longer HadUK-Grid dataset corroborates the regression slopes from E-OBS (panels b and f) and highlights smaller-scale variations in spatial structure with a notable east–west gradient over the UK in DJF and more uniform values in JJA. The correlation values (shown in panels a and d, just for the HadUK-Grid data) are as large as 0.8 over several western Scottish river catchments in DJF and over most of the English river catchments in JJA. When averaged over the UK, the regression slopes are 10.0%–10.6% per m s^{-1} in DJF and −6.9% to −6.1% per degree in JJA, depending on which observational dataset is used (Table 1). The weaker relationship present in DJF for the ERA5 precipitation index arises because our UK precipitation index for ERA5 includes more sea points.

To demonstrate the strength of these relationships and their consistency in time, Figure 5 shows an example time series of rainfall from the Argyll catchment in DJF, and the SW England catchment in JJA, where the correlations with the jet indices are largest. There are clear and strong similarities on both interannual and multi-decadal timescales. Notable extreme seasons from the historical period are present in this time series including the dry summer of 1976, which was associated with an anomalously poleward jet, and the recent wet summers of 2007 and 2012 which were associated with an anomalously equatorward jet. These two datasets are completely independent and the close agreement back to 1836 is notable and provides confidence in the representation of historical seasonal jet variations in the 20CRv3 reanalysis.

4 | DEVELOPMENT OF STORYLINES OF FUTURE JET CHANGES

4.1 | Model projections of future jet changes

As hinted in Figure 2, the North Atlantic jet is expected to respond differently to increasing global temperatures in summer and winter. In JJA, a poleward shift is projected whereas DJF exhibits an eastward extension towards Europe. To quantify these changes, Figure 6 shows time series of the 20-year running mean summer and winter jet indices computed from the CMIP6 SSP5-85 simulations. In the multi-model mean, the summer jet latitude index increases by 2.3° by the end of the 21st century and the winter jet speed index increases by

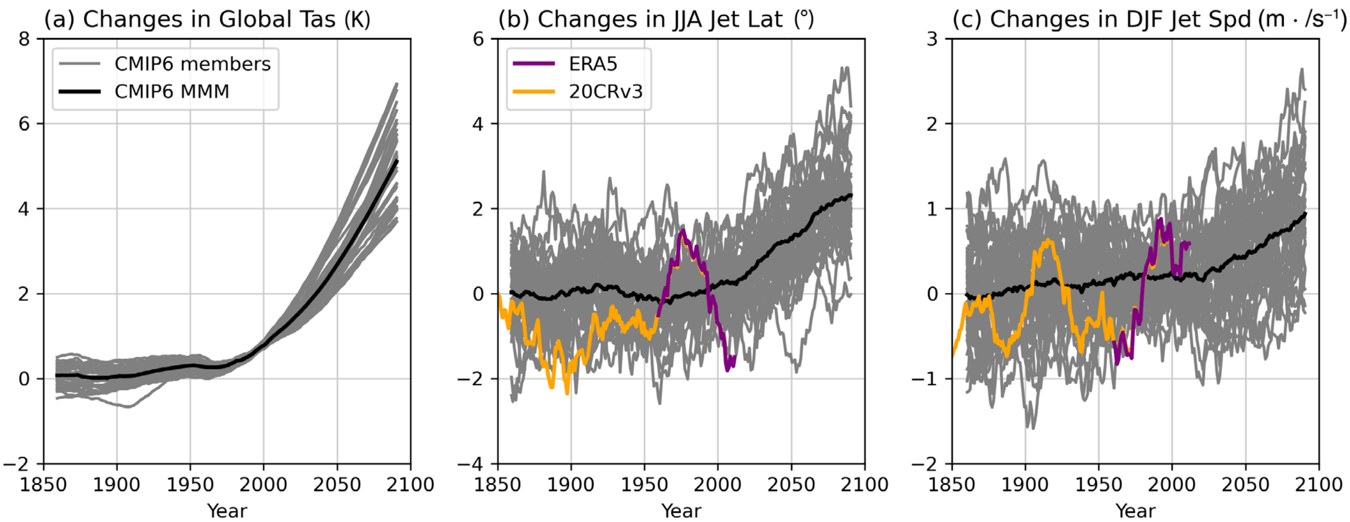

FIGURE 6 Sixth coupled model intercomparison project (CMIP6) projections of changes in (left) global mean temperature (centre) June, July, August (JJA) jet latitude and (right) December, January, February (DJF) jet speed. All values are 20-year running mean anomalies relative to a quasi-preindustrial value, as described in the text. All panels show (grey) the 38 CMIP6 models together with (black) their multi-model mean and (purple, orange) the observed time series from European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) and Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3), respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

0.94 m s^{-1} (or 14%). The vast majority of models agree on the sign of the changes, but there is a substantial spread between the simulations.

The spread arises from three sources. First, the simulations exhibit a wide range in projected global mean temperature increases, as shown in Figure 5a. Second, the atmospheric circulation likely responds differently in different models to a given rise in temperature. Finally, there is a large inherent internal variability associated with the North Atlantic circulation. In this work, we explicitly consider the impact of climate sensitivity by conditioning the jet changes on global mean temperature. We reduce the impact of internal variability by considering 20-year running means, but we do not attempt to distinguish between model uncertainty and the remaining internal variability since the CMIP6 ensemble is not large enough to enable this to be done robustly. Therefore, the results presented here will depend on the averaging period used, with longer averaging periods reducing the influence of internal variability at the expense of temporal resolution. The choice of 20-year was made to retain decadal variability which is important for precipitation impacts.

4.2 | Developing a set of storylines for future changes in the North Atlantic jet

In this section, we condense the wide range of model projections into a small set of plausible storylines for future changes in the North Atlantic jet. These are informed by the CMIP6 projections presented and motivated by the large model spread. Each storyline takes the form of a single number representing a change in either the summer or winter jet index. The philosophy adopted is to be as simple as possible by employing only a small number of storylines and using round numbers for the jet changes. The aim is that the storylines will allow a physically self-consistent interrogation of a wide range of projected climate change impacts conditioned on changes in the jet.

Given the large range of climate sensitivities present in CMIP6, the jet storylines are constructed relative to GWLs (as described in Section 2.4) and we focus here on GWLs 2°C and 4°C. Figure 7 shows the jet projections as a function of GWL. In JJA, the jet moves poleward by around 0.5° latitude per degree of warming in the multi-model mean. In DJF, the jet intensifies by around 0.2 m s^{-1} per degree of warming. For each GWL, we construct two sets of storylines:

- '*Core storylines*' which aim to partition the uncertainty present in the CMIP6 model projections (forced response + internal variability). These are informed by the CMIP6 data and chosen to represent the multi-model mean (the 'core mean' storyline) and the upper decile (the 'core high' storyline).
- '*Extreme storylines*' which aim to examine how impacts would change if the jet responded more or less strongly than the CMIP6 models project (e.g., due to

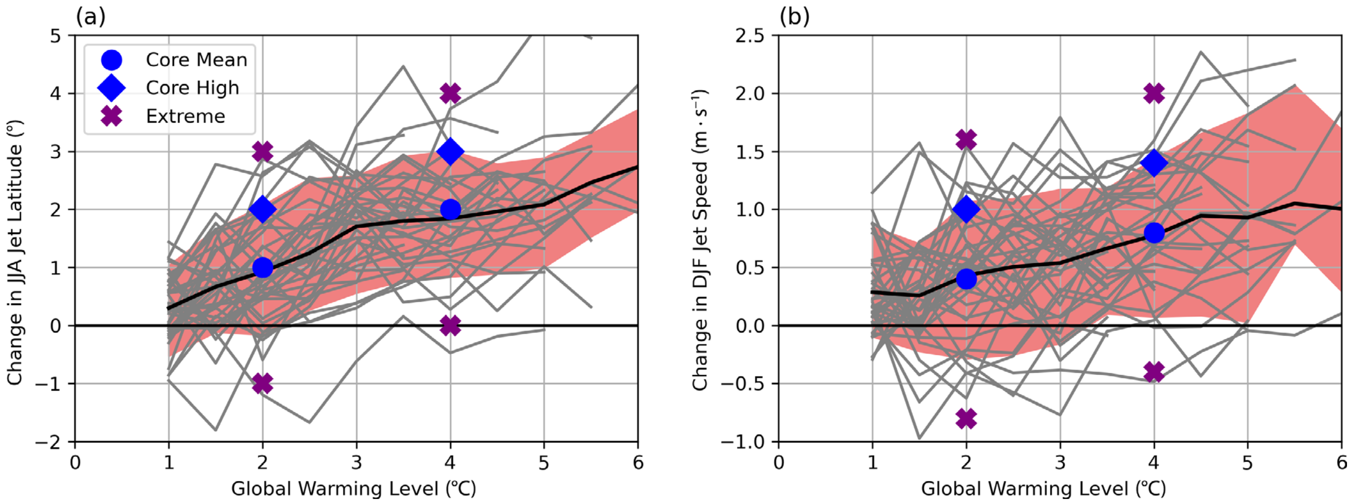

FIGURE 7 Jet indices as a function of global warming level for (a) June, July, August (JJA) and (b) December, January, February (DJF). Each grey line is a sixth coupled model intercomparison project (CMIP6) model, the black line is the multi-model mean and the shading shows the 10%–90% model range. The symbols indicate the eight jet storylines for summer and winter as listed in Table 2. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 The eight jet storylines for summer and winter.

	Global warming level	2°C	4°C
JJA jet latitude	Core mean	1°	2°
	Core high	2°	3°
	Extreme low	−1°	0°
	Extreme high	3°	4°
DJF jet speed	Core mean	0.4 m·s^{-1}	0.8 m·s^{-1}
	Core high	1.0 m·s^{-1}	1.4 m·s^{-1}
	Extreme low	−0.8 m·s^{-1}	−0.4 m·s^{-1}
	Extreme high	1.6 m·s^{-1}	2.0 m·s^{-1}

Abbreviations: DJF, December, January, February; ERA5, European Centre for Medium-Range Weather Forecasts Reanalysis v5; JJA, June, July, August.

signal-to-noise issues discussed in the Introduction). These are informed by the current extreme range of the CMIP6 models and are chosen to represent a plausible but extreme high jet change (the 'extreme high' storyline) and a plausible but extreme low jet change (the 'extreme low' storyline).

The resulting eight jet storylines are listed in Table 2 and indicated by the blue and purple symbols in Figure 7. For JJA, all jet storylines exhibit a poleward shift of the jet except the 2°C Extreme low storyline which has a small equatorward shift. For DJF, all jet storylines exhibit an intensification of the jet except the extreme low storylines at both 2°C and 4°C which exhibit a small weakening. In both seasons, the extreme low storylines are weaker (i.e., more negative) for 2°C than 4°C, reflecting the potential range of internal variability in the near term.

5 | CONSEQUENCES OF THE JET STORYLINES FOR THE UK AND NW EUROPE

Having constructed a set of plausible storylines for future changes of the jet, the impacts associated with each storyline can be estimated. A number of different methodologies exist for inferring the impacts associated with atmospheric circulation change, including: internal variability analogues, in which future changes are assumed to follow present-day relationships; analysis of multi-model ensembles, in which uncertainty is assumed to be characterised by differences between model responses; and bespoke modelling experiments in which future circulation changes are artificially controlled in a model simulation in order to infer their impacts.

In the spirit of simplicity, we consider the first two approaches here. Specifically, we construct impacts associated with each storyline by (i) assuming the influence of a future jet change on a given impact is characterised by the present-day interannual dynamical relationship between the jet and that impact, and (ii) assessing the extent to which the CMIP6 model spread in the projection of the impact correlates with the simulated jet changes.

This approach necessarily requires that uncertainty in the jet response to rising global temperatures plays a dominant role in the projection uncertainty of a particular impact. As we show below, this is the case for many UK weather impacts, notably precipitation. If uncertainty in other aspects of the forced response to climate change influenced the impact, then the jet-based storylines would not characterise the projection uncertainty in a useful way and the other factors would need to be explicitly included in a storyline description.

5.1 | Summer jet storylines

The CMIP6 models project JJA UK precipitation to reduce in future, by approximately 5% per degree of warming (Figure 8a). However, there are large differences between model simulations. For example, at 4°C warming, some simulations exhibit little or no reduction whereas others exhibit an almost 40% reduction (Figure 8c).

At both 2°C and 4°C of warming, there is a clear relationship across the models between the magnitude of the poleward shift of the jet and the reduction in precipitation (Figure 8b and 8c, respectively). Indeed, the y-intercept is small and the slope of this relationship is close to the observed interannual relationship, indicating that the jet uncertainty is dominating the uncertainty in the precipitation response. As such, both methods for constructing storylines give similar results and in the following, we restrict attention to the observed interannual relationship. More precisely, the precipitation changes associated with each storyline are defined here as

$$\Delta P_{story} = \Delta P_{MMM} + \beta_{obs} \left(\Delta J_{story} - \Delta J_{MMM} \right) \quad (1)$$

where ΔP_{MMM} and ΔJ_{MMM} are the CMIP6 multi-model mean precipitation and jet changes at a given GWL, β_{obs} is the observed interannual regression slope and ΔJ_{story} are the jet storylines constructed in Section 4.2.

The resulting UK precipitation changes are indicated by the symbols in Figure 8. At 2°C, the core mean and core high JJA precipitation reductions are 8.4% and 15.4%, respectively, the extreme high JJA precipitation reduction is 22.3% whereas the extreme low JJA precipitation exhibits an increase of 5.5% consistent with the weak equatorward shift of the jet in that storyline. At 4°C, the core mean and core high JJA precipitation reductions are 19.3% and 26.3%, and the extreme low and extreme high JJA precipitation reductions are 5.4% and 33.2%, respectively. Therefore, at 4°C all storylines exhibit a drying in summer including the extreme low case in which the jet does not shift.

To examine local variations, Figures 9 and 10 show maps of JJA U850 and precipitation changes associated with each storyline. These are constructed by applying Equation (1) at each grid point. As expected, U850 exhibits a dipole structure across the jet core under all storylines, associated with a shift of the jet, and with stronger jet shifts resulting in stronger dipoles. The positioning of the dipole is such that JJA winds are weaker over southern UK and France, and stronger over the north of Scotland.

The core mean precipitation changes show substantial spatial variations, with stronger drying in southern UK and France than in Scotland. The impact of the jet has a similar spatial variation, resulting in the core high precipitation changes having stronger drying everywhere but also a stronger N–S contrast over the UK. For example, at 2°C, the fractional precipitation reduction varies from 3% in Scotland to 15% in SW England under the core mean storyline, but from 5% to 22% under the core high storyline. Therefore, the magnitude of the poleward jet shift is expected to influence both the magnitude of the UK-wide precipitation reduction and the magnitude in the N–S gradient of the change.

As an alternative perspective to these time mean values, Figure 11 shows an estimate of changes in the return periods of extreme dry summers for the UK, obtained by (1) computing the UK mean precipitation anomaly associated with a current 1-in-10-year dry summer, (2) shifting the observed distribution of JJA precipitation values by the ΔP for each storyline, and (3) counting the exceedances of the current 1-in-10 year threshold under the shifted climatology. This simple approach therefore takes account of the shift in the distribution of UK mean summer precipitation but neglects any change in its shape. Figure 11 shows that at 2°C warming the core mean and core high storylines have what is currently a 1-in-10-year dry summer (i.e., 10% of years) in 24% and 31% of years, respectively. At 4°C warming, the core mean and core high storylines have dry summers in 41% and 48% of years, and the extreme low and extreme high storylines have dry summers in 15% and 62% of years respectively. Whilst more sophisticated estimates of variability should be developed, these numbers show how strongly the future evolution of the summertime jet latitude impacts projected changes in

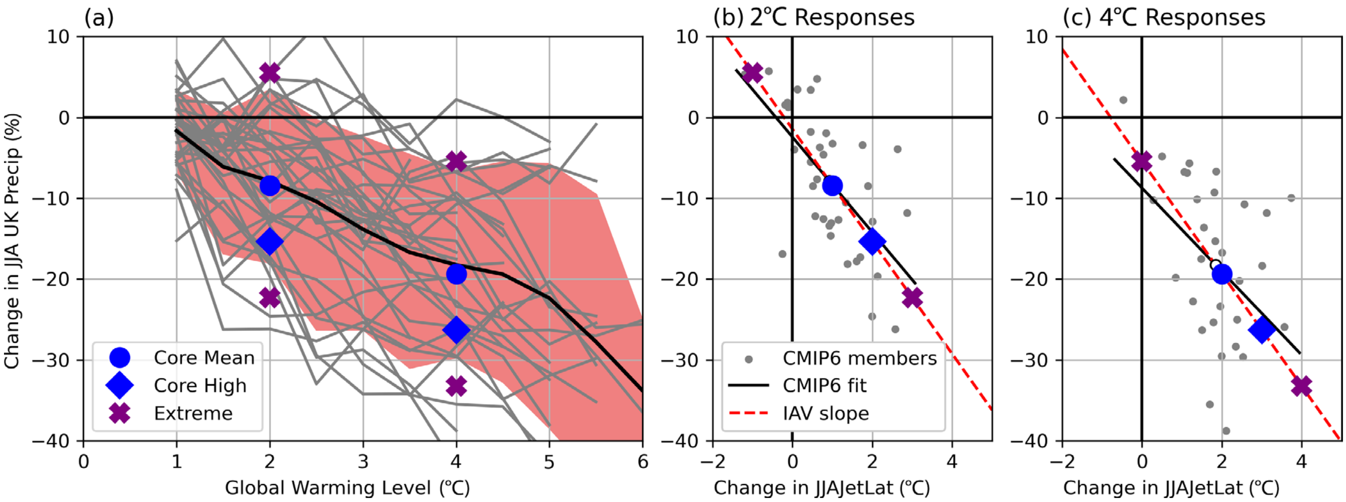

FIGURE 8 June, July, August (JJA) UK precipitation change under the eight jet storylines: (a) UK precipitation change as a function of global warming level for (grey lines) each sixth coupled model intercomparison project (CMIP6) model, (black line) the multi-model mean, and (shading) the 10%–90% model range. (b) UK precipitation changes at 2°C warming for (grey dots) each CMIP6 member, (black line) the linear fit to the CMIP6 members, and (dashed line) the observed interannual regression from ERA5. (c) As (b) but for 4°C warming. The symbols indicate the jet storylines for summer as in Figure 7a. [Colour figure can be viewed at wileyonlinelibrary.com]

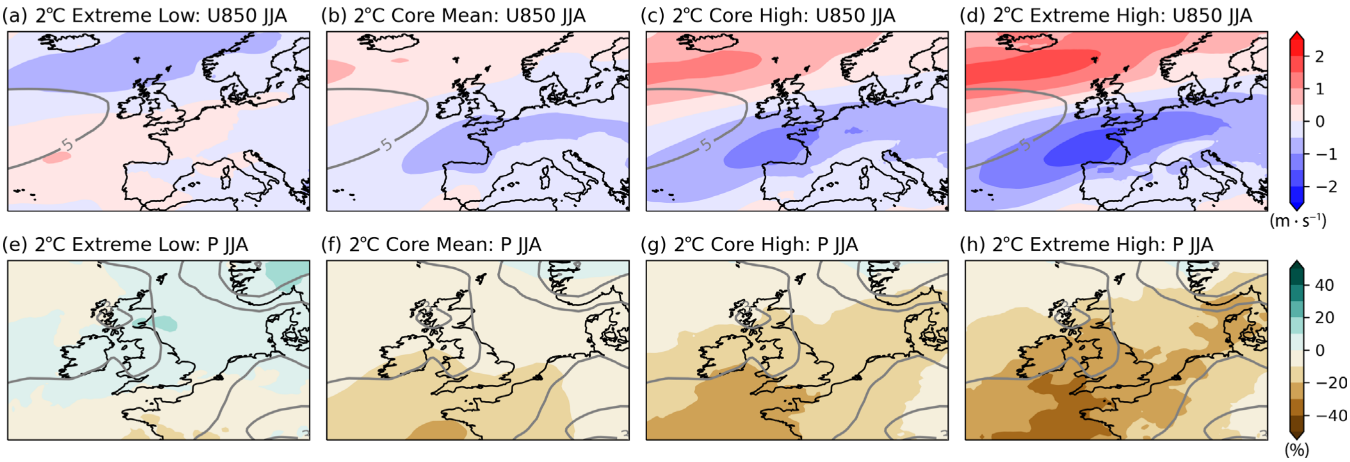

FIGURE 9 U850 (top row; units of $m \cdot s^{-1}$) and precipitation (bottom row; units of %) changes under the four 2°C June, July, August (JJA) jet storylines. The grey isolines show the 1850–1900 multi-model mean fields (units of $mm \cdot day^{-1}$ for precipitation). [Colour figure can be viewed at wileyonlinelibrary.com]

UK precipitation. Furthermore, these estimates apply to UK mean precipitation values and larger impacts can be expected in some regions.

5.2 | Winter jet storylines

The same approach is applied to wintertime UK precipitation, and Figures 12–15 show results analogous to the summertime Figures 8–11. In contrast to summer, the CMIP6 models project DJF UK precipitation to increase in future, by approximately 5% per degree of warming (Figure 12a). However, there are again large differences between model simulations. For example, at 4°C warming, some simulations exhibit an increase of less than 10% whereas others exhibit an increase over 25% (Figure 12c).

As with summertime, there is a clear relationship across the models between the magnitude of the eastward extension of the jet in winter and the increase in UK precipitation (Figure 12b and 12c, respectively). The slope of this relationship is again very close to the observed interannual relationship, indicating that the jet uncertainty is dominating the uncertainty in the precipitation response. As such, both methods for constructing storylines give similar results and we again restrict attention to storylines

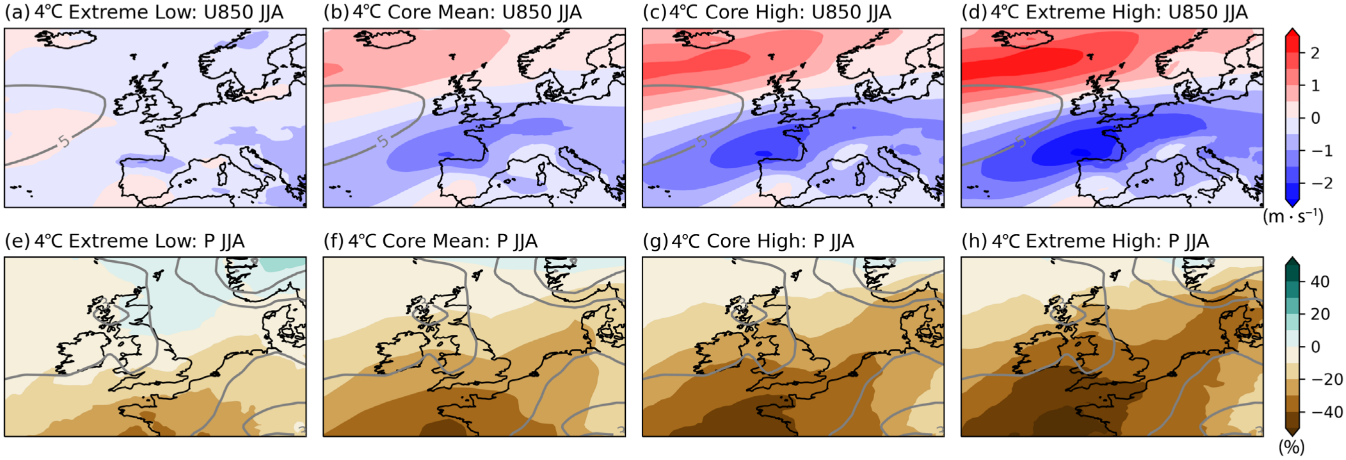

FIGURE 10 As Figure 9 but for the four 4°C June, July, August (JJA) jet storylines. [Colour figure can be viewed at wileyonlinelibrary.com]

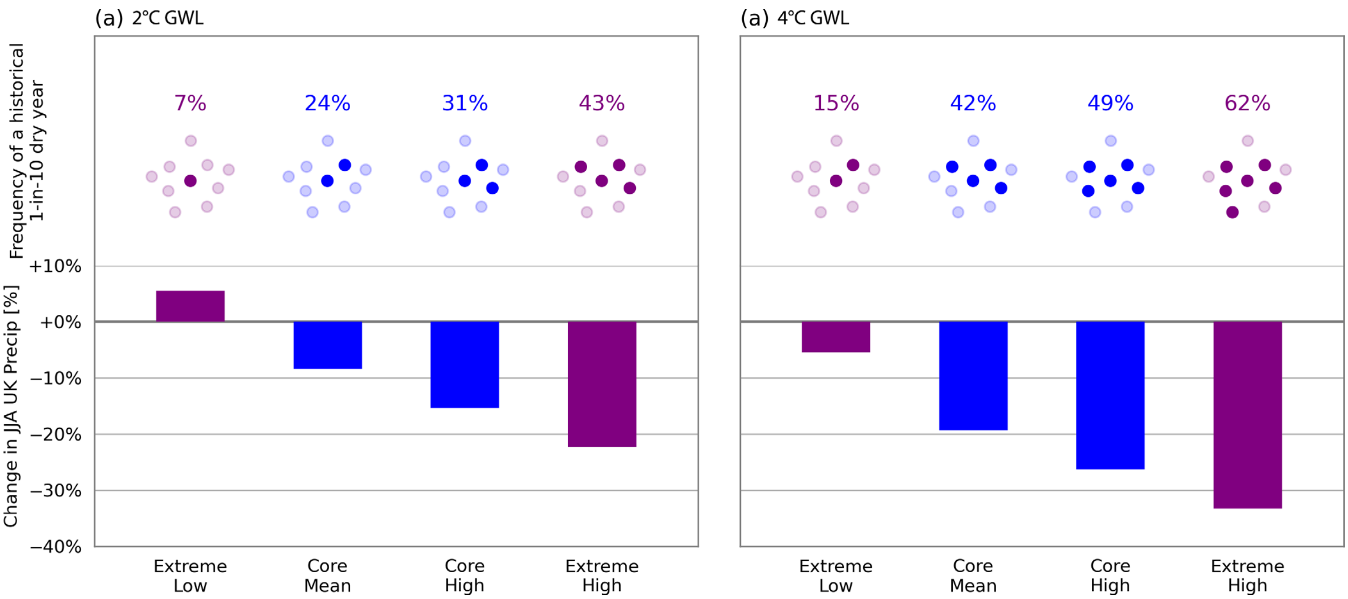

FIGURE 11 Summary of June, July, August (JJA) UK precipitation changes under the eight JJA jet storylines. Bars show the mean UK precipitation change under each storyline and dots show the expected frequency of a 1-in-10 dry year under each storyline, as described in the text. [Colour figure can be viewed at wileyonlinelibrary.com]

constructed from the observed interannual relationship as in Equation (1). An important difference between summer and winter is that the wintertime jet-precipitation relationship at any given GWL (Figure 12b,c) has a non-zero y-intercept. This indicates that a precipitation increase is expected in winter even in the absence of a jet change, and uncertainty in this non-jet change is not captured by our storylines approach.

The UK precipitation changes associated with each wintertime jet storyline are indicated by the symbols in Figure 12. At 2°C, the core mean and core high DJF precipitation increases are 8.4% and 12.5%, and the extremely low and extreme high DJF precipitation increases are 0.2% and 16.6%, respectively. At 4°C, the core mean and core high DJF precipitation increases are 18.4% and 22.5%, and the extreme low and extreme high DJF precipitation increases are 10.2% and 26.6%, respectively. Therefore, all jet storylines are associated with increases in UK wintertime precipitation except for the extreme low 2°C storyline where the precipitation change is small due to a cancellation between the non-jet change (wetter) and a weakened jet (drier) in that case.

Local variations are examined in Figures 13 and 14 which show maps of DJF U850 and precipitation changes associated with each storyline. As expected, U850 exhibits an intensification over the UK with a stronger

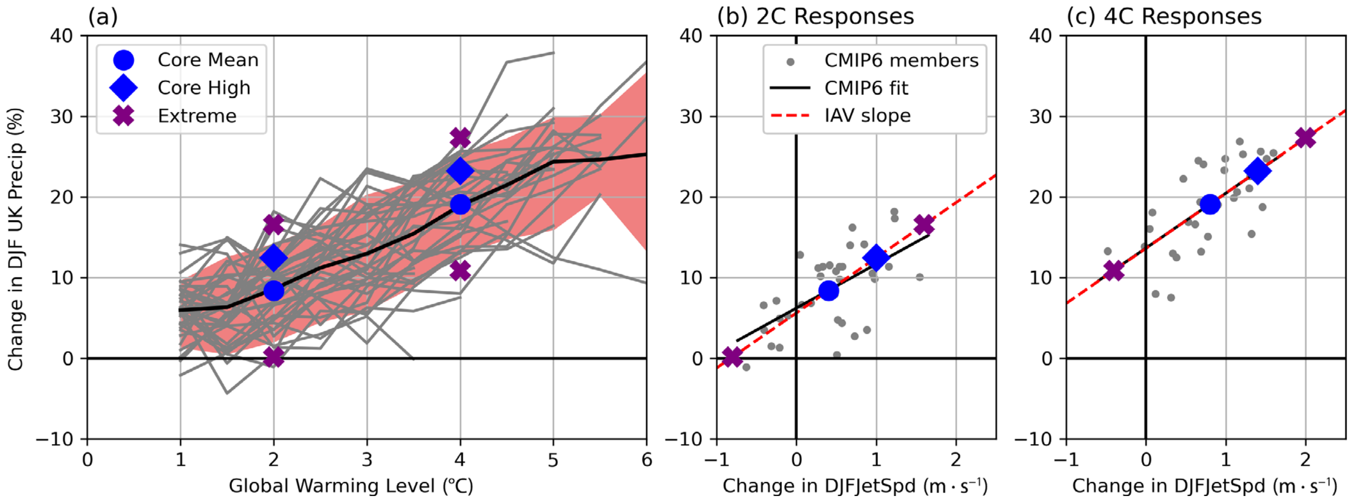

FIGURE 12 December, January, February (DJF) UK precipitation change under the eight jet storylines: (a) UK precipitation change as a function of global warming level for (grey lines) each CMIP6 model, (black line) the multi-model mean, and (shading) the 10%–90% model range. (b) UK precipitation changes at 2°C warming for (black dots) each CMIP6 member, (black line) the linear fit to the CMIP6 members, and (dashed line) the observed interannual regression from ERA5. (c) As (b) but for 4°C warming. The symbols indicate the jet storylines for summer as in Figure 7a. [Colour figure can be viewed at wileyonlinelibrary.com]

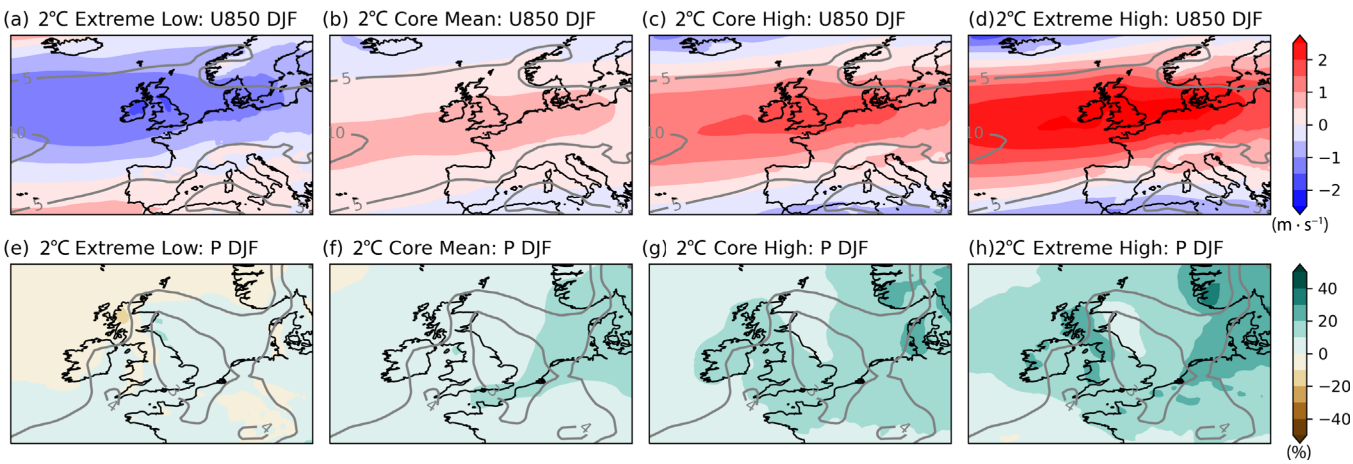

FIGURE 13 U850 (top row; units of $m{\cdot}s^{-1}$) and precipitation (bottom row; units of %) changes under the four 2°C December, January, February (DJF) jet storylines. The grey isolines show the 1850–1900 multi-model mean fields (units of $mm{\cdot}day^{-1}$ for precipitation). [Colour figure can be viewed at wileyonlinelibrary.com]

intensification under the strong jet storylines. The spatial pattern exhibits a large-scale coherent strengthening of the jet in a band extending from the eastern North Atlantic across much of central Europe. The core mean precipitation changes show substantial spatial variations, with stronger wetting over orography when the jet intensifies. For example, at 2°C the fractional precipitation increase is spatially uniform over the UK under the core mean storyline but exhibits a pronounced E–W gradient under the core high storyline. Therefore, the magnitude of the eastward extension of the jet is expected to influence both the magnitude of the UK-wide precipitation increase and also the magnitude in the E–W gradient of the change.

Finally, Figure 15 shows our simple estimate of changes in the return periods of extremely wet UK mean winter seasons, obtained as described above. At 2°C warming the core mean and core high storylines have what is currently a 1-in-10 year (i.e., 10% of years) wet winters in 17% and 27% of years respectively. At 4°C warming, the core mean and core high storylines have wet winters in 34% and 39% of years, and the extreme low and extreme high storylines have wet winters in 20% and 46% of years. These changes cover a smaller range than the corresponding changes in dry summers (see the end of Section 5.1) in part because the dynamical response to the jet change only accounts for around half

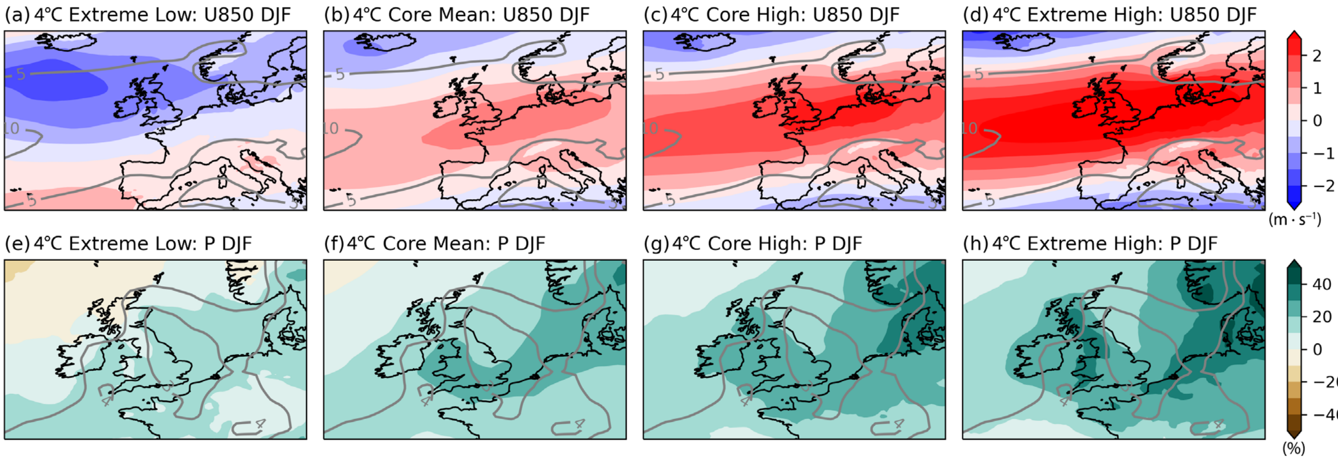

FIGURE 14 As Figure 13 but for the four 4°C December, January, February (DJF) jet storylines. [Colour figure can be viewed at wileyonlinelibrary.com]

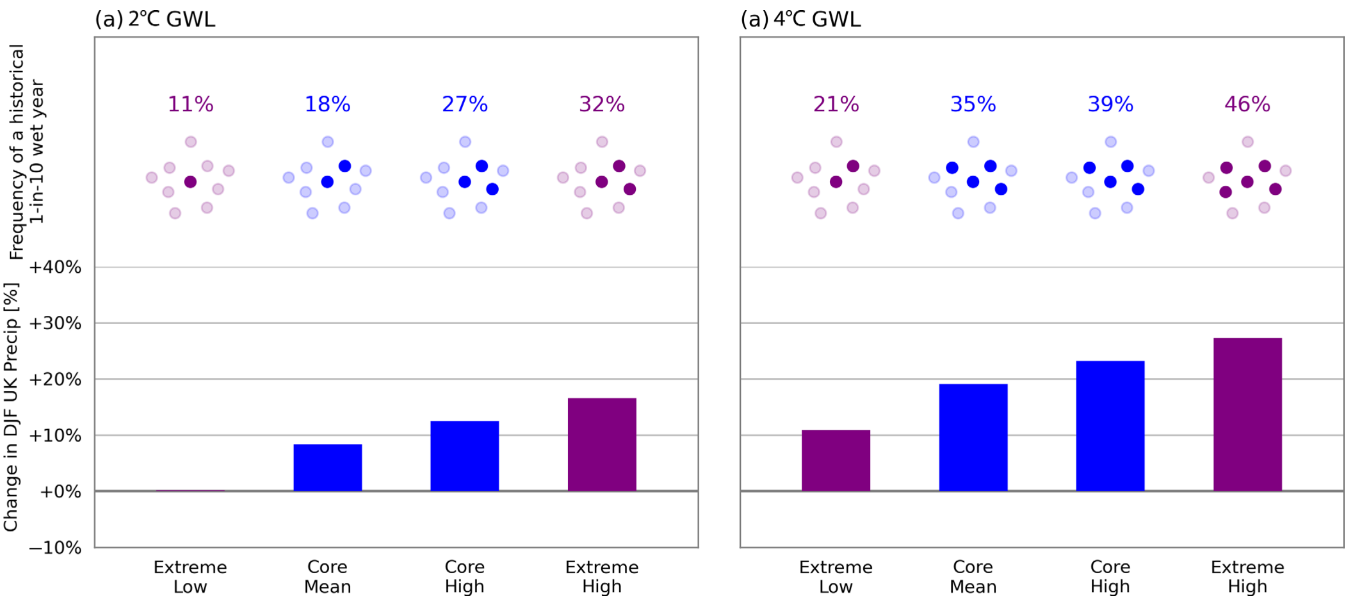

FIGURE 15 Summary of December, January, February (DJF) UK precipitation changes under the eight DJF jet storylines. Bars show the mean UK precipitation change under each storyline and dots show the expected frequency of a 1-in-10 wet year under each storyline, as described in the text. [Colour figure can be viewed at wileyonlinelibrary.com]

of the mean precipitation response in winter under the core mean storyline.

6 | SUMMARY AND DISCUSSION

The North Atlantic jet has a strong influence on weather and climate over the UK and NW Europe in all seasons. Climate models project robust changes in the North Atlantic jet, with a notable poleward shift in JJA and an eastward extension in DJF. However, there is substantial uncertainty associated with the magnitude of these changes, and this contributes substantial uncertainty to climate change projections for the region.

Here, we constructed a set of storylines of plausible future changes to the North Atlantic jet in summer and winter and used these to relate uncertainty in projections of UK climate to changes in the jet. There are two motivations for this:

1. Explore the inter-model uncertainty present in climate model simulations.
2. Examine plausible futures not captured by the climate models by asking how projections would change if the

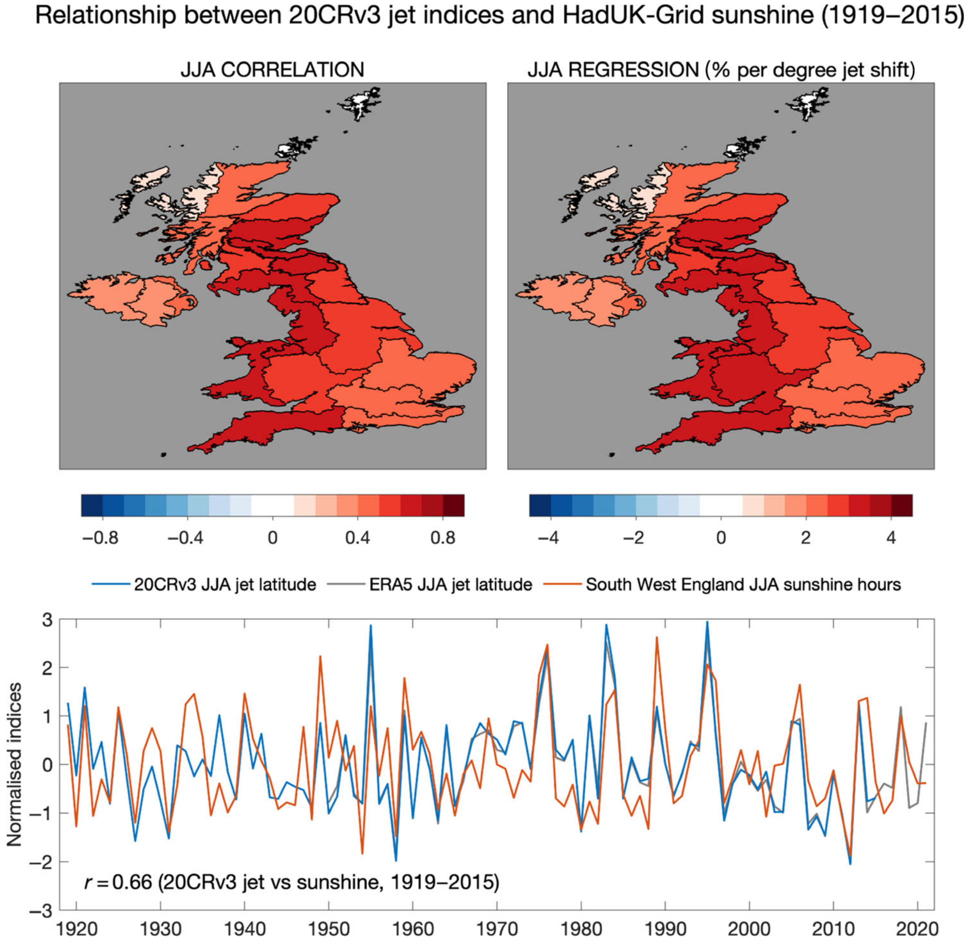

FIGURE 16 The relationship between June, July, August (JJA) mean sunshine hours from HadUK-Grid and JJA jet latitude from Version 3 of the NOAA-CIRES-DOE 20th Century Reanalysis (20CRv3) for 1919–2015: (top left) interannual correlation, (top right) the corresponding regression slopes (in % per degree), and (bottom) normalised time-series of JJA jet latitude and southwest England JJA mean sunshine hours. The bottom panel also includes the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) JJA jet latitude index for 1950–2021 (grey). [Colour figure can be viewed at wileyonlinelibrary.com]

jet responded more or less strongly than the models suggest (e.g., due to signal-to-noise issues).

We defined two sets of jet storylines for global warming levels of 2°C and 4°C. The first set (*Core Storylines*) aims to span the inter-model spread present in CMIP6 simulations and thereby address point 1. The second set (*Extreme Storylines*) aims to capture a plausible high-end range of future jet changes and thereby address point 2. For both sets, the storylines are defined in the simplest possible fashion to capture the essence of the poleward shift of the jet in JJA and the eastward extension in DJF.

This study focused on UK seasonal mean precipitation, for which the North Atlantic jet plays a particularly strong role. We demonstrated that the relationships between the jet and UK precipitation are consistent between observed interannual variability and projected changes, a finding which increases our confidence in projecting changes in UK precipitation associated with each storyline. However, many other climate variables are also intimately linked with the North Atlantic jet stream. Figure 16 shows the relationship between JJA means sunshine hours in the UK (Hollis et al., 2019) and the JJA jet latitude index as an example. Several regions have correlations greater than 0.6, and regression slopes above 3% of sunshine hours per degree latitude, indicating that a future poleward shift may contribute to sunnier UK summers. Future work will consider a range of impacts and the extent to which the jet dominates uncertainty in the climate change response.

A key strength of the storylines approach is that it explicitly deals with multivariate and spatially correlated uncertainties, allowing for a more holistic assessment of projection uncertainty. For example, a strong poleward jet shift may be expected to produce drier, warmer, calmer and sunnier summers in the UK. Traditional approaches, considering the uncertainty in future projections associated with each variable in isolation, may miss important correlated information. A jet storylines approach provides a means to answer questions such as 'how robust is the UK renewable energy generation system to climate change under the extreme high summertime jet shift storylines?'.

A further important application is near-term climate projections. Both the summer and winter jet indices exhibit variations on decadal timescales. As an example, Figure 6b shows how the summertime North Atlantic jet has undergone a marked equatorward shift of around 3°

over the last 40 years and associated with this UK-wide summertime precipitation during 2011 to 2020 was 17% higher than the 1961 to 1990 average (Kendon et al., 2022). Both trends are in stark contrast to the climate model projections which show a mean poleward shift of 3° by the end of the 21st century and a drying of 20%. The reasons for this observed summertime trend are not yet settled and are the subject of ongoing research. The extent to which it results from internal variability (and, therefore, may be expected to reverse over coming decades) or is a forced response to anthropogenic emissions (which may or may not continue) is a critical question for understanding near-term projections for the UK summer climate. Conditioning such near-term UK projections on a set of plausible changes to the jet would isolate this major source of epistemic uncertainty.

A third strength of the storylines approach is their use in communicating uncertainties. With this in mind, we propose that there would be benefits for climate practitioners to adopt phrases such as the following to communicate uncertainty in climate change projections: 'under the extreme high jet shift storyline, impact X is expected to change by Y%, whereas under the core mean jet shift storyline the change is only Z%'.

Finally, we note that the aim of this study is to provide a brief proof of concept illustration to motivate the use of jet-based storylines in future. There are several limitations in the present study which should be addressed to develop the methodology further. First, we note that we have produced single estimates of the precipitation change associated with each storyline. Whilst this fits our 'simple as possible' philosophy guiding this work, a more complete description would be obtained by estimating the full conditional probability distribution of a given impact for each jet storyline, that is P (impact = X|jet storyline Y), thereby truly conditioning the probability distribution of the future changes in an impact on the jet change and thus also incorporating uncertainties not captured by the jet change. This approach would allow, for example, the fraction of variance explained by the jet storylines to be estimated. Second, we note that we have estimated the impact associated with each jet storyline via the two simplest approaches of internal variability analogues and an analysis of multi-model ensembles. Other approaches, for example, bespoke downscaling simulations, could provide further insight and should be explored in future. However, we stress that the process of constructing the jet storylines and the process of estimating their associated impacts are two separate steps. Once the first step has been performed, various avenues can and should be explored to produce evidence for the second step.

AUTHOR CONTRIBUTIONS

Ben Harvey: Conceptualization; methodology; software; formal analysis; visualization; writing – review and editing; writing – original draft; investigation. **Ed Hawkins:** Conceptualization; methodology; writing – review and editing; software; formal analysis; visualization; supervision; investigation. **Rowan Sutton:** Conceptualization; methodology; writing – review and editing; funding acquisition; supervision.

ACKNOWLEDGMENTS

We acknowledge the HadUK-Grid dataset from the UK Met Office and CEDA; the E-OBS dataset from the EU-FP6 project UERRA (https://www.uerra.eu) and the C3S, and the data providers in the ECA&D project (https://www.ecad.eu); the 20CRv3 dataset provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research, by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Earth System Research Laboratory Physical Sciences Laboratory; the ERA5 data from the C3S CDS, noting our results contain modified Copernicus Climate Change Service information 2022 and that neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains; and, finally, the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6.

FUNDING INFORMATION

This work was supported by the Natural Environment Research Council (NERC) North Atlantic Climate System Integrated Study (ACSIS) and Climate Change in the Arctic-North Atlantic Region and Impacts on the UK (CANARI) projects. All authors were also supported by the UK National Centre for Atmospheric Science, funded by NERC.

DATA AVAILABILITY STATEMENT

The HadUK-Grid data used in this study is archived at the Centre for Environmental Data Analysis (CEDA) and is available at https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb. The E-OBS data is archived at the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) and is available at https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php. The ERA5 reanalysis is also archived at the CDS and is available at https://climate.copernicus.eu/climate-reanalysis. The 20CRv3 reanalysis data is available at https://psl.noaa.gov/data/20thC_Rean. The CMIP6 simulations analysed in this study are the versions archived at CEDA and are available at https://help.ceda.ac.uk/article/4801-cmip6-data.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Harvey, B., Hawkins, E., & Sutton, R. (2023). Storylines for future changes of the North Atlantic jet and associated impacts on the UK. *International Journal of Climatology*, 1–18. https://doi.org/10.1002/joc.8095