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A storyline view of the projected role of remote drivers on summer air stagnation in Europe and the United States

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Abstract

Storylines of atmospheric circulation change, or physically self-consistent narratives of plausible future events, have recently been proposed as a non-probabilistic means to represent uncertainties in climate change projections. Here, we apply the storyline approach to 21st century projections of summer air stagnation over Europe and the United States. We use a Climate Model Intercomparison Project Phase 6 (CMIP6) ensemble to generate stagnation storylines based on the forced response of three remote drivers of the Northern Hemisphere mid-latitude atmospheric circulation: North Atlantic warming, North Pacific warming, and tropical versus Arctic warming. Under a high radiative forcing scenario (SSP5-8.5), models consistently project increases in stagnation over Europe and the U.S., but the magnitude and spatial distribution of changes vary substantially across CMIP6 ensemble members, suggesting that future projections are not well-constrained when using the ensemble mean alone. We find that the diversity of projected stagnation changes depends on the forced response of remote drivers in individual models. This is especially true in Europe, where differences of ∼2 summer stagnant days per degree of global warming are found amongst the different storyline combinations. For example, the greatest projected increase in stagnation for most European regions leads to the smallest increase in stagnation for southwestern Europe; i.e. limited North Atlantic warming combined with near-equitable tropical and Arctic warming. In the U.S., only the atmosphere over the northern Rocky Mountain states demonstrates comparable stagnation projection uncertainty, due to opposite influences of remote drivers on the meteorological conditions that lead to stagnation.

1. Introduction

Poor air quality contributes to ∼4.5 million premature deaths annually (Cohen *et al* 2017). Air pollutants accumulate in the near-surface atmosphere when atmospheric scavenging, horizontal dispersion, and vertical escape are reduced —a phenomenon known as air stagnation (Leibensperger *et al* 2008, Jacob and Winner 2009, Tai *et al* 2010, Schnell and Prather 2017, Huang *et al* 2018, Wang *et al* 2018). Given the importance of stagnation for our exposure to air pollutants, and therefore public health, several studies have investigated recent observed changes in stagnation frequency and duration (Wang *et al* 2016, Huang *et al* 2017, Garrido-Perez *et al* 2018). Using various combinations of weather station, radiosonde, and reanalysis data these studies have found that over some regions of the world, the occurrence of stagnation has increased over the past decades.

Multi-model ensemble-based Earth System Model projections of stagnation suggest that changes in regional patterns are not unexpected. Previous studies have projected increases in the future occurrence and persistence of stagnation over some of the most populated areas of the globe, to include portions of India, China, the U.S., and Europe (Leung and Gustafson 2005, Horton *et al* 2012, 2014, Cai *et al* 2017, Caserini *et al* 2017, Han *et al* 2017, Hong *et al* 2019, Gao *et al* 2020, Lee *et al* 2020). These probabilistic multi-model ensemble projections of future climatic change have been considered a community best practice. However, recent work has suggested that regional projections based on multi-model ensemble means should be considered with care due to low confidence and high uncertainty in the forced response of atmospheric dynamics, which exerts a strong control on regional climates (Shepherd *et al* 2014).

As an alternative to probabilistic projection, the identification of 'storylines', or plausible and physically self-consistent combinations of climate change responses in well-known drivers of regional climate, can be used to characterize uncertainties within multi-model ensembles (Shepherd *et al* 2018, Zappa 2019, Mindlin *et al* 2020). This approach simplifies the spread of atmospheric circulation responses into a few plausible dynamically-driven scenarios, allowing for a better understanding of the changes simulated by the multi-model ensemble. Zappa and Shepherd (2017) followed this approach to show that the severity of the decline in Mediterranean winter precipitation and the increase in central European windiness projected by the models of the Climate Model Intercomparison Project Phase 5 (CMIP5) strongly depend on a few remote drivers of the atmospheric circulation in the Euro-Atlantic sector. Likewise, Peings *et al* (2018) dissected climate projections of different features of the winter eddy-driven jet over the North Atlantic and found that changes in the ratio between upper tropospheric tropical warming and lower tropospheric Arctic warming can explain a considerable fraction of the multi-model spread. Models with the largest change in this ratio projected a reinforcement and slight poleward shift of the jet, while a significant reduction in the westerlies on the poleward flank of the jet occurred in models with the smallest change in ratio. Kornhuber and Tamarin-Brodsky (2021) classified CMIP5 models by the sign of the trend in their future equator-to-pole temperature gradient to investigate different regional patterns of summer weather persistence, namely the zonal propagation speeds of anticyclones and warm temperature anomalies. They found the best agreement between both subsets over southern North America, whereas the sign of the projections strongly disagreed over Europe.

Using a storyline framework and a CMIP6 multi-model ensemble, this study develops for the first time plausible storylines of regional changes in stagnation by the end of the century. We focus our investigation on the contiguous U.S. and Europe, where the CMIP3 and CMIP5 multi-model ensemble means have consistently projected regional stagnation increases (Horton *et al* 2012, 2014). In particular, we address summer (JJA) as this is the season with the largest projected changes (figure S3 available online at stacks.iop.org/ERL/17/014026/mmedia). Our study also provides further insights into potential remote drivers of stagnation changes and associated components of the mid-latitude circulation during summer, which has received less scientific attention than in winter (Coumou *et al* 2018). Following this, the three main objectives of this paper are (a) to explore the degree of influence of future changes in different remote drivers on stagnation over Europe and the U.S.; (b) to identify the regions where future stagnation is most sensitive to those driver responses (storyline uncertainty hereafter); and (c) to provide a quantitative analysis of future changes in stagnation for different storylines and levels of warming.

2. Data and method

2.1. CMIP6 meteorological data

We investigate changes in regional stagnation due to the forced response of remote drivers in a multi-model ensemble. Meteorological variables, including daily 500 hPa wind speed, near-surface wind speed, and precipitation, as well as monthly 2 m, 850 hPa and 250 hPa temperatures, and sea surface temperatures (SSTs) were obtained from a 22-member CMIP6 ensemble of opportunity (table S1; Eyring *et al* 2016). All simulated data have been interpolated to a common grid with 2.5° × 2.5° horizontal resolution. For each individual model realization, the end-of-century climate change response is defined as the 2071–2100 mean in the shared socioeconomic pathway SSP5-8.5 scenario minus the 1981–2010 mean in the historical simulation. Although realization of this high emission scenario is considered unlikely, the corresponding simulated climate futures cannot be ruled out (IPCC 2021). Moreover, the results from the storyline framework are scaled by global warming (GW) to account for the uncertainty in climate sensitivity to GW (section S3). This approach assumes that the amplitude of the atmospheric response depends on the GW signal and not the pathway of radiative forcing (i.e. the chosen scenario; Zappa and Shepherd 2017).

2.2. Air stagnation index

We define air stagnation using the National Climate Data Center Air Stagnation Index (ASI; Wang and Angell 1999) adaptation by Horton *et al* (2012), a commonly used metric in air quality meteorology studies (Leung and Gustafson 2005, Horton *et al* 2012, 2014, Huang *et al* 2017, Maddison *et al* 2021). This index considers a day as stagnant when three conditions are simultaneously fulfilled within a grid cell: near-surface wind speed <3.2 m s^{-1}, 500 hPa wind speed <13.0 m s^{-1}, and accumulated precipitation <1.0 mm. Previous analyses have found that this formulation of the ASI outperforms others in capturing the links among large-scale circulation, stagnation, and air pollution in Europe (Garrido-Perez *et al* 2021, Maddison *et al* 2021). This index is also commonly used for air pollution studies in the U.S. (Schnell and Prather 2017, Sun *et al* 2017). We note however, that the use of absolute thresholds can be problematic due to model biases. Previous threshold-based model investigations have surmounted this challenge by employing bias correction techniques (Ashfaq *et al* 2010, Horton *et al* 2012, 2014). Here we employ an alternative percentile-based approach. First, we computed the percentiles corresponding to the mentioned stagnation thresholds in ERA5 (Hersbach *et al* 2020) for the 1981–2010 period (see figure S1). Next, we computed the values of the meteorological fields that correspond to those percentiles for each CMIP6 model and grid cell, resulting in new ASI thresholds. The multi-model ensemble mean thresholds are displayed in figure S2. More details on this methodology are provided in section S1.

Due to spatial heterogeneities in stagnation over Europe and the U.S., we use k-means clustering on the gridded monthly frequency of stagnation days for the 1981–2010 historical period to define regions with consistent stagnation patterns in the multi-model ensemble. This results in a spatial division of nine regions (four in the U.S. and five in Europe): northwest U.S., central and northeast U.S., southwest U.S., southeast U.S., Scandinavia, northern Europe, central Europe, southwest Europe, and southeast Europe. Full details are given in section S2.

2.3. Definitions of remote drivers

Remote drivers of regional circulation change define the storylines. We construct stagnation storylines by investigating the forced response (future minus baseline) of three remote drivers with known influences on summer weather patterns over Europe and the U.S.: (a) ratio between the tropical and Arctic warming (RTAW): it measures the differential warming rate between tropical and Arctic latitudes. A higher Arctic than tropical warming is associated with a decrease in equator-to-pole temperature gradients, which leads to a weakened storm track and a southward shift in the mid-latitude jet, with notable implications for European and U.S. climates (Coumou *et al* 2018). Following Zappa and Shepherd (2017) and Peings *et al* (2018), this driver is computed from regional averages of temperature change in the tropical upper troposphere (30° S–30° N at 250 hPa) and Arctic lower troposphere (60°–90° N at 850 hPa). (b) North Atlantic warming (NATLW): anomalously cold SSTs around the subpolar gyre associated with the slowdown of the Atlantic Meridional Overturning Circulation (AMOC) during the last few decades have been related to weakened westerlies in summer over the North Atlantic sector and persistent dry hot extremes in Europe (Haarsma *et al* 2015, Rahmstorf *et al* 2015). Following this, NATLW is defined as the SST change averaged in the [50°–65° N, 40°–10° W] domain, which is the area with the lowest projected warming by the end of the 21st century in the multi-model ensemble mean (Atlantic box in figure S13), resembling that considered by Rahmstorf *et al* (2015) as the most sensitive region to a reduction in the AMOC. (c) North Pacific warming (NPACW): studies have linked extratropical North Pacific SSTs with atmospheric circulation anomalies over the contiguous U.S. (Ting and Wang 1997, Alexander *et al* 2002, Lau *et al* 2004, Wang *et al* 2014, Eden *et al* 2015, Jia *et al* 2016, Chen *et al* 2020), and more specifically, with high pressure systems, which are symptomatic of air stagnation conditions (e.g. McKinnon *et al* 2016). NPACW is defined here as the SST change averaged in the [30°–50° N, 150° E–150° W] domain. This region is influenced by the Pacific Decadal Oscillation (Deser and Trenberth 2016) and is expected to experience high SST increases (Pacific box in figure S13). Additional analyses confirm that the results presented here are not sensitive to the choice of the domains over the North Atlantic and North Pacific oceans (not shown). All spatial averages are area-weighted. The computation of the remote drivers and stagnation responses has been made for each individual model realization prior to the regression analysis involved in the storyline approach (see section S3).

3. Spatial and inter-model variability of projected changes in air stagnation occurrence

By the end of the 21st century, under a high emission scenario, stagnant conditions are projected to be more common in summer over most of the U.S. and Europe (figures 1(b) and 2(b)–(j)). In Europe, the greatest changes are projected in the southeast and, to a lesser extent, the centre of the continent (figure 1(b)), areas that have historically experienced high summer stagnation (figure 1(a)). In the U.S., the largest changes are located over the northwest (figure 1(b)), with average increases in the absolute frequency of stagnation of around 7%–12% (6–11 days).

Figures 2 and S4(d)–(f) assess the projected changes in the frequency of stagnant conditions separately for each ASI component. Although the pattern of projected changes for stagnant near-surface wind is heterogeneous, most of the U.S. and Europe show comparatively small increases (below 8%) in the frequency of this condition (figure S4(e)). For mid-tropospheric winds, the spatial pattern suggests a generalized poleward shift of the North Atlantic westerlies, with the 35°–50° N (50°–65° N)

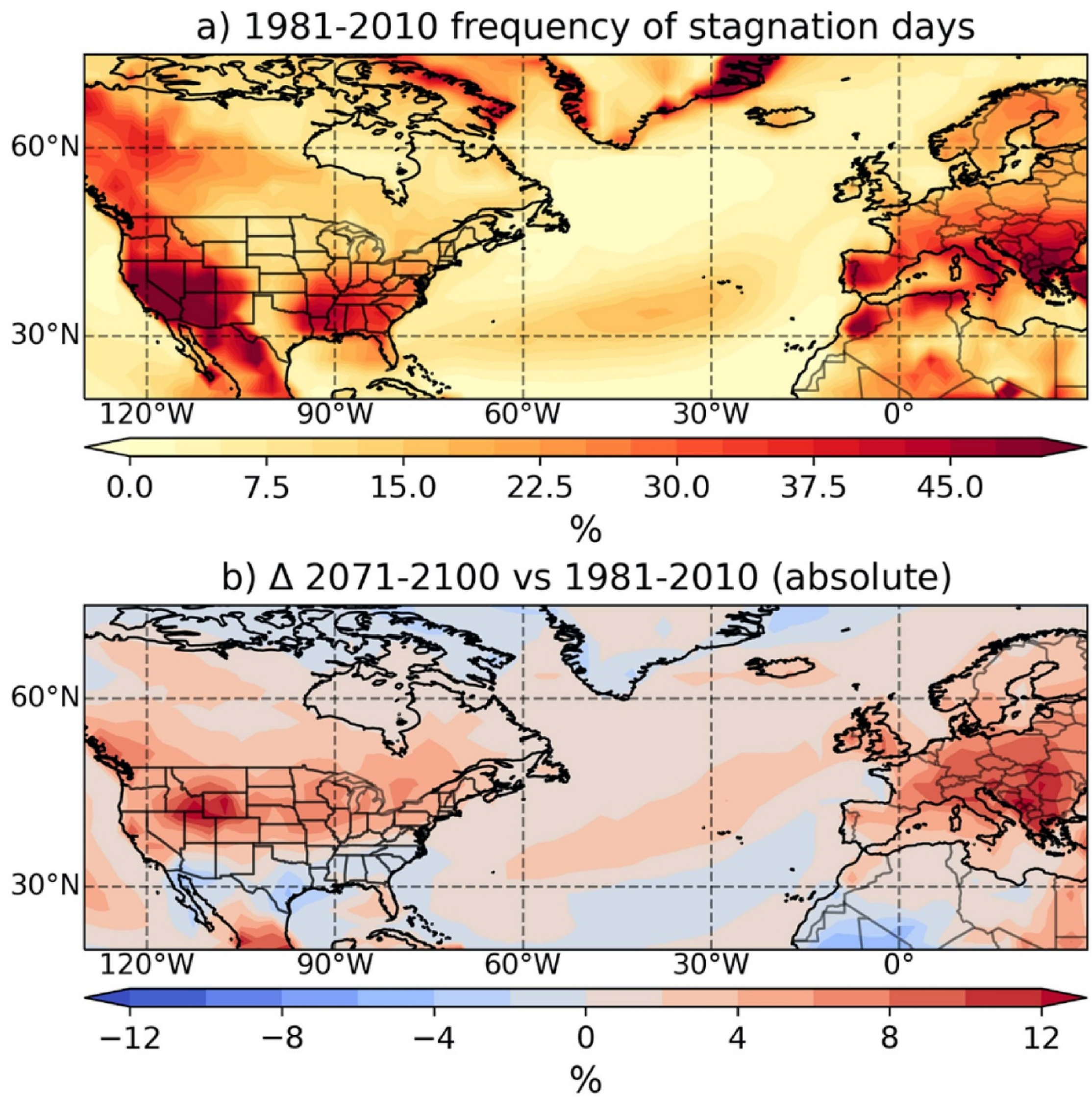

Figure 1. CMIP6 multi-model ensemble mean summer stagnation. (a) Percentage of stagnation days (%) during the period 1981–2010. (b) Absolute change in stagnation occurrence (%) from 1981–2010 to 2071–2100 under the SSP5-8.5 scenario.

latitudinal band exhibiting a 10%–14% increase (1%–4% decrease) in the frequency of stagnant mid-tropospheric wind conditions, more pronounced in the U.S. than in Europe (figure S4(f)). The change in the frequency of dry days is small for the U.S., but exhibits substantial increases over most of Europe, with the exception of Scandinavia (figure S4(d)). Therefore, the projected increases in stagnation days over Europe and the U.S. are largely caused by enhanced frequency of dry days and stagnant mid-tropospheric winds, respectively.

The boxplots in figure 2 illustrate the inter-model spread for the projected changes in stagnation frequency and its components. Increases in stagnation are projected for most regions, with the only interquartile range indicating lesser stagnation in the southeast U.S. However, the interquartile ranges still show considerable spread among the models and therefore large uncertainty in the projections of stagnation. This indicates that there are regions where model projections are not robust and the multi-model mean blurs the large range of potential responses. To investigate this in more detail and constrain the dynamical uncertainty, a storyline approach for plausible future regional stagnation changes is presented in the next section.

4. Remote driver responses and sensitivity of stagnation

Figure 3 shows the spread of near-surface GW and driver responses (2071–2100 minus 1981–2010) among the model simulations. The driver responses are characterized by large uncertainty, with interquartile ranges exceeding 2 °C for NATLW. Although the tropics and the Arctic will warm at a faster rate than the rest of the globe, the projected warming is larger in the tropics than in the Arctic (RTAW > 1), leading to an increase in the pole-to-equator temperature gradient. The fact that

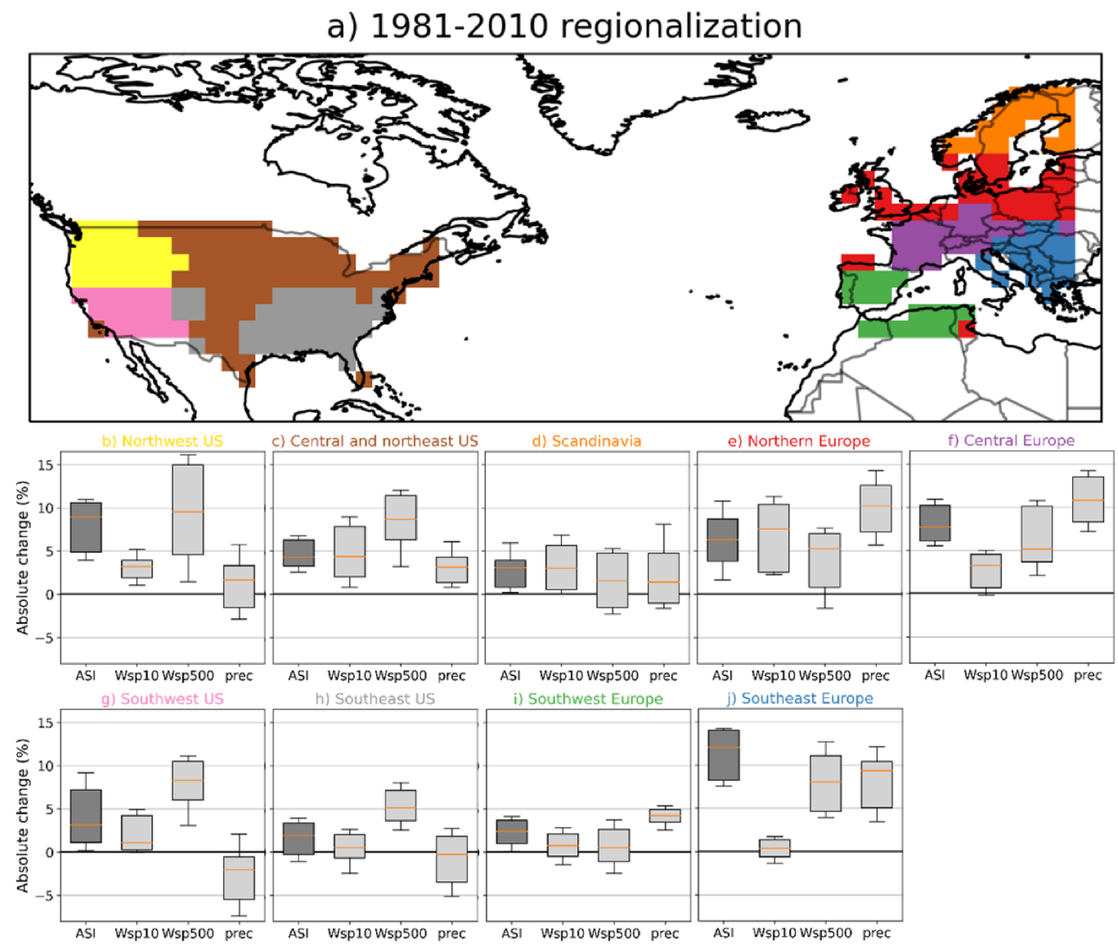

Figure 2. (a) Regionalization of monthly stagnation frequency during 1981–2010 in the U.S. and Europe, as derived from the multi-model ensemble. (b)–(j) Absolute change in the summer frequency (%) of stagnation days (dark grey) and of days that fulfil each of the stagnation conditions (light grey), calculated as the difference between the future (2071–2100) and historical (1981–2010) periods under the SSP5-8.5 scenario. The boxes extend from the lower to the upper quartile values of the data, with a horizontal line indicating the position of the median. The whiskers extend from the boxes to show the range of the data between the 10th and 90th percentiles. The colours in the headings of panels (b)–(j) correspond to those used to depict each region in panel (a). Abbreviations: ASI—air stagnation index, Wsp10—10 m wind speed, Wsp500—500 hPa wind speed, and prec—precipitation.

RTAW ranges from 1 to 1.4 (10th–90th percentiles) indicates that models with large tropical warming do not necessarily show strong Arctic amplification. On the other hand, the warming (and spread) over the North Pacific is only slightly higher than GW. This occurs because land areas warm faster than oceans, although the North Pacific is among the oceanic regions that will experience the highest increase in SSTs (Lauvset *et al* 2017, Mamalakis *et al* 2021). Conversely, the projected warming over the North Atlantic is considerably lower (albeit more uncertain) than GW.

To better understand the influence of these driver responses on stagnation, we use the storyline regression framework of Zappa and Shepherd (2017). We assess the stagnation response separately for each grid cell by applying multi-linear regression analysis on the responses of the three remote drivers for all models. For each model, the driver and stagnation changes are scaled by GW. The resulting regression coefficients give the sensitivity per degree of GW of the regional stagnation response to anomalies (with respect to the multi-model ensemble mean) in the remote driver responses. This is illustrated in figure 4 for stagnation and in figures S6–S8 for each of its components. An anomalously high RTAW in the multi-model ensemble tends to reduce (enhance) the frequency of stagnation over the northern (southern) regions of the U.S. and Europe (figure 4(a)). The associated strengthening and poleward shift of the westerlies decrease the days fulfilling the wind conditions for stagnation over most of Europe and northern U.S., while the opposite occurs over southwest Europe and the southeast U.S. (figure S6). Nevertheless, the differing effects of this driver on precipitation and winds may cancel out over the U.S. On the other hand, enhanced warming of the North Pacific is associated with an increase in the frequency of stagnation over a large part of the U.S., with the most notable exception being the southwest (figure 4(b)). This is mainly due to an increase in the frequency of days fulfilling stagnant wind conditions, while the

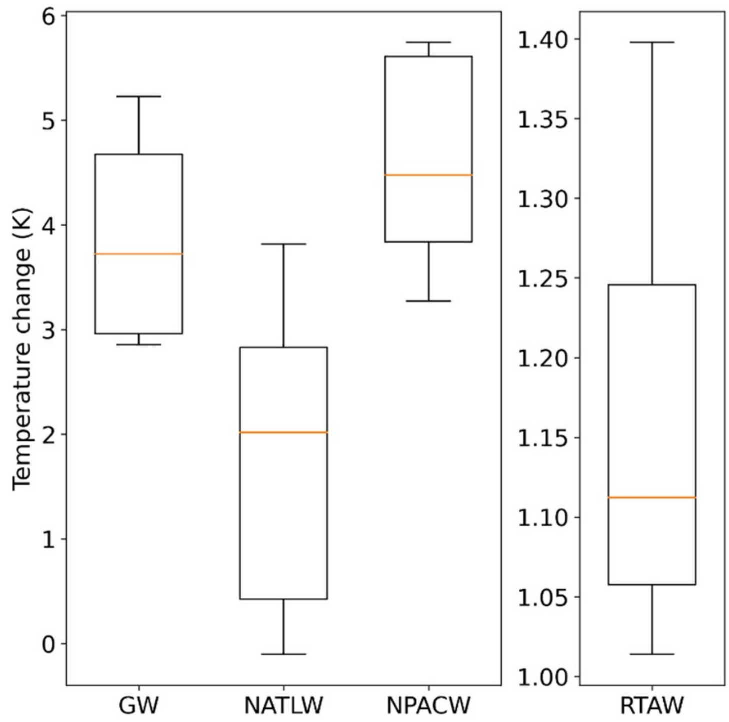

Figure 3. Spread of climate change responses (2071–2100 minus 1981–2010) simulated by the CMIP6 models under the SSP5-8.5 scenario: global near-surface warming (GW), North Atlantic warming (NATLW), North Pacific warming (NPACW) and ratio between tropical and Arctic warming (RTAW). GW is evaluated based on annual means, while the other quantities are evaluated for summer (JJA). See caption of figure 2 for the definition of boxplots.

influence of North Pacific warming on precipitation over the U.S. is small (figure S7). Finally, NATLW negatively correlates with the stagnation responses over most of Europe (figure 4(c)), indicating that reduced sea surface warming associated with a slowdown of the AMOC would lead to enhanced stagnation over Europe. This is mainly explained by the negative association of this driver with the occurrence of dry days in Europe (figure S8).

5. Storylines of future regional changes in air stagnation

Based on the identified driver responses, we have generated a range of extreme but plausible storylines of future changes in stagnation. Figure 5 illustrates the regional stagnation responses to four storylines based on the combination of RTAW and NPACW for the U.S. and of RTAW and NATLW for Europe (more details on the methodology are provided in section S3). In the U.S., stagnation seems to increase for all storylines, but with considerable uncertainty. In particular, the northwest U.S. has the largest stagnation changes projected across the storylines considered (i.e. the strongest sensitivity to the driver responses). The combination of low RTAW and high NPACW is associated with an increase in stagnation frequency of $\sim$3% K^{-1} in contrast to $\sim$1% K^{-1} when the opposite occurs. This difference ($\sim$2 d K^{-1}) is mostly caused by a large uncertainty in the mid-tropospheric wind response, with an inter-storyline variability close to 4% K^{-1} ($\sim$4 d K^{-1}). The storyline uncertainty is comparatively low for the stagnation projections in the rest of U.S., though some stagnation components deserve attention. In particular, the decrease in frequency of dry days over the southwest U.S. projected by the multi-model mean could intensify substantially under low RTAW or turn to a small increase in the opposite case. This component tends to dominate the ASI responses over the southwest U.S. In general, the storyline uncertainty of stagnation is moderate (as compared to that of some of the components) for the U.S. This occurs because the stagnation components respond differently to the driver changes and therefore such responses tend to cancel out. For example, while low RTAW and high NPACW promote stagnant winds and yield stagnation increases in the northwest U.S., this storyline also decreases the frequency of dry days (and vice-versa for the opposite storyline).

Figure 5 also displays relevant storylines of future stagnation in Europe. Overall, the European regions present higher sensitivity to the storyline uncertainty than those in the U.S. This is partially due to the reinforcement of the individual responses in the stagnation components, which contrasts with the opposing effects of the storylines reported for the U.S. In all regions except southwest Europe, the highest stagnation increases are expected in the low RTAW and weak NATLW storyline, which is associated with

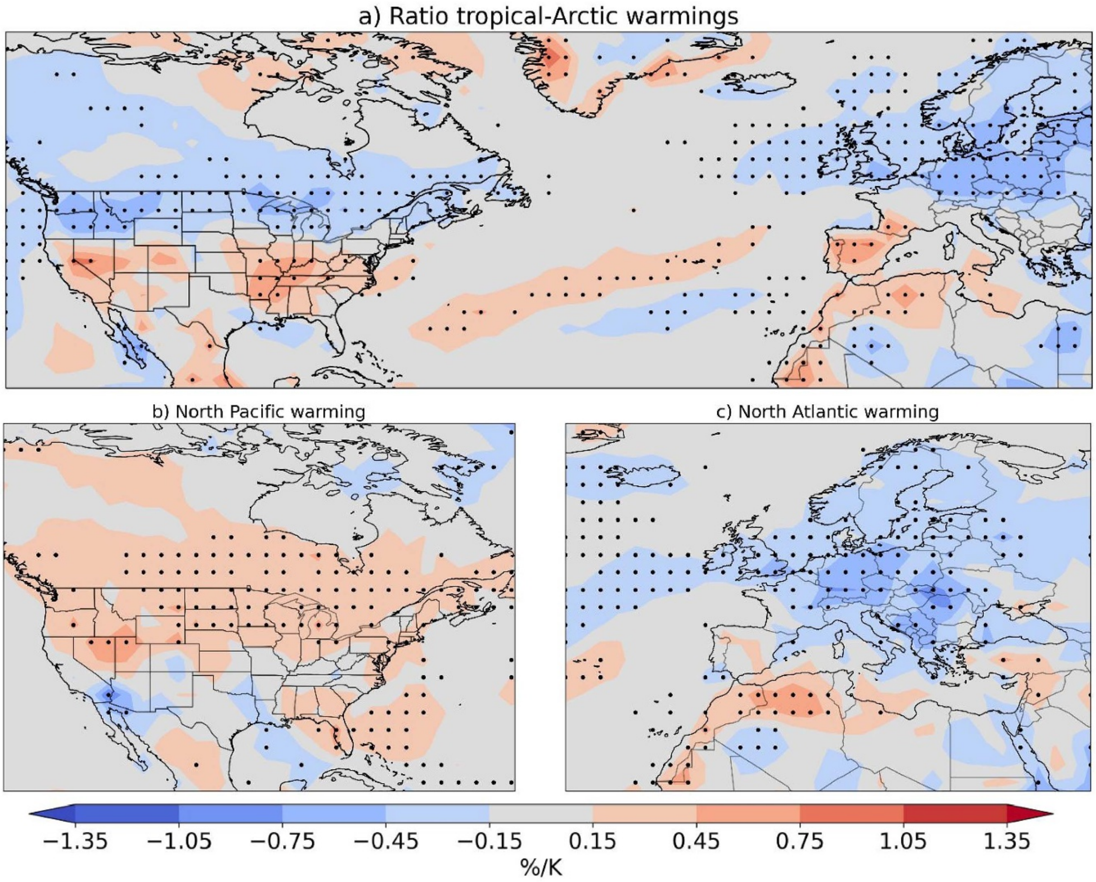

Figure 4. Sensitivities of summer stagnation changes (2071–2100 minus 1981–2010) associated with the uncertainties in the climate change driver responses: (a) ratio between the tropical and Arctic warming (RTAW), (b) North Pacific warming (NPACW) and (c) North Atlantic warming (NATLW). These sensitivities correspond to the coefficients obtained from equation S1 (b_x for RTAW, c_x for NATLW and d_x for NPACW). Colours show the air stagnation index (ASI) responses scaled by global warming (% K^{-1}) due to one sigma positive anomaly of the driver with respect to the multi-model mean. Stippling indicates regions where the regression coefficients are statistically significant at the 90%.

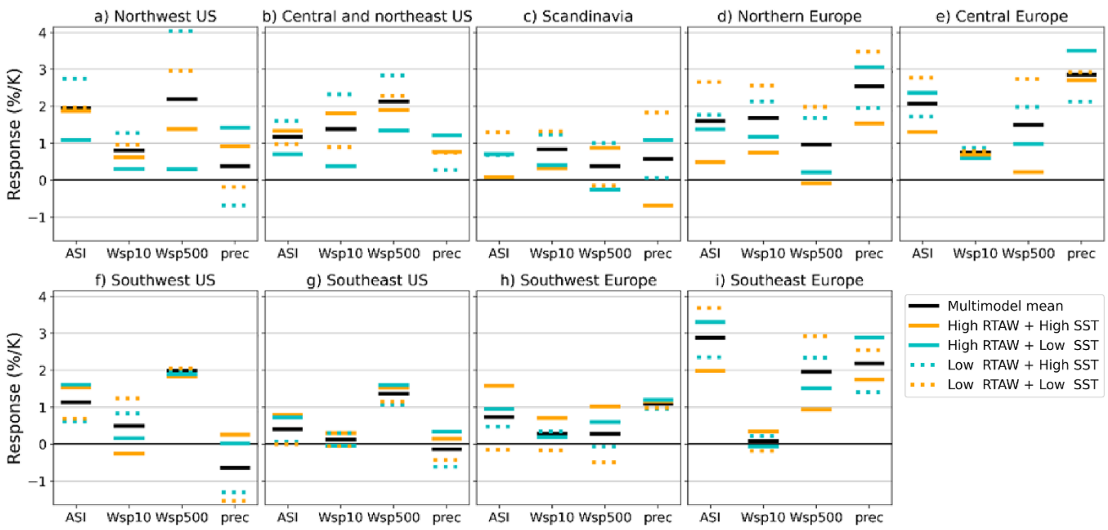

Figure 5. Summer stagnation response (JJA 2071–2100 minus JJA 1981–2010) per degree of global warming (% K^{-1}) according to four plausible storylines of climate change. These are conditioned on the ratio between the tropical and Arctic warming (RTAW) for all regions as well as the North Pacific warming (NPACW) responses in the U.S. and the North Atlantic warming (NATLW) responses in Europe. Abbreviations: ASI—air stagnation index, Wsp10—10 m wind speed, Wsp500—500h Pa wind speed, and prec—precipitation.

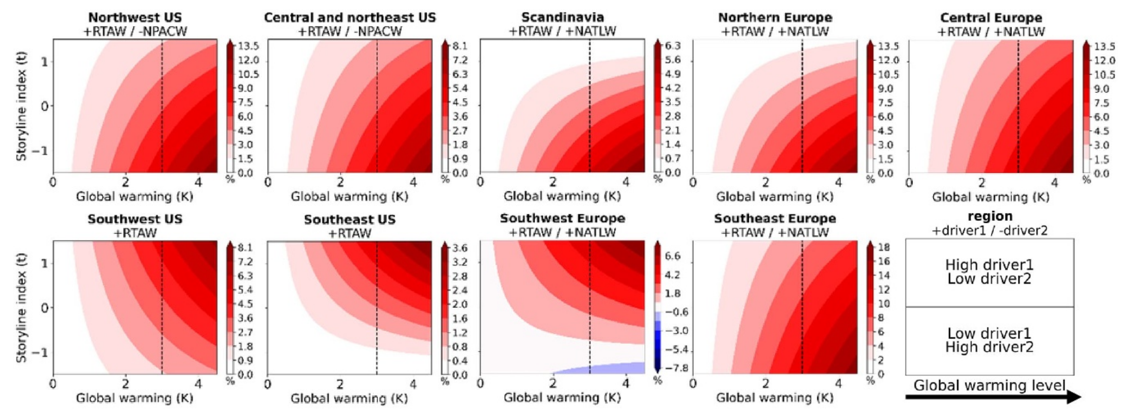

Figure 6. Projected changes of regional stagnation frequency as a function of global warming and storyline index. The index represents the standardized anomaly of the combined driver responses. The text on the top of each panel indicates the drivers used to generate the storylines in each region, with the signs specifying how they are combined. For example, positive values of the storyline index represent high RTAW and low NPACW for northwest U.S., and vice versa. The right bottom panel shows a schematic diagram to interpret the plots. More details on the storyline index are provided in section S3. Note the different colour scales for each region.

larger precipitation and wind decreases than in the multi-model mean. The opposite occurs for the high RTAW and NATLW storyline, which yields the largest rise in stagnant days over southwest Europe but the lowest increase for the rest of Europe.

The amplitude of the projected stagnation increases also follows that of GW. Figure 6 displays the regional stagnation change as a function of GW and a storyline index that represents the standardized anomaly in the driver responses (Zappa and Shepherd 2017). In other words, the storyline index measures how large the responses of the remote drivers are. High values indicate strong responses, while zero values mean absence of changes. This storyline index has been chosen for the combination of driver responses leading to the highest storyline uncertainty in ASI for each region. This way, positive values of this index represent high RTAW and low NPACW for northwest, central, and northeast U.S., high RTAW for southwest and southeast U.S., and high RTAW and NATLW for the European regions, with the opposite driver responses for negative values. Note that we only use RTAW for the southern regions of the U.S. because the effect of NPACW is negligible there (see figure 5). Further details are provided in section S3 of the supplement.

Overall, figure 6 shows similar spread of stagnation responses across the range of values of GW and the storyline index. For a 3 °C GW, the increase in stagnation frequency ranges from 3% to 9% (3–8 days) in northwest U.S. depending on the storyline, while the width of this range drops below 4% (3–4 days) for the rest of U.S. regions. On the other hand, the strongest sensitivity to the responses of RTAW and NATLW in Europe is found in northern and, to a lesser extent, southeast and southwest regions (figure 6). For a 3 °C GW, the increase in stagnation frequency ranges from 1% to 9% (1–8 days) in northern Europe, from 5% to 12% (5–11 days) in southeast Europe and from −1% to 5% (−1 to 5 days) in southwest Europe depending on the storyline. Although stagnation frequency is projected to increase in the multi-model mean for these regions, the magnitude of the changes seems uncertain and might be rather moderate for Scandinavia and southwest Europe. This illustrates the difficulty of establishing a GW threshold to limit future stagnation increases.

6. Discussion and concluding remarks

Recent studies have investigated the influence that climate change could exert on the frequency of stagnation in different regions of the globe throughout the 21st century (Horton *et al* 2012, 2014, Caserini *et al* 2017, Han *et al* 2017, Gao *et al* 2020, Lee *et al* 2020). Although they provide a probabilistic view based on multi-model means, there are still large discrepancies among climate model projections. For instance, under the SSP5-8.5 forcing scenario, the interquartile ranges of the changes in summer stagnation frequency can be as high as 8% (7 days) for some regions by the end of the 21st century (see figure S14). While different sources of uncertainty (e.g. internal variability, model formulation) potentially contribute to these differences, previous analyses have shown that the careful examination of the circulation response to external forcings may provide some constrains on model projections (e.g. Shepherd 2014, Zappa and Shepherd 2017).

In this study we have explored the relationship between stagnation changes in the U.S. and Europe and three different remote drivers of the mid-latitude atmospheric circulation in summer, when the projected stagnation changes are the highest. While models consistently report future increases in stagnation for the high forcing scenario considered here, the magnitude and spatial distribution of these changes vary substantially across the model ensemble depending on the driver responses. Overall, our results indicate that strong tropical warming relative to Arctic warming is associated with a strengthening and poleward shift of the upper westerlies, which in turn would lead to decreases in stagnation over the northern regions of North America and Europe, as well as increases in some southern regions, as compared to the multi-model mean. Opposite responses occur for larger Arctic warming levels, consistent with the projected weakening and equatorward shift of the mid-latitude jets associated with the Arctic amplification (Screen 2013, Coumou *et al* 2018, Zappa *et al* 2018). On the other hand, North Pacific warming tends to increase the frequency of stagnation over some regions of the U.S. by enhancing the frequency of stagnant winds, while reduced North Atlantic warming does the same over Europe by promoting the frequency of dry days. The latter finding is consistent with Jackson *et al* (2015), who reported summer precipitation deficits over most Europe for a decline of the AMOC. One could expect that moderate surface warming will limit evaporation over the North Atlantic, although dynamical processes might play a role too due to the influence of North Atlantic SSTs on the eddy-driven jet and the storm track (Woollings *et al* 2012, Hall *et al* 2017, Baker *et al* 2019, Ruggieri *et al* 2021).

Given the response of stagnation to these remote drivers, their evolution in future projections will substantially determine the magnitude of the stagnation increases. Following this, we have generated extreme but plausible storylines based on the modelled response of the three remote drivers. The results show differences up to 2% K^{-1} (∼2 stagnant days in summer per degree of GW) between the storylines for some regions. As an illustration, for a 3 °C GW, the uncertainty in northern Europe is high (around 8%, i.e. ∼7 days) compared to the observed 1981–2010 frequency of stagnation (∼20%). This high inter-storyline variability implies that future projections of stagnation depend substantially on the atmospheric circulation and cannot be well constrained based on multi-model means, even for specific GW levels. The most sensitive regions to the driver responses are not necessarily those with the highest inter-model variability. In fact, European regions present higher storyline uncertainty than those in the U.S., except for northwest U.S., despite displaying comparable inter-model variability. This is at least partially due to the reinforcement of the individual responses in the stagnation components over Europe as opposed to the offsetting effects of the storylines generated for the U.S.

The resulting storylines have also shown that the worst-case scenario for one region can be the best-case scenario for another. For instance, the storyline characterized by the combination of a high ratio between tropical and Arctic warming with strong North Atlantic warming is associated with the largest stagnation increase in southwest Europe and the lowest in the rest of the continent. These regional differences may imply uneven impacts of future stagnation changes on air quality. Although the projections of increases in stagnation cannot always be translated into enhanced air pollution (e.g. Kerr and Waugh 2018, Garrido-Perez *et al* 2019), they are valuable indicators in the absence of air quality output from climate models, especially for those regions where the sensitivity of air pollution to stagnation has been proven. Interestingly, previous studies have reported high increases in summer near-surface ozone concentrations on stagnant days over southeast and central Europe (Garrido-Perez *et al* 2018, 2019), where we project some of the highest stagnation increases and considerable spread among the storylines. This suggests that future air pollution in these and other regions could be especially sensitive to mid-latitude dynamical changes associated with climate change. Thus, the analysis of plausible storylines of future regional changes in stagnation could be instrumental in understanding divergent model responses when assessing future changes in weather conditions conducive to poor air quality in those regions.

Despite the underlying assumptions (i.e. the amplitude of the atmospheric response depends on GW but not on the chosen scenario) and approaches (percentile-based bias correction), our results show substantial spread in future regional stagnation as mediated by the considered drivers. Additional studies are encouraged to uncover the physical mechanisms linking these drivers with regional stagnation as well as to explore potential remote drivers not considered herein.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/projects/esgf-llnl/.

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