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A storyline attribution of the 2011/2012 drought in Southeastern South America

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Introduction

Often it is assumed that increased dryness will lead to increased droughts, the same for wetness and floods. Dryness refers to the climatological hydrological state of a region, whereas drought refers to an extreme event. However, in some regions, climate change is expected to increase both wetness *and* the intensity of droughts (Ault, 2020).

Southeastern South America (SESA) is a region of South America centred in the La Plata Basin, which includes Uruguay, the northeast of Argentina, the southern tip of Brazil and the southeastern tip of Paraguay. The climate in SESA experienced a pronounced wetting during the second half of the twentieth century. The regional precipitation trends are among the largest regional trends in the world (Vera and Díaz, 2015). This includes both an increase in mean annual rainfall (Doyle *et al.*, 2011) and the frequency of extreme rainfall events (Penalba and Robledo, 2010). However, the SESA region also suffers from regular droughts, approximately every 5–10 years, which are part of the regional climate and are to a large extent associated with strong La Niña events (Grimm *et al.*, 2000). Both short-term (3 months) and long-term (10–12 months) droughts impact SESA; the first affecting the agricultural sector and the second affecting water supplies.

Two examples of exceptionally severe droughts, in both extent and intensity, occurred during summer 1988/1989 and summer 2008/2009. In Uruguay, the 2008/2009 drought caused hydropower production (which normally accounts for roughly 80% of the national energy supply) to plummet to 20%. In Argentina, that same drought reduced grain production by 39%, and an estimated 1.5 million livestock were lost (Peterson and Baringer, 2009). The extent of agricultural impacts depends on the timing of each drought. Soybean and corn production will be hampered if a drought occurs in summer (December–February), whereas wheat is more sensitive to precipitation deficiency in spring (October–November). For this reason, shorter droughts may have equivalent impacts on crop loss as more persistent droughts if they occur during critical growth periods. The 2011/2012 summer drought is an example of such a short but devastating event, with damages to corn and soybean production running up to USD 2.5 billion (Sgroi *et al.*, 2021). Since the strongest climate change signal in SESA is an increase in mean precipitation, drought impacts in this region have not received as much attention as might be needed for adaptation. However, one of the few studies available for SESA (Penalba and Rivera, 2013) showed that the frequency, duration and severity of these droughts are expected to increase under future climate scenarios. Thus, understanding the influence of a warmer climate on droughts in SESA is of clear societal relevance.

Drought attribution typically relies on statistical approaches that focus on changes in frequency, duration and severity. These aspects are essential and relevant, but the approaches struggle with large uncertainties. Such issues often are connected to our limited knowledge of climate change effects on dynamics and on the variability related to droughts in the present climate (Shepherd, 2014). Moreover, to allow for statistical significance, these methods depend on grouping similar events, resulting in the blurring-out of important details.

Conditional attribution–the attribution of the thermodynamic part of weather events–takes the uncertainties connected to the dynamics out of the equation. With spectrally nudged storylines (introduced in the next section), we can simulate historical events under different climatological backgrounds. Consequently, the method allows for specific event attribution of aspects we have physical understanding of, with limited loss of detail and without having to deal with uncertainties related to changes in frequency or duration (Shepherd *et al.*, 2018; van Garderen *et al.*, 2021).

In this study, we look at the effect of climate change on the thermodynamics of the 2011/2012 SESA drought. We focus on the differences between the storylines to conditionally attribute the event and subsequently place the results in climatological context.

Data

To produce our simulations, we use the ECHAM6 atmospheric model (Stevens *et al.*, 2013) with T255 horizontal spectral resolution and 95 vertical levels (T255L95). This is the atmospheric component of the MPI-M coupled model (Tebaldi *et al.*, 2021) used in the sixth coupled model intercomparison project (CMIP6). Boundary conditions such as sea surface temperature (SST) and sea ice concentration are prescribed using NCEP R1 reanalysis data (Kalnay *et al.*, 1996). We spectrally nudge the large-scale free atmosphere of ECHAM6 with the divergence and vorticity from the NCEP R1 reanalysis data. Since we nudge in spectral space, we can use NCEP R1 reanalysis to nudge wavelengths in ECHAM6 that represent patterns of approximately 1000km and larger (Schubert-Frisius *et al.*, 2017). Moreover, NCEP R1 captures the dynamical conditions of the drought well (see Figure 1). The 1948–2015 spectrally nudged simulation (ECHAM_SN) is used through-

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RMetS Royal Meteorological Society

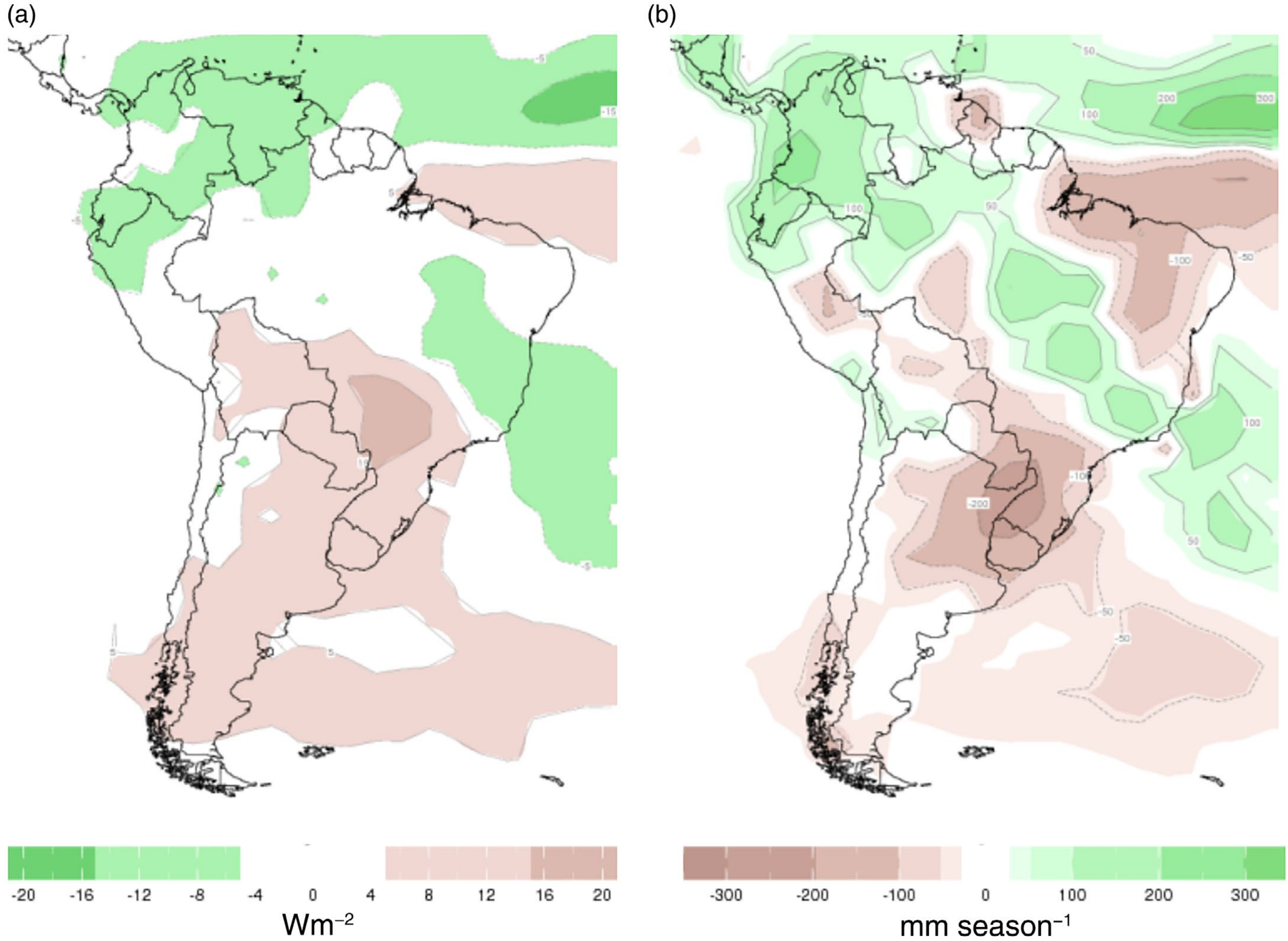

Figure 1. Drought characterisation. Seasonal anomalies with respect to the 1979–2020 climatological average over November–January of (a) outgoing longwave radiation (Wm^{-2}) (b) precipitation (mm season^{-1}). The data are from the NOAA NCEP Climate Prediction Center and were plotted using https://iridl.ldeo.columbia.edu/maproom/ (International Research Institute for Climate and Society, Columbia University, New York, USA).

out this study to compute the climatology (Schubert-Frisius *et al*., 2017). We compare our precipitation results with Global Precipitation Climatology Centre (GPCC) observations (Schneider and Fuchs, 2008), and compare both the temperature and precipitation results with ERA5 reanalysis (Hersbach *et al*., 2020).

Spectrally nudged storylines

Spectral nudging has been applied in regional models for a wide range of extreme weather event research (Feser and von Storch, 2008; von Storch *et al*., 2018). We apply the spectral nudging technique to a global model and use this setup to create three storylines: (i) a world without climate change (counterfactual), (ii) the world as we know it (factual) and (iii) a world warmed by 2 degC above pre-industrial (plus2).

The factual and counterfactual simulations are according to van Garderen *et al*. (2021). The plus2 storyline is based on the same principle, but uses different SST and greenhouse gas (GHG) levels. The ssp585 scenario is based on the representative concentration pathways 8.5 global forcing in combination with the shared socioeconomic pathway (ssp) number five; both are simulating a future with high-end climate forcing (O'Neill *et al*., 2014). The 2m temperature (T2m) in CMIP6 MPI-ESM ssp585 scenario simulations exceed 2 degC of global warming (with respect to pre-industrial) between 2044 and 2053. That time period is then used to create an SST warming pattern and to set the GHG levels accordingly. Land use is kept equal between the storylines to ensure conditional attribution of global warming aspects only. For each of the three different storylines, we simulated three members each of 5 years (2010–2014). The average global T2m in the counterfactual storyline is 13.60°C; in the factual storylines, 14.28°C and in the plus2 storyline, 15.15°C.

2011/2012 SESA drought

Despite the 2011/2012 SESA drought having a short 3-month duration, neither as severe nor as persistent as, for example, the 2008/2009 drought, the timing of the event during crop-sensitive months caused large yield losses. The November 2011–February 2012 Standardized Precipitation Index in the Argentinian part of SESA indicates moderate to extreme drought conditions. The 3-month Palmer Drought Severity Index, for the same period and region, indicates a severe to extreme drought event (CREAN, 2017).

The dynamic situation, including La Niña and an intensified South Atlantic Convergence Zone (SACZ), favoured dry conditions. The event started in December 2011, during the second consecutive summer with a La Niña. The 2-year La Niña event of 2010–2012 was one of the strongest such events on record and caused extreme weather across the world (Blunden and Arndt, 2012). In South America, positive El Niño-Southern Oscillation (ENSO) phases (i.e. El Niño) are characterised by increased precipitation anomalies and negative ENSO phases by reduced precipitation anomalies (Grimm *et al*., 2000). The influence of La Niña on precipitation is strongest during the spring and summer following the event. Moreover, the SACZ intensified during the late spring–early summer season (NDJ) of 2011/2012, as shown using NCEP

R1 data in Figure 1(a) (negative outgoing longwave radiation anomalies indicating increased cloudiness). An intensified SACZ favours subsidence and clear sky conditions over SESA, hindering precipitation and increasing incoming shortwave radiation. Therefore, the state of the SACZ leads to anomalously high temperatures and dry conditions (Figure 1b). The atmospheric dynamical conditions for these types of droughts are well understood and explain a significant fraction of the summer variability (Cerne and Vera, 2011). It is reasonable to expect events of this kind in the near future as La Niña events combined with an active SACZ are part of the local climatology (Cerne and Vera, 2011).

In Figure 2(a), we show a domain average time series of T2m for each storyline, with ECHAM_SN climatology and ERA5 reanalysis (Hersbach *et al*., 2020) for comparison. The temperatures between the three storylines evolve comparably but are clearly separated in magnitude, revealing a strong climate change signal. The factual temperatures do not exceed the ECHAM_SN (1981–2010) climatological 95th percentile, except for two instances in February. The plus2 storyline, however, peaks beyond the 95th percentile nearly every 6–12 days, which is about three times more often than the factual storylines. The November to February average temperature difference between counterfactual and factual is 1.0 degC; between factual and plus2, 1.4 degC and between counterfactual and plus2, 2.4 degC, which is in line with the mean global warming over land. There is strong intra-seasonal variability in the daily temperature signal (10- to 90-day period oscillations) with particularly strong and significant 10- to 15-day variability. Such variability has been found in various summer seasons that were dominated by an active SACZ (Cerne *et al*., 2007; Cerne and Vera, 2011).

In Figure 2(b), we show the domain average of daily total precipitation for the three storylines, climatology and ERA5 reanalysis. For daily and cumulative precipitation, the results match well with both ERA5 and GPCC, up until 10 January. Following that period, the timing of precipitation events remains well-simulated; however, there is some mismatching of peak precipitation volume. For this reason, there is an overestimation in cumulative precipitation starting in the second half of January and throughout February. Just like temperature, the precipitation events can be explained by the intra-seasonal variability, where Rossby wave activity forces pulses of diagonally aligned precipitation events (van der Wiel *et al*., 2015) controlling the wet and dry conditions over the SACZ and SESA regions, respectively (Nogués-Paegle and Mo, 1997). However, there is no apparent climate change signal between storylines as there is considerable overlap in total precipitation. In Figure 2(c), the cumulative precipitation of the different storylines, the climatological background and ERA5 reanalysis, confirms the lack of a climate change signal given the dynamic situation. It was a dry season in all storylines, with precipitation well below the climatological mean for December and January. In other words, the drought would have been there, with or without climate change.

The potential evapotranspiration (PET) according to Thornthwaite (1948), as shown in Figure 3, directly reflects the impact of increased temperatures between the storylines. Such increased temperatures cause a deficit in water vapour pressure, which in turn increases the PET. Higher PET values can be interpreted as a higher risk of drought, as the soil loses an increased amount of moisture to the atmosphere. In SESA, the PET peaks in January with values around 14cm for counterfactual, 15cm for factual and 17cm for plus2. Between factual and counterfactual, the largest difference of 1.2cm is in February. The largest difference between plus2 and factual, 2cm, and plus2 and counterfactual, 3cm, is in January. The highest difference in PET is thus found in the months with the largest PET values.

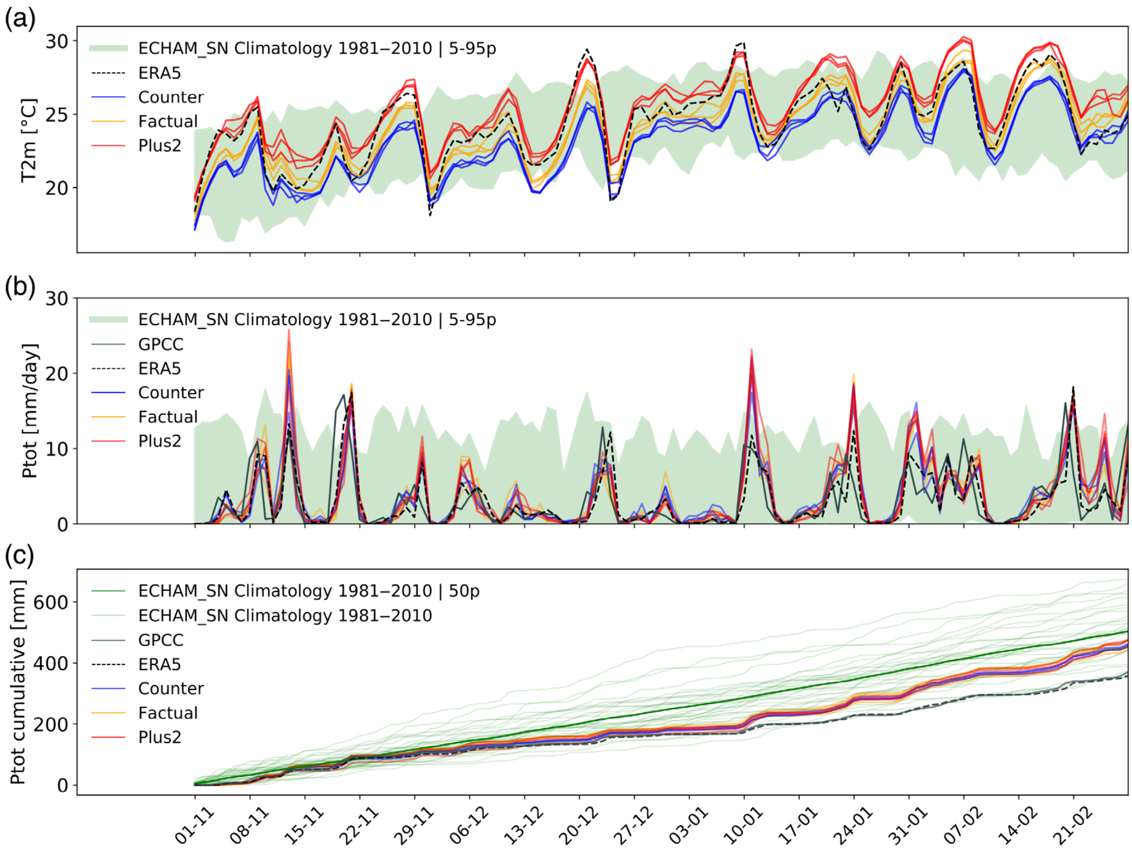

Figure 2. (a) Daily 2m temperature (T2m) averaged over SESA from November 2011 until February 2012 for counterfactual, factual and plus2 storylines, climatology 1981–2010 5th–95th percentile and ERA5 reanalysis (°C), (b) same as (a), but for daily total precipitation over SESA (mm day^{-1}), (c) daily cumulative total precipitation over SESA (mm) for counterfactual, factual and plus2 storylines, climatology is taken from yearly ECHAM_SN values from 1981 to 2010 (Schubert-Frisius et al., 2017). ERA5 reanalysis for comparison.

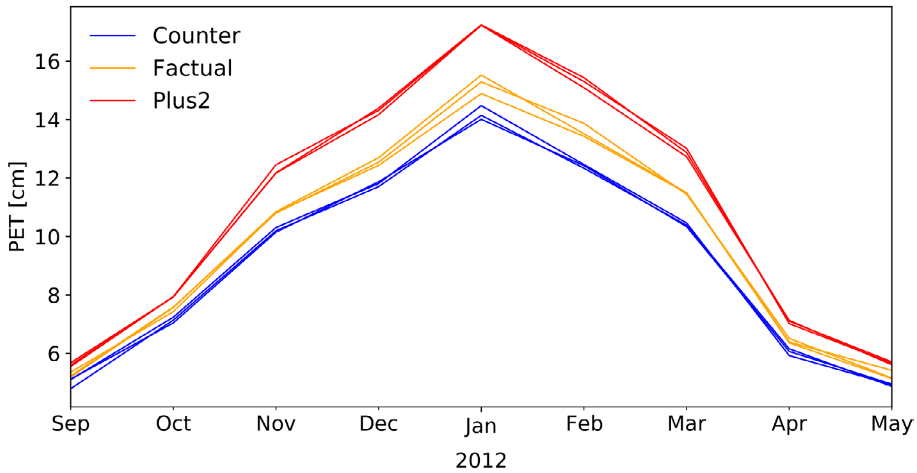

Figure 3. Monthly potential evapotranspiration (PET) (cm) over SESA according to Thornthwaite from September 2011 until April 2012.

In Figure 4, the half-monthly averaged water budget (WB) for the factual, factual minus counterfactual, plus2 minus factual and plus2 minus counterfactual, shows the difference of input (precipitation) minus output (evapotranspiration) between the storylines. Especially in January, there are pockets of robust signal (stippling), meaning a true split between the members of each world, for both reduced and increased WB. Nonetheless, in the WB, the effect of increased T2m and PET is not visible on a regional scale, as precipitation shows locally varying patterns. It is surprising that with increased temperatures and PET, in combination with an equal volume of precipitation, the WB is not showing a clearer drought severity change between the different storylines.

Dryness in SESA

To place the 2011/2012 SESA drought in a hydroclimatological context, we use the Budyko framework (Budyko, 1951). The Budyko framework provides physical insight on the climatological dryness or wetness of a specific region by evaluating both the atmospheric demand and water balance. The Budyko graph (Figure 5) could be interpreted as a hydrological supply-and-demand graph. The atmospheric water 'demand' on the *x*-axis is the Budyko aridity index ($\varphi = (R/\lambda)/P$, where R is net surface radiation, λ is latent heat of vaporisation (2.45×10^6 Jkg^{-1}) and P is precipitation). The water 'supply' on the y-axis is the balance between precipitation and evapotranspiration (E/P). E/P is limited to 1 (marked with a horizontal black line), as income (P) limits outflux (E). Above the supply limit, other sources of water such as surface and groundwater are evaporated.

In Figure 5, we present a Budyko graph that shows the hydrological state of SESA's climate for the counterfactual, factual and plus2 storylines. In the period between 2010 and 2014, SESA becomes slightly more humid in warmer storylines (round markers, average of three members, each 5 years). The plus2 storyline has increased wetness due to a decrease of E/P, meaning a larger water availability. Coincidently, there is a decrease in the aridity index, meaning the precipitation increase (i.e. plus2-counter 2010–2014 is 66mm) is larger than the change in atmospheric water demand (i.e. plus2-counter 2010–2014 is 52mm). This places the plus2 storyline left and below the counter and factual storylines (labelled with a grey arrow), as was also found by Zaninelli *et al.* (2019). The 2011/2012 hydrological year (June 2011–May 2012, average of three members, each 1 year) (squared markers) is to the right and above the reference years, indicating a drier year than the reference. Nevertheless, the change in this specific year and drought is in line with the mean increase towards wetness.

Discussion and conclusion

By using spectrally nudged storylines, we have conditionally attributed the climate change effect specific to the 2011/2012 summer drought in SESA, which had a devastating effect on corn and soybean production. We approached this event from an event attribution perspective and additionally included a climatological background analysis to place the event in climatological context. Understanding drought impacts in a region that exhibits a climatological wetting trend, like SESA, is relevant for decision-making and adaptation.

Conditional attribution allows for new insights in understanding the effect of climate change on thermodynamic aspects of extreme events. We therefore took the dynamic field as a given and set the dynamics to be the same for all storylines by nudging the large-scale vorticity and divergence in the free atmosphere. Our analysis is complementary to extreme event attribution, as fully understanding the climate change effect on this event would also require dynamical attribution. To address changes in drought due to altered circulation patterns, which influence drought frequency and duration, dynamical storylines could be added to the attribution toolbox. Dynamical storylines represent uncertainties related to dynamics and involve a better understanding of the remote physical drivers of regional circulation anomalies and their response to a warming climate (Mindlin *et al.*, 2020).

The total precipitation compares well to GPCC and ERA5 (regridded to T255), although peak precipitation volume tends to be slightly overestimated. This precipitation bias can be associated to the resolution being too crude to resolve convective precipitation correctly. Our storylines are simulated using ECHAM6_SN in T225L95 resolution. The 2011/2012 drought is connected to a large-scale pattern, namely the South American Convection Zone (SACZ), which is well resolved by the model. Smaller scale precipitation events, either in space or in time, would require a higher resolution model. Our results are computed with one model only, a comparison with several other models would clarify the influence of model bias uncertainties on the results.

In our framework, we consider GHG and SST changes to create a storyline of a possible 2 degC warmer world and keep land use and aerosols unchanged. Note that there is an indirect aerosol influence alteration through the changed SSTs. Therefore, these results do not predict the future, and it should be taken into account that land use and landscape changes such as deforestation can have a significant effect on the hydroclimate. Our storylines could be expanded to consider these factors. Even so, our results do give an insight on how thermodynamic aspects of a past event may be influenced by a possible future world. In addition, applying our method to longer droughts, outside our present simulation time frame, is needed to fully understand the balance between drought extremes and the climatological wetting.

Throughout our study, we have considered temperature, evapotranspiration (PET) and precipitation as the main contributors to drought. For temperature, the counterfactual, factual and plus2 storylines show a climate change induced warming in line with the mean global warming over land. The temperature peaks, passing the 95th percentile, are more frequent in the plus2 storyline, compared to counter and factual. The impact and frequency of heatwaves can thus be expected to increase with a plus2 degree warming in seasons with similar dynamical conditions (e.g. active SACZ conditions). The Thornthwaite method

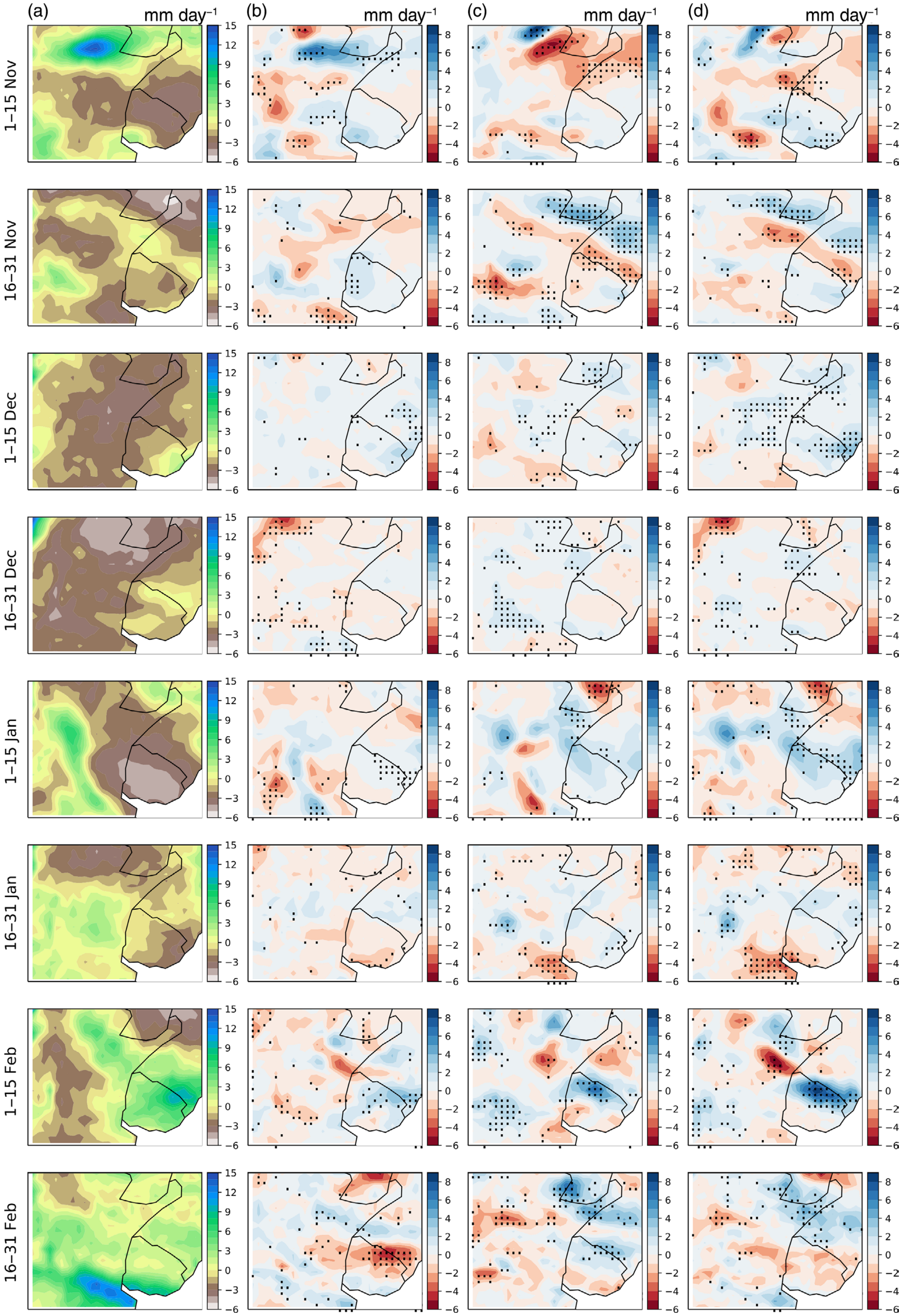

Figure 4. Half-month average WB (precipitation–evaporation) (mm day^{-1}) between November 2011 and February 2012 for ensemble member averages of (a) factual, (b) difference between factual and counterfactual, (c) difference between plus2 and factual and (d) difference between plus2 and counterfactual. Stippling shows robustness, meaning the three members of the first storylines are split by at least 0.1 mm day^{-1} from the three members of the second storyline.

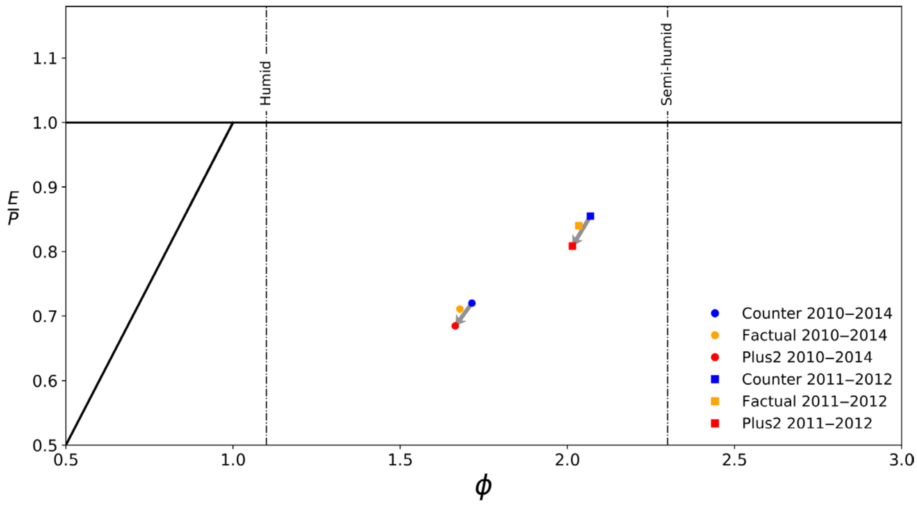

Figure 5. Budyko analysis over SESA for 2010–2014 (circles) averaged over the three members and the hydrological year of 2011/2012 (squares) averaged over the three members. Blue for counterfactual, yellow for factual and red for plus2. The Budyko aridity index (ϕ) is on the x-axis and evapotranspiration divided by total precipitation (E/P) on the y-axis. Grey arrows show the direction from the counterfactual towards the plus2 storyline.

for calculating PET is temperature-based and may have a non-linear temperature forcing bias when used in the light of climate change induced warming (Shaw and Riha, 2011). That said, PET is clearly higher in the factual and plus2 storylines, compared to counterfactual. However, we do not see differences in daily average nor cumulative precipitation between the storylines. Consequently, higher temperature and PET with equal amounts of precipitation place the region at a higher risk of drought. Be that as it may, we found no large-scale decrease or increase in the half-monthly WBs: the drought is not stronger in climate change impacted storylines.

These apparently contradictory results can be explained by taking into account the climatological hydrological background. We found that the general climate change induced trend in SESA is wetting. In the 2011/2012 hydrological year, storylines with increased climate change signal show increased precipitation volume before and after the drought. When considering both the atmospheric water demand and the water balance, we see that the precipitation increase is large enough to outweigh the increased evapotranspiration and PET during the drought. Hence, the wetting background counters the increased temperature and PET, reducing the potential impact on agriculture. Whether the effect of climate change on drought extremes would bypass the wetting background under a different level of warming remains unclear.

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The Bristol CMIP6 Data Hackathon

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The Bristol CMIP6 Data Hackathon (BCD Hackathon; Figure 1) formed part of the Met Office Climate Data Challenge Hackathon series during 2021 (Climate Data Challenge Hackathon series, 2021), bringing together around 100 UK early career researchers (ECRs) from a wide range of environmental disciplines. The purpose was to interrogate the under-utilised climate model intercomparison project datasets to develop new research ideas and create new networks and outreach opportunities in the lead up to COP26. Experts in different science fields, supported by a core team of scientists and data specialists at Bristol, had the unique opportunity to explore together interdisciplinary environmental topics summarised in this article.

The BCD Hackathon was set up noting that data from the most advanced climate model intercomparison projection (CMIP6) was significantly under-utilised. Academics from Met Office Academic Partnership (MOAP) universities were asked to develop a research question that could employ CMIP6 data, even if they had never used that data before, with the advanced data science methods being facilitated by a core team of scientists at the University of Bristol. Centralising CMIP6 expertise meant academics from different fields could pose climate change questions that they normally would not have been able to. An overview of the BCD Hackathon projects is described below, and a companion paper (Thomas *et al*., 2022) gives a full description of how to run a data hackathon, including software and code examples.

Project 1 focused on sea level rise (SLR), one of the more certain consequences of global warming. However, predicting the amount of future SLR is complicated because

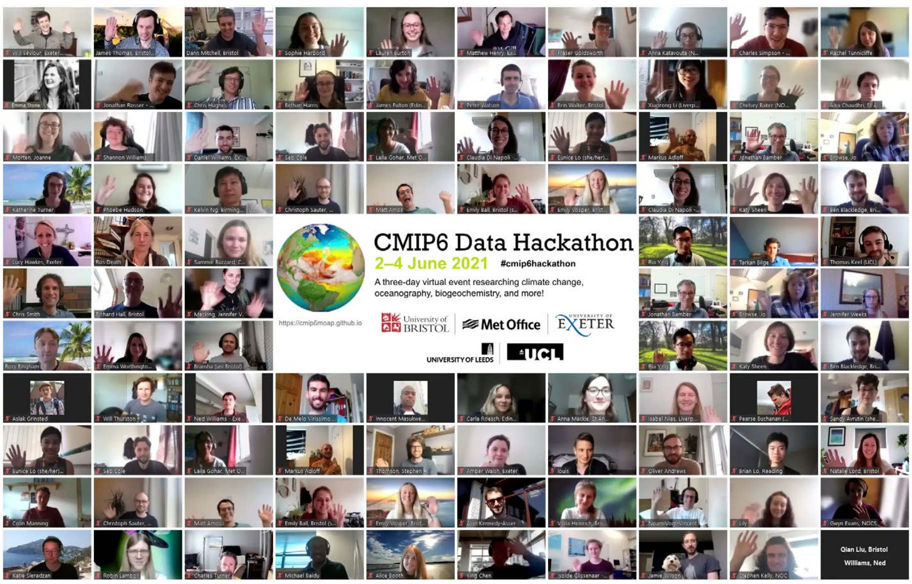

Figure 1. Group photo of the CMIP6 Data Hackathon Participants that took place virtually from 2 to 4 June 2021.