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Climate Services 34 (2024) 100480

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

Original research article

Assessment of plausible changes in Climatic Impact-Drivers relevant for the viticulture sector: A storyline approach with a climate service perspective

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ARTICLE INFO

Keywords:
Climatic impact-drivers
Viticulture
Storylines
Model uncertainty

ABSTRACT

Under the pressing warming of climate, interpretable and useful-for-adaptation information has become a need in society and has promoted rapid methodological advances in climate science. One such advance is the development of the dynamical-storyline approach, with which the spread in multi-model scenario projections can be represented as a set of physically plausible scenarios (storylines) defined by (a) a global warming level and (b) changes in large-scale dynamical conditions that arise from climate forcing. Moreover, if changes in regional climate are assessed in such a way that they can clearly inform societal systems or management of natural ecosystems, they can potentially aid decision-making in a practical manner. Such is the aim of the climatic impact-driver (CID) framework, proposed in the Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change. Here, we combine the dynamical-storyline approach with the CID framework and apply them to climate services. We focus on CIDs associated with the viticulture sector and the region of the South American Andes, where currently both Argentina and Chile produce wine. We explain the benefits of this approach from a communication and adaptation perspective. In particular, we found that the CIDs related to seasonally aggregated temperatures are mainly dependent on the global warming level although in some regions, but they can also be sensitive to changes in dynamical conditions. Meanwhile, CIDs related to extreme temperature values and precipitation depend strongly on the dynamical response. We show how adaptation to climate-related compound risks can be informed by a storyline approach, given that they can address compound uncertainty in multiple locations, variables and seasons.

Practical implications.

Chile and Argentina are two relevant wine-producing countries worldwide, positioned in the 6th and 7th place in the ranking of 2021 (OIV, 2021). Global climate change is driving and has the potential to further drive changes in agricultural production (Hannah et al., 2013; Jones et al., 2005). In particular, grapevines are extremely sensitive to mean climatic conditions as well as climate variability (Santos et al., 2020). Despite its potential impact, research on how climate change can affect the wine sector in Argentina and Chile has not received much attention compared to other regions such as Australia, Europe or the United States (Webb et al., 2008; Lereboullet et al., 2013; Schultze & Sabbatini, 2019; Santos et al., 2020 and references therein).

Climate is not the only factor considered in the complex decision-making context of viticulturists, as it is subject to socio-economic factors such as changes in the market, competitors, labor and

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https://doi.org/10.1016/j.cliser.2024.100480
Received 21 February 2024; Received in revised form 20 April 2024; Accepted 28 April 2024
Available online 10 May 2024
2405-8807/

machinery availability, etc. (Resco et al., 2016; Vigo et al., 2021). However, decisions on the quality of the wine, phenology, incidence of pests and diseases, as well as phytosanitary treatments that the grapevine receives will be affected by changes in climate (Cabré & Nuñez, 2020; Mihailescu & Bruno Soares, 2020; Grander et al., 2021), and therefore the sector's decision-making and practices require climate information for adaptation. In addition, climate information can support the identification of new areas with suitable climatic conditions to meet production and quality goals in the next decade, as well as the selection of grape varieties and rootstocks for planting that could match the expected climate (Dell'Aquila et al., 2023; Terrado et al., 2023 and citations therein). Moreover, information about future climatic conditions will be useful for wineries in their strategies to transition to new wine styles that will emerge under changing climate conditions (Schultz & Jones, 2010; Fraga et al., 2012).

Although the viticulture sector is already used to dealing with large uncertainties, climate change has put farmers' adaptive capacities at stake. In this context, climate services can be a useful tool to identify windows of opportunity to inform adaptation actions. Adaptation planning can be supported in the face of multiple future outcomes by means of a storyline approach, which provides a limited number of plausible futures relevant for viticulturists. In this article, we show how storylines also offer a way of assessing correlated risks, which can be relevant for growers with a portfolio of vineyard assets, and who are thus interested in changes affecting different locations. The concept of correlated agricultural risk has been addressed in the year-to-year variability; for example, ENSO teleconnections can affect crop production in several sites during the same season (Anderson et al., 2018). The same can occur with long-term changes, where one plausible outcome of climate change can be dramatic for two regions but beneficial for another, and vice-versa.

The work that has been published to date dedicated to climate change impacts in wine production in South America shows that there may be potential changes that will require adaptation, as well as promising opportunities to expand the viticulture region farther south. However, this work has been produced without assessing the regional uncertainty related to global climate model uncertainty, which the latest IPCC assessment report has identified as one of the most important sources of uncertainty at the regional scale (Doblas-Reyes et al., 2021). With this article we adapt the storyline approach to provide climate services for the viticulture sector in a manner that takes model uncertainty into account and communicates it in a comprehensible way. In particular, we show how in the near future climate change can be beneficial for wine production in the south of Argentina and Chile. In particular, we find that some regions could transition from one Winkler zone to the next or even transition from Winkler zone II to zone IV. Changes in precipitation in the study region are projected to be small. All of this information could be useful information for decision-makers who are planning to invest in the production of wine in the near term.

Introduction

Storyline approach

Under the pressing warming of climate, the need for interpretable and relevant information for adaptation has promoted rapid methodological advances in climate science. Interpretable climate information must be able to deliver a clear representation of the uncertainty in climate projections, such as probabilistic forecasts do. When presenting climate change projections, there are three sources of uncertainty that have to be reported together, namely: (1) the unknown anthropogenic and natural external forcings in the future, the former of socio-political nature and the latter largely unknowable; (2) incomplete knowledge on how the climate system will respond to the external forcings (also known as model uncertainty), of epistemic nature; and (3) the internal or unforced natural climate variability, which is not only involved in daily to seasonal timescales but also in decadal to multi-decadal timescales, of aleatoric nature.

Until the IPCC AR6 report (IPCC, 2023), however, the mainstream way of producing regional climate information was either by studying regional changes with one regional model nested in a global climate model and running experiments with one or more emission scenarios, or using an ensemble of global climate models. Many works opted for using regional climate models nested in global climate models but have mainly focused on model performance and independence for the global climate model selection, neglecting the representation of the spread in the climate change signal (Di Virgilio et al., 2022). Recently, new methods have gained popularity because of the way that they are able to represent scenario, model and internal variability uncertainty. One of these methods has been used under the name of the "dynamical-storyline" approach, which consists in representing the spread in multi-model scenario projections with a set of physically plausible scenarios (called storylines) defined by (a) a global warming level and (b) particular dynamical conditions based on the responses of large-scale climate phenomena to climate forcing (Shepherd, 2019). This approach is grounded in the fact that regional climate change is affected by uncertainty in large-scale circulation (Shepherd, 2014), and the assessment of one global climate model is not enough to produce an accurate representation of the uncertainty that cascades from the global to the regional scale. Large-scale uncertainty is associated with the limitations that state-of-the-art models have, which do not agree in the response of fundamental features such as the displacements of the jet streams, the response of the Intertropical Convergence Zone, and sea surface temperature warming patterns, among others. These large-scale uncertainties act as remote drivers of uncertainty at the regional level (Doblas-Reyes et al., 2021). Moreover, reporting changes for future time horizons under two or three emission scenarios has no interpretable physical meaning, due to model uncertainty in climate sensitivity. The uncertainty in climate sensitivity is compounded with emission scenario uncertainty in traditional approaches, whereas in a storyline approach, the changes are reported as physically plausible changes per degree of warming (Tebaldi & Arblaster, 2014). This move links the uncertainty in climate sensitivity to the emissions pathways consistent with a given global warming level. Dynamical storylines are further grounded in previous knowledge on how the large-scale atmospheric circulation can condition regional climate change. The qualitatively different changes in large-scale atmospheric circulation, that represent the spread in the model responses, can explain qualitatively different regional changes (Zappa & Shepherd, 2017; Mindlin et al., 2020).

So far and to our knowledge, these methods have only been applied to study physical climate variables such as regional winds and precipitation or large-scale atmospheric circulation. While a better understanding of such variables is deemed necessary, reporting changes in the climate system studied from the perspective of physical climate science only is not enough for climate information to be actionable (Ruane et al., 2022; Baulenas et al., 2023). If the changes in the regional climate are assessed in relation to their effects either on societal systems or natural ecosystems, they can potentially inform decision- and policy-makers in a more meaningful way. This resonates with the climatic impact-driver (CID) framework in the IPCC's AR6. This framework builds on years of refinement in climate services approaches and can help bridge the gap between physical climate science approaches and climate services (Ranasinghe et al., 2021). CIDs are defined as "physical climate system conditions (e.g., means, events, and extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions" (Ruane et al., 2022p. 1).

In this work we aim to show how the dynamical-storyline approach can be applied to research questions that are relevant for the climate services community, using a case study from the viticulture sector. The work is shown in a stepwise manner, explaining the steps that are needed to adapt knowledge from the field of atmospheric circulation dynamics to the very applied framework of CIDs.

Climate change projections and viticulture

Globally, changes in temperatures are expected to have an effect on wine production, given that some regions will become too warm to continue producing wine at all, or some varietals in particular (Jones et al., 2005). The length of the growing season, to which variety is also dependent, is expected to change as well as the onset of the growing season itself, given that warmer temperatures lead to earlier bud bursts (Dinu et al., 2021), and earlier bud bursts might lead to an overlap of the frost season with the growing period (Schultze & Sabbatini, 2022). The number of growing degree days and therefore the speed of the growing phenological phase can affect the wine quality, given that the ripening conditions and the time to accumulate sugars will affect the final harvest (Mullins et al., 1992; L. B. Webb et al., 2008). At the same time, changes in precipitation during spring can affect vineyard vulnerability to pests, water supply from rainfall and access to water for irrigation. Recently, Verdugo-Vásquez et al. (2023) showed that some valleys in Chile have already changed from what are characterized as cool to intermediate regions and from intermediate to warm regions. For example, the Valle del Elqui changed from intermediate to warm and Valle del Bío Bío changed from cool to warm. No such study has been produced for Argentina.

Research on how future climate change can affect the wine sector in Argentina and Chile has not received much attention compared to other regions. However, the work that has been done has led to the conclusion that there could be favorable conditions for wine production in the region in response to climate change. Rössler & Barbero (2008) first proposed that there could be beneficial changes in regional climate in Argentina which could lead to the appearance of new wine regions at high latitudes. In another study, Cabré et al. (2014) used the MM5 regional climate model nested in the Hadley Centre global climate model to show the plausibility of displacements of areas suitable for grapevine production under the SRES A2 climate change scenario. This was done using viticultural zoning indices. Additionally, Cabré & Nuñez (2020) used the IPSL-CM5A-MR model under the emissions scenarios RCP4.5 and RCP8.5 and found that favorable conditions for winegrowing might arise in new regions in Argentina both for the near and far future. However, they point out that adjusting the production to these beneficial conditions will require climate-intelligent adaptation plans.

Previous works on regional climate changes relevant for viticulture in Argentina and Chile have thus shown promising results. However, these studies have been produced using either a single model (Cabré et al., 2014; Cabré & Nuñez, 2020) or multi-model ensemble means, treating the ensemble probabilistically (Hannah et al., 2013; Nesbitt et al., 2022). As mentioned in the previous section, this has been the mainstream way of working with regional uncertainty for the last few decades. In this work, we want to (1) understand how different sources of uncertainty affect the results when working with CIDs based on temperature and precipitation changes, (2) show the benefits of using a storyline approach to work with climate change projections as opposed to the mainstream methods from a climate services perspective, (3) contribute to previous work that assessed climate changes and its impacts on the viticulture sector in Chile and Argentina by addressing correlated risks (or benefits) with a small set of storylines, and (4) expand the ways in which regional adaptation plans can be designed.

The remainder of the article is organized as follows: Section 3.1 introduces the study domain, Section 3.2 explains how the storyline approach was adapted for a climate services study and Section 3.3 introduces the CIDs used. Section 3.4 presents the data used for the study, followed by Section 3.5 where the limitations of GCMs are acknowledged and the applied bias adjustments are explained. Section 3.6 explains how the large-scale remote drivers are defined and how they are linked to regional climate change and Section 3.7 explains the calculations performed to apply the storyline approach. Section 4.1 introduces the extreme storylines identified, while Sections 4.2 and 4.3 analyse the thermal and "hydro" CID changes and their uncertainty. Section 5 focuses on explaining what the benefits of this approach can be from a communication and adaptation perspective, and what are the fundamental gains with respect to traditional approaches where uncertainty is represented and communicated as a spread around a multi-model ensemble mean response. Section 6 gives a short overview and conclusions.

Materials and methods

Study domain

The study domain is the western south of South America (25S-47S, 75 W-65 W). Fig. 1 shows the domain, the topography and a number of selected locations. The domain comprises Cuyo, Patagonia and the northwest of Argentina. Eight wine producing valleys were selected to focus on the local changes in different latitudes and on one side and the other of the Andes. The locations and grape varieties are summarised in Table 1.

Tailoring storylines to a climate services case study

The storyline approach has been shown to be useful to represent model uncertainty in the Southern Hemisphere (Mindlin et al., 2020). However, in the cited study the approach was applied to develop storylines of large-scale circulation and precipitation changes without a focus on local impacts. The question was framed from a physical climate perspective following a top-down approach and served to show how propagating the uncertainty in remote drivers' response to climate change (i.e., upper-tropospheric tropical warming and stratospheric polar vortex changes) to surface variables could help explain the spread in regional climate. That approach led to a particular selection of the aggregating months, motivated by large-scale circulation dynamics rather than surface climate conditions of interest for a particular sector or user. Combining the dynamical-storyline approach with a specific climate services question requires a compromise between finding physically plausible storylines from a dynamical perspective and addressing changes in the relevant variables and timing. Fig. 2 illustrates the framework, and how it links the sources of climate change uncertainty to the sector's variables of interest. Global warming affects both large-scale drivers of the climate system and mean warming conditions at the regional scale. The changes in circulation can affect moisture fluxes into land, precipitation and even temperature variability, which combined with regional warming affect regional climate. A set of CIDs can be used to study sector-relevant regional climate changes. In order to apply this framework, we started by selecting a subset of the relevant CIDs for the viticulture sector based on prior analysis of the literature.

CIDs

Based on a literature review designed to identify CIDs relevant for this specific service (Ruane et al., 2022), we selected eight bioclimatic indices as CIDs, which are listed below. These indices have been developed and widely used in the literature focused on providing climate information for the viticulture sector. The growing season for grapes in the Southern Hemisphere (SH) goes from October to April.

CID definitions

Mean growing season temperature (GST, Hall & Jones 2009): Mean temperature in October-November (ON), December-February (DJF), and March-April (MA) separately. This CID can represent a first-order viticulture suitability range (traditionally, between 12 and 22 °C).

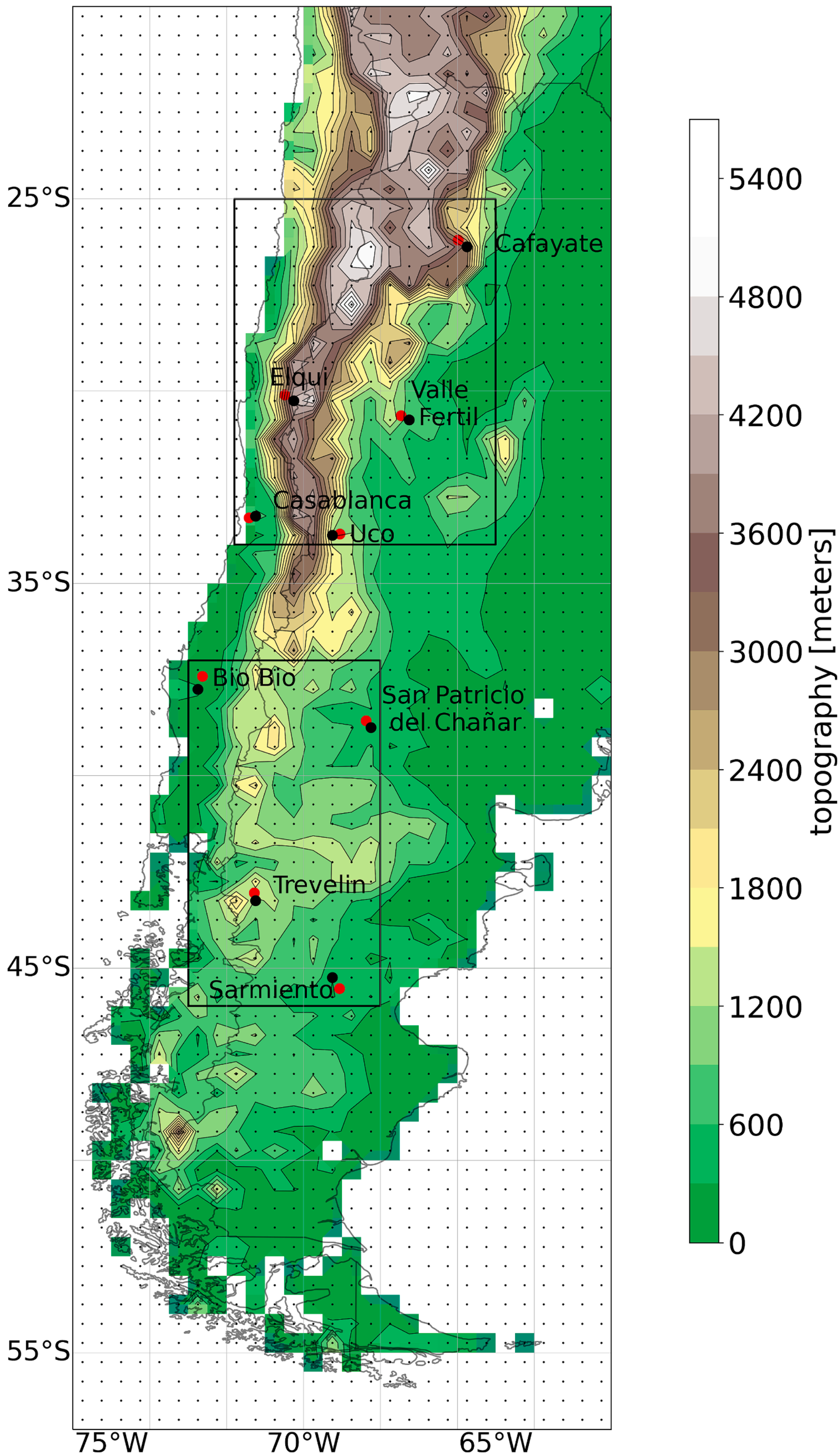

Fig. 1. Study region and spatial distribution of vineyard locations. The red dots indicate the vineyard location and the black dots indicate the nearest data gridpoint. The reference grid is that of CRU TS v.4.06. Color shading shows topography. The two black squares comprise the northern and southern sectors of the study region, which we found are affected differently by large-scale circulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Wine producing valleys and study sites for this work. Valley latitude and longitude and nearest grid point in reticulated data (in italics). Principal grape varieties produced in each valley: italic font indicates late ripening, bold font indicates early ripening and non-stylized font indicates mid-season ripening. The Winkler region and mean growing degree days (GDD) of each valley/region are shown for reference.

	lat	lon	Wine varieties	Mean altitude [m]	Winkler Region	Mean GDD
Cafayate	−26.07 *−26.3*	−65.98 *−65.75*	Malbec, *Cabernet Sauvignon*, Tannat, Torrontés, *Merlot*	1550-2020	V	2483
Valle del Elqui	−30.1 *−30.3*	−70.49 *−70.3*	*Cabernet Sauvignon*, *Merlot*, Carménère, Syrah, **Chardonnay**, Zinfandel	1000-1200	III	1840
Valle Fértil	−30.63 *−30.8*	−67.46 *−67.3*	Malbec, *Cabernet Sauvignon*, Syrah, Tannat, Torrontes	750-900	IV	2200
Casablanca	−33.3 *−33.3*	−71.42 *−71.3*	*Merlot,* Syrah, **Sauvignon Blanc**, **Chardonnay**	290	I	1376
Valle de Uco	−33.72 *−33.8*	−69.06 *−69.3*	Malbec, Caladoc, *Garnacha*, *Cabernet Sauvignon*, **Pinot Noir**, **Chardonnay**, **Sauvignon Blanc**	860-1620	III	1800
Valle del Bío Bío	−37.41 *−37.8*	−72.63 *−72.8*	**Chardonnay**, **Pinot Noir**	200	I	1282
San Patricio del Chañar	−38.57 *−38.8*	−68.37 *−68.3*	*Cabernet Sauvignon*, Malbec, *Merlot*, **Pinot Noir**, Syrah, **Sauvignon Blanc**, **Chardonnay**, **Semillón**, *Viognier*	260	IV	2000
Sarmiento	−45.53 *−45.3*	−69.07 *−69.3*	**Pinot Noir**, *Merlot*, **Chardonnay**, Malbec, **Gewürztraminer**, **Pinot Gris**	250-280	I	1188
Trevelin	−43.05 *−43.3*	−71.28 *−71.3*	**Pinot Noir**, **Chardonnay**, **Gewürztraminer**	200-270	I	865

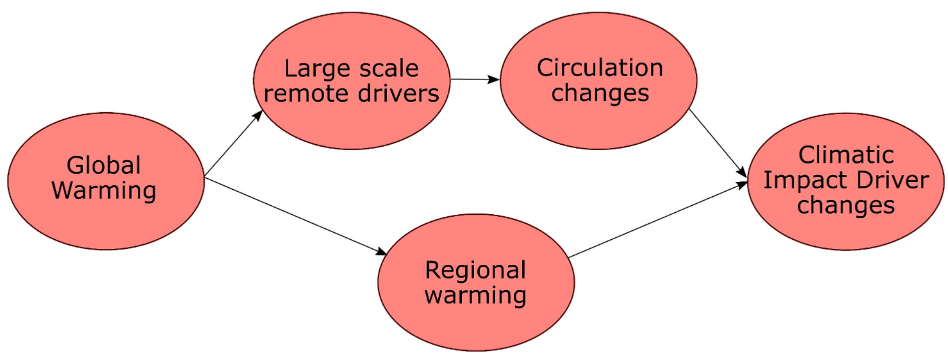

Fig. 2. Causal network representing the sources of uncertainty that influence the viticulture-relevant CIDs and their responses to anthropogenic forcing. Global warming leads to amplified warming in the tropics, strengthening of hemispheric winds and asymmetric sea surface temperature warming among other elements of large-scale remote drivers. Changes in these large-scale remote drivers lead to circulation changes that, combined with the regional thermal response to global warming, determine the CID responses. In this study the two sources of uncertainty, dynamical and thermodynamical, represented in the two arrows leading to the "Climatic Impact-Driver changes" ellipse, are studied jointly. This provides a tool to understand and communicate the degree to which circulation changes can explain part of the uncertainty in CID changes.

Maximum growing season temperature (maxGST): Daily maximum temperature in DJF, which is summer in the SH. This CID can pose a suitability limit, given that under very high temperatures, above 35 °C (photosynthesis limit), the quality of the berry can be affected and it is also associated with a higher water demand.

Growing degree days (GDDs, Winkler et al., 1974): Temperature in degrees over 10 °C accumulated during the growing season, evaluated for ON, DJF and MA separately. This CID can be used to identify suitability changes and opportunities to grow different varieties. In addition, large changes in GDDs can affect the phenological cycle of the plant.

Winter severity (WS, Winkler et al., 1974): Daily minimum temperature during the coldest month (July) in the dormant season (JJA). This CID can pose a suitability limit, given that if this index is below −25 °C conditions are lethal for the plants. In addition, if it is below −12 °C, the productivity is affected. Normally, a temperature below −15 °C is classified as unsuitable.

In the SH, the three main phenological stages occur in spring (September-October, bud-break), summer (November-December, flowering) and autumn (January-April, *véraison* and harvest). Water stress or excess water in particular moments of the grapevine cycle can affect the grape and wine quality in different ways. Therefore, not only the accumulated precipitation during the growing season is relevant but also how precipitation is distributed (Prichard and Verdegaal, 2001; Cabré & Nuñez, 2020). This is of particular interest for our study, as we want to address how large-scale circulation can affect viticulture-related activities, and the effect of circulation can be different across seasons. Although water stress can be handled with irrigation (Pérez-Álvarez et al., 2021), disease impacts can also be affected by precipitation changes and require adaptation (Bois et al., 2017).

Spring precipitation anomaly (Bois et al., 2017): Change in the mean precipitation amount in October-November. Humid conditions combined with warm temperatures during spring can increase the risks of pests and diseases and affect bud-break.

Harvest season precipitation anomaly (Bois et al., 2017): Change in mean precipitation amount in March-April. Large precipitation during this season can impact the phenology, *véraison* or berry maturation and the harvest labor itself.

Summer precipitation anomaly (Cabré et al., 2014; Bois et al., 2017; Solman et al., 2018)*:* Change in mean precipitation amount in December-February. Large anomalies can impact the flowering phenological phase.

Accumulated growing season precipitation (GSP) (Bois et al., 2017)*:* Accumulated precipitation in October-April. Large precipitation amounts can impact the phenology and the berry maturation. Suitable regions receive less than 700 mm during the growing season. Among those regions, if the accumulated precipitation is less than 250 mm/growing season the region is considered dry; sub-humid regions are those with 250–500 mm/growing season and humid regions receive more than 500 mm/growing season. Although irrigation can overcome limitations related to water scarcity, excessive humidity can also restrict suitability for growth of the vines.

The most recent literature also addresses CIDs related to cold and warm spells, heatwaves and frost. Given that the aim of this study is to evaluate the usefulness of storylines to provide climate services, which involves connecting CIDs with large scale circulation changes, we only considered well established CIDs based on seasonally aggregated variables. The exploration of changes in extreme event frequency and intensity under climate projections has not been studied yet by means of a storyline approach.

Coupled Model Intercomparison Project and observational data

We used historical climate simulations and climate projections under the SSP5-8.5 emissions scenario from the 6th phase of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016) to evaluate climatic changes in the future. This scenario was used in order to capture the strongest physical response to forcings, under the premise that the circulation storylines will be the same under any transient scenario (Zappa & Shepherd, 2017). This premise is anchored in the fact that patterns that scale with global warming (as those studied here) also scale linearly with the amount of GHG forcing, regardless of the forcing's rate of change unless the scenario stabilizes. The models used were: ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CAMS-CSM1-0, CanESM5, CESM2, CESM2-WACCM, CMCC-CM2-SR5, CMCC-ESM2, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, FGOALS-g3, HadGEM3-GC31-LL, HadGEM3-GC31-MM, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KACE-1–0-G, MIROC6, MIROC-ES2L, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM, NorESM2-MM, TaiESM1, UKESM1-0-LL. All of these models have a good representation of the main features of South American climate, and furthermore, no bias in the observed climate has yet been shown to be significantly correlated with future changes (Almazroui et al., 2021). They also show a good representation of observed trends over central South America (Rivera & Arnould, 2020). Nevertheless, all GCMs have problems representing the climate in areas of pronounced topography like the Andes. This is further discussed in Section 3.5. Temperature data from the CRU TS v4 dataset (Harris et al., 2020) and precipitation data from the GPCP v2.3 dataset (Huffman et al., 2009) were used to evaluate the observed changes.

We analyzed monthly fields of temperature (ta) at 200 hPa, zonal wind (ua) at 850 hPa and sea surface temperatures (tos, hereafter SSTs) to evaluate the changes in the selected remote drivers of large-scale circulation changes. To evaluate the selected bioclimatic indices (the CIDs relevant to this case study) we analyzed monthly fields of precipitation (pr) and daily surface temperature fields (tas).

We evaluated climatologies for three periods: a reference period (1950–1979), a present period (1989–2018) and a future period (2070–2099). The CID responses were evaluated by taking the difference between the CID values in the future and the reference periods. As mentioned before, to separate the uncertainty in the global warming level from the circulation uncertainty in the storyline approach, pattern scaling was applied to every target field, in this case to each of the CID responses (Tebaldi & Arblaster, 2014). Although this is in principle an assumption, if it failed badly we would be able to detect it, given that the individual model responses would not be reproducible with the linear model. The pattern sensitivity to the large-scale remote drivers was evaluated with a multiple linear regression (see Mindlin et al., 2020 for method details). Finally, the observed change was evaluated as the difference between the present period and the reference period. Natural climate variability was estimated based on the standard deviation of interannual variability in the detrended present period. Detrending was done with a simple linear regression with time as the independent variable.

Limitations of global climate models (GCMs) and bias adjustment

Global climate models (GCMs) are not suited for the production of regional information or specific climate services and therefore their use for such purposes can lead to uncertainty propagation, even if bias adjustments are applied to the data (Prudhomme et al., 2010; Maraun & Widmann, 2018). This is especially the case for the region selected in this study, which is located over the southern Andes. The Andes produce a huge disturbance of the atmospheric circulation over South America and over and leeward of the mountain range the models struggle with its representation (Gultepe et al., 2014; Pabón-Caicedo et al., 2020). This makes the Andes a particular challenge for global models. Significant biases in both precipitation and temperature are found in this region, and they are difficult to work with, given the lack of observational datasets and deficient gridded datasets (Solman et al., 2013) needed for a robust bias correction. Moreover, working with a GCM ensemble in this region is complex, since the representation of the mountains differs between models and the temperature extremes in coarse and fine grid models can greatly differ (Tovar et al., 2022). However, GCMs remain the main tool for projecting future climate and regardless of all the misrepresentation of local processes, regional climate change will always be conditioned by large-scale circulation changes –- which can only be addressed with GCMs. This is why in this work, we do not provide a final information product for users. Instead, our aim is rather to illustrate the uncertainty range that can be addressed with a dynamical-storyline approach and the benefits that it can provide from a communication and adaptation perspective. Potentially, the impact-relevant dynamical-storylines identified with this approach could be used to select the optimal set of GCMs to be downscaled with a Regional Climate Model (RCM) or a statistical approach.

A subset of our CIDs are based on threshold values of accumulated temperature, for which the values show great dependence on the reference climatology. The climatology differences among models is large among models with different grids, especially in regions of complex topology. We therefore applied a first-order bias correction to the temperature simulations and appropriate regridding of the model output (Maraun & Widmann, 2018; Di Luca et al., 2020). Given that the CIDs based on precipitation only involve climatological differences in anomalies and no fixed thresholds, and the gridded datasets available are not reliable, we did not apply any bias correction to the precipitation model output. For temperature, the bias correction was based on the "delta change" or "perturbation" method using the daily climatology of the gridded dataset CRU TS v.4.06 dataset. The most reliable dataset in the region would be the CLARIS LPB dataset (Penalba et al., 2014), but it does not fully cover the study region. CRU TS v.4.06 was selected instead, because it was found to better adjust to CLARIS LPB over the area covered by CLARIS LPB. For the "delta change" approach we evaluated the daily climatology using the period 1950–1979. Then, we evaluated the temperature anomalies for the whole historical and SSP5-8.5 simulation with respect to the reference period in the same model and regridded using conservative remapping to the grid of CRU TS v.4.06. Finally, the regridded anomalies were added to the reference climatology. This simple method guarantees a comparable temperature distribution in all models despite the different original resolutions, and we work with the hypothesis that this allows us to assess the forced response in the CIDs (Diaz-Nieto & Wilby, 2005). For precipitation, the model output was regridded to the grid of CRU TS v.4.06 using conservative remapping in order to have data in the same locations for the two variables.

Remote drivers of large-scale circulation change and regional impacts

To span the vine growing season in the SH we considered the dynamical changes in spring, summer, autumn and winter. Given that the large-scale circulation is projected to change differently in each of these seasons, the influence of each remote driver (RD) on the selected CID in each season was assessed separately. This is one of the main differences of the implementation of the storyline approach in this study with respect to most of the previous applications, as it analyses circulation changes that are relevant for the needs of the specific climate service.

To a large extent, the large-scale circulation change in the SH during this century is projected to be characterized by a strengthening and poleward shift of the eddy-driven jet. Mindlin et al. (2020) used CMIP5 models to show that two remote drivers, namely the warming of the tropical upper-troposphere (Tropical Warming, TW) and a delay in the late-spring polar vortex breakdown in the stratosphere (Vortex Breakdown delay, VB_{delay}), can explain the spread in modeled eddy-driven jet responses in DJF, and that TW and the change in the strength of the winter stratospheric polar vortex (SPV) can explain the modeled eddy-driven jet responses in JJA. This is also true for CMIP6, and in addition, zonally asymmetric warming patterns (Central Pacific (CP) and Eastern Pacific (EP) warmings) in the tropical Pacific can further explain the uncertainty in regional climate change in South America, given that these drive asymmetric circulation changes in the SH (Mindlin et al., 2023). In this study, we use the same remote drivers as in Mindlin et al. (2023) for DJF, namely TW, VB_{delay}, CP and EP, and the same drivers as in Mindlin et al. (2020) for JJA, namely TW and SPV. To evaluate the whole growing season, we also estimated the changes in ON and MA by using the same drivers as for DJF, except for VB_{delay}, which is only relevant for summer. To capture the changes in the stratosphere in ON and MA we used the same index used for JJA, namely SPV.

It is not the purpose of this article to describe in detail the circulation responses in ON and MA, which were not analysed in Mindlin et al. (2020) or Mindlin et al. (2023), and their links to regional climate. However, to confirm that the storylines can be interpreted as physically plausible responses of the climate system, we analysed the tropospheric circulation changes driven by the RDs for those bimesters, and confirmed that they are consistent with the dynamical responses that could be expected from previous literature (see supporting information).

Storyline approach

To deal with climate sensitivity uncertainty, we first applied pattern scaling to each of the CIDs (Tebaldi & Arblaster, 2014), which means scaling the CID response in each model (m) by the global warming level in that same model (ΔT_m). In a second step, to deal with large-scale circulation uncertainty, we evaluated the CID sensitivity to each large-

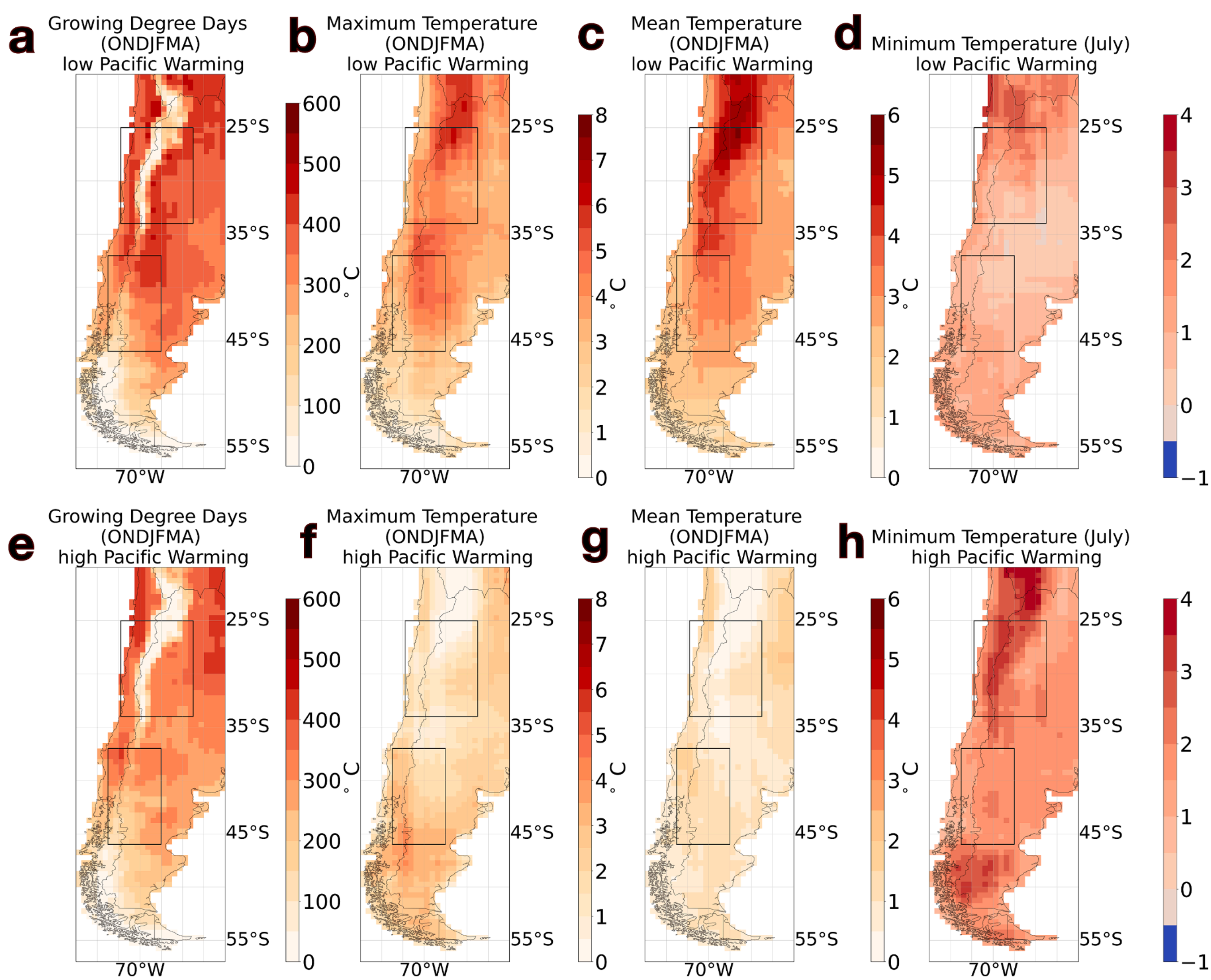

Fig. 3. Temperature-based CID responses under the low and high PW storylines (see Section 4.1 for storyline definition).

scale RD of change using a multiple linear regression (MLR) statistical model as in Mindlin et al. (2023):

$$\frac{\Delta CID_m}{\Delta T_m} = \beta_{x0} + \beta_{x1}\left(\frac{TW_m}{\Delta T_m}\right)' + \beta_{x2}\left(\frac{\Delta SPV_m}{\Delta T_m}\right)' + \beta_{x3}\left(\frac{CP_m}{\Delta T_m}\right)' + \beta_{x4}\left(\frac{EP_m}{\Delta T_m}\right)' + \epsilon_x$$

where the independent variables are the standardized (′) RD responses. This results in a regional map β_{xi} of CID sensitivity to each remote driver (i) at grid point (x), which represents the CID response to one standard deviation in the RD changes simulated in the CMIP6 ensemble and per degree of global warming. As explained above, for the summer season, the remote driver representing the change in the stratosphere is not ΔSPV but VB_{delay}. In the seasons where the remote driver indices are correlated, the sensitivities were also evaluated by controlling for the remaining RDs as for the winter season in Mindlin et al. (2020). These correlations can be addressed by evaluating the CID responses that would result from RD values that lie in some confidence region of the observed distribution, which takes the correlations into account (Fig. 3). Here we follow Zappa & Shepherd (2017) and evaluate the 80 % confidence region of the 4D ellipsoid that characterizes ON, DJF and MA and the 2D ellipse that characterizes JJA.

We evaluated all the physically plausible storylines within the model ensemble by sampling the distribution of RD responses (Fig. S3). Then, we selected a pool of the driest and wettest 1 % of these storylines in the two sectors of active vineyard locations (Fig. 1). Finally, we identified which RD combinations lead to the most extreme climate responses in the region (this approach is fully described in Mindlin et al. (2023)). With this approach, we were able to identify which remote driver responses lead to the most extreme storylines in terms of precipitation changes. The results are presented in terms of the two most extreme storylines mentioned above for a 2 °C global warming in Section 4 and per level of global warming in Section 5. Being able to express storylines associated with particular levels of warming and not a time horizon is what allows us to address climate sensitivity and scenario uncertainty separately. Similar approaches have referenced this as a scenario-neutral approach (Prudhomme et al., 2010).

Results

Selected extreme storylines based on precipitation changes

We evaluated the seasonal coherence between the RD responses in the four seasons and found that the tropical RD responses are coherent across the model ensemble by evaluating the RD index correlation across seasons (see supporting information). Although all models show correlation for TW, CP and EP changes across seasons, the response of the stratosphere shows more independence between seasons, meaning that a model with high SPV response in July does not necessarily project a late VB_{delay} in spring. This was taken into account to build physically plausible storylines and the high and low-impact storylines. Given that the spatial distribution of the precipitation and temperature sensitivity to RD signals are not homogeneous, we defined two regions to analyze the CIDs. The northern region comprises five vineyards: Cafayate, Valle del Elqui, Valle Fértil, Casablanca and Valle de Uco, and the southern region four vineyards: Valle del Bío bío, San Patricio del Chañar, Trevelin and Sarmiento (see boxes in Fig. 1).

We found that in both regions the combination of RD responses that lead to the largest changes in CIDs are the same. These are represented with a red and a blue dot in Figure S3. These storylines are characterized by a strengthened SPV/low TW/positive CP and EP indices (red) on the one hand and weakened SPV/high TW/negative CP and EP indices (blue) on the other hand. As mentioned above, the RD responses across seasons are not independent, hence we considered the combinations of RD responses that are plausible across seasons. This is why for the harvest season (MA), the RD response coherent with the spring and summer responses has inverted signs, namely, weak SPV is combined with low TW and a strong SPV combined with high TW. Considering a storyline with opposite signs for MA would have led to representing a more extreme regional climate response, but this is not a plausible response within the CMIP6 ensemble. We refer to the supporting information for details on how the calculation is done.

Figs. 3 and 4 show the temperature- and precipitation-based CID responses under these two extreme storylines. The global warming level in both storylines is 2 °C. Depending on the emissions scenario, this warming level can be reached by different time horizons. For simplicity we refer to the storyline with positive CP and EP indices as "high Pacific Warming (PW)" and the storyline with negative CP and EP indices as "low PW".

Thermal CID responses under extreme storylines

Growing degree days

Panels a and e in Fig. 3 show the spatial pattern for the changes in GDDs under the two storylines described in Section 4.1. According to the models' response, regardless of the large-scale circulation response, there will be an increase of more than 200 GDDs under 2 °C warming. However, under a low PW storyline GDDs can locally increase up to 500 GDDs, and on both sides of the Andes 400 GDD increases can be expected. In a high PW storyline, the projected increase in GDDs is not larger than 350 GDDs. This is interesting because it means that the long-term circulation change in the region can modulate the seasonally integrated temperature changes to a significant extent.

Maximum and mean growing season temperature

Panels b and f in Fig. 3 show the change in maximum temperature during the growing season under the two storylines described in Section 4.1, and panels c and g show the same but for the mean growing season temperature. According to the models' responses, the low PW storyline shows the largest maximum and mean temperature increase. The largest differences between storylines are seen where the topography is more prominent. These regions are the most difficult to model, and although there is higher confidence in the way that temperature is modeled compared to precipitation, temperature responses to climate change will be subject to precipitation changes due to the snow-albedo feedback (Pepin & Lundquist, 2008). This can be further explained by the concept of elevation-dependent warming (Pepin et al., 2022). The interplay between thermodynamics and dynamics in orographic regions can result in very specific horizontal temperature gradients, given that changes in the jet stream affect the lee cyclogenesis. This shows the large role of circulation in driving uncertainty at the regional scale. Meanwhile, the high PW storyline shows a small change in the maximum temperature, near 0 °C over the Andes and around 2 °C in the rest of the study region.

Regarding the impacts that this can have for viticulture, a 3 °C warming increase at the regional level can lead to zoning shifts. According to Hall and Jones (2009), regions can be separated into categories by the mean growing season temperature: cool (13 °C-15 °C), intermediate (17 °C-19 °C), hot (19 °C-21 °C) and very hot (21 °C-24 °C). According to the models' projections for a 2 °C global warming, under a low PW storyline, the east of Cuyo could potentially transition to very hot conditions, and Cafayate in Salta could be affected by a mean growing season warming of more than 4 °C, while in a high PW storyline we do not find the models responding with large changes.

Minimum temperature (or winter severity index)

Panels d and h in Fig. 3 show the minimum temperature response under the low PW storyline and the high PW storyline, respectively. During the dormant season this index is between 2 and 8 °C in areas with viticultural activity (Cabré and Nuñez, 2020). These results are consistent with those reported for these regions in previous work. In particular, Cabré and Nuñez (2020) showed that over San Juan, Catamarca and Salta the maximum increase in winter minimum temperature can locally reach values between 4 and 6 °C. The results are in agreement

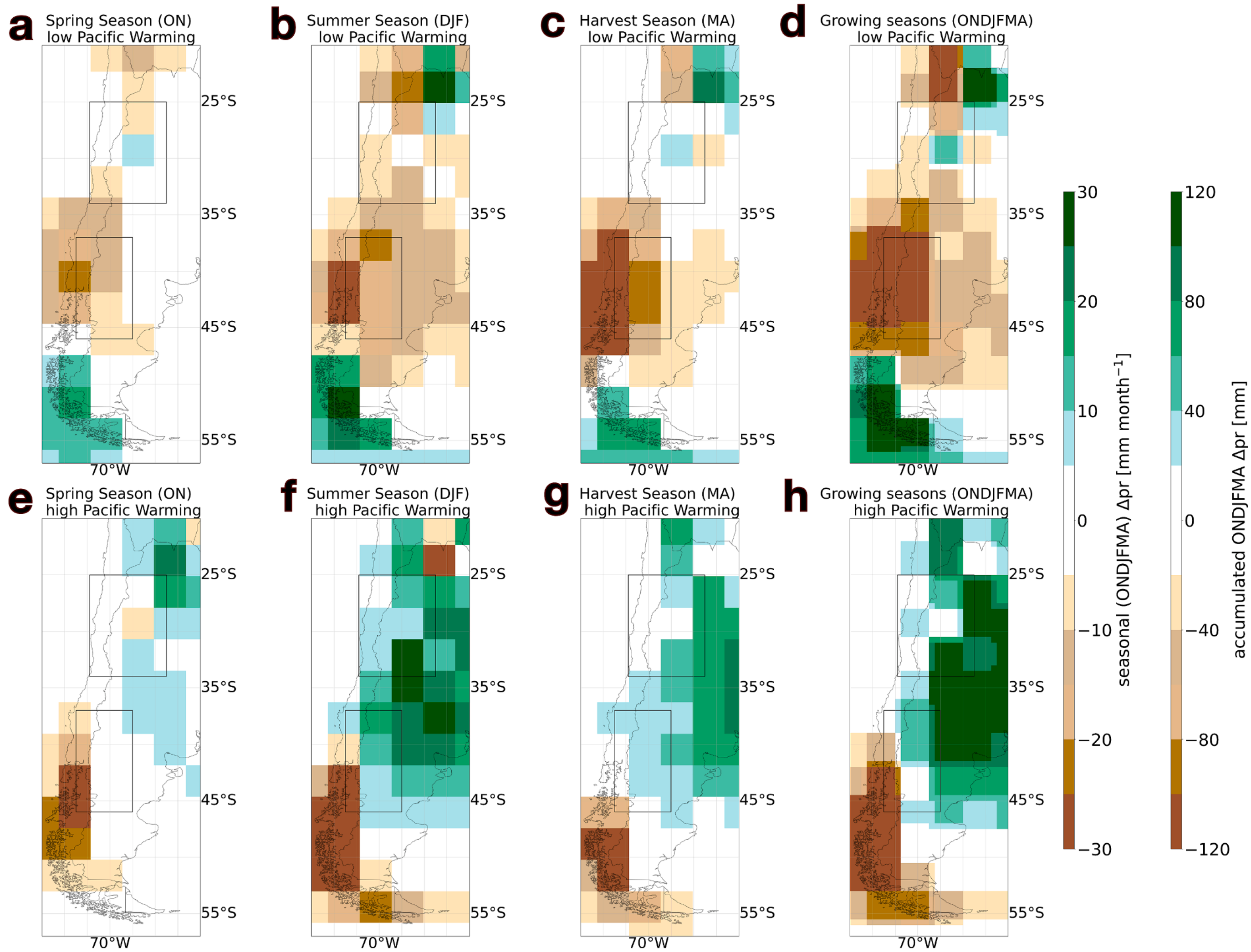

Fig. 4. "Hydro" CID responses across different seasons (spring, summer, harvest and growing seasons) under the low and high PW storylines (see Section 4.1 for storyline definition).

with other assessments of winter projections for equivalent emission scenarios which reported a global decrease in winter chill as a response to GHG forcing (Luedeling et al., 2011). When considering the differences between storylines, we can see that under the low PW storyline the temperature increases are smaller than for the high PW storyline. This means that overall and during winter the circulation changes in the high PW storyline can favor warmer temperatures. The opposite is found when assessing the sensitivity in the other seasons.

"Hydro" CID responses under extreme storylines

Fig. 4 shows the precipitation changes for spring (ON), summer (DJF), the harvest season (MA) and the accumulated growing season under the low PW (panels a, b, c, d) and high PW (panels e, f, g, h) storylines, respectively. Overall the spatial patterns differ in the same way across seasons. The models show that in a low PW storyline the precipitation projection is characterized by a relatively small drying over the northern section of the study area and a strong drying in the southern section. Meanwhile, the high PW storyline is associated with large wetting over most of the study area, although a drying pattern in the tip of Patagonia affects the southwest of the southern section.

Spring season precipitation

Panels a and e in Fig. 4 show the precipitation changes for spring in the low and high PW storylines. Overall, the precipitation for this season in the region is lower than 100 mm, although locally it reaches more than 200 mm. In general, none of the storylines present large changes in spring.

Summer season precipitation

Panels b and f in Fig. 4 show the precipitation changes for summer in the low and high PW storylines. The changes are up to +- 20 mm month^{-1}, but locally can reach more than +- 30 mm month^{-1}. Considering that in most of the region the summer precipitation is less than 80 mm month^{-1}, this represents more than a 30 % increase/decrease, which can represent a large change. The spatial pattern of the high PW change shows similarities with the changes for the same CID reported by Cabré et al. (2014). However, the authors show the index in absolute values, and the level of warming that their model reaches for the time horizon (2080–2099) is not reported, which makes the results of their study difficult to compare to.

Harvest season precipitation

Panels c and g in Fig. 4 show the precipitation changes for the harvest season in the low and high PW storylines. We find almost no change in the two storylines in the northern section of the study region. In the southern section, we see a strong drying signal in the low PW storyline, where the changes are larger than −30 mm month^{-1}. In the high PW storylines the changes locally reach less than 15 mm month^{-1}. It is relevant to note how different storylines show different signs of change, which would lead to very different adaptation strategies. Small changes in this season represent favorable conditions for viticulture, given that heavy precipitation events can affect the harvest process and the quality of the product itself.

Precipitation accumulated during the growing season

Panels d and h in Fig. 4 show the change in precipitation accumulated over the growing season. Given that none of the storylines shows a strong signal for the spring season, the accumulated precipitation is mainly dominated by the changes in summer and the harvest season. Indeed, in summer and the harvest season, the low PW storyline is associated with drying in the southern sector. Conversely, the high PW storyline is associated with a wetting signal over the northern section and a drying signal in southern Patagonia. In the northern section, seasonal precipitation does not exceed 150 mm in the western side of the Andes but reaches 600 mm in the easternmost side, over Cafayate. Rainfall is mainly concentrated in the summer (DJF). In the southern section, the mean precipitation is around 300 mm, reaching values of up to 600 mm in the south west, and is evenly distributed throughout the season. This means that changes of around 100 mm in the upper section, projected in the high PW storyline, could represent large changes. On the other hand, a 100 mm drying in the southern section represents almost a 30 % decrease in the growing season rainfall.

Winter precipitation

We do not show winter precipitation here given that JJA precipitation was already addressed in Mindlin et al. (2020). However, results there showed that all storylines are associated with drying over the extratropical Andes, which is one of the most robust regional climate responses across the world. This drying trend has been observed for the last decades and the region has already been affected by the mega drought of the last 13 years (Garreaud et al., 2020).

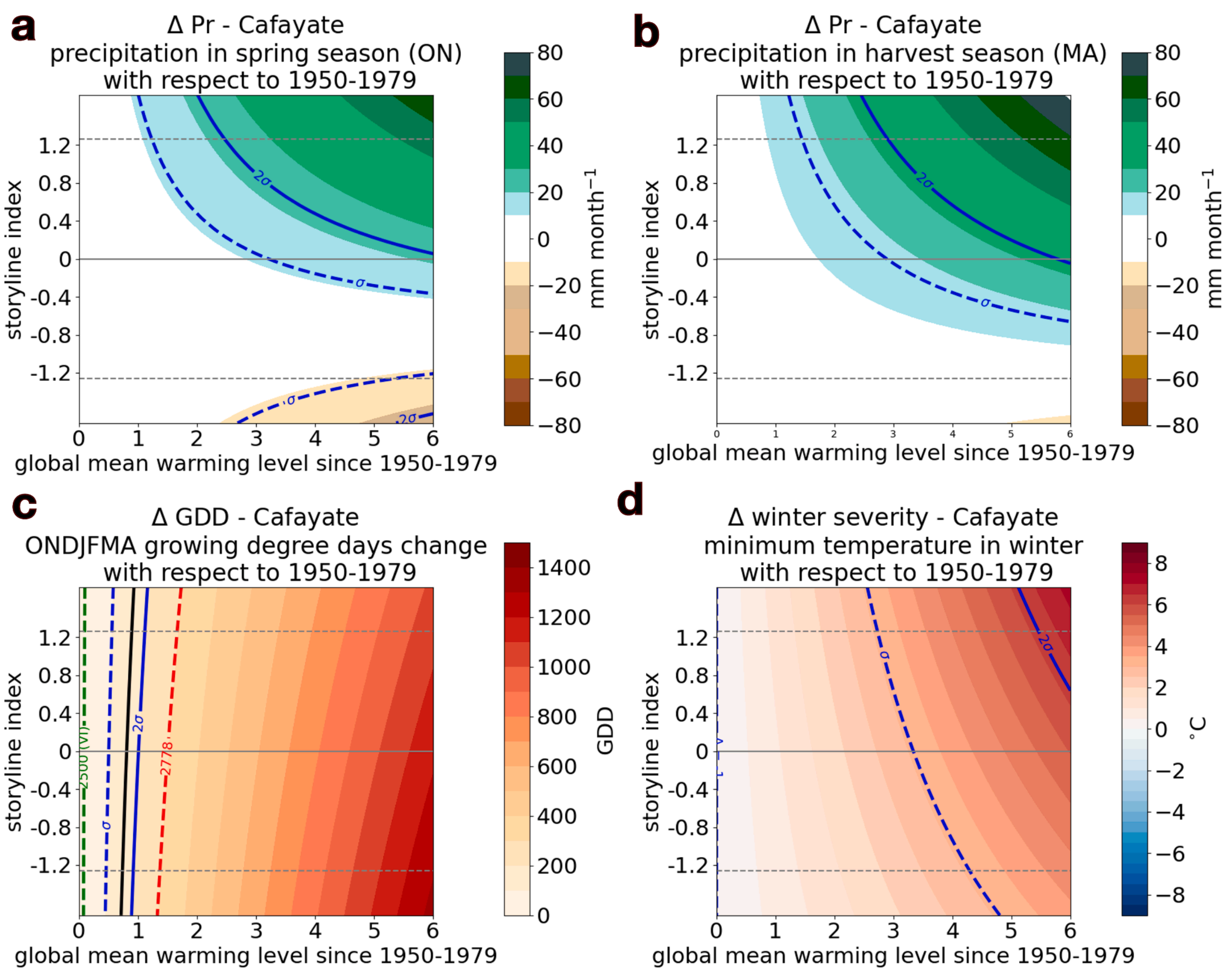

Fig. 5. Change in CIDs as a function of global warming and atmospheric circulation storyline uncertainty from the low-impact storyline to the high-impact storyline as defined in Section 4.1. a Shows precipitation in ON, b precipitation in MA, c growing degree days and d winter severity. The values are estimated at the nearest grid point to the indicated location of Cafayate (red dot in Fig. 1). The dashed blue curve represents one standard deviation in the interannual variability of the CID. The solid blue curve shows two standard deviations in the interannual variability. The black curves in the GDD panel show observed changes evaluated with the CRU TS v. 4.06 dataset between the reference period and the recent past (1989–2018). The dashed green curves represent suitability thresholds for different wine varieties as in Cabré et al. (2014) based on the Winkler index (Winkler, 1974). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Discussion

Correlated risk and climate suitability for viticulture

Overall, the results, especially the changes in CIDs related to changes in temperatures, are in agreement with previous results from Aruani (2010) showing the potential to expand to new wine areas in Argentina, both farther south into Chubut or in altitude, above 2000 m in Cafayate. After having evaluated how different dynamical conditions lead to extreme and different CID changes, in this section we are interested in discussing how the storyline coefficient (deviation from the mean in the dynamical conditions) and the global warming level affect the magnitude of the CID changes. In addition, we want to find under which storylines the thresholds for viticulture suitability could be met and discuss how the storyline approach provides a simple set-up to make this type of assessment. For this, we evaluated the CID response as a function of the storyline coefficient and the level of global warming in the form of maps as in Fig. 5. The response was evaluated for the nine grid points that are closest to the nine selected valleys where viticultural activity is developed in the present (Fig. 1).

The grid points were selected in order to compare differences between latitudes and between the two sides of the Andes under the same storyline. The maps allow a quick interpretation of future suitability, the uncertainty of the response and the differences between regions. If the isolines are vertical, the CID shows no dependence to the storyline coefficient, and the change depends mostly on the level of global warming. If the isolines are curved, there is greater storyline dependence. In order to contextualize the results, we show, for each location, the CID's interannual standard deviation in the recent past (1989–2018) as a measure of the CID variability that the sector has experienced in the past. If the changes are greater than two standard deviations, the response to climate change can be considered highly significant and interpreted as a change in the conditions and plausible suitability. Present GDDs are considered in order to interpret the changes in GDDs in terms of the Winkler scale (Table 1). The observed changes (1989–2018 vs. 1950–1979) were evaluated with the reference observation data and shown in each plot. If the sign or magnitude of the observed change is such that it does not appear in the map it is reported in the text.

Cafayate (A)

Cafayate is the northernmost region with viticulture activity in the study area and vineyards are located at a mean altitude of 1650 m.a.s.l. (Table 1). The present climatological accumulated precipitation in the growing season is 480 mm, 80 mm in spring (ON), and 100 mm in the harvest season (MA). We find that precipitation changes have a strong dependence on the circulation storyline. Under high PW conditions and a 3 °C global warming storyline, precipitation can increase between 25 and 35 mm/month in ON and up to 40 mm/month in MA. This means that CMIP6 projects either a small drying or wetting depending on the storyline index (Fig. 5a,b). On the other hand, the GDD index has a weak dependence on dynamical conditions and is largely independent of the RD responses. In a 2 °C global warming storyline, the region can shift from Winkler region V to a region of low suitability, according to the Winkler scale, exceeding 2778 GDDs. The risks associated with low temperatures (Winter Severity, WS) will decrease regardless of the storyline, although extreme winter temperatures are much higher in the high PW storylines, given that the index shows a high dependance on the level of warming (Fig. 5).

Valle del Elqui (C) and Valle Fértil (A)

In Valle del Elqui the rainy season is winter and during the growing season precipitation does not exceed 1 mm. In Valle Fértil the rainy season is summer whereas in spring and harvest season the mean precipitation is 100 mm. We find no projected changes in growing season precipitation over Valle del Elqui, at the west side of the Andes. On the east side, a storyline shows a maximum wetting of 10 mm month^{-1} under a 3 °C warming, which is not a big change relative to the recent past observed variability (Fig. 6a,b). However, the decrease in precipitation in winter under all storylines (Mindlin et al., 2020) can lead to impacts in viticulture, as winter precipitation is the main source of water supplies in the region (Fuentes et al., 2021).

From a climate services' perspective, the differences found between one side and the other of the Andes can be relevant for decision-making and cannot be addressed in a correlated manner with a traditional approach. Under the same storyline, namely a high PW and a global warming of 3 °C, Valle del Elqui presents no change in spring (ON) precipitation while in Valle Fértil we find a drying of 15 mm month^{-1} (Fig. 6a,b). These precipitation changes might not have a large impact. However, differences might be more relevant for temperature-based indices such as the GDD. We find that under that same storyline, GDDs can increase by 300 degree days in Valle del Elqui and between 600 and 800 degree days in Valle Fértil (Fig. 6a,b). Under a global warming of 2 °C, Valle del Elqui would still be suitable for wine production, transitioning from being a Winkler region III to a Winkler region IV, while Valle Fértil could become too warm, reaching extreme values of GDD of around 2600 (Fig. 6a,b).

Casablanca (C) and Valle de Uco (A)

In these latitudes, near the southward edge of the steepest sector of the Andes, the precipitation and GDD responses show agreement between the valleys. However, the winter severity shows more sensitivity on the Argentinian side (Fig. 6c,d). Casablanca and Valle de Uco have comparable climatology. The climatological precipitation is 150 mm month^{-1} in Casablanca and below 100 mm month^{-1} in Valle de Uco. Under 2 °C warming storylines the precipitation changes could reach one standard deviation of the climatological variability. With respect to GDDs, we find that the dynamical storyline has a larger influence in Valle de Uco than in Casablanca. GDDs increase more rapidly in Casablanca than in Valle de Uco and Valle de Uco shows greater dependence on the dynamical storyline (Fig. 6c,d). Under a global warming of 2 °C Casablanca would shift from being a Winkler region II to a Winkler region III and Valle de Uco from III to IV.

Valle del Bío Bío (C) and San Patricio del Chañar (A)

These two valleys in Patagonia are almost at the same latitude. However, because of the strong differences between west and east of the Andes in terms of precipitation changes, we find diverging results for the two valleys. These complex responses become interpretable in terms of correlated risk when addressed with a storyline approach. While in Bío Bío a high PW storyline is associated with weak negative precipitation changes in ON and MA, San Patricio del Chañar (SPdC) shows weak yet positive changes. The opposite is true for the low PW storyline. In terms of temperature changes, Bio Bío shows larger GDD changes in a high PW storyline than in a low PW storyline, while in SPdC the GDD index behaves in the opposite way (Fig. 7a,b). Under 2 °C of global warming both regions could transition to the next Winkler region.

Trevelin and Sarmiento

Trevelin and Sarmiento are the southernmost wine producing valleys in the study region, with a very small number of vineyards each. Although Sarmiento is farther south, Trevelin is subject to the climate of the Andes, and hence has a cooler climate. These two locations were included in the analysis in order to assess the viticulture suitability in high latitudes. In both regions we find weak drying trends in a low PW storyline, and overall, the storylines show an increase in GDDs which could favor the growth of grapevines in these latitudes, making them more suitable for wine production. We found that GDDs and winter severity are not independent from the dynamical conditions in Sarmiento and this dependence is even higher in Trevelin. Under a global warming of 2.5 °C Trevelin could reach Winkler region I and Sarmiento could reach Winkler region II (Fig. 7c,d).

In agreement with previous works, these results overall confirm that

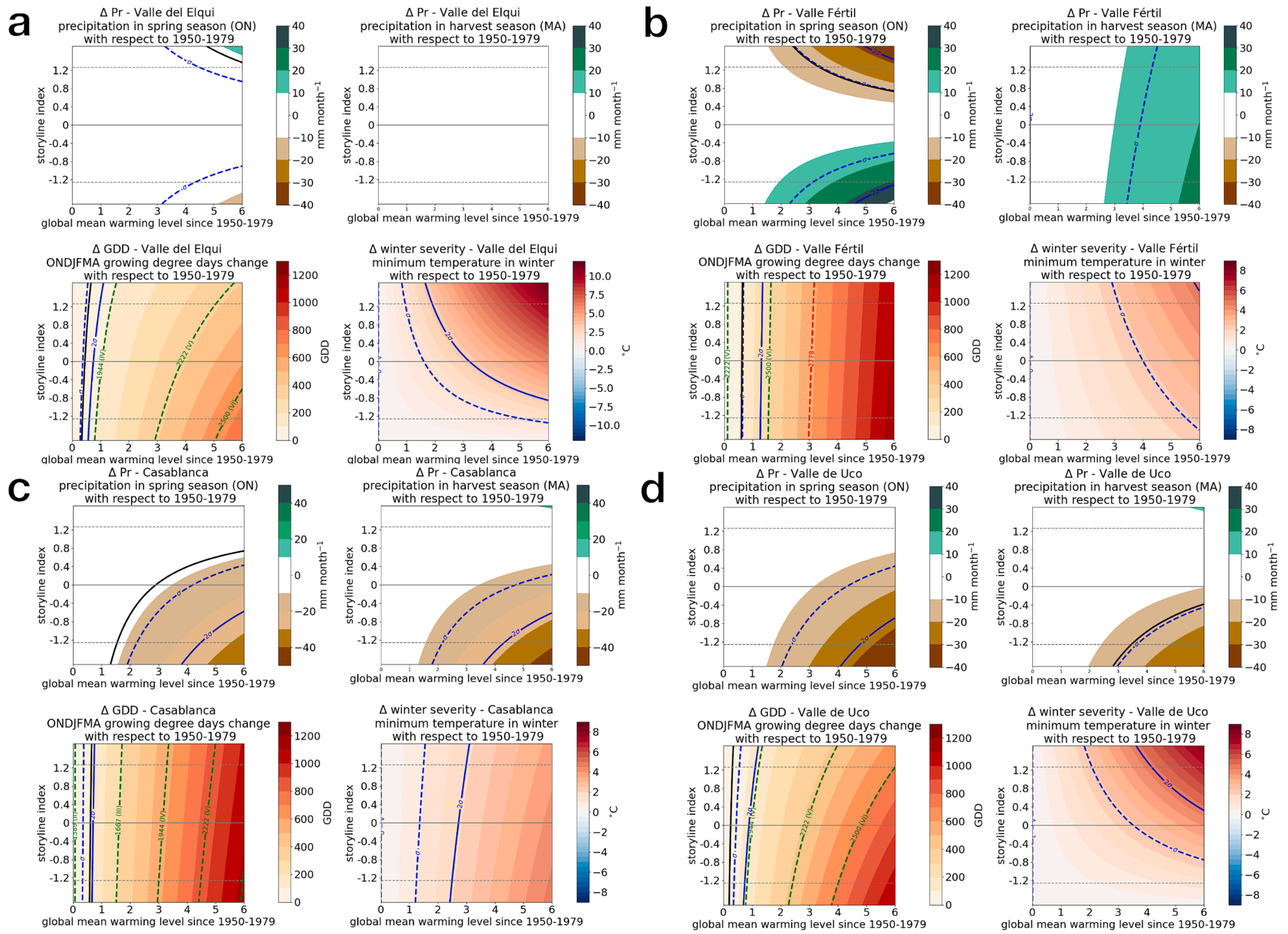

Fig. 6. Same as in Fig. 5 but for Valle del Elqui (a), Valle Fértil (b) Casablanca (c) and Valle de Uco (d).

suitability for viticulture may increase in higher latitude and possibly in higher altitudes both in Argentina (Aruani, 2010; Cabré et al., 2014; Cabré and Nuñez, 2020) and in Chile (Hannah et al., 2013). However, some regions that are warm in the present can be negatively impacted by future warming, since too warm conditions in summer can lead to poor grape quality (Pons et al., 2017). These changes have also started to show in the observed records; Verdugo-Vásquez et al. (2023) analyzed viticulture CIDs based on station data in the valleys of Chile and showed that Coquimbo and Central valleys (Valle del Elqui and Casablanca) have already changed from warm to hot climates and Quilaco (Valle del Bio Bio) has changed from a cool climate to a warm one. In terms of precipitation changes for the rainy season, which is winter for this region, all storylines show a decrease in precipitation (Mindlin et al., 2020), a trend that is already being observed and causing hydrological drought impacts (Rivera et al., 2021). This can be aggravated in the future by the projected precipitation decrease that one of the storylines shows in the growing season, even though this is not the main source of water supply (Fuentes et al., 2021) and the changes are small. No statistically significant changes have been observed in this season (Verdugo-Vásquez et al., 2023).

Planification will therefore require more research and understanding of present and future climate in the Argentinian side of Patagonia, where suitability may increase. In Patagonia, many aspects of climate variability and change are still unknown (IPCC, 2023) as well as how other environmental threats can affect or limit viticultural activities, which will require complex adaptation strategies (Straffelini et al., 2023). For example, Patagonia is a particularly windy region; windiness changes in future projections have not been addressed at the local scale and should be evaluated in order to know if this will continue to be a hazard, as it has already been shown in other regions that strong winds have effects on vineyards (Alonso et al., 2024). In addition, fire weather is an important part of the Patagonian ecosystem, which is affected by human agricultural interventions and activities which can increase wildfire risks (Iglesias & Whitlock, 2014) and could also affect potential vineyard development. It would then be relevant to develop CIDs related to wind and fire meteorology to understand their future changes and associated impacts in the context of anthropogenic climate change. Moreover, our results show that although mean temperature depends mainly on the level of global warming, temperature extremes and precipitation depend on circulation changes and this is the case for windiness and is likely to be the case for fire weather as well.

Given all of the above, it becomes clear that further research is necessary to underpin adaptation strategies and planning for agriculture activities in the region, and although the CIDs used for this study suggest a suitability increase, expanding this agricultural activity to Patagonia poses new challenges which require an interdisciplinary understanding of this ecosystem's dynamics and climate.

Conclusions

The analysis of different climate variables has shown that the CIDs related to seasonally aggregated temperatures are largely dependent on the global warming level and, depending on the region, they can also be sensitive to the future large-scale dynamical conditions. Meanwhile,

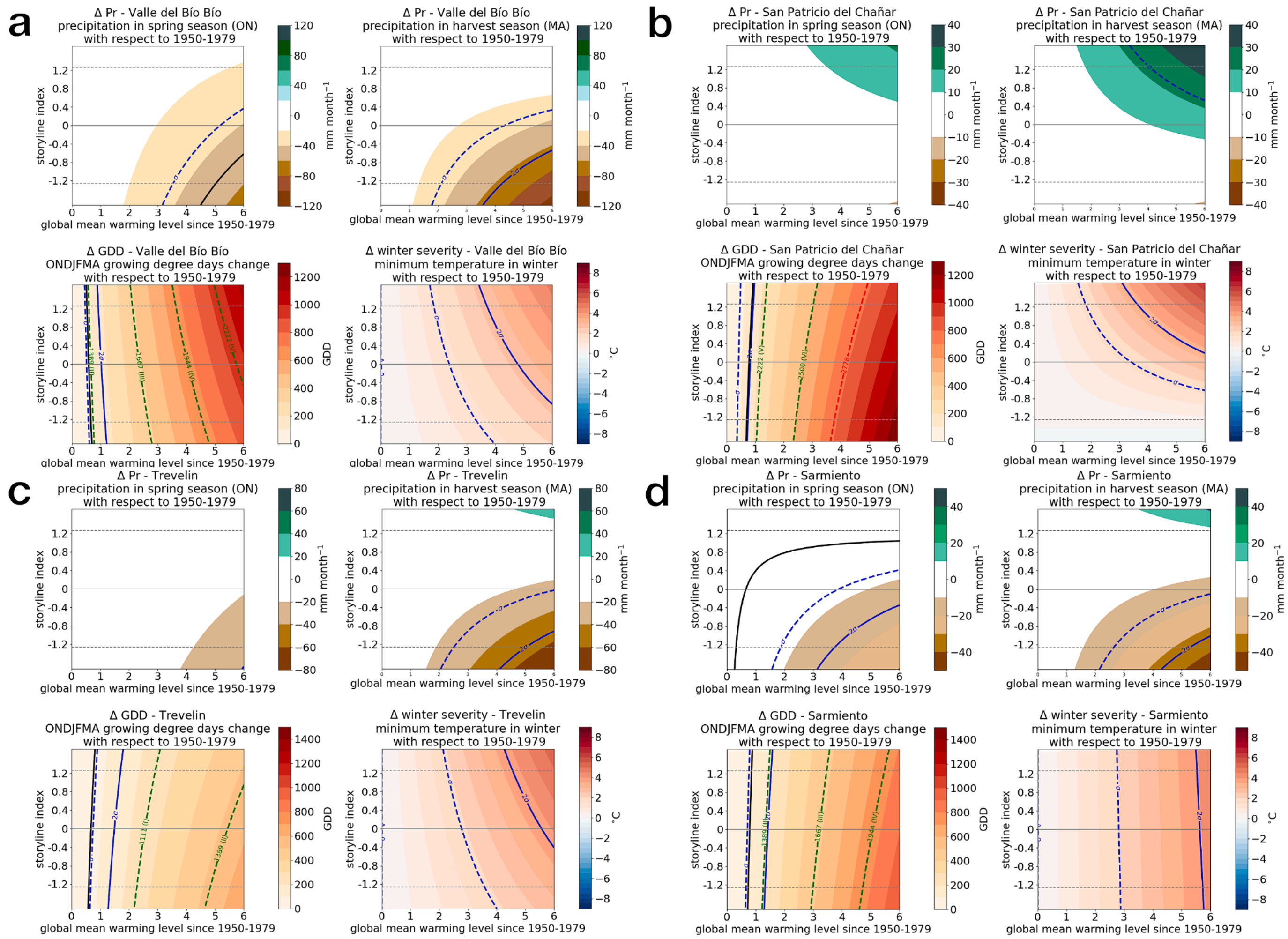

Fig. 7. Same as in Fig. 6 but for Valle del Bío Bío (a), San Patricio del Chañar (b), Trevelin (c) and Sarmiento (d).

CIDs related to extreme temperature values and precipitation strongly depend on the dynamical response as well as the global warming level. This points out once again that one-model or ensemble mean assessments are not suitable for climate services aimed for long-term decisions.

Applications related to agriculture, and viticulture in particular, require the analysis of climate-related compound risks, since grape growers and wine producers need to assess changes in different climate processes and/or variables that may occur at the same time in different regions. This is why there is value in communicating a set of physically plausible dynamical scenarios if oriented according to the sectoral needs and context. Using this type of information, adaptation plans for the sector should consider the different regional impacts that can occur simultaneously and select the plausible ones.

Moreover, given their capacity to relate societal impacts with the level of global warming, recently developed storyline approaches are an alternative to the traditional emission scenarios for communicating uncertainty in climate services' studies. We illustrated how storylines can show the qualitatively different changes that may occur in several relevant variables at the same time in a physically meaningful way. Therefore, they can provide climate information that feeds directly into a particular decision-making context.

Our results show that, overall, global warming could favor viticultural activities in the south of South America, in particular in Patagonia and in high altitude valleys in both Chile and Argentina. Given that the main goal of this article was to test the benefits of the storyline approach while assessing the impacts of climate change in viticulture for Chile and Argentina, the analysis was developed based on conservative indices that have been extensively used in literature. However, the suitability of new regions in high latitudes and altitudes is subject to new challenges and threats related to the nature of changes such as late frosts and the climate conditions of the new suitability area, Patagonia, which is already affected by strong windiness and active fire weather. Therefore, a future and more detailed analysis should be focused on assessing the threats related to frosts, fire weather, windiness and changes in extremes, which based on the results of this article are likely to depend on the circulation changes and therefore need to be addressed with a storyline approach.

CRediT authorship contribution statement

J. Mindlin: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C.S. Vera:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **T.G. Shepherd:** Writing – review & editing, Supervision, Methodology. **F.J. Doblas-Reyes:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **N. Gonzalez-Reviriego:** Writing – review & editing, Supervision, Project administration, Conceptualization. **M. Osman:** Writing – review & editing, Supervision. **M. Terrado:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Julia Mindlin reports financial support was provided by Belmont Forum. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for this article is publicly available. We have added a statement with a link to a download source.

Acknowledgments

We acknowledge the World Climate Research Programme Working Group on Coupled Modelling, responsible for CMIP, and the modeling groups responsible for producing the simulations. This work/result is part of the project TED2021-129543B-I00 (GLORIA), funded by the Spanish Ministry of Science and Innovation/National Research Agency/10.13039/501100011033 and the European Union 'NextGenerationEU/PRTR'. It has received funding from the European Union's Horizon Europe – the Framework Programme for Research and Innovation (2021-2027) under grant agreement No. 101081460. JM is supported by a Ph.D. grant from CONICET, Argentina, and a Microsoft Research Ph.D. Fellowship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100480.

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