

Despite known coastal cooling trend, risk of deadly wildfires in central Chile increasing with changing land management in a warming climate.

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Main findings

There is significant interaction between extreme climate conditions and land management policies, leading to particularly devastating impacts in informal settlements.

- Fire weather is one important factor that drives wildfires, although changes in vegetation (wildfire fuel), ignition factors, and fire management strategies also contribute to future wildfire risk¹.
- To combine the different variables leading to high fire danger we compute the hot dry windy index (HDWI) that combines high temperatures, high wind speeds and low humidity. In this index, we find that the hot, dry and windy conditions that drove the wildfires of February 2024 are characterised as a 1 in 30-year event in today's climate.
- To assess the role of climate change, we combine observation-based products and climate models and assess changes in the likelihood and intensity of a 1-in-30-year 4-day event over the region of the most devastating fires (fig. 2).
- We find that overall, there is a small increase in the HDWI in the observations and some models, but it is not significant. This is also true for the individual components of the index: maximum temperature, relative humidity and wind speed, none of which show a significant trend.
- These results are not surprising, given the coastal location of the region which has a well established wind-driven sea surface temperature cooling.
- The fires occurred in the coastal range of central Chile, right in the transition of coastal cooling and inland warming, rendering it difficult for most climate models to represent the event well. Only 5 models were able to simulate the event, and only 2 of these performed well in the model evaluation, thus results are very uncertain. Furthermore, the observation-based data are also comparably short and highly uncertain, particularly with respect to the wind component.
- Nevertheless, unless the world rapidly stops burning fossil fuels, fire danger due to high HDWI will increase. Using the same limited models as above, in a world 2°C warmer than preindustrial, the trend towards higher HDWI becomes significant.
- We conclude that despite the trend in HDWI not yet being significant, the risk of an increase in dangerous fire weather conditions attributable to human-induced climate change needs to be taken very seriously.
- We then assess to what extent El Niño is related to dangerous fire weather conditions. We test two different indices to characterise the influence of El Niño and find that El Niño has no significant influence on the HDWI.
- Across the studied area, fire risk is increasing notably due to current land management practices, such as the expansion of Wildland-Urban Interface areas (including the growth of informal settlements in forest zones) and widespread conversion from native to foreign and monoculture plantations.
- The existing investments in fire prevention and adaptation measures, coupled with low-risk perception among residents in fire-prone areas, have shown limited effectiveness in adequately mitigating the fire risk.
- Spared by the deadly flames, the pilot fireproofing program of Villa Botania showcases the life-saving potential of preparedness, including measures such as community-led vegetation control, embedding water points across the land, and robust emergency training.

¹ Risk refers to the combination of hazard, exposure and vulnerability, following common usage in climate science.

- Measures to address the significant fire risk should encompass improved spatial planning; enhanced coordination, resource allocation, and community engagement in fire prevention and adaptation; and awareness raising campaigns.

1 Introduction

In early February 2024, wildfires ravaged central and southern Chile, particularly in Valparaíso, O'Higgins, and Maule regions, causing casualties and extensive damage. On February 2, 2024, fires ignited in the mountainous forested areas east of Viña del Mar. Despite authorities' efforts to curb their spread, news reports indicate the flames rapidly advanced into densely populated city outskirts ([AP, 2024](#)). As of February 5, the Chilean National Disaster Prevention and Response Service reported 112 deaths, with the Complejo las Tablas-Reserva Lago Peñuelas area being severely affected. Media sources indicate 200 individuals went missing in Viña del Mar City. Copernicus Emergency Management Service (EMSR715) is actively providing damage assessments. The flames were exacerbated by high winds and unusually hot temperatures. In the days leading up to the fires, Santiago, southeast of Viña del Mar, experienced temperatures as high as 37 degrees Celsius, prompting many residents to seek refuge in coastal areas ([Reuters, 2024](#)). The humanitarian impact continues to worsen, with over 29,000 hectares burnt since February 2, resulting in 132 deaths, over 300 missing, 1,250 injured, 7,200 homes damaged, and 40,000 people affected, including at least three elderly homes evacuated ([SENAPRED, 2024](#); [IFRC, 2024](#); [The Guardian, 2024](#)). Moreover, public transportation was severely disrupted, while 121 telephone antennas burnt and water services were cut, limiting people's mobility and access to telecommunications and water at a critical time ([IFRC, 2024](#)). The fire danger forecast remains significant over central and northern Chile.

Chile has experienced persistent and intense weather conditions conducive to extreme wildfires since the start of the year. The severe fires in Valparaíso followed a very hot January 2024 with smaller fires in different parts of the country ([Meteored, 2024](#)).

During the timeframe of the catastrophic wildfires in Viña del Mar, the mid-level circulation over southwestern South America was marked by the presence of a mid-latitude ridge moving eastward from the ocean. At the surface, a migratory anticyclone, dynamically connected with the mid-level ridge, drifted to the east at approximately 40-45°S, while a low-pressure core formed along the coast of central Chile. These features are part of a recurring synoptic-scale phenomenon affecting the western coast of subtropical South America, known as the *coastal low* ([Garreaud et al., 2002](#)).

During the development of coastal low episodes, intensified subsidence and increased incoming solar radiation due to clearer skies can lead to higher-than-average daily maximum temperatures. Additionally, since the climatological equatorward surface pressure gradient along the coast is reversed, intense southerly low-level winds dominate the coastal zone. In concordance, extreme near-surface weather conditions were observed during the wildfires in Viña del Mar. For instance, on February 2, 2024, the Rodelillo weather station (33.07°S, 71.56°W) recorded a daily maximum temperature of 33.1 °C and maximum minute wind intensities of approximately 25 knots. This temperature threshold corresponds nearly to the 90th percentile of the empirical distribution of daily maximum temperatures in January-February since 1980, while the wind intensity registered during the wildfires is the highest on the available record (started in 2019).

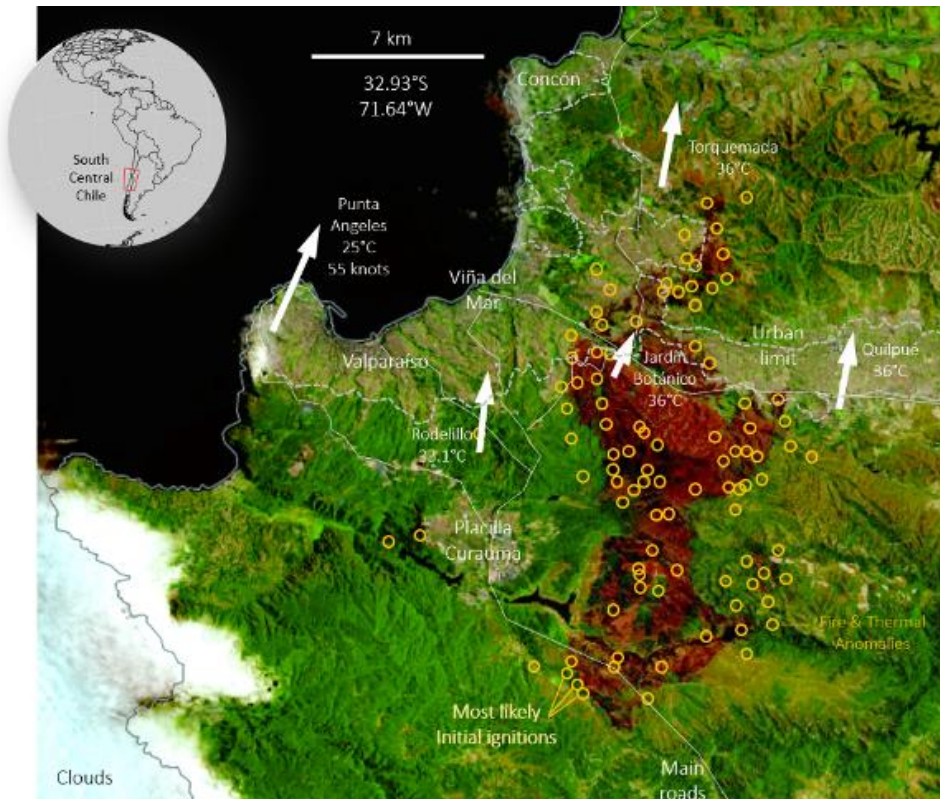


Figure 1. Scars of the 2-Feb-2014 fire in central Chile's Viña del Mar – Valparaíso sector. The background image is the Shortwave Infrared, Bands 7-5-4 from Landsat 8/9 OLI acquired on 5 February 2024. The scar stands out in red against the non-burned vegetation in green. The yellow dots are active fires detected from MODIS Terra/Aqua on 2 February 2024. Also shown are the urban limits and main roads, plus the meteorological conditions (Max wind and Max Temperature) during 2 February 2024 from DMC + SERVIMET

Chile has experienced prolonged drought conditions since 2008, the so-called mega-drought ([Rene et al., 2019](#); [Aldunce et al., 2017](#); [Urrutia-Jalabert et al., 2021](#); [Alvarez-Garreton et al., 2021](#)), partly attributable to human influence ([Boisier et al., 2015](#)). Notably, the mega-drought has coincided with the warmest decade on record for central Chile. Projections show an increased likelihood of prolonged and recurrent droughts in central Chile ([Boisier et al., 2015](#)). Furthermore, there is an established cooling trend along the Chile coast, due to increase in wind speeds along the coast, primarily influenced by the latitudinal movement of the southeast Pacific subtropical anticyclone ([Aguirre et al., 2021](#); [Ramajo et al., 2020](#)). During the austral spring and summer, there is a prevailing equatorward flow that encourages coastal upwelling. Upwelling events coincide with the formation of a low-level coastal jet triggered by a pronounced along-shore pressure gradient. At this time, the near-surface wind pattern often features a strong southerly low-level jet due to transient reinforcement of the alongshore sea level pressure gradient between a central Chile coastal low and a migratory anticyclone farther south ([Renault et al., 2009](#)).

1.2 Event Definition

Fire weather is defined by a combination of elevated temperatures, reduced humidity, minimal rainfall, and heightened winds persisting over a period. The combination of these meteorological conditions significantly elevates the risk of wildfires, particularly when there is a continuous presence of flammable organic matter for fuel and ignition sources ([Pausas & Keeley, 2021](#)). Among these weather factors, temperature is particularly crucial, as excessively high temperatures can reduce fuel moisture through increased evapotranspiration, lower humidity, and are linked to a higher likelihood of lightning activity, a significant ignition source ([Flannigan et al., 2009](#)). Additionally, heightened temperatures may extend fire seasons, especially in dry conditions, leading to more critical fire weather days characterised by high temperatures, low humidity, and strong winds ([Boegelsack et al., 2018](#)).

For event definition (both spatial and temporal) two things are important: the relation to the impact of the event, and the climatological homogeneity of the area. We investigate a Hot-Dry-windy index (HDWI) that combines high temperatures, high wind speeds and low humidity to assess a combination of different variables that increase fire risk. HDWI is based on the multiplication of the maximum wind speed and the maximum vapour pressure deficit (VPD) within the lowest 50 millibars of the atmosphere ([Srock et al., 2018](#); [HDWI, 2024](#)). VPD has a linear effect on the rate of evapotranspiration, meaning that the maximum fire fuel flammability is strongly affected by the daily maximum VPD. Surface windspeed also has a strong control on moisture transport from fuels, as well as being key to the rate of fire spread. We chose the HDWI as it is a straightforward daily index directly proportional to physical drivers of wildfire severity, and was not developed for a specific context, such as the widely used Canadian Fire Weather Index. Scaling with fuel flammability and likely wildfire spread rate, the HDWI is therefore a useful hazard metric for estimating threat to communities and difficulty of containment. Whilst more complex indices account for long term drying effects on the fuel bed, the HDWI is solely focussed on daily extrema in fire weather conditions. HDWI is expressed as follows:

$$HDW = U \times VPD(T,q)$$

Where U wind speed and VPD is Vapour pressure deficit (a function of temperature T and relative humidity q).

We select a spatially and climatologically homogeneous area [72°W, 69°W, 33.9°S, 32°S] in central coastal Chile which comprises Valparaíso, O'Higgins, and Maule regions. Temporally, we use December-January-February (DJF) maximum of 4-day running mean daily HDWI. The highest 4-day average HDWI was recorded in the period 31st January - 3rd February (Figure 2). Figure 3 shows the December-January-February maximum of 4-day running mean HDWI averaged over the study region for the period December 1979- February 2024. The 2024 value is the highest on record in MSWX. Figures 4 show the December-January-February maximum of 4-day running mean for the individual components used in the calculation of HDWI: near-surface temperature, relative humidity (which alternatively can be calculated from dew point temperature and near-surface temperature), vapour pressure deficit, and wind in MSWX dataset. The 2024 value is the highest on record in temperature and vapour pressure deficit.

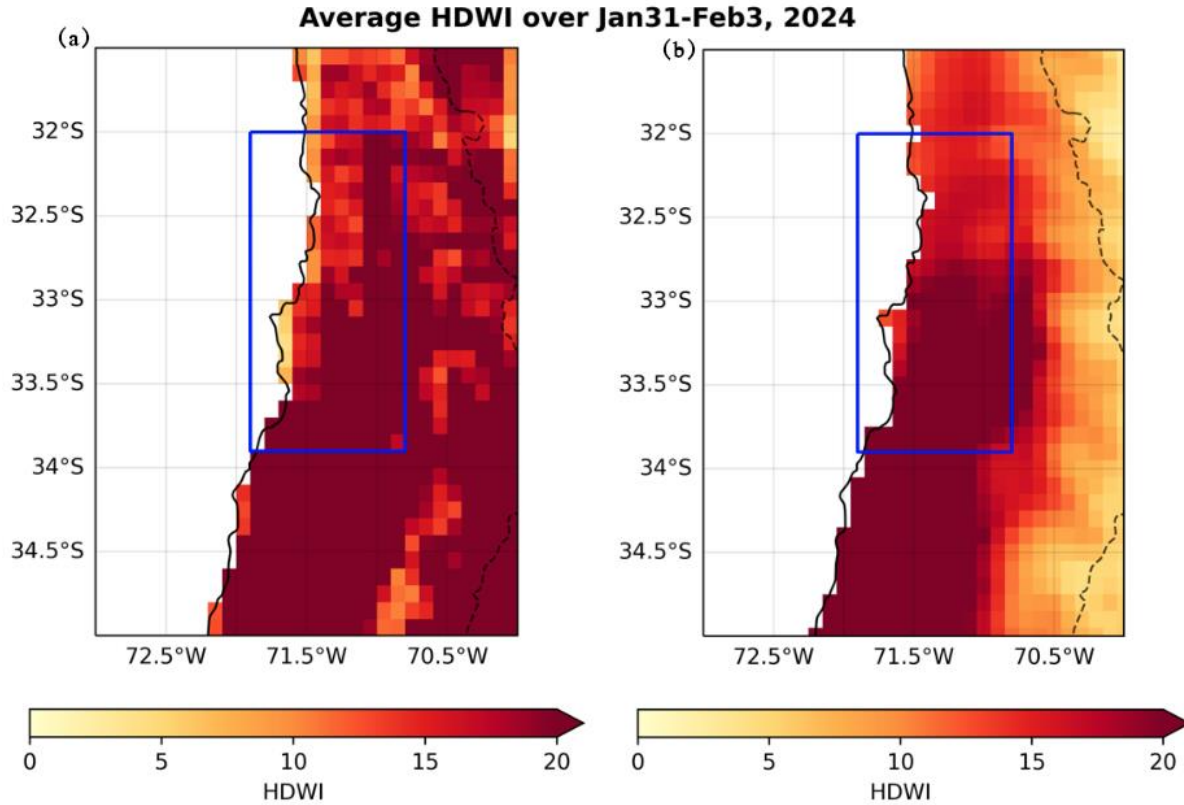


Figure 2. Maximum of average 4-day Hot-Dry-Windy-Index (HDWI) that occurred between January 31 to February 3, 2024 over central Chile in MSWX (a) and ERA5-Land (b) datasets. The blue outlines show the region used in this study.

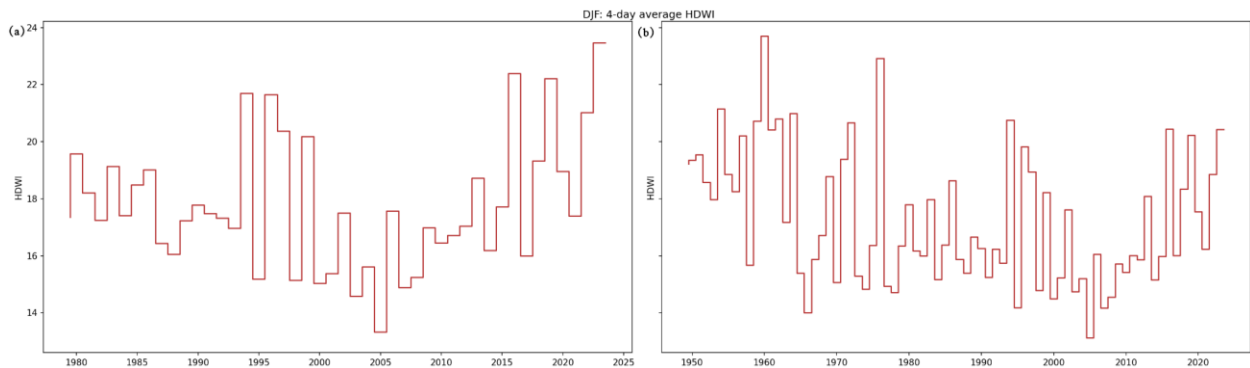


Figure 3. Maximum of average 4-day Hot-Dry-Windy-Index (HDWI) over December-January-February for the period 1979-2024 over central Chile in MSWX (a) and ERA5-Land (b) datasets.

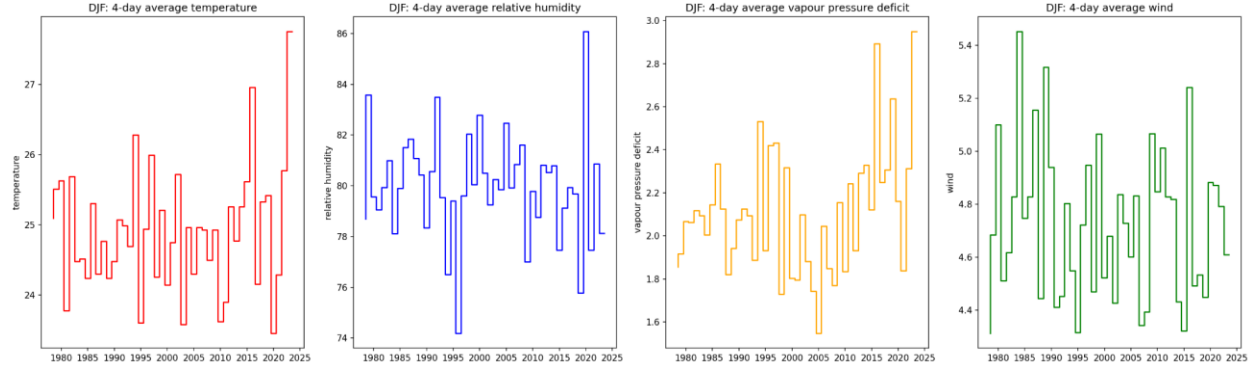


Figure 4. *Maximum of average 4-day near-surface temperature, relative humidity, vapour pressure deficit, and wind over December-January-February for the period 1979-2024 over central Chile in MSWX dataset.*

2 Data and methods

2.1 Observational data

2.1.1. Gridded products

We use daily data for two gridded observational datasets: (i) Multi-Source Weather (MSWX) is an operational, high-resolution, bias-corrected (based on ERA5 data bias-corrected and downscaled using high-resolution reference climatologies) meteorological product with global coverage from 1979 to 7 months from now ([Beck et al., 2022](#)). We utilised the near-surface temperature, relative humidity and wind speed products featuring a high 3-hourly 0.1° resolution (ii) ERA5-Land product from the European Centre for Medium-Range Weather Forecasts (ECMWF), a high resolution product that is produced only for the land surface, available from 1950-present. The differences in the estimates from ERA5 and ERA5-Land are attributed to the model formulation and resolution. The land-atmosphere interactions in the IFS for ERA5 are fully coupled, whereas for ERA5-Land, the land surface model H-TESSEL is run offline, forced by ERA5 atmospheric conditions ([Muñoz-Sabater et al., 2021](#); [Rosnay et al., 2016](#)). For this product, we utilised near-surface temperature, dew point temperature and u (zonal) and v (meridional) wind components. Due to the unavailability of wind measurements in Chile prior to 1980, we used only from 1980 onwards from both datasets. Both datasets were used to define the event, evaluate the models and conduct attribution analysis.

2.1.2. Observed global mean surface temperature

As a measure of anthropogenic climate change, we use the (low-pass filtered) global mean surface temperature (GMST), where GMST is taken from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, [Hansen et al., 2010](#) and [Lenssen et al. 2019](#)).

2.2 Model and experiment descriptions

Due to the small size of the study region, thus requiring simulations at fine resolution together with the need for the variables at sub-daily resolution, we utilised only one climate model ensemble - the Coordinated Regional Climate Downscaling Experiment CORDEX-CORE multi-model ensemble (Gutowski et al., 2016; Giorgi et al., 2021), comprising of simulations resulting from pairings of 3 Global Climate Models (GCMs) and 2 Regional Climate Models (RCMs). These simulations are composed of historical simulations up to 2005, and extended to the year 2100 using the RCP8.5 scenario. For the region considered in this study, five model runs are available at 0.22° resolution (SAM-22 domain).

2.3 Statistical methods

We analyse time series of the December-January-February maximum of 4-day running mean daily maximum HDWI over the study region. Methods for observational and model analysis and for model evaluation and synthesis are used according to the World Weather Attribution Protocol, described in [Philip et al. \(2020\)](#), with supporting details found in van [Oldenborgh et al. \(2021\)](#), [Ciavarella et al. \(2021\)](#) and [here](#). The analysis steps include: (i) trend calculation from observations; (ii) model evaluation; (iii) multi-method multi-model attribution and (iv) synthesis of the attribution statement.

We calculate the return periods, Probability Ratio (PR; the factor-change in the event's probability) and change in intensity of the event under study in order to compare the climate of now and the climate of the past, defined respectively by the GMST values of now and of the preindustrial past (1850-1900, based on the [Global Warming Index](#)). To statistically model the event under study, we use a Generalised Extreme Value (GEV) that shifts with GMST. Next, results from observations and models that pass the evaluation tests are synthesised into a single attribution statement.

3 Observational analysis: return period and trend

3.1 Analysis of gridded data

While focusing on such a small region is essential for capturing the typical characteristics of the region, it also implies that results are valid for this region and not for all of Chile's recent fire events. The return period estimated here therefore might be higher than expected when counting all fires over all of Chile. Figs. 5(a-b) shows the results from the trend-fitting methods applied to the DJF maximum 4-day HDWI in the study region, from ERA5-Land and MSWX for the period 1979/80-2023/24. Fig. 5(a) shows the variable as a function of the GMST anomaly. The plot for GEV return period curves for this variable in the present 2023/24 climate (red lines) and a hypothetical past climate when the global mean temperature was 1.2°C cooler (blue lines) is shown in Fig. 5(b). There is a marginal increase in the DJF maxima of 4-day HDWI in this region as GMST increases. The 2023/24 event is a moderately rare event, with a return period of 21 years (uncertainty: 8 to 87 years). The 4-day HDWI associated with the fires that is estimated to be 20.38 units in the ERA5 dataset, which would have been lower by 1.38 unit in a 1.2°C cooler climate, although this is not strong enough to be statistically significant (95% confidence interval, CI: -2.164 to 4.353 units). The trends also suggest a likely doubling to tripling of the chances of an event with similar

magnitude in the current climate, as compared to the pre-industrial past (PR=2.65 uncertainty:0.3 to infinity). Similar plots from the MSWX dataset are shown in Figs 5(c-d). The small increase in trend in the 4-day HDWI with GMST that was observed in ERA5-Land is observed in this dataset too. The 2023/24 event is more rare with a return period of 53 years (uncertainty: 17 to 1538 years). As with ERA5-Land, the trends suggest a likely doubling of the likelihood of an event such as the 2023/24 event in the current climate as compared to the pre-industrial past (PR=2.03 uncertainty: 0.142 to infinity) and intense by factor of 1 (uncertainty:-3.517 to 6).

For the model analysis we use a return period of 30 years. The return period of 30 years is seemingly higher than expected, considering that five of Chile's six most destructive fire seasons have unfolded in the past decade ([Cordero et al., 2024](#)). However, it should be noted that factors other than climate change, such as unsustainable land use management, are often the major drivers of ignition and spread of fires and subsequent devastating impacts. The primary metric investigated in this study - the HDWI - is an indicator of the weather conditions alone that are conducive for wildfires, and does not factor in the non-climatic factors such as changes in land management. Therefore, this (arguably) higher return period is not unexpected for the selected small study region, given that the region has several unique dynamics associated with coastal cooling that are responsible for the local climate (discussed in Section 1).

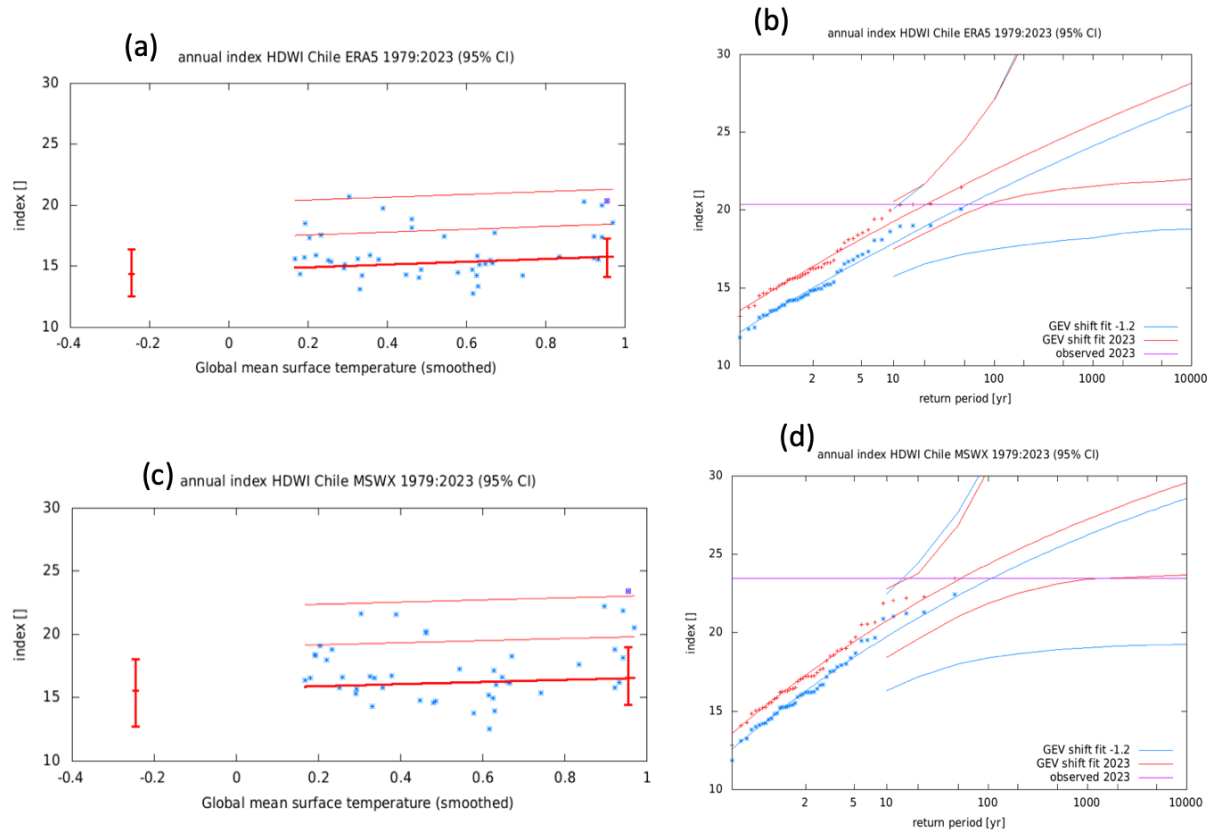


Figure 5. (a) DJF maximum of 4-day rolling average HDWI over the study region estimated from ERA5-Land records shown against the change in global mean temperature. The thick red line denotes the time-varying mean. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2023/24 climate and the hypothetical, 1.2°C cooler climate. The 2023/24 observation is

highlighted with the magenta box **(b)** Return periods for the 2023/24 climate (red lines) and the 1.2°C cooler climate (blue lines with 95% CI), based on ERA5 data (1949/50-2023/2024). **(c)** same as (a), based on the MSWX dataset. **(d)** same as (b), based on the MSWX dataset.

3.2 Influence of modes of natural variability

Following findings from past studies that demonstrate linkage between wildfire activity in Chile and ENSO conditions, we additionally evaluate whether these dependencies exist over the (much smaller) study region selected for this study. We focus on two established linkages that showed the most significant correlations- (i) Between wildfire activity and Nino 3.4 in the preceding winter before the onset of the current wildfire season ([Urrutia-Jalabert et al., 2018](#)): This study infers that central Chile, a fuel-limited region will have more flammable vegetation in the season following a good-rainfall year, which in turn is modulated by the ENSO conditions in winter.

(ii) Between fire weather conditions and Nino 1+2 in the same season ([Cordero et al., 2024](#)): This study finds significant correlation between maximum temperatures and Fire Weather Index over Central Chile, albeit a larger area.

To do this, the method used in observational and model analysis is modified from the standard approach method outlined in the WWA protocol to include Nino SSTs as an additional covariate along with GMSTs. Table A1 (in the Appendix section) summarises the trends in the HDWI variable from the two observation datasets with respect to (i) GMST and Nino 3.4 (lagged by 18 months), and (ii) GMST and Nino 1.2 (not lagged). We find that the trends are not statistically significant for either of the Nino-covariates in both datasets. Therefore, we do not include the Nino index in the attribution analysis.

4 Model evaluation

In this section we show the results of the model evaluation for the study region. For computing HDWI, we need model simulations at sub-daily scales for multiple variables, namely near surface temperature and dew-point temperature (or relative humidity if dew point temperature is not available) for calculating the daily maximum vapour pressure deficit, and daily maximum surface wind speed, the product of which gives the daily HDWI. For the selected small spatial domain, there are only five models that have high spatial resolution and sub-daily temporal resolution with all the required variables (see Section 2.2 for details). Table 1 shows the results from evaluating these models with regard to the spatial patterns, seasonal cycles and parameters from fitting the GEV model as compared to those from the observed datasets. All evaluations are carried out for the 1990-2020 climatology. The seasonal cycles and spatial patterns from the five climate models are found to be consistent with those from the observed datasets, allowing them to be ranked ‘reasonable’ or ‘good’ (Table 1), following the protocol developed for the rapid attribution studies.

It may be noted that the performances of the models in terms of the seasonal cycle and spatial pattern is noteworthy for such a localised context. The variability is higher in the models compared to the observations, as indicated by the higher value of the scale parameter (sigma) in the models (Table 1). Two out of five models- namely the downscaled HadGEM2-ES global climate model (GCM) using REMO2015 and RegCM7 regional climate models (RCMs) - are ranked ‘reasonable’ in their performance with regard to this parameter, while the other three GCM-RCMs are ranked ‘bad’. The magnitude of DJF maximum 4-

day HDWI with a return period of 1-in-30 years is much higher in all five models. However, we do not place emphasis on these high magnitudes, as the models are compared against each other. We note that the model simulations are not bias-corrected; HDWI is calculated from different variables that all have their own biases, making an assessment of what magnitude is acceptable more complex. Further, the consistency between observations and models in terms of the other metrics discussed suggests that if these models were bias-corrected, they would likely not be rejected. While we did not do the bias correction, we checked the seasonal cycles and spatial patterns of wind speeds and vapour pressure deficits that were also ‘reasonable’ to ‘good’ as compared to the respective patterns from the observed datasets. For the reasons discussed above, we include all five models in the synthesis step (section 6). Note that if we only used the ‘reasonable’ models and reject the ‘bad’ models, we would have only one GCM driving two regional climate models. However, as a sensitivity check, we also repeat the synthesis including only the two ‘reasonable’ downscaled HadGEM2-ES models (highlighted in yellow in Table 1) for investigating whether there are discernible differences from excluding the ‘bad’ models (highlighted in red in Table 1). The results are discussed in Section 6.

Table 1. Evaluation results of the climate models considered for attribution analysis of HDWI over the region. For each model, the expected temperature of a 1-in-30 -year event is shown, along with the best estimate of the Sigma and Shape parameters and a 95% confidence interval for each, obtained via bootstrapping. Based on overall suitability, the models are classified as good, reasonable or bad, shown by green, yellow and red highlights, respectively.

Observations	Seasonal cycle	Spatial pattern	Sigma	Shape parameter	Event Magnitude
MSWX			2.07 (1.34 ... 2.85)	-0.089 (-0.48 ... 0.29)	23.45
ERA5-Land			1.62 (1.08 ... 2.10)	-0.042 (-0.36 ... 0.31)	20.376
Model					Threshold for 30-year return period[units]
<u>CORDEX</u>					
HadGEM2-ES_GERICS-REMO2015_r1i1p1	good	good	4.13 (2.48 ... 5.86)	0.25 (-0.22 ... 0.84)	47.155
HadGEM2-ES_ICTP-RegCM4-7_r1i1p1	reasonable	good	4.12 (2.78 ... 5.05)	-0.051 (-0.25 ... 0.27)	74.603
MPI-ESM-MR_ICTP-RegCM4-7_r1i1p1	reasonable	good	6.51 (4.62 ... 7.92)	-0.19 (-0.42 ... 0.019)	81.702
NorESM1-M_GERICS-REMO2015_r1i1p1	good	good	4.79 (3.01 ... 5.91)	-0.12 (-0.39 ... 0.29)	43.741
NorESM1-M_ICTP-RegCM4-7_r1i1p1	reasonable	good	4.90 (3.61 ... 6.27)	-0.017 (-0.38 ... 0.25)	74.434

5 Multi-method multi-model attribution

Table 2 shows the changes in intensity (ΔI) and Probability Ratios (PR) estimated from each observational dataset and for all five models.

Table 2: Change in intensity and probability ratio of maximum DJF 4-day HDWI due to changing GMST: (a) from pre industrial climate to the present and (b) from the present to 2C above preindustrial.

Model / Observations	a. Past vs. present		b. Present vs. future	
	Probability ratio PR [-]	Change in intensity ΔI []	Probability ratio PR [-]	Change in intensity ΔI []
MSWX	2.0 (0.14 ... ∞)	1.0 (-3.5 ... 6.0)		
ERA5	2.7 (0.30 ... ∞)	1.4 (-2.2 ... 4.4)		
HadGEM2-ES_GERICS-REMO2015_r1i1p1 ()	0.84 (0.66 ... 1.5)	-1.5 (-3.4 ... 2.1)	1.1 (0.95 ... 1.5)	0.39 (-0.45 ... 1.5)
HadGEM2-ES_ICTP-RegCM4-7_r1i1p1 ()	2.1 (0.75 ... 7.5e+4)	2.3 (-1.1 ... 5.3)	1.9 (1.3 ... 4.6)	2.0 (1.2 ... 3.0)
MPI-ESM-MR_ICTP-RegCM4-7_r1i1p1 ()	0.82 (0.0029 ... 32)	-0.65 (-6.1 ... 5.2)	1.3 (0.85 ... 2.0)	1.3 (-0.67 ... 3.5)
NorESM1-M_GERICS-REMO2015_r1i1p1 ()	3.4 (0.62 ... ∞)	3.5 (-1.4 ... 8.5)	1.5 (0.73 ... ∞)	1.0 (-0.77 ... 3.0)
NorESM1-M_ICTP-RegCM4-7_r1i1p1 ()	0.42 (0.018 ... 5.2)	-3.3 (-10 ... 4.2)	1.2 (0.58 ... 1.8)	0.70 (-1.2 ... 2.3)

6 Hazard synthesis

For the event definition described above, we evaluate the influence of anthropogenic climate change on the event by calculating the change in likelihood as well as in intensity using both observations and climate models. All evaluated models in Section 4 were included for the analysis. The aim is to synthesise results from models that pass the evaluation along with the observations-based products, to give an overarching attribution statement for the change in likelihood, expressed as probability ratio and the change in intensity. Due to the small size of the study region, thus requiring simulations at fine resolution together with the need for the variables to be available at sub-daily resolution, we utilised five model simulations from combinations of only three regional and two global models. As discussed in section 2.3, we present results here only for the effect of GMST on the intensity and frequency of such events, as ENSO does not exhibit a significant influence on the event.

Figure 6 shows the changes in likelihood and intensity for the observations (blue) and models (red) for the past and future. The dark red bar shows the model average, consisting of a weighted mean using the (uncorrelated) uncertainties due to natural variability. Observation-based products and models are combined into a single result in two ways. Firstly, we neglect common model uncertainties beyond the intermodel spread that is depicted by the model average, and compute the weighted average of models (dark red bar) and observations (dark blue bar): this is indicated by the magenta bar. As, due to common model uncertainties, model uncertainty can be larger than the intermodel spread, secondly, we also show the more conservative estimate of an unweighted, direct average of observations (dark red bar) and models (dark blue bar) contributing 50% each, indicated by the white box around the magenta bar in the synthesis figures.

More details on the computation of the synthesis can be found in [Li and Otto \(2022\)](#).

Despite the limited number of models used in the analysis, there is agreement among them indicating no significant change over the past and a slight increase into the future. The models furthermore agree with the observational products which taken together enhances confidence in the qualitative synthesis results. Confidence in the quantitative results is limited however, as despite the agreement between observations and model results, the credibility of the model outcomes is constrained due to the limited number of models and their performance at such a localised scale (the confidence in the model results remains limited as there are only 5 models used in the analysis and no models that validated very well, with the best two labelled as 'reasonable', see Sect. 4). Nonetheless, results show that future hazard increases in comparison with present conditions, although specific causative components warrant further investigation. Due to these constraints on the data, we only give a qualitative conclusion without quantifying the synthesised results. Note that for this qualitative statement it is not important whether we use all 5 models or only the 2 'reasonable' models. By combining evidence from past climate, future projections, and physical understanding, it is inferred that despite the current lack of statistical significance in the HDWI trend, the future hazard increases with respect to the present. Therefore, the hazard component of the risk of increased dangerous fire weather conditions due to human-induced climate change should be taken seriously.

The recent Chile mega-drought, with a quarter of its rainfall deficit attributed to climate change, provides valuable context for understanding the risk of increased dangerous fire weather conditions in addition to the HDWI assessed here. The drought conditions, combined with intensive land use changes, corroborate the finding of increased risk of dangerous fire weather conditions.

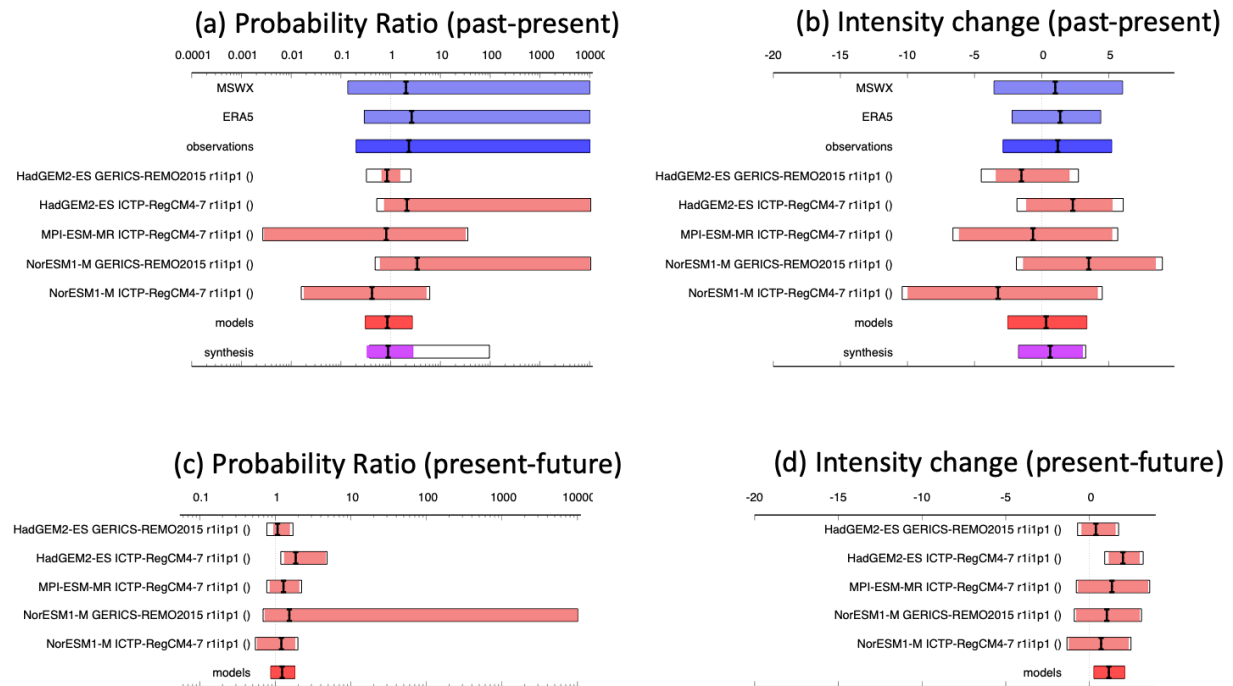


Figure 6. (a) Probability Ratio (PR) and (b) change in intensity in HDWI from past to present. (c) same as (a), from present to future. (d) same as (b), from present to future.

In an effort to understand how climate change influenced the major contributing climate variables that influenced the fire weather conditions of 2023/24 DJF over the study region, we repeat the trend detection based on observed datasets and hazard attribution analysis by combining with climate models as we already showed for HDWI. The two variables included in this analysis are (1) the 1-in 2 year prevailing 4-day wind

speed, which had a magnitude of 4.69m/s; it may be noted that the highest wind speed in the season was recorded during 9-12 December, 2023 with a magnitude of 4.72m/s in the MSWX dataset, and (2) the 1-in-100 year maximum VPD that was incidentally also the highest in the season, based on the MSWX dataset. Figures A3-A4 show the synthesised results for these variables. The wind speeds do not show significant changes in the probability and intensity attributable to the warming since pre-industrial times and under future warming levels (Fig. A3(a-d)). Between now and the pre-industrial climate, the probability ratio and intensity changes in the vapour pressure deficit encompass no change i.e not statistically significant. However, the best estimates suggest that the chances of the high VPD observed during the event are likely doubled due to warming until now and a further doubling in the likelihood of such events is expected in a future 2°C warmer world. The trend-fitting and attribution results for VPD are in line with the respective results for HDWI, suggesting that the trends in HDWI is seemingly explained by the accompanying large VPDt, which in turn is driven by high temperatures and low humidity. These results serve as an indication of the dominant role of prevailing hot and dry weather conditions in driving fire weather conditions in the region.

7 Vulnerability and exposure

Chilean wildfires have become a critical hazard that have taken the lives of hundreds of people over the years. Although fires are common, a small proportion of these events escalate into substantial incidents with significant ecological and socioeconomic impacts ([Ubeda & Sarricolea, 2016](#)). According to the news, the fires started accidentally on February 2, 2024 in the eastern region of Viña del Mar and nearby Quilpué, and Villa Alemana, all cities located in the Valparaíso Metropolitan Área (VMA), where fires spread quickly amidst dry weather and strong winds ([CDP, 2024](#) and [CNN 2024](#)). Over 29,000 hectares burned, leading to significant loss of life, while it is estimated that up to 12,000 residents in Viña del Mar and 2,000 in Quilpué in the VMA are affected ([Act Alliance, 2024](#)). Previously, the combination of a severe drought and persistent heat waves have led to extreme fire weather conditions in Central Chile in 2017 exposing over 9.5 million people to increased concentrations of particulate air pollution ([Bowman et al., 2019](#); [Garreud et al., 2020](#)), and now also in the deadly fires of 2023.

The rapid spread of the VMA fire in Chile was most likely fostered by a combination of factors - including high temperatures, low humidity, dryness, and strong winds - that increased the conditions favourable for wildfires to spread rapidly ([Jones et al., 2022](#)). These environmental conditions, exacerbated by human-induced factors such as land-use changes and agricultural practices, likely amplified the intensity and extent of the fires ([Cordero et al., 2024](#)). According to the International Disaster Database (EM-DAT), the recent VMA fire is one of the deadliest wildfires since 1900, surpassing even the tragic blazes in Paradise, California, in 2018 and those in Maui, Hawaii last year. The 2014 Valparaíso fire devastated the city, affecting over 12,000 people, destroying 2,910 homes across seven hills, resulting in 15 fatalities, and impacting 148 hectares of the urban area ([Ubeda & Sarricolea, 2016](#)). Similarly, wildfires in Chile in 2017 and the more in February 2024 have caused significant devastation and garnered international attention. In 2017, the fires affected 3,782 individuals, with a similar number of people being impacted in 2024. Around 1,151 people sought shelter during the 2017 fires⁵, while in 2024, an undisclosed number sought refuge in the 46 activated shelters across affected regions. In all instances, the wildfires caused widespread destruction, with 1,025 homes lost to the flames in each event. Tragically, 11 lives were lost in 2017 and 131 in 2024 due to the wildfires.

The VMA wildfires mark a sombre milestone in Chile's recent history, as not only the country's deadliest natural hazard since the 2010 8.8 earthquakes, but also the world's deadliest wildfire since the 2009 Australia bushfires ([UNDRR, 2024](#)). Additionally, while the fire weather conditions present during the 2024 wildfires is a 1-in-30 year event in today's climate, six of Chile's seven most destructive fire seasons have occurred since 2014 ([Cordero et al., 2024](#)). This underlines the country's vulnerability to wildfires, and notably, the central role of non-weather factors in driving impacts.

In this section, we provide a review of the vulnerability, exposure, and coping capacity factors which increased or reduced the fire risk and impacts in the 2024 Chile wildfires. After-action reviews and further research will be necessary to fully understand the key drivers in the event, and to inform improved disaster risk management including fire prevention and adaptation.

7.1 Exposure and spatial planning

Due to climate-driven extreme heat and prolonged drought, Chile faces high vulnerability, particularly due to increased fuel aridity of the forests, shrublands, and grasslands across vast geographical areas ([Pliscoff et al., 2020](#); [McWethy et al., 2018](#); [Miranda et al. 2023](#)). Wildfires predominantly affected the regions between Valparaíso and Araucanía due to a combination of dry summer conditions and a thriving forest industry, incentivising the exploitation of non-native species like *Pinus radiata* and *Eucalyptus globulus* ([Pozo et al., 2022](#)). In creating these monocultures, natural barriers present in native forests have been eliminated ([Heilmayr et al., 2016](#)). Human factors, such as population density, also influence wildfire activity in south-central Chile ([Pozo et al., 2022](#)), which are the most inflammable species in the Valparaíso region ([Guerrero et al, 2020, 2021](#)). The most devastating fires occur in areas with significant land-use change and inadequate urban planning regulations, proper building regulations are less commonly enforced, and emergency services have limited access due to narrow streets ([Braun et al., 2021](#)).

Renowned for its beaches and botanical gardens, the seaside town of Valparaíso and Viña del Mar are popular tourist destinations. As the fires struck during the holiday season, there was an increase in people exposed to the fires. The fires consumed densely populated hilltop communities, especially in Viña del Mar and Quilpué and Villa Alemana ([Washington Post, 2024](#)). In Viña del Mar, one suburb alone, Villa Independencia, saw 19 people killed and thousands of homes razed. Here, families live crowded in homes built of light materials like wood ([NY Times, 2024](#)).

Wildland Urban Interface (WUI) areas, prevalent in and around the VMA, pose a higher wildfire risk as they expose human lives and property to greater danger. With an estimated 99,7% of wildfires ignited due to human negligence, continued urbanisation can exacerbate this risk by bringing communities closer to forestry plantations ([Ubeda & Sarricolea, 2016](#); [Sarricolea et al., 2020](#); [CONAF, n.d.](#)). Factors such as dwelling proximity to neighbours, distance from vegetation, proximity to dwelling groups' borders, and distance from the fire's origin significantly influence fire damage predictions. Additionally, structural attributes associated with less affluent homes may further increase the likelihood of damage, although more data is needed for confirmation ([Aguirre et al., 2023](#)). An estimated 70% of the homes destroyed in the wildfires were concentrated in informal settlements where improper forest management in nearby wildland and plantations, trash-strewn streets, and houses predominantly built with flammable materials increased

the fire risk ([CPI, 2024](#)). Media reports that some of these communities were ravaged in a matter of minutes ([Washington Post, 2024](#)).

To highlight the potential risks, vulnerabilities and challenges faced by individuals, organisations, and response services, it is essential to link the exposure with the legislation and policy.

7.2 Legislation, policy, and funding

Chile has a comprehensive disaster risk management and policy framework, including the 2002 National Civil Protection Plan, 2012 National Platform for Disaster Risk Reduction ([Government of Chile, 2022](#)), 2014 National Plan for Adaptation to Climate Change, 2017 National Emergency Plan, 2020 National Policy on Disaster Risk Reduction ([BCN, 2021](#)), and 2021 National Disaster Prevention and Response System ([Government of Chile, 2022](#)). Notably, the 2023-24 National Forest Fire Prevention, Mitigation, and Combatting Plan outlines the government's strategy to increase connectivity for at-risk areas which are prone to isolation in case of emergency, in part by equipping the country with 260 heliports used for emergency response, benefitting approximately 2.5 million people ([Government of Chile, 2024](#)).

Since its establishment in the 1970s, Chile's fire authority, CONAF, under the Ministry of Agriculture, is responsible for coordinating wildfire prevention programs and organising the logistics of fighting wildfires ([ITA, 2021](#)). It is supported by the National Service for Disaster Prevention and Response (SENAPRED). CONAF has its own fleet of aeroplanes and helicopters for firefighting, and it also collaborates with other institutions such as CORMA, a Chilean trade association that brings together entities from the forestry sector. In addition to its aerial resources, CONAF also has an annual budget for regular planned acquisitions and basic equipment that needs to be replaced every year. These acquisitions include various firefighting and prevention equipment such as motor pumps, hoses, manual tools, and fire extinguishers. Chile is estimated to invest \$100m a year in firefighting, which was extended by a further \$50m after 2023's deadly fires ([Meadows, 2024](#)).

In 2016, CONAF signed an agreement with the the Department of Forestry and Forest Fire Protection of the State of California (Cal Fire), of the United States of America to collaborate on fire prevention and learn from new global models for addressing forest fires. The key focus has been on active involvement of local governments and communities in initiatives like creating firebreaks and clearing vegetation to lower the risk in urban-rural interface zones. ([CONAF, 2017](#)). CONAF has been instrumental in organising international workshops focused on the central themes of climate change, atmospheric conditions, technological advancements, and global measures implemented to address forest fires ([CONAF, 2020](#)). More recently, a national delegation of CONAF firefighters have been sent to fight fires in Canada in 2023 ([CONAF, 2023a](#)). The inaugural meeting of the Forest Fire Innovation Community in the Biobío Region, part of the FIRE-RES project coordinated by Centre for Forest Science and Technology of Catalonia (CTFC) in Spain and funded by the EU's Horizon 2020 program, aimed to develop cutting-edge fire management technologies. Chile's participation was based on its experience with the 2017 sixth-generation fires and the meeting focused on analysing the 2022-2023 fire season, identifying gaps, and discussing innovations for provincial and regional fire management ([CONAF, 2023b](#)).

These initiatives show that CONAF has been making significant strides in ensuring that the agency is well equipped to prevent and control wildfires. Moreover, CONAF implements rules in protected areas which

prohibit free campfires under any circumstances (Law N° 20.653), and strict compliance with trail closing times, registration at ranger stations, and removal of all litter. Specifically for fire safety, there is prohibition of campfires except in designated areas, prohibition of using fire for waste disposal, with penalties for causing forest fire risks, including fines, jail, or deportation for foreigners. Users are advised to exercise caution, follow safety measures, and never act independently near a fire. Smoking is strictly forbidden within Protected Areas ([CONAF, n.d.](#)).

7.3 Fire risk management

7.3.1 Adaptation and fire prevention

Chile's early warning system (EWS), hosted by the National Service for Disaster Prevention and Response (SENAPRED), is largely shaped by the aftermath of the 8.8-magnitude earthquake in 2010. Sirens have been installed across coastal regions, and mass alerts are disseminated via text, audio, and vibration to compatible cell phones ([CFE-DM, 2021](#)). SENAPRED coordinates disaster response at various levels, including the issuance of said warnings ([CFE-DM, 2021](#)). Despite a 100% increase in funding for combating wildfires over the past decade, the severe 2023 wildfire season in Chile showcased the urgent need for further investment in adaptation, including improving the country's EWS such as by incorporating meteorological indicators, technology such as radars and remote sensing monitoring, which can be complemented by an ENSO forecast relevant to Chile ([Cordero et al., 2024](#)). Further, research by Sarricolea et al. ([2020](#)) suggests a range of measures for mitigating fire risk, such as wildfire prevention protocols, controlled fires, firewall creation by reintegrating native species, housing protection radios, and improved spatial planning and monitoring systems.

In addition, since 2022, Chile has a Climate Change law in place. One of the objectives of the law is to build resilience against the adverse effects of climate change, such as wildfires. To this aim, all regions and municipalities will have to design and implement climate action plans. While still in the process of being designed, together with the disaster risk reduction plans mandated by SENAPRED, they prompt regions and municipalities to build resilient landscapes, urban-rural interfaces, and urban areas and communities.

Unscathed by the fires which ravaged its surrounding communities, Villa Botania, near the city of Quilpué, has emerged as an example of where a prevention plan indeed fends off disaster. With a pilot fireproofing program developed by CONAF and Cáritas Chile, and funded by USAID, residents were prepared and the land managed ([Washington Post, 2024](#)). Over the course of the past year, plants have been controlled and pruned regularly to limit the available combustible material, and water points implemented to maintain soil moisture ([News Breezer, 2024](#)). Additionally, residents have enrolled in a year-long training which centered on emergency drills ([News Breezer, 2024](#)). The neighborhood's resilience serves as a stark reminder that disasters are not natural but a result of natural hazards meeting vulnerability and a lack of coping capacity - both of which are determined by political and social processes ([Raju et al., 2022](#)).

7.3.2 Response and recovery

In the first week of December 2023, SENAPRED issued early preventive alerts for increased risk conditions for the Biobío and Valparaíso regions ([IFRC GO, 2024](#); [BNN, 2023](#)). Towards the end of December, a fire

started near Viña del Mar, prompting SENAPRED to issue a red alert and order evacuations ([IFRC, 2024](#)). Almost two weeks ahead of the peak of the fires, on 20 January, the Chilean Red Cross (CRC) launched an emergency operation in response to the wildfires ([IFRC, 2024](#)). Later, on 10 February, CRC was granted a CHF 496,982 Disaster Relief Emergency Fund allocation to cover their four-month emergency response during which they are targeting nearly 10,000 people across Valparaíso ([IFRC GO, 2024](#)).

By 2 February, hundreds of fires had ignited and were increasing in intensity while approaching densely populated areas, prompting evacuation across the VMA. That afternoon, the President of Chile declared a State of Catastrophe for the Valparaíso region, and on the next day, a State of Constitutional Exception of Catastrophe for Biobío, Nuble, and La Araucaria regions ([IFRC, 2024](#)). On the evening of 3 February, and subsequently on 4 February, curfews were implemented across Viña del Mar, Quilpué, Villa Alemania, and Limache to expedite the deployment of emergency vehicles including firefighting, rescue, and healthcare personnel teams, and distributing material assistance ([France24, 2024](#); [Yahoo, 2024](#); [UN RC Chile, 2024](#)). After the declaration of catastrophe, SENAPRED was involved in the process of evaluating and designing response measures, while the Executive Power called for a meeting of the Disaster Risk Management Committee (COGRID), headed by the Interior Minister, to plan and fund institutional priorities, encompassing mitigation and reallocation measures ([Act Alliance, 2024](#)).

As of 5 February, SENAPRED had delivered over 560 tons of aid ([UNDRR, 2024](#); [IFRC, 2024](#); [SENAPRED, 2024](#)), and deployed at least 31 firefighting aircrafts, 1,400 firefighters, and 1,300 military personnel to combat the deadly fires ([France24, 2024](#)). Meanwhile, the government has implemented initial assistance programs for those affected by the wildfires in Valparaíso, identified as affected individuals through the Basic Emergency Sheet (FIBE). These packages include housing rental subsidies, recovery bonuses for damaged homes, reception bonuses for displaced individuals, monetary transfers for moderate damage, and the provision of temporary housing. Additionally, 19 emergency shelters and 8 storage centers have been established by national authorities to provide support to the affected population ([Cooperativa.cl, 2024](#); [UN RC Chile, 2024](#)). Meetings have also been held with the international community to ensure timely and coordinated action in responding to Chile's call for international assistance ([IFRC, 2024](#)).

While several alerts were issued between December and February, the government reports that a number of communications antennas had been scorched and left inoperable around the peak of the wildfires, in combination with widespread power outages, ultimately preventing warning messages from reaching at-risk populations ([Subsecretaría de Telecomunicaciones, 2024](#)). Already on 6 February, President Boric asked the European Union to investigate the functioning of the Emergency Alert System (SAE) ([Duna, 2024](#)). Further, there is anecdotal evidence suggesting that some of the warning messages which were disseminated only stated “evacuate”, without additional instructions about where to go, creating confusion among recipients ([The Conversation, 2024](#)). The scope of these challenges and their respective roles in the materialisation of the disaster remain to be confirmed by after-action reviews.

V&E conclusions

Increasingly frequently, Chile and the Valparaíso region are faced with devastating wildfires. Keeping in mind the 30-year return period of the studied event, however, it is clear that non-weather factors play central roles in driving impacts. In this vulnerability and exposure analysis, we showcase how risks faced are

worsened by current land management practices, such as the expansion of Wildland-Urban interfaces (including the growth of informal settlements in forest zones) and widespread conversion of native forest areas to foreign and monoculture plantations. Significant investments into fire prevention and adaptation have been made over the recent decade, but they have shown limited effectiveness in adequately mitigating the fire risk, in part due to low risk perception and awareness among residents in fire-prone areas. A salient example of successful fire prevention can be found in the pilot fireproofing program of Villa Botania. The area remained unscathed from the surrounding flames, thanks to water-based firebreaks, community-led vegetation control, and robust emergency training. To reduce the risk of similar disasters, measures should encompass improved spatial planning; enhanced coordination, resource allocation, and community engagement in fire prevention and adaptation; and continued awareness raising campaigns. Additionally, after-action reviews and further research will be essential to fully understand the factors at play and learn from the disaster.

Data availability

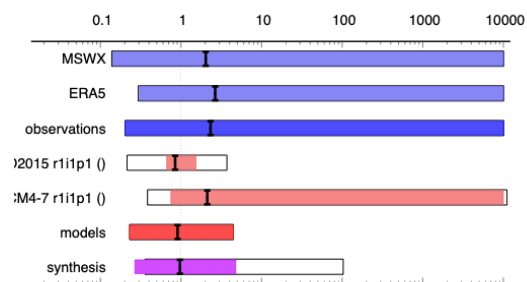
Almost all data will be available via the [Climate Explorer](#). For those not, they can be availed upon request.

Appendix

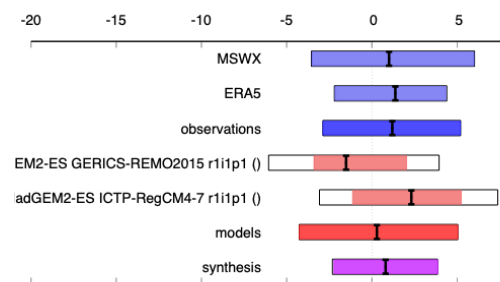
Table A1. The trend in DJF maxima of HDWI4day with respect to GMST and Nino index in the ERA5-Land and the MSWX datasets.

Dataset	Covariates	Trend_ GMST	Trend_ Nino
ERA5-Land	GMST, Nino12 at lag 0	1.810 (-1.618 ... 4.144)	0.729 (0.118 ... 1.654)
ERA5-Land	GMST, Nino34 at lag 18	0.388 (-2.55 ... 3.386)	-0.603 (-1.485 ... 0.503)
MSWX	GMST, Nino12 at lag 0	1.838 (-2.344 ... 4.958)	1.039 (0.355 ... 2.132)
MSWX	GMST, Nino34 at lag 18	-0.201 (-4.624 ... 4.212)	-0.691 (-1.912 ... 0.688)

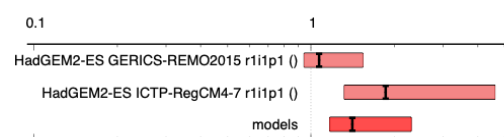
(a) Probability Ratio (past-present)



(b) Intensity change (past-present)



(c) Probability Ratio (present-future)



(d) Intensity change (present-future)

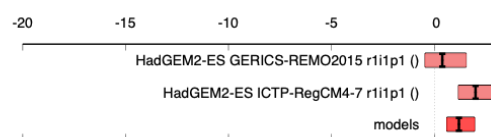
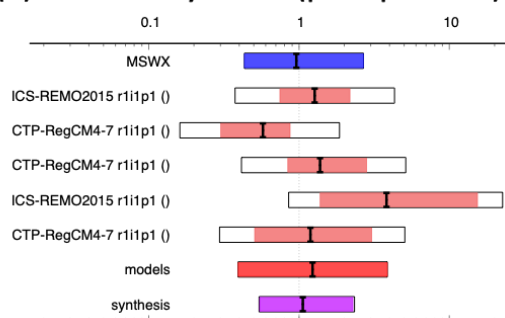
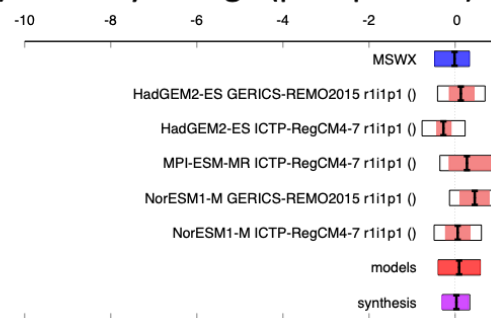


Figure A1. (a) Probability Ratio (PR) and (b) change in intensity in HDWI for the selection of 2 reasonable models from past to present. (c) same as (a), from present to future. (d) same as (b), from present to future.

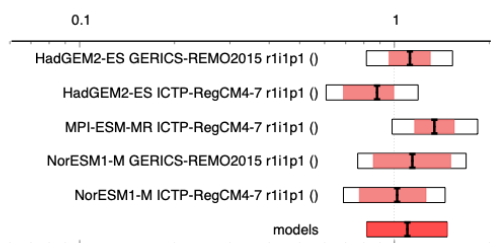
(a) Probability Ratio (past-present)



(b) Intensity change (past-present)



(c) Probability Ratio (present-future)



(d) Intensity change (present-future)

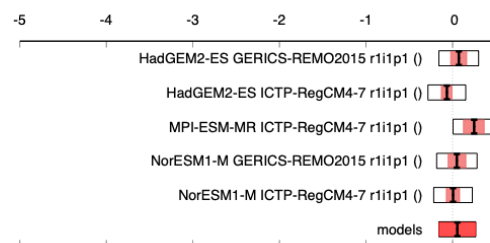


Figure A2. (a) Probability Ratio (PR) and (b) change in intensity in 4-day max wind speed from past to present. (c) same as (a), from present to future. (d) same as (b), from present to future.

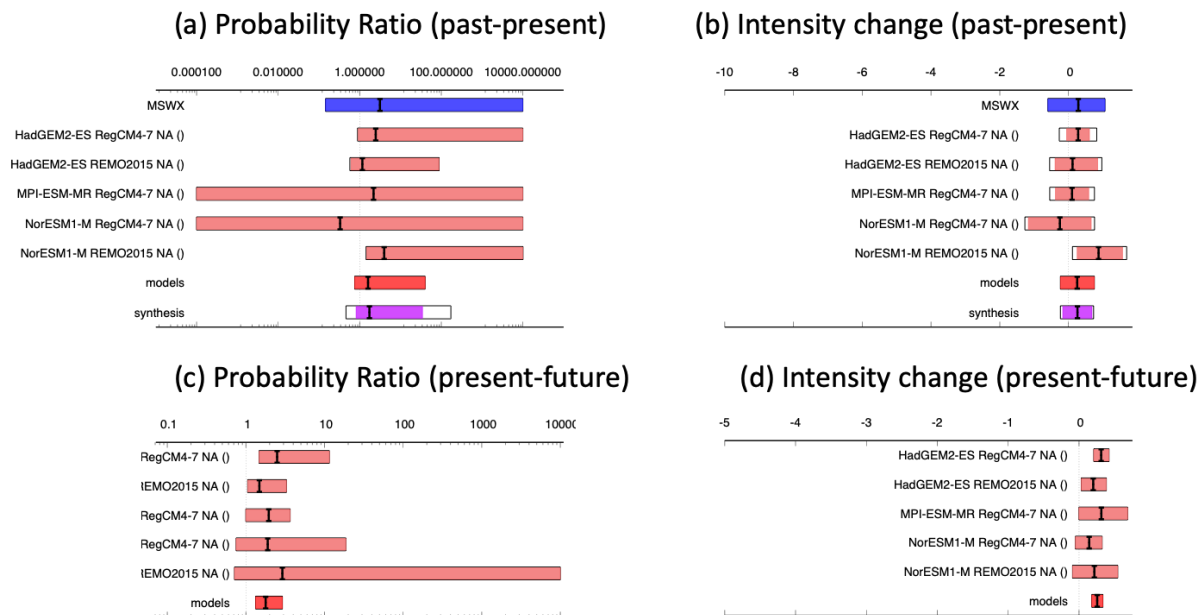


Figure A3. (a) Probability Ratio (PR) and (b) change in intensity in 4-day max vapour pressure deficit from past to present. (c) same as (a), from present to future. (d) same as (b), from present to future.

References

All references are given as hyperlinks in the text.