III. SCIENTIFIC SUMMARY/ RESUMEN CIENTÍFICO (The maximum length for this section is 4 pages)

SUMMARY

Chile is increasingly affected by multiple hazardous extreme events occurring either simultaneously, as compound events, or consecutively, as cascading events.

Multiple hazardous events are considered compound when they occur at the same time. For example, central Chile (the most populated region in the country) has been hit by frequent and severe droughts worsened by increasing heatwaves (HWs) that have fueled persistent wildfires. These frequently concurrent “dry” hazards have affected crops, led to food shortages for livestock, and heavily impacted the economy.

Cascading events act as a series of toppling dominoes. For example, in southern Chile, heavy orographic rainfall associated with potent Atmospheric Rivers (ARs) has led to severe flooding, that by carrying nutrient-rich sediments into lakes and fjords, has in turn favored Harmful Algal Blooms (HABs). In the same region, the rapid melting of the Patagonian icefields is not only funneling reactive iron into lakes and fjords (favoring more algal blooms) but has also resulted in the formation of hundreds of new lakes. Sudden lake drainage events (so-called Glacial Lake Outburst Floods or GLOFs) have led to catastrophic landslides and flooding erasing small villages in the region.

As with other climate-related impacts, increasing compound and cascading events disproportionally affect vulnerable populations and minorities. Improving the adaptive capacity of Chile to deal with climate extremes requires improved understanding of the underlying physical mechanisms driving their occurrence. This proposal, involving an interdisciplinary group of researchers (climatologists, meteorologists, hydrologists, glaciologists, oceanographers and data scientists), aims to address this challenge.

Our main goal is to assess the severity and frequency of compound and cascading events in Chile. We will focus on six costly and/or deadly hazards (heatwaves, droughts, wildfires, atmospheric rivers, GLOFs, and algal blooms) that often occur as compound or cascading events. Rather than applying the traditional risk assessment methods (that typically only consider one driver and/or hazard at a time), we will investigate spatial-temporal patterns of concurrent hazards (for example, HWs-fires-droughts) and consecutive hazards (for example, heatwaves-> droughts-> fires; or atmospheric rivers -> flooding -> algal blooms).

We aim to reconstruct the changes that have occurred in the last four decades, project future increases and unveil physical mechanisms responsible for such changes. We will combine existing datasets of individual hazards with climate observations to identify hotspots of compound effects and associated trends, as well as to identify main drivers. In addition, by using Regional Climate Models (RCMs), and assuming an array of emission scenarios, we will assess the expected increase by mid-century in the risk of compound and cascading events.

Our three-year interdisciplinary research will pursue these goals in closely connected tasks that will deliver models for wildfire ignition/spread in central Chile (1) and glacial lake outburst floods for benchmark catchments (Baker River, Exploradores River, Manflas River) (2). We will also assess recent changes in the frequency of intense atmospheric rivers (3) flash droughts in central Chile (4) and algal blooms in Patagonian fjiods (6), while investigating the influence on climate extremes of large-scale climate modes (such as the Madden Julian Oscillation (MJO), El Niño Southern Oscillation and the Southern Annular Mode (SAM)) (6), as well as the current

spatial-temporal patterns (7) and expected progression of compound and cascading events in Chile (8). All these tasks encompass activities related to training, outreach, and networking.

Our team is collaborative and diverse and has a proven record of successful partnership in the form of joint publications. We have significant experience leading dozens of research projects (including two prior *Anillos*). Our prior work on climate extremes has been published in high-impact journals such as the Bulletin of the American Meteorological Society (BAMS) and Nature Sustainability.

Also, our researchers collaborate with colleagues from world-class research centers such as the National Aeronautics and Space Administration (NASA), the Deutsches Zentrum für Luft und Raumfahrt (DLR), and Earth System Science Department at Stanford University. Our researchers have strong local ties with the Chilean Weather Service (DMC), the Chilean Agency for Water Resources (DGA), and the Chilean Emergency Agency (ONEMI).

Although our team has a record of successful collaboration, as this research crosses disciplinary, organizational, national, and/or cultural boundaries, we have adopted a collaboration scheme that includes: a clear strategy (to provide a communal sense of purpose and identity), flexible structures and customized processes (that will facilitate the participation of national and international partners), and extensive use of technology (that will enable quality cross-border collaboration and virtual teaming). Our collaboration scheme will lead to improved governance through strengthened relationships, information exchange and joint problem solving.

In addition to delivering leading edge research on climate extremes in Chile, we are committed to ensuring a strong linkage between basic science and applied research, providing hands-on mentoring and exciting opportunities for early-career researchers in a collaborative, diverse, open and welcoming environment; four new postdoc positions will be offered at the very beginning of the project.

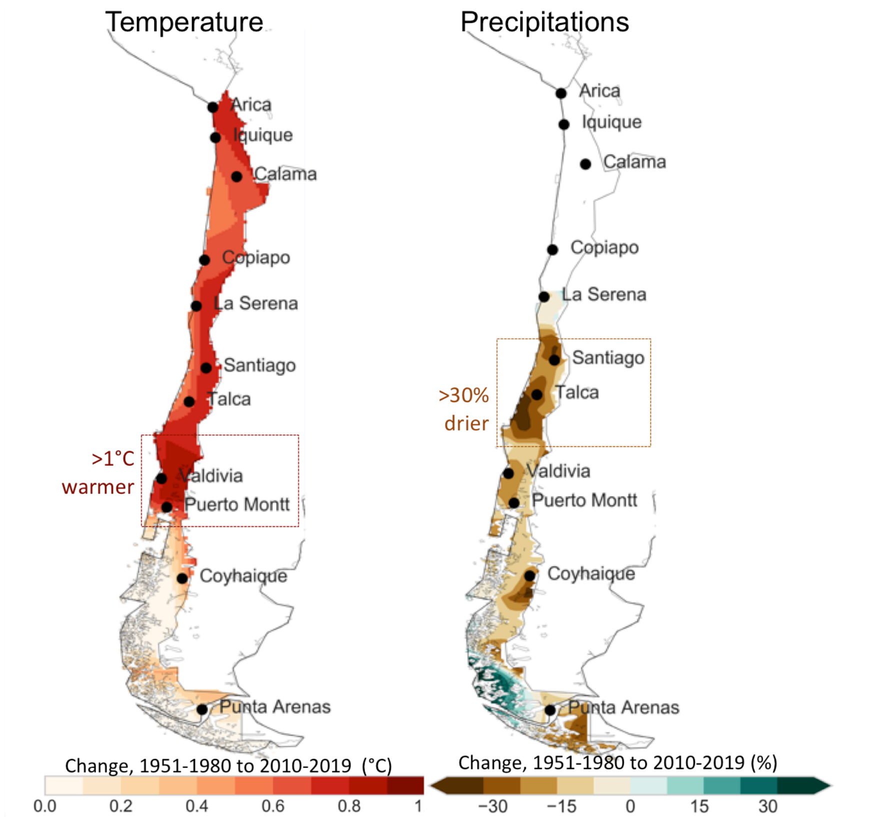
We also place a high priority on disseminating the results of their research to the wider community. Hence in addition to our research activities, particular attention will be paid to bridging science and society and communicating complex research findings to decision makers. We are committed to provide a scientifically sound foundation for debate and policy development on climate change adaptation and risk mitigation, and to engage the public.

The climate extremes pose serious challenges to Chile due to its vulnerability (determined by population density, percentage of the low-income population and their spatial distribution) and its limited adaptive capacity (determined by limited access to information/ resources and a weak institutional framework /governance). These challenges underline the importance of this proposal. We expect that, by leading to an improved understanding of extreme events in our country, we will ultimately contribute to build a more resilient society.

IV. PROJECT DESCRIPTION Maximum extension **20 pages** *(does not include appendices)*

CLIMATE EXTREMES IN CHILE

Chile is a 4,300 km-long, narrow country between the Andes to the east and the Pacific Ocean to the west subjected to different climate regimes and exposed to a wide range of damaging and dangerous weather-related hazards.



Data Source: GISS Surface Temperature Analysis (GISTEMP) and https://precip.gsfc.nasa.gov/gpcp_v2.2_comb_new.html.

Central Chile is becoming rapidly warmer and drier.

The Andes Mountains span along most of the country and act as a barrier to moisture transport from either Amazon basin or the Pacific Ocean, which often leads to heavy orographic precipitation. Even cities in the hyperarid Atacama regions of northern Chile are subject to rare episodes of flooding due to orographic rainfall (Bozkurt et al., 2016). Atmospheric Rivers (ARs), that can transport an amount of water vapor from the tropical Pacific equivalent to tens of times the flow of terrestrial rivers, are an increasing threat. In southern Chile, potent ARs have dropped a month's worth of precipitation in a few hours, increasing the discharge of some rivers by ten-fold (Aceituno et al., 2021).

Central Chile (the most populated region in the country) has been hit by frequent and severe droughts (Garreaud et al., 2020) worsened by increasing heatwaves (HWs) (Feron et al., 2019) that have in turn fueled persistent wildfires (Dacre et al., 2018; Úbeda & Sarricolea, 2016). Central Chile has experienced a severe megadrought during the last decade, and 2020 was the warmest year on record for central Chile with 16 HWs hitting Santiago (DMC, 2021). These recurrent extremes have affected crops, led to food shortages for livestock, increased wildfire risk and impacted the economy (Aldunce et al., 2017). Nearly two million of ha. burned during the last decade in central Chile, enveloping towns and cities in toxic haze and smoke (González, et al., 2020).

The Patagonian icefields, that stretch over hundreds of kilometers atop the Andes mountain range in southern Chile, are rapidly melting at one of the highest rates on the planet. Glacier retreat has resulted in the formation of hundreds of new lakes and sudden lake drainage events (so-called Glacial Lake Outburst Floods or GLOFs) that have erased small villages (Ross et al., 2020). Glacial melt is also funneling reactive iron into lakes and fjords, boosting Algal Blooms (ABs) (Glesecke et al., 2019) that often have become Harmful Algal Blooms (HABs) (Meerhoff et al., 2019).

	Hazard	What we know	What we do not know
1	**Heatwaves** (HWs) can be understood as a period of consecutive days with considerably warmer conditions than normal for a specific region and time of the year (Perkins, 2015; Perkins and Alexander, 2013). HWs are of great importance not only for ecosystems, but also for socioeconomic systems, since extreme temperatures may lead to heat strokes, blight of crops, and may also have negative impacts on the water- and electricity supply (Ragone et al., 2017; Chen and Li, 2017). HWs can also significantly increase morbidity and mortality rates (Franzke et al., 2017; Muthers et al., 2017).	Globally, HWs have already increased and/or intensified over the last few decades, and climate projections reveal a further intensification in many regions. (Feron et al., 2019; Dosio et al. 2018; Coffel et al. 2017; Perkins-Kirkpatrick & Gibson, 2017; Baker et al. 2018; Franzke et al., 2017; Horton et al., 2016; Russo et al., 2014). In Chile, the number of HWs has surged in recent decades, in particular, in central and southern Chile (Feron et al., 2019; Piticar, 2018). Although significant, the surge has so far been less pronounced in northern Chile.	Further research is needed on the spatial-temporal occurrence of heatwaves and other frequently concurrent dry hazards (such as wildfires and droughts) as well as the effect of large-scale climate modes (such as the Madden Julian Oscillation (MJO), El Niño Southern Oscillation and the Southern Annular Mode (SAM)) on the frequency of heatwaves in Chile.
2	**Wildfire** season in central Chile reaches a peak in January, and since the 1980s, on average 5,500 events are recorded per year, with an annual burned area of about 55,000 ha. (CONAF, 2020). However, forest fire risk in central Chile is increasing (González, et al., 2020). In 2017, unusually hot weather and a drought caused the wildfire season to start in December (Bowman et al., 2018; De la Barrera et al., 2018). Two months later, fires in central Chile had burned more than 500,000 ha, enveloping towns and cities in toxic haze and smoke.	Recent droughts (Damiani et al., 2020; Garreaud et al., 2017) and high temperatures (Feron et al., 2019) have made forests more vulnerable. Eastward winds in central Chile play a large role in fanning the flames and quickly spreading fires (Montecinos et al., 2017). These winds are fueled by high-pressure air moving toward lower-pressure areas and lower elevations near the coast. On the way, the air masses pass over the Andean mountain ranges and down through valleys, which causes the air to compress, heat up, and dry out (Montecinos et al., 2017).	Despite the sharp increase of forest fire risk in central Chile (González, et al., 2020), the effect of different combinations of pre-existing fuel conditions and weather (temperature, humidity, winds, etc.) on wildfire ignition/spread has not been comprehensively studied in Chile. To date, no model for wildfire ignition/spread tailored to local conditions exists in the country.
3	**Drought** is a moisture deficit serious enough to have environmental, economic or social effects (Bachmair et al., 2016). According to the World Resources Institute (WRI, 2019), Central Chile (28-36°S) faces "high" levels of water stress, as on average more than 40% of available supply is withdrawn annually. Such a narrow gap between supply and demand leaves more than 80% of the Chilean population vulnerable to fluctuations from increased water withdrawals or droughts (WRI, 2019).	Central Chile has experienced a megadrought since 2008 that has devastated crops, led to food shortages for livestock, increased wildfire risk, and negatively impacted the economy (Garreaud et al., 2017). The situation puts pressure on key sectors of the local economy such as mining and agriculture. By mid 2020, Local Governments had to supply water to hundreds of thousands in the worst hit areas by using water tankers (MOP, 2020).	Despite the "high" levels of water stress in central-southern Chile (and the high incidence of HWs and wildfires), the role of droughts (and flash droughts) on the number and duration of compound dry events (concurrent hazards: heatwaves-fires-droughts) and cascading events (consecutive hazards: heatwaves -> droughts-> fires) has not yet been studied in Chile.

	Hazard	What we know	What we do not know
4	**Glacier hazards** such as glacial-lake outburst floods (GLOFs) and rock–ice avalanches cause significant socioeconomic damages worldwide, and the frequency of these events is expected to increase as temperature rises (Anacona et al., 2018; Ross et al., 2020).	Recent glacier retreat in Chile resulted in the formation of hundreds of new lakes and several existing lakes are growing (Wilson et al., 2018). Associated floods are very common phenomena in Patagonia but have also been observed in the Chilean Dry Andes. Also, important rock-ice avalanches have been observed in Chile in recent years. In December 2017 a rock-ice avalanche of an estimated volume of 7 million cubic meters reached the location of St Lucia (43ºS), killing 21 persons (Somos-Valenzuela et al., 2020).	Despite the thousands of glacier in the Chilean Andes, no glacier hazard maps exist in Chile at the moment. In benchmark catchments (Baker River, Exploradores River, Manflas River), lakes susceptible to trigger GLOFs still need to be identified.
5	**Algal blooms** occur naturally but under certain conditions (warm water, high solar irradiance, plus nutrients that often washed off agricultural fields or aquaculture centers by extreme precipitations) they can multiply and form potentially toxic blooms (Meerhoff et al., 2019). When toxin-containing aquatic organisms multiply and form a bloom, it can contaminate drinking water and sicken marine organisms. Due to its long Chilean coast and the hundreds of in-land lakes, the country is vulnerable to Harmful Algal Blooms (HABs)-related hazards (which is particularly critical in lakes and reservoirs that people use for both recreation and water supply).	Recent harmful algal blooms along the Pacific coast of North and South America as well as major lakes have exhibited an unprecedented extent and intensity (Müller et al., 2020). A HAB event during the 2016 austral, causing the worst mass mortality of fish and shellfish ever recorded in the coastal waters of western Patagonia (Mardones et al., 2021; León-Muñoz et al., 2018). Some algae only develop HABs when their cells attain very high concentrations, like the 2016 event in Chilean Patagonia (Mardones et al., 2021).	Chile has no record of algal blooms beyond a reduced set of lakes and fjords. No assessment has been conducted in Chile neither on the sensitivity of algal blooms to projected changes in weather extremes (at different timescales), nor the effects of concurrent or consecutives extremes events on algal bloom thresholds. There is also a lack of understating on the density-dependent thresholds driving the transition from algal blooms into HABs.
6	**Atmospheric Rivers** (ARs) stretch tens to hundreds of kilometers wide, can carry an amount of water vapor equivalent to tens of times the flow terrestrial rivers (Viale et al., 2018). These weather systems are essentially jet streams of moist air. When an AR makes landfall, particularly against mountainous terrain (such as the Andes), it releases much of that water vapor in the form of rain or snow. In subtropical and midlatitude Chile, ARs contribute 45 to 60% of the annual precipitation, most of it in the winter rainy season.	AR-related events have enhanced the discharge on some rivers by ten-fold, carrying nutrient-rich sediments into the coastal zone. Such outflows of nutrients promote and sustain algal blooms in the austral winter. In late June 2019, a potent AR event carried soaking rain into southern Chile, dropping nearly a month's worth of precipitation in just 48 hours. Up to 200 mm of rain fell over a wide area near Concepcion, leading to landslides and severe flooding in the Biobio and Araucania regions (Fustos et al., 2020).	Although Chile has made significant progress on local nowcasting and forecasting of ARs, special attention needs to be paid to the better understanding the role of ARs on triggering severe flooding, algal blooms and glacier hazards. It is unknown if the frequency of ARs making landfall in Chile has changed in recent decades and the influence of changes in large-scale climate modes (like MJO, ENSO or SAM).

COMPOUND AND CASCADING EVENTS

Extreme events often do not occur alone. According to the United Nations Office for Disaster Risk Reduction (UNISDR), any disaster entails a potentially compounding process, whereby one event precipitates another (Peduzzi, 2019). Climate extremes have serious environmental, economic, and social impacts on their own, but they can have devastating effects when they occur in combination (Zscheischler & Seneviratne, 2017).

Multiple hazardous events are considered compound when they occur at the same time, such as frequently concurrent dry hazards (heatwaves, droughts and wildfires) (Zscheischler et al, 2018). Cascading events act as a series of toppling dominoes, such as landslides and GLOFs that may occur after intense precipitations associated with ARs, or HABs triggered by changes in nutrient loads caused by flooding.

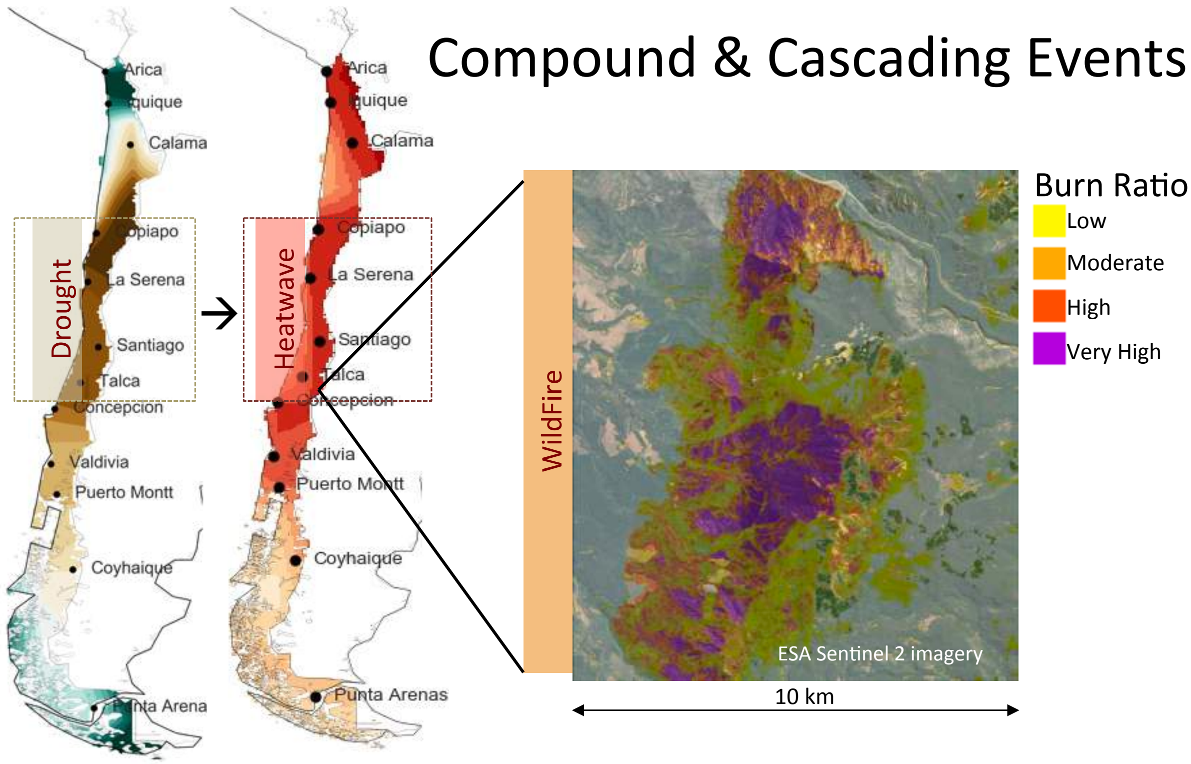
Compound and cascading events intensify the impacts of isolated hazards and may turn them into catastrophes affecting larger areas and causing expensive socioeconomic damages. The individual events are not necessarily extreme themselves, but collectively the physical drivers lead to an extreme event (Leonard et al., 2014, Sadegh et al., 2018). Compound events can even result from contrasting extremes (e.g., heavy rains and droughts) (Seneviratne et al., 2012).

Compound events may depend on the nature and number of physical variables as well as their physical and temporal extent (Leonard et al., 2014). Although the individual events may be causally unrelated, causes are often correlated, including:

1) a common external forcing factor that changes the probability of two or more events (e.g., due to the large-scale nature and intensity of the intraseasonal tropical variability, anomalies in the tropics can trigger cascading and compound events, as it has already being demonstrated for flash floods in the Atacama deserts, tornadoes in Southern Chile and heat waves Southeastern South America (e.g. Rondanelli et al, 2019, Barret et al, 2020 Jacques-Coper et al, 2021));
2) reinforcement of one event by another due to systemic feedbacks; and
3) conditional dependence of the occurrence of one event on the occurrence of another event (Seneviratne et al., 2012).

Climate change may alter the dependence between multiple contributing variables that lead to compound events (Hao and Singh, 2020). For example, for the Northern Hemisphere, Wang et al (2020) have shown that during 1960–2012, the average frequency (~1.03 days per decade) and intensity (~0.28 °C per decade) of summertime compound hot extremes was attributable to rising greenhouse gases (GHGs). It is therefore important to get a better understanding of compound events both for the present as well as for future climate scenarios.

Most research and practical risk studies have so far focused on estimating the frequency of occurrence of individual extreme events. Hence, there is an urgent need to better understand the likelihood and impacts of compound and cascading events in Chile as well as unveil physical mechanisms driving such events. This need is more pronounced considering that a significant fraction of the Chilean critical infrastructure (bridges, power plants, water reservoirs, etc.) has not been designed to account for the effects of cascading and compound events. This proposal, involving an interdisciplinary group of researchers (climatologists, meteorologists, hydrologists, glaciologists, oceanographers and data scientists), aims to address this need. We will focus on a number of costly and deadly hazards that, according to the available information, point to an increase in the risk of compound events (concurrent hazards) and cascading events (consecutive hazards) in Chile: HWs, droughts, wildfires, ARs, algal blooms and GLOFs.



One of the largest wildfires registered in Chile affected the "Radal Siete Tazas" national park, in the Maule Region, 50 kilometers east of Talca city. A severe drought worsened by increasing an persistent heatwave fueled a wildfire that burned more than 12 thousand ha. in February 2020.

OUR MISSION

Our mission is to assess the severity and frequency of compound and cascading events in Chile. Rather than applying the traditional risk assessment methods (that typically only consider one driver and/or hazard at a time), we will investigate spatial-temporal patterns of concurrent hazards (for example, heatwaves – fires - droughts) and consecutive hazards (for example, heatwaves-> droughts-> fires and atmospheric rivers -> flooding -> algal blooms). We will combine existing datasets of individual hazard identification with climate observations to identify hotspots of compound effects and associated trends, and to determine the main drivers. Moreover, by using Regional Climate Models (RCMs) and assuming an array of emission scenarios, we will also assess the expected increase by mid-century in the risk of compound and cascading events, as well as unveil physical mechanisms responsible for these increases.

In addition to delivering cutting-edge research on climate extremes in Chile, we are committed to providing hands-on mentoring and exciting opportunities for early-career researchers in a collaborative, diverse, open and welcoming environment; four new postdoc positions will be offered at the very beginning of the project.

By providing an improved understanding of extreme events in our country, we expect to build bridges between science and society and raise awareness, ultimately contributing to building a more resilient society.

OBJECTIVES

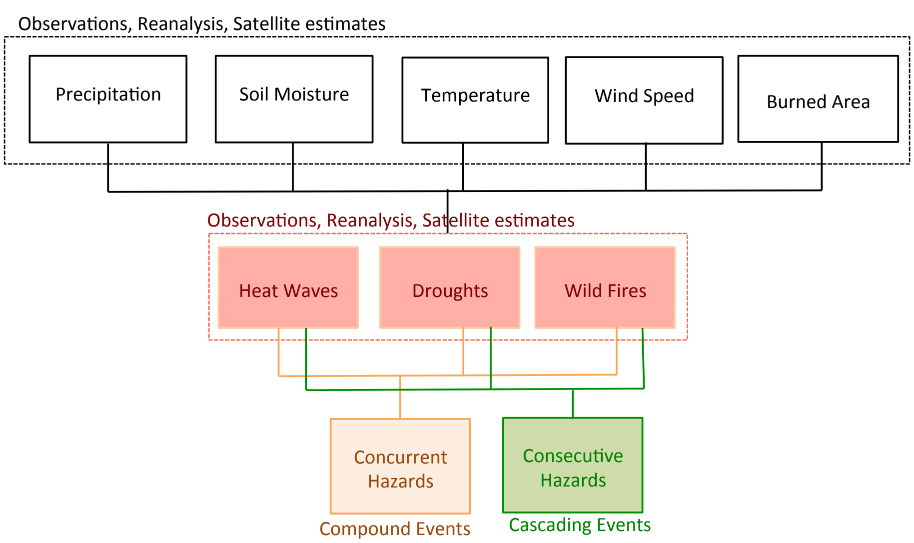
General Objective

The main aim of this project is to assess recent and projected changes in the occurrence of compound and cascading events in Chile. We will focus on a number of costly and deadly hazards that point to an increase in the risk of compound events (concurrent hazards) and cascading events (consecutive hazards) in Chile: HWs, droughts, wildfires, ARs, algal blooms and GLOFs.

Specific Objectives

1) Assess the influence of the recent changes in air temperature and soil moisture on the wildfire ignition/spread conditions in central Chile (30°-40°S).
2) Study the effect of large-scale climate modes (such as the Madden Julian Oscillation (MJO), El Niño Southern Oscillation and the Southern Annular Mode (SAM)) on the frequency of heatwaves and flash droughts in central Chile (30°-40°S) and in the Patagonia (40°-52°S).
3) Assess correlated changes since 1990 in the frequency/intensity of satellite-detected algal blooms in Patagonian fjords and Atmospheric rivers (ARs) making landfall in southern Chile.
4) Evaluate the risk of glacial-lake outburst floods (GLOFs) in benchmark catchments (Baker River, Exploradores River, Manflas River) and assess if heavy precipitations associated with high intensity atmospheric rivers (category 3 or higher) can trigger GLOFs.
5) Investigate recent spatial-temporal changes in compound events (concurrent hazards: HWs-droughts-fires) and cascading events (consecutive hazards: HWs-> droughts-> fires) by using observations and reanalysis dataset.
6) Project the expected changes by mid-century in the risk of compound and cascading dry hazards in central-southern Chile under different emission scenarios by using outcomes from regional climate models.

We will assess the recent changes (since 1980) in compound and cascading dry hazards (HWs, droughts and fires).



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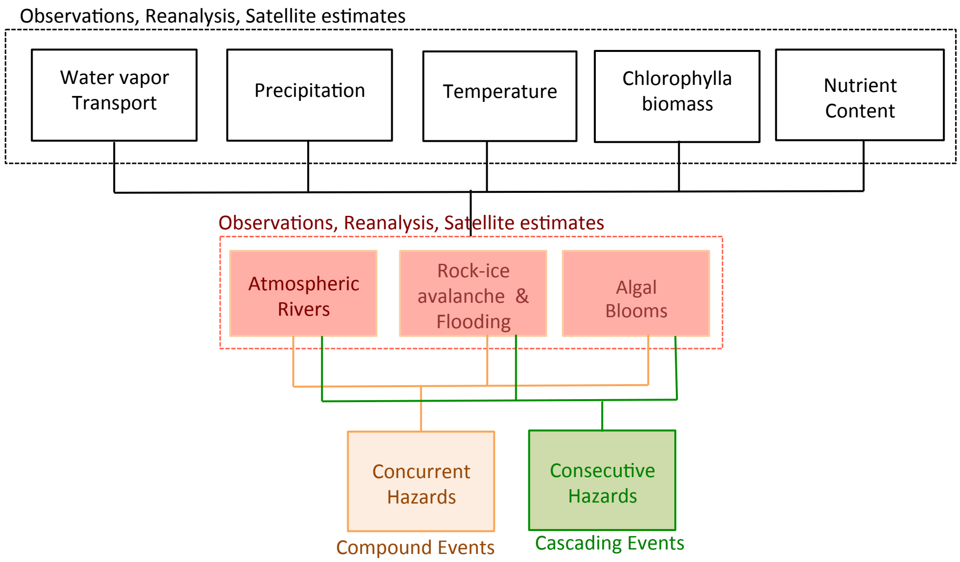
We will assess the recent changes (since 1980) in compound and cascading of hazards (Atmopsheric Rivers, Rock-ice avalanche & Flooding, and Algal Blooms).



HYPOTHESES

We will test the following hypothesis:

1) The wildfire ignition/spread conditions have significantly changed in the last four decades in central Chile (30°-40°S), which has been mostly driven by changes in the frequency of warm dry days (the effect of other parameter such the wind is not expected to be significant);
2) The frequency of flash droughts has significantly increased since 1980 in central Chile (30°-40°S). The changes are expected to be less moderate in southern Chile and Patagonia (where the influence of the Southern Annular Mode (SAM) is more important);
3) Atmospheric rivers (ARs) making landfall in Chile have significantly changed since 1980; while ARs decreased in central Chile (32°-40°S), they surged in Patagonia (40°-52°S). Satellite-detected algal bloom detections in fjords are correlated with AR landfalls.
4) The frequency of satellite-detected algal blooms has significantly changed since 1980 in fjords along the Chilean coast (36°-52°S). Due to fecal fertilization from fishes, changes in areas where the salmon industry operates are expected to be larger, hence promoting their transit into HABs due to density-dependent thresholds
5) The risk of glacial-lake outburst floods (GLOFs) has significantly increased due to heavy precipitations associated to the AR landfalls in Patagonia (40°-52°S). High intensity atmospheric rivers (category 3 or higher) can trigger GLOFs in benchmark catchments (Baker River, Exploradores River, Manflas River).
6) Regardless of the emissions scenario, changes in the number and duration of compound and cascading hazards associated to dryness (HWs, droughts and wildfires expected by midcentury) are expected to be greater in central Chile than in Patagonia.
7) Changes in the number and duration of compound and cascading hazards (HWs, droughts and wildfires) since 1980 have already exceeded the bounds of natural variability in most of the country. Although the frequency of individual hazards may have varied, changes in the number and duration of compound and cascading hazards related to ARs, GLOFs, and algal blooms are still masked by natural variability.