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Assessment of the impacts of climate change on the spatio-temporal patterns of freshwater sources to the coastal system of western Patagonia

Tesis para optar al grado de

Doctor en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales

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CONCEPCIÓN-CHILE
2023

SUMMARY

The western region of Patagonia is characterized by an almost pristine environment, with aquatic ecosystems composed of a great diversity of lakes, rivers and glaciers. The influence of westerly winds from the Southern Hemisphere results in high precipitation in the region, which determines large freshwater inputs to the coastal-marine system. In this vast (~400,000 km^2), narrow (~200-300 km) and transboundary (Chile and Argentina) area, freshwater ecosystems interact with one of the most complex and extensive fjord systems in the world. In these systems, freshwater produces a pronounced vertical stratification of two or three layers, which is a key regulator of circulation patterns and primary production, and limits the depth of turbulent mixing. Turbulent mixing determines the exchange of nutrients between the different layers of the water column, a process that can trigger pulses of primary productivity and thus an increase in autotrophic biomass in the western Patagonian inland seas.

Climate projections for most of Western Patagonia indicate a prolongation of the dry and warm conditions that have affected it in recent decades. Overall, the climate impacts recorded in Western Patagonia have been attributed to the Southern Annular Mode (SAM), which has shown a significant trend towards its positive phase. Given the heterogeneous and incomplete monitoring network of hydro-meteorological stations, most studies performed in this region have used only a very small subset of meteorological stations, satellite imagery or climate proxies to study environmental changes. Despite the low use of ground-based information, the region has shown evidence of a decrease in snow cover extent, an increase in forest fires, unusual tree growth patterns, a decrease in water availability and significant trends in major lakes, rivers and glaciers.

Considering the threads posed by climate change scenarios, the main objective of the present doctoral thesis is to assess the impacts of anthropogenic climate change on the spatio-temporal patterns of freshwater inputs to the coastal system of western Patagonia. To this end, four specific objectives have been proposed, each associated with a different phase of the present thesis.

The **first objective** explored the main trends, challenges and gaps in hydrological drought projections, using northern Patagonia (40-45ºS) as a study case. For this purpose, historical severe droughts and their climatic drivers in northern Patagonia were evaluated. In addition, a hydrological model was calibrated using a combination of satellite, reanalysis and ground-based data. To assess the impact of climate change on future severe droughts, 90 scenarios were used to account for multiple sources of uncertainty in the climate impact modeling chain. The projections obtained with the Coupled Model Intercomparison Project (CMIP) 6 and CMIP5 models showed significant climatic (greater trends in summer and autumn) and hydrological (longer droughts) differences, and therefore it is recommended that future climate impact assessments adapt the new simulations as more CMIP6 models become available.

Based on the detected hydrological gaps, the **second objective** was to develop PatagoniaMet (PMET) to analyze the hydrological consistency between atmospheric reanalysis models, ground-based meteorological observations and stream gauges. PMET is a compilation of ground-based hydrometeorological data (PMET-obs), and a daily gridded product of precipitation and maximum and minimum temperature (PMET-sim). PMET-obs was developed considering a 4-step quality control process applied to 523 hydrometeorological time series obtained from eight institutions in Chile and Argentina, while PMET-sim used statistical bias correction procedures, spatial regression models and hydrological methods. PMET-sim was compared against other bias-corrected alternatives using hydrological modelling, and achieved Kling-Gupta efficiencies greater than 0.7 in 72% of the catchments, while other alternatives exceeded this threshold in only 50% of the catchments.

Considering the hydrological importance of glaciers in the region and their uncertain evolution, the **third objective** used the Open Global Glacier Model (OGGM) to estimate the evolution of each glacier (area > 1 km^2) in the Patagonian Andes (40-56°S) over the period 1980-2099. To generate these projections, different glacier inventories (n = 2), ice thickness datasets (n = 2), reference climates (n = 4), general circulation models (n = 10), emission scenarios (n = 4), and bias correction methods (n = 3) were used to disentangle the importance of different sources of uncertainty from a hydrological perspective. Overall, the projections suggest that the northern area is expected to experience a steady decline, while the Patagonian Icefields should increase or maintain their glacier runoff in the coming decades. Considering the melt on glacier signatures, the future sources of uncertainty (GCMs, SSPs and BCMs) were the main source in only 18% ± 21% of the total catchment area. In contrast, the reference climate was the most important source in 78% ± 21% of the catchment area, highlighting the importance of the second objective.

Based on recent advances in regional and global datasets (second objective), and the potential trajectory of evolution of each glacier in the Patagonian Andes (third objective), the **fourth objective** generated state-of-the-art projections of freshwater inputs to the coastal system. Specifically, Long Short-Term Memory (LSTM) neural networks in combination with the Open Global Glacier Model (OGGM) were used to estimate the runoff evolution from non-glacier and glacier areas, respectively. The total runoff of the study area was 23,533 ± 1,399 m^3 s^{-1} in the historical period (1985-2019). From this total, the glacier runoff contributed 5,185 ± 471 m^3 s^{-1}. While the northern area is expected to experience the greatest relative reductions with values close to -22%, the central and southern areas are expected to show slight increases with relative changes of 6% and 13% (Figure 6.1), respectively.

Finally, the results showed in this thesis provides: i) a basis for an open collaborative dataset that outperforms all current alternatives, ii) the first large-scale evaluation of the impact of various sources of uncertainty (historical and future) beyond future glacier mass loss, and iii) state-of-the-art projections of freshwater inputs to the coastal system that will contribute to future climate change adaptation plans for Western Patagonia.