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Review Article

Reviewing the Heat: Exploring Global Warming Patterns in the Southern Hemisphere

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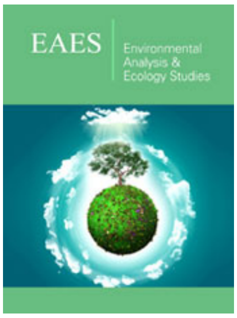
ISSN: 2578-0336



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Submission: June 13, 2024
Published: August 01, 2024

Volume 12 - Issue 3

How to cite this article: Federico Ferrelli*, Andrea Soledad Brendel, Pamela Mendioroz and Ignacio Agustín Ferrelli. Reviewing the Heat: Exploring Global Warming Patterns in the Southern Hemisphere. Environ Anal Eco Stud. 000789. 12(3). 2024. DOI: 10.31031/EAES.2024.12.000789

Abstract

This manuscript presents a review of the effects of global warming in the Southern Hemisphere (SH), serving as a tool to summarize the primary impacts. Given the varying degrees of development across the study area, understanding the consequences that each continent is relevant for effective action and raising awareness about the significance of this phenomenon. The results are presented by dividing the study area into South America, Africa, Oceania, and the Southern Ocean. It was observed that each continent experiences diverse effects: in South America, major ecosystems such as the Amazon and Pampas are undergoing continuous degradation, posing a threat to CO2 absorption and food security; in Africa, a progressive warming affecting the entire continent is observed, with harmful impacts on the population due to its high dependence on precipitation for regional economies. In Oceania, the effect of rising sea levels is more pronounced, resulting in climate refugees and the imminent disappearance of countries. Similarly, oceanic ecosystems show degradation, changes in marine currents, and the emergence of increasingly intense meteorological phenomena. Given the analysis, the importance of raising awareness about the need to reduce emissions and educate the entire population becomes evident.

Keywords: Global warming; Southern Hemisphere; Mitigation and adaptation strategies

Introduction

Global warming, driven by human-induced factors such as fossil fuel combustion, large scale deforestation, and wildfires, has led to the emission of greenhouse gases, resulting in the retention of heat in the Earth's atmosphere [1]. Since the Industrial Revolution, anthropogenic Greenhouse Gas (GHG) emissions have significantly warmed the planet, albeit with varying rates across different regions [2-4].

This phenomenon has brought about notable changes in climate patterns, including warmer summers and a decline in frost days, with detrimental impacts on biodiversity and ecological interactions [5]. Consequently, global warming has emerged as a pressing concern, garnering widespread attention due to its detrimental effects on various facets of human life and ecosystem integrity [6]. Notably, it poses a significant threat to biodiversity, with its adverse impacts escalating annually, directly affecting species fitness and altering ecological dynamics [7,8]. Furthermore, the phenomenon is intricately linked to extreme sea levels, driven by changes in storm patterns, atmospheric pressure systems, and rising sea temperatures [9] resulting in heightened risks of flooding and erosion in vulnerable coastal areas worldwide [10,11].

In light of global efforts to mitigate climate change, several studies focused on the lower end of the Global Warming Level (GWL) range, aligning with the objectives outlined in the Paris Agreement, which emphasize the measurable differential impacts between a world at

1.5 °C and one at 2 °C above pre-industrial levels [12-14]. However, it's crucial to acknowledge the complexities in understanding sea-level rise concerning different warming scenarios, underscoring the dynamic nature of global mean sea level changes. While the GWL framework naturally applies to variables where climatological changes with warming are largely time-independent over a century-scale, the effects of different GWLs on sea-level change cannot be examined in a time-independent manner. Global mean sea level is more closely related to time-integrated temperature change than to the temperature value at any given point in time [15]. As a result, the sea level can vary considerably once a specific level of warming is attained, compared to the sea level once the system has reached equilibrium at that same level of warming [9]. Moreover, the balance of surface heat fluxes is being significantly influenced by global warming [16], as evidenced by the altered dynamics of soil moisture–atmosphere coupling (SA), leading to intensified high-temperature extremes and heatwaves in certain regions [17-19].

Against this backdrop, our objective is to delve into the specific impacts of global warming on the Southern Hemisphere, where comprehensive studies comparing its effects are notably lacking. With its diverse landscapes, climates, and ecosystems spanning continents like South America, Africa, Oceania, and Antarctica, the region is also distinguished by vast oceans, including the Southern Ocean surrounding Antarctica. The Southern Hemisphere holds immense environmental significance, characterized by diverse ecosystems, unique wildlife, and varied climates, ranging from tropical in the north to polar in the south.

The effects of GW on the Southern Hemisphere

In this section, we provide an overview of the impact of global warming within the Southern Hemisphere. We categorize these effects across South America, Africa, Oceania and the Southern Ocean, recognizing the nuanced differences in impacts shaped by their geographic locations, diverse ecosystems, and varying levels of development.

South America

South America boasts diverse and crucial ecosystems, among which the Amazon rainforest stands as one of the world's most vital carbon sinks, sequestering substantial amounts of carbon in its biomass [20]. However, this ecological treasure faces significant threats from deforestation and forest degradation, largely driven by global warming [21]. Despite its importance, accurately measuring the local carbon balance within many Amazonian ecosystems remains challenging due to restricted accessibility [22]. Satellite observations reveal that drought and fire play significant roles in altering the carbon balance. While Northwestern Amazonia experiences minimal seasonal variations in growth and decay, remaining close to carbon equilibrium [23], the story is different in the southern and eastern regions. There, dry seasons are lengthening, lasting up to five months, and transitioning the forest into a savanna-like landscapes during prolonged droughts [24]. Consequently, carbon balance in these areas occurs primarily during wet seasons [22,23].

Warming trends are particularly pronounced in eastern Amazon forests, where rising temperatures have transformed this region into a carbon source during the dry season [23]. Over the past four decades, Eastern Amazonia has experienced a warming of 0.6 °C, a rate comparable to Arctic trends, primarily attributed to deforestation and forest degradation processes that amplify carbon loss and reshape local ecosystems, leading to reduced CO_2 absorption by rainforests [22]. The critical challenges faced by the Amazon include shifts in soil moisture and evapotranspiration patterns due to prolongued dry seasons. Ritchie et al. [24] highlight a temperature increase of approximately 1 °C during these periods. Furthermore, the observed expansion of the temperature seasonal cycle by 0.4 °C over the last three decades suggests a drying trend in the Amazon, as determined in the absence of soil or energy flux measurements. This drying trend is expected to persist with future climate change [24]. Moreover, soil moisture dynamics in the Amazon are closely linked to temperature anomalies during heatwaves, accounting for up to 30% of the global signal. Therefore, understanding the intensification, spatial extension, and duration of heatwave occurrences, under different Global Warming Levels is crucial for assessing temperature rise impacts. While tropical regions such as the Amazon and the Arabian Peninsula will face the most significant impacts in terms of frequency and duration of heatwaves, mid-latitude regions will also experience considerable increases in maximum temperatures [25]. Turning to another relevant landscape in South America, the Pampas region in Argentina emerges as a key agricultural area, supplying food to a considerable portion of the global population. Covering an area of 613,532 km2 in eastern Argentina, the Pampas is characterized by its plains, with altitude increasing from east to west and falling within subtropical and temperate climate zones [26]. Influenced by the Atlantic Ocean, the Pampas experiences relatively low daily and annual thermal amplitudes compared to similar latitudes in the Northern Hemisphere. Furthermore, the Pacific Ocean also influences the climate of the Pampas through frontal rains generated by the longitudinal and latitudinal movements of air masses [26]. Temperature trend analyses in the Pampas reveal evidence of global warming, with significant implications for the region's agriculture. Examination of trends in daily temperature extremes over the past six decades highlights spatial and temporal variations, indicating changes in temperature and rainfall patterns at different temporal and spatial scales. Consequently, the region faces an increased frequency of extreme thermal events, primarily characterized by heatwaves that can lead to soil dryness and hinder vegetation growth. As a result, staple crops in the area are at risk of damage [27]. Rising temperatures also result in increased energy availability, impacting crop flowering, delaying the growing season, and shortening the critical periods, ultimately reducing yields [28]. This delay in the growing season is observed when the minimum temperature increases. An earlier start of the growing season may allow for additional cropping cycles, such as wheat-soybean rotation [28]. Additionally, favorable growing conditions during spring and autumn due to temperature increases may extend the vegetation growth period [29]. Observations also reveal positive trends in cold extremes events, potentially leading to an increase in the frequency of coldest nights. Conversely, reductions in frost days highlights significant daily climate variability over the Pampas, surpassing other regions of the world (a decrease of -12.3 days in the last six decades). For instance, Chen et al. [30] reported daily temperature and precipitation extremes over south-central China and found that frost days decreased by about 10 days during the 1960–2013 period. Worku et al. [28] analyzed the Upper Blue Nile Basin in Ethiopia and observed a decrease of 10 days in the 1981-2014 period. These results align with studies conducted in the extreme south of the Pampas region, where frost days decreased by about 16 days in the plains and increased by 13 days in the Ventania hills, Argentina, during the period 1970-2017 [5]. Finally, Fernandez-Long et al. [27] concluded that frost days in the middle of Argentina decreased by 14 days in the 1940-2007 period. Understanding daily rainfall patterns becomes critical for assessing their societal impacts, including infrastructure damage, disease, poverty, loss of life, and biodiversity loss [31]. Additionally, these events drive changes in ecosystem structure and function. Trend analyses allow for quantifying spatiotemporal changes in precipitation patterns, offering insights into modifications that have occured during the period 1960-2018 [28,30].

In conclusion, South America faces significant challenges from rising temperatures and decreasing soil moisture, with implications ranging from the gradual replacement of tropical forests with savanna landscapes [32]. to exacerbated drought severity in drier regions, leading to the degradation of arable land, salinization, and desertification [33]. These changes threaten agricultural productivity, livestock welfare, and water availability for human consumption, agriculture, and energy production, underscoring the urgency of addressing climate change impacts in the region [34-36].

Africa

Encompassing over 30 million square kilometers of land, Africa stands as the world's second-largest continent after Asia, covering vast and diverse landscapes with weather and climate patterns increasingly prone to variability, leading to disruptive disasters affecting economic, ecological, and social systems [37]. From the perspective of climate change, Africa emerges as exceptionally vulnerable, with direct implications for its people, governments, and the African Union (AU), pervading various aspects of daily life [38]. Over the twentieth century, the continent witnessed a warming of 0.7 °C, with projections indicating further increases ranging between 0.2 °C and 0.5 °C per decade [39,40]. Similarly, historical data illustrates precipitation variability, with notable increases observed in rainfall across East and Central Africa [39,40]. Climate change in Africa also correlates with shifts in the frequency and intensity of extreme events, such as El Niño-Southern Oscillation (ENSO) episodes [41], with forecasts foreseeing significant impacts on biodiversity and agricultural production in the coming decades [41,42]. Numerous regions in Africa grapple with substantial interannual variability in precipitation, exacerbated by heavy reliance on rain-fed agriculture, which is often hampered by insufficient rainfall. Projections suggest that temperatures will exceed global averages, particularly in arid regions, while precipitation changes are expected to vary across models, generally increasing with rising global temperature, albeit with region-specific responses. In 2019, mainland Africa experienced an average temperature exceeding the long-term mean of 1981-2010 by 0.56 °C to 0.63 °C, ranking as the third warmest year on record after 2010 and 2016. The average annual temperature increase in Africa stands at 1 °C, with certain areas such as South Africa, Namibia, and parts of Angola witnessing temperatures more than 2 °C above the 1981-2010 normal [37]. Savannah burning and forest fires, inherent to grass plains in tropical or subtropical countries, contribute to air pollution [43]. According to the 1997 Kyoto Protocol, forest loss has historically been a significant source of greenhouse gas emissions, comprising approximately 47% of total emissions since 1750 [44]. Despite declines in tropical deforestation rates, forest loss remains substantial, significantly contributing to global emissions degradation [44]. Forest conservation play a crucial role in climate change mitigation efforts, which is reflected in their integration into international policy frameworks [45]. Remarkably, over 60% of global fires occur in sub-Saharan African savannas [46], with human ignitions predominantly driving fire activity, particularly during harsh fire weather conditions in the latter stages of the dry season [46]. Tropical savannas, accounting for about 90% of the world's burned land and 62% of global fire carbon emissions annually, are particularly susceptible to fires. The overall fire activity in tropical Africa has been relatively low, with the fire season in northern tropical Africa lasting from November to April and the southern season from May to October.

In conclusion, despite some exceptions, activity levels in these regions have been lower than average, contributing to reduced carbon dioxide emissions in 2020 compared to previous years. While these fires are essential for ecosystem renewal, they pose risks to human settlements, ecosystems, and respiratory health [37].

Oceania

Anthropogenic sea-level rise looms as a formidable challenge, potentially uprooting a significant portion of the population due to inundation and increased hazards associated with Sea-Level Rise (SLR). As the global coastal population is forecasted to exceed one billion people by the end of this century, SLR could emerge as one of the most costly and enduring repercussions of climate change [47].

Oceania, notably the Pacific Islands region, confronts heightened susceptibility to environmental extremes, compounded by a longstanding tradition of population mobility, often dictated as consequence of natural disasters. Small island developing states are particularly vulnerable to the impacts of climate change. Across Oceania, these impacts may encompass SLR, more frequent and severe floods and droughts, coral degradation, intensified tropical cyclones, and shifts in disease vector distribution. Certain locations, such as atolls, coastal areas (where the majority currently reside), deltas, and river floodplains, risk becoming uninhabitable [48]. In Australia and New Zealand, concerns over water security are poised to escalate with a 1 °C rise in the global average temperature, particularly affecting northern and eastern regions of New Zealand, as well as southwestern and southeastern Australia. Southern Australia and the northern and eastern regions of New Zealand are projected to experience declines in agricultural and forestry productivity due to heightened drought and fire risks. Coastal areas will confront ongoing challenges from SLR, intensified storms, and coastal flooding. The burgeoning coastal development and population growth, notably in areas like Cairns and Southeast Queensland (Australia) and Northland to Bay of Plenty (New Zealand), will amplify the exposure of more people and infrastructure to risk. By 2050, ecologically important areas such as the Great Barrier Reef and Queensland Wet Tropics are anticipated to grapple with significant biodiversity threats [36]. Another pressing concern in the tropical regions of Oceania revolves around diseases. There is mounting concern regarding new and emerging infectious diseases, potentially linked to short-term environmental changes and long-term global warming. Projections indicate that with global warming, the tropical northern regions of Australia will see increased heat and rainfall, expanding the suitable habitat for mosquito-borne diseases such as malaria, as well as arboviruses like Murray Valley Encephalitis (MVE), Japanese encephalitis, and dengue [49]. In Australia, evidence suggests that global warming triggers specific climate extremes, including an increasing frequency of cold nights and days, alongside a growing number of warm days and nights [6]. The analysis of extreme hot events has revealed a generally positive trend, indicating the region's susceptibility to the effects of global warming, a phenomenon observed in other temperate areas of the Southern Hemisphere and many other regions worldwide.

In conclusion and considering the scenario unfolding in Australia, it is imperative to emphasize that the southwestern region will experience elevated temperatures and corresponding increases in heat extremes attributed to greenhouse gas-induced forcing. The annual mean temperature is projected to rise by over 6 °C by the year 2100 under a high greenhouse gas emission scenario. Additionally, a significant increase in drought occurrences is anticipated, coupled with a decrease in precipitation during the southern hemisphere's winter season. Extreme precipitation events may lead to an increase in flooding intensity and frequency, inflicting substantial costs on aquatic and terrestrial ecosystems, human societies, and the economy. Changes in flood characteristics hinge not only on the spatial distribution, time evolution, and rarity of precipitation but also on antecedent soil moisture conditions.

Effects of GW on the southern ocean

Increased retention of greenhouse gases has disrupted the global climate balance, resulting in more energy entering the atmosphere than being emitted back into space. Since the mid-20th century, over 90% of the surplus energy in the climate system has been absorbed by warming the Earth's oceans [50]. However, limited historical data on Southern Ocean temperatures make it challenging to gauge the extent to which the ocean has absorbed anthropogenic heat. Nevertheless, observations from Argo floats between 2006 and 2013 indicate that the Southern Ocean is the primary contributor to changes in global upper ocean heat content [51]. Recognizing the Southern Ocean's (south of 30°S) significance in mitigating greenhouse warming stems from understanding its role in regulating the global thermohaline circulation [52]. Changes in surface salinity and density continue to escalate for centuries during periods of elevated stable CO_2, with no recovery in convection and Antarctic downwelling. The entire deep ocean below about 1.5km remains stagnant during these periods, maintaining a density too high for replenishment from any source [53]. Southern Ocean warming has been substantial, with Antarctic stratospheric ozone depletion and rising atmospheric CO_2 exacerbating it until the early 21st century.

The warming of the Southern Ocean is unique compared to other oceans. South of 55°S, surface warming is slower than in the subsurface and the rest of the global surface ocean. For instance, the surface ocean south of the ACC has warmed at a rate of 0.02 °C per decade since 1950, compared to the global mean surface temperature warming rate of 0.08 °C per decade [54].

Concurrent with subsurface warming on the shelf, substantial mass loss has occurred in Antarctic ice shelves and ice sheets, particularly in West Antarctica, notably from the Pine Island and Thwaites Glacier catchments of the Amundsen Sea Embayment [52,55], and the Antarctic Peninsula, including recently collapsed or rapidly thinning Larsen ice shelves [56,57].

Mitigation and Adaptation Strategies

In the Southern Hemisphere, countries exhibit widely disparate levels of development, presenting a significant challenge in devising strategies to mitigate and adapt climate change effects. However, as the negative impacts become increasingly evident, it becomes imperative to propose a series of measures to adapt and mitigate to this increasingly warmer world and reduce greenhouse gas emissions. There are localized regions in the Southern Hemisphere facing similar challenges, requiring a reevaluation and adaptation plans for global warming and the imminent impacts of climate change [58,59].

The critical need to address climate change and GW and achieve sustainable development is accelerating the global shift towards renewable energy. This change is becoming more feasible due to advancements in green building practices, environmentally friendly industrial energy use, sustainable transportation, the decrease in renewable energy costs, improved energy efficiency, ongoing technological developments, and effective policymaking [60].

Renewable energy is gaining popularity, particularly in low and middle-income countries where future energy demand is projected to rise the most. As costs decrease, a substantial share of future power generation is expected to come from low-carbon sources. By 2030, renewable energy could contribute to 65% of the global electricity supply, and by 2050, it could decarbonize 90% of the electricity sector. This transition would significantly lower carbon emissions and help mitigate climate change [61].

From a techno-economic standpoint, wind energy is regarded as the most developed form of clean or renewable energy [62]. Renowned for its ecological soundness, it stands out for its greater adaptability to human and animal habitats compared to other renewable energy systems [63,64]. While offshore wind energy does not require large land areas, the construction and grid connection of offshore wind farms are costlier than onshore farms due to technological and logistical difficulties [65].

Water-based energy systems, including hydroelectric energy, wave energy, and ocean thermal energy conversion, incur expenses influenced by construction, equipment, operation, and maintenance costs. Micro-hydropower plants play a crucial role in supplying electricity to rural and underdeveloped areas [66-68].

Biomass, which is integral to various life cycles and ecosystems, serves as a primary energy source [69]. However, biomass-based power generation often faces misconceptions or negative perceptions due to a lack of understanding or association with conventional energy systems. Some biomass power technologies, including pyrolysis and gasification, are still under development but undergoing commercial trials. Other established technologies include direct co-firing, combustion in stoker boilers, anaerobic digestion, landfill gas, municipal solid waste incineration, and combined heat and power systems. While low-cost biomass, such as agricultural by-products, provides a highly competitive and reliable source of electricity, the elevated costs associated with transporting it remain a downside of these technologies [70,71].

Geothermal energy may not be the foremost choice due to its comparatively lower efficiency and performance, yet it is a promising alternative when considering its environmental impacts. There is significant potential for improvement in geothermal technology driven by ongoing technical research and development, which has spurred environmental investigations [72].

In addition, the solar energy reaching Earth daily holds the potential to meet the planet's entire energy demand [73,74]. This solar irradiance can be captured through various technologies, such as solar thermal systems, which convert photons into heat, and photovoltaic systems, which transform them into electrical energy [75-77]. In the former case, the heat generated is used to warm a working fluid, which is then used for both space and water heating purposes [77-80]. Notably, solar optical efficiency has reached 86.2% using nanofluids, whereas PV panel efficiency typically ranges from 15-20% [81]. Solar energy plays a crucial role in reducing global emissions, balancing environmental, social, and economic factors, enhancing energy security, and aiding in mitigating climate change [77].

The historical reliance on gas sectors and fossil fuels has inflicted significant harm on the global environment, resulting in substantial emissions of carbon and other hazardous gases, exacerbating global warming [82] and degrading the quality of life in affected areas. Moreover, fossil fuel-derived energy is often costly and fails to meet the demand for clean and affordable energy. In contrast, solar energy provides clean, affordable energy, fostering sustainable development. It addresses environmental concerns, promotes economic growth, enhances grid security [83,84], and is the fastest-growing renewable energy source globally due to its cost-effectiveness and environmental benefits. Despite being relatively new compared to traditional renewable resources, solar energy shows promise for the future, driven by significant cost reductions [77].

Developing countries are turning more to solar energy for its cost benefits and because of limited infrastructure for traditional energy sources. Cheaper than coal, oil, and gas, solar power gains popularity in these regions, supporting various Sustainable Development Goals with its provision of clean and affordable energy. Creutzig et al. [85] underscore its crucial role in mitigating climate change, reducing the impact of extreme weather events, and addressing rising sea levels. Solar energy, compared to fossil fuels, enhances land, air, and water quality, making it a pivotal investment for energy goals and environmental protection [77].

Fossil fuel usage remains the primary driver of climate change and global warming. Transitioning to renewable energy sources like solar, wind, hydropower, and biomass is essential to curb carbon emissions and mitigate climate change. However, to accurately assess the feasibility of low-carbon energy technologies a comprehensive understanding of future climate impacts and potential fluctuations in renewable energy sources is needed. Climate change-induced phenomena such as rising temperatures, extreme weather events, sea-level rise, and altered precipitation patterns are expected to present significant societal challenges in the coming decades.

On the other hand, we present different adaptation strategies to address global warming tailored to the varying levels of development among countries in the Southern Hemisphere:

As urbanization progresses in the Southern Hemisphere, the resilience of infrastructure becomes central in addressing GW. The concept of Green Infrastructure (GI) has primarily been applied for urban settings to enhance city structures and integrate the benefits of natural capital into built environments [86]. Urban green and blue spaces offer a wide range of ecosystem services, such as provisioning, regulating, and cultural services, which are vital for the well-being of urban populations [87,88]. These green spaces support biodiversity, provide habitats, contribute to agricultural connectivity and food security, improve air and water quality, moderate local climate, sequester CO_2, reduce soil erosion, mitigate noise pollution, enhance real estate values, and improve neighborhood aesthetics [86,89].

Urban green infrastructure plays a crucial role in enhancing a cities' resilience to climate change. Extensive research highlights the significance of green spaces in providing climate adaptation services, including mitigating the urban heat island effect through the presence of urban forests, parks, and street trees [90]. Implementing strategies such as replacing impermeable surfaces with permeable and vegetated alternatives, adopting green walls and roofs for improved building insulation, and maintaining private gardens contribute significantly to moderating temperature fluctuations and managing surface water runoff [91].

The role of GI in mitigating the impacts of global warming can be further strengthened through integration with open water systems. With climate events growing more uncertain and unpredictable, the retention and utilization of stormwater, along with the restoration of rivers, lakes, and ponds, assume greater importance. Embracing comprehensive approaches in urban water management can effectively address extreme weather events and influence microclimates. Open water surfaces, such as urban lakes, ponds, and streams, serve as valuable water storage and retention areas, bolstering urban resilience and climate adaptation efforts [86].

Furthermore, flood infrastructure and water management are essential elements of infrastructure resilience to GW. Recent years have witnessed a notable surge in pressures on water resources, both in terms of quality and quantity, along with unprecedented flood risks. Global challenges such as increased urbanization, heightened run-off volumes, and climate change have strained existing hard systems, resulting in escalated design, operation, and maintenance costs [92]. Consequently, sustainable water management and flood resilience have emerged as critical challenges for coastal areas and surrounding cities. Climate change further exacerbates these challenges by altering rainfall patterns, intensities, and frequencies. Extreme precipitation events often overwhelm current urban drainage systems, especially in areas along rivers, coastlines, and inland regions not adjacent to water bodies, heightening the risks of flooding, rising sea levels, and uncertain precipitation patterns [93]. Various approaches such as 'building with nature' (BwN), 'Low Impact Development' (LID), 'Sustainable Drainage Systems' (SUDS), 'green infrastructure', Water-Sensitive Urban Design (WSUD), and sponge cities highlight the importance of sustainability, resilience, and climate change adaptation in urban planning and water management strategies. These approaches prioritize the integration of natural processes and green spaces into urban environments to enhance environmental sustainability and the resilience of cities to climate change and global warming impacts while fostering sustainable growth and development [94].

In the Southern Hemisphere, croplands are vital to most economies, with GW and climate change presenting significant threats to the region's agriculture. However, farmers can mitigate these negative impacts by adopting adaptive strategies to climate change, assessing factors such as soil conditions, climate patterns, and socio-economic considerations. Agricultural adaptation includes technological advancements, government initiatives, insurance, production practice changes, and financial management. Effective planning requires analyzing these options, and considering their potentials, limitations, and uncertainties associated with climate change [95].

Crop diversification has been widely recognized in the literature as a key adaptation practice [96] and a promoter of sustainable agricultural systems [97]. Asfaw et al. [96] noted that crop diversification has positive and significant welfare impacts, particularly for more vulnerable farmers who rely on it to adapt to climate variability. Crop diversification is also a component of Climate-Smart Agriculture (CSA), which considers climate risks, improves food security, and enhances productivity, resilience, and GHG emission mitigation [98].

Developing drought-resistant crops for Southern Hemisphere regions is essential for adapting to GW. Extensive research is ongoing to understand their role, varying by area but closely linked to climate adaptation. The success of these emerging technologies depends on identifying mechanisms regulating plant productivity, growth, and yield under field conditions and stress. Understanding metabolic, cellular, and developmental pathways will prove key, as new crop varieties must possess "balanced" genetic content to mitigate losses from environmental stresses and pests [99].

Finally, it is important to note that health and social systems need to adapt to address the effects of global warming on populations. According to the study by Zhao et al. [100], adaptation strategies generally encompass four main aspects:

A. Regularly assess health vulnerabilities and adaptation capacities.

B. Develop and implement an evidence-based adaptation plan for health.

C. Strengthen the climate resilience and environmental sustainability of healthcare systems and facilities.

D. Protect health and advance climate justice by implementing health-promoting interventions in other sectors.

E. Additionally, early warning systems should incorporate additional modules, including early forecasting of extreme weather, climate-related diseases prediction, health risks and damage levels evaluations, preventative strategies proposals, as well as medical and rescue plans, and establishing programs for post-disaster reconstruction.

Sustainable land management policies are crucial in the Southern Hemisphere, particularly in the Amazonia and Pampas regions, to address GW [101]. It is worth noting that the Pampas Region is one of the most fertile and important plains in the world, with the capacity to produce food for a significant portion of the planet. On the other hand, the state of South Australia has a significant regional and global interest due to its crops, extensive livestock activities, among other factors. In this context, it is important to raise awareness about mitigation and adaptation plans [28].

Given the backdrop of global warming and climate change, specific policy recommendations are necessary to address the heightened risks and difficulties stemming from the continuously shifting environmental conditions [28]. Within this framework, consistently update land management plans and conduct thorough assessments are crucial to evaluate the impacts comprehensively. This entails examining historical and current climate data alongside projected alterations in temperature and precipitation patterns within the context of climate change. Such a context amplifies the susceptibility of ecosystems and communities to daily extreme events. Identifying and delineating high-risk and vulnerable areas is crucial for effectively prioritizing resources and directing efforts accordingly [25]. Moreover, providing crucial information for stakeholders to design adaptation and mitigation strategies is imperative. These strategies will be aimed at, ultimately, mitigating adverse impacts on crop yield, grasslands, livestock, and water availability, and improving human life quality [28]. Temperate climate regions in the Southern Hemisphere may be undergoing widespread warming, posing new challenges and the urgent need to implement adaptation and mitigation strategies [6,8]. While the temperature increases homogeneously, precipitation has a heterogeneous pattern, as is common worldwide. Changes in thermal and rainfall patterns evidence the effects of global warming, impacting ecological environments [102], and the hydrological cycle due to the increase in evapotranspiration and extreme rainfall events. The recent advancement of smart technologies has enabled smart farming practices (also known as smart agriculture) based on precision agriculture, aiming to enhance productivity while reducing environmental impact through various techniques including efficient irrigation, targeted and precise use of pesticides and fertilizers for crops, etc. Additionally, IoT enables the reduction of environmental impact by enabling real-time detection of weeds or infestations, monitoring weather conditions, soil conditions, etc., thereby promoting efficient use of inputs such as water, pesticides, or agrochemicals. Smart livestock farming helps monitor animal grazing in open pastures or location in large stables. Smart farming also assists in detecting and maintaining air quality, ventilation in farms, and detecting and reducing GHG emissions from farms [6].

It is noteworthy that knowledge of daily rainfall events for a productive area are essential, as it provides relevant information for local actors and decision-makers at local, regional, and national levels to design adaptation plans and strategies to address the area's exposure to various situations [5] and reduce agricultural losses [28]. It is anticipated that rainfall variability will generate more negative impacts in the future, especially in rainfed crop areas. Hence, the design of a territory management plan aimed at conserving natural resources and oriented towards the continuity of economic activities.

For all the review made, it is crucial to recognize global warming and climate change as drivers for environmental impacts across the Southern Hemisphere [103]. Adaptive measures tailored to social, economic, and environmental differences across continents are essential, with focus on the implementation of carbon capture and storage technology to mitigate emissions. Industries involved in energy generation, cement production, iron and steel manufacturing, as well as petrochemicals, demand heightened attention due to their significant emission potential [103], emphasizing the need for strategies to address and mitigate climate change in light of increasing emissions since the industrial revolution.

Conclusion

Global warming stands as one of the most significant challenges humanities must face due to high emissions levels. This review has highlighted the profound effects observed in the Southern Hemisphere, which endanger not only ecosystem development but also human settlements and health. Across continents, irreversible changes are evident in resource degradation, ecosystem deterioration, soil quality reduction, and agricultural production decline. Anthropogenic processes are driving increasingly irreversible impacts in regions such as the Amazon, fertile areas like the Pampas, and certain regions of Africa. While the countries in the Southern Hemisphere exhibit varying levels of development, several measures are being implemented to achieve emission reductions. Each country, for instance, has programs for waste management, reforestation and afforestation, international cooperation, and innovation and research. Nonetheless, countries such as Australia and New Zealand demonstrate more advanced progress in education and awareness, carbon pricing, and the implementation of renewable energy. Finally, mitigation and adaptation measures serve as a tool to prevent or reduce excessive emissions worldwide, thereby alleviating the effects of global warming. However, it is imperative to recognize that global warming affects all aspects of life on the planet, necessitating immediate action to address this issue. Failure to act will intensify the effects outlined in this review, progressively damaging ecosystems as we know them.

Funding

Projects PICT-2021-I-INVI-00580 and PIBAA 28720210100943CO from CONICET and FONCYT, Argentina.

Acknowledgment

We duly acknowledge the National Council of Scientific and Technical Research and the FONCYT.

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