Albedo as a Measure of Climate Change for Civil War Research

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Abstract: Despite a wealth of studies exploring the nexus between climate change and civil conflict, the field is rife with null findings, which should raise questions about the efficacy of traditional research methods and variables. I propose that the high incidence of null findings may stem from an imprecise alignment between climate measurements and their actual impact on agrarian communities, especially in the developing world, where agriculture serves as a cornerstone for employment and survival. This study bridges this gap by zeroing in on the changes to the land's "carrying capacity," the maximum sustainable agricultural output the land can support. I propose researchers use Albedo as a key proxy for capturing these changes to land, particularly desertification. The study also challenges the notion that rainfall is always beneficial and challenges whether rainfall, a weather variable, should be used to measure climate change. I posit that as the carrying capacity of an area declines, especially in rural communities, competition for dwindling resources intensifies, thereby increasing the risk of conflict. Machine learning and regression models find a positive relationship between Albedo changes and conflict onset. The findings emphasize the need for nuanced environmental metrics in understanding the complex relationship between climate change and civil conflict, offering new avenues for research and policy.

1 Introduction:

Climate change is an urgent global issue with well-documented impacts such as sea-level rise, extreme weather events, and shifting precipitation patterns (Nerem et al. 2018; National Academies of Sciences, Medicine et al. 2016; Stott 2016). However, its influence on civil conflict, particularly in the developing world, remains a subject of intense debate (Mach et al. 2019). Most of the existing research has sought to understand this relationship through variables like Rainfall and temperature, which may not fully capture the nuances involved. This is especially true in economies where herders and farmers make up a large share and are directly affected by changes in the land they depend on. This paper argues for a shift in focus and proposes the use of Albedo, a measure that directly reflects changes in land conditions, as a more relevant

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and nuanced indicator for studying the link between climate change and civil conflict.

This paper argues that the carrying capacity of a region a term defined as the maximum population an area can sustain without degrading its natural resources, is critical for understanding the likelihood of civil conflict. The carrying capacity directly influences economic output in economies where herders and farmers are significant contributors. Albedo serves as a key metric for quantifying changes in this carrying capacity. Specifically, shifts in Albedo are indicative of desertification, a process that severely limits a region's carrying capacity and, consequently, its economic viability. As desertification progresses, it undermines the economic foundation of herders and farmers, escalating competition for dwindling resources. Given that weak economies are well-established as a precursor to civil war (Fearon and Laitin 2003; Cederman, Weidmann and Gleditsch 2011; Mach et al. 2019), it is imperative to understand how climate-induced changes in carrying capacity contribute to the likelihood of conflict.

Albedo's capacity to measure a wide array of climatological phenomena, such as flooding and desertification, makes it a uniquely versatile and comprehensive tool for understanding climate change (Henderson-Sellers and Wilson 1983; Ingram, Wilson and Mitchell 1989; Stephens et al. 2015). This paper emphasizes the use of Albedo as a long-term variable that provides a more reliable and robust measure for analyzing the complex relationship between climate change and political violence.

The use of Albedo as a primary measure of climate change introduces a nuanced perspective on the relationship between climate change and civil war. Specifically, this paper discusses the concept of "winners" and "losers" of climate change. "Winners" might be regions that experience positive environmental shifts improving the land's carrying capacity, while the "losers" suffer detrimental effects such as increased desertification. Such regional disparities affect resource distribution and amplify existing vulnerabilities, thereby exacerbating tensions and the likelihood of conflict.

This research enriches our understanding of the intricate relationship between climate and conflict by focusing on Albedo changes as a key variable. By analyzing Albedo data from 1980 to 2020 in conjunction with conflict incidence, this study adds a new dimension to the growing body of literature examining climate-related factors in predicting political violence. Importantly, the analysis reveals a strong correlation between Albedo and measures of carrying capacity. An increase in Albedo over the long term is tightly associated with a reduction in a region's carrying capacity, thereby validating its utility as a climate measure relevant to conflict studies.

The findings reveal a consistent, positive, and significant correlation between changes in Albedo and conflict across various regression models. These models examine different aspects of conflict, such as conflict onset, the number of civil wars, and the overall number of conflict events. The results underscore the importance of considering Albedo as a reliable measure of climate change, particularly in its capacity to predict political violence. This study also questions the reliability of commonly used indicators like Rainfall, pointing out their limited variability and their inadequacy for a nuanced understanding of climate change's impact on conflict.

The paper begins with an overview of the existing literature on climate and conflict, emphasizing that Rainfall and temperature have traditionally been the primary metrics for studying climate change. It critically evaluates the adequacy of these conventional metrics, arguing that they fall short in capturing the nuances needed to understand climate change's impact on conflict.

Next, the paper explores the scientific principles behind Albedo and its dual relevance to measuring the changes to the land brought on by climate change. The paper also shows how Albedo can serve as a key indicator for a region's carrying capacity, providing a nuanced framework to understand the environmental factors contributing to conflict.

Finally, the paper empirically tests the relationship between Albedo and civil war. Strikingly, the results across multiple models indicate a positive and significant correlation between Albedo changes and conflict events. The Civil War Onset model reveals that an increase in Albedo is associated with a higher probability of conflict initiation. The Onset Count model corroborates this, showing that increased Albedo correlates with a greater number of civil wars within a country. These models collectively highlight the rising likelihood of conflict as soil conditions deteriorate, as measured by Albedo.

This paper underscores the significance of Albedo as a measure of land degradation induced by climate change, with direct implications for conflict dynamics. By employing a robust metric that reflects the real-world impacts of climate change, effects that range from economic hardship to life-or-death situations, this study aims to deepen our understanding of the intricate relationship between climate change and political violence. The insights gained have the potential to inform more targeted and effective policy interventions, thereby mitigating the harmful consequences of climate change on conflict and global security.

2 Climate and Conflict

Much of the political science on climate change examines the relationship between climate and conflict. This body of work primarily investigates how precipitation, drought, and temperature influence the likelihood, intensity, and duration of different types of conflict. Table 1 highlights a summary of articles that examine the links between climate change and conflict. Precipitation and Rainfall are heavily featured in the literature as proxies for climate change, but the relationship between climate change and civil war as measured by precipitation remains contentious.

Hsiang, Burke and Miguel (2013) provide a comprehensive analysis of the relationship between climate change and human conflict. They find that deviations in precipitation and temperature from historical norms significantly increase the risk of human conflict. The authors also emphasize the importance of understanding the underlying mechanisms driving this relationship, such as resource scarcity or economic instability. Similarly, Hendrix and Salehyan (2012) demonstrate that extreme precipitation and temperature events can exacerbate existing

Table 1: Summary of articles with precipitation/drought, temperature, and dependent variables

Article	Precipitation/Drought	Temperature	Dependent Variable(s)
Hsiang, Burke and Miguel (2013)	X	X	Human conflict
Buhaug (2010)	X	X	African civil wars
Raleigh and Urdal (2007)	X	X	Armed conflict
Reuveny (2007)	X	X	Migration, violent conflict
Adger et al. (2014)	X	X	Human security
Fjelde and von Uexkull (2012)	X		Communal conflict
Schleussner et al. (2016)	X		Armed conflict
Hendrix and Salehyan (2012)	X	X	Social conflict
Kelley et al. (2015)	X	X	Syrian drought
O'Loughlin, Linke and Witmer (2014)		X	Violence
Maystadt and Ecker (2014)	X		Civil war
Ide (2018)	X		Reconciliation
Busby et al. (2014)	X	X	Security vulnerability
von Uexkull et al. (2016)	X		Civil conflict
Koubi et al. (2014)	X	X	Civil conflict
Gleick (2014)	X		Conflict in Syria
Theisen (2012)	X		Organized violence
Von Uexkull (2014)	X		Civil conflict
Uexkull, d'Errico and Jackson (2020)	X		Support for violence
Bollfrass and Shaver (2015)		X	Political violence
Feng, Krueger and Oppenheimer (2010)	X		Migration
Hendrix and Glaser (2007)	X		Civil conflict
Koubi et al. (2016)	X		Migration
Lobell and Burke (2010)	X		Crop yield responses
Scheffran et al. (2012)	X		Violent conflict
Carleton and Hsiang (2016)	X	X	Social and economic impacts
Hsiang, Meng and Cane (2011)	X		Civil conflicts
Adams et al. (2018)	X		Climate-conflict research
Anita, Dominic and Neil (2010)	X		Agriculture impacts & mitigation
Burke, Hsiang and Miguel (2015)	X	X	Conflict
Buhaug (2015)	X	X	Climate-conflict research

social tensions, leading to social conflict.

Buhaug (2010) examine the links between precipitation, temperature, and African civil wars, finding that changes in precipitation patterns, rather than temperature, are more strongly associated with conflict. Raleigh and Urdal (2007) also study the impact of climate variability on armed conflict in Africa, arguing that both precipitation and temperature can contribute to conflict onset. Schleussner et al. (2016) and Theisen (2012) focus on precipitation as a key driver of armed conflict and organized violence, respectively, while O'Loughlin, Linke and

Witmer (2014) find that temperature is the more important predictor of violence.

Civil conflict has been a major focus of climate-conflict research. Fjelde and von Uexkull (2012) demonstrate that fluctuations in precipitation increase the likelihood of communal conflict, while Maystadt and Ecker (2014) explore the role of drought and precipitation in the onset of civil wars. Koubi et al. (2014) show that precipitation and temperature anomalies contribute to the escalation of civil conflict, while Bollfrass and Shaver (2015) argue that temperature alone is a significant predictor of political violence. Furthermore, von Uexkull et al. (2016) find that drought conditions can lead to civil conflict, while their later work Uexkull, d'Errico and Jackson (2020) explores how drought affects support for violence.

Another strand of literature investigates the connections between climate change and migration. Reuveny (2007) demonstrates that both precipitation and temperature anomalies can lead to increased migration and violent conflict. Feng, Krueger and Oppenheimer (2010) find that droughts, driven by changes in precipitation, lead to migration from rural to urban areas. Koubi et al. (2016) also explore the role of precipitation in migration patterns, showing that water scarcity can lead to increased migration flows. Overall, this literature highlights the importance of understanding how climate change impacts the movement of populations and the potential for conflict as a result.

A related area of research investigates the broader implications of climate change for human security. Adger et al. (2014) explore the connections between precipitation, temperature, and human security, arguing that climate change exacerbates existing vulnerabilities and disproportionately affects marginalized populations. Busby et al. (2014) develop a security vulnerability index based on precipitation and temperature data, suggesting that the most vulnerable countries face significant threats to their stability and human security.

The socio-economic impacts of climate change, including effects on agriculture and livelihoods, have also been a focus of research. Lobell and Burke (2010) examine the relationship between precipitation, temperature, and crop yield responses, finding that both factors play a critical role in determining agricultural outcomes. Anita, Dominic and Neil (2010) provide a comprehensive review of the impacts of precipitation and temperature on agriculture, as well as potential adaptation and mitigation strategies. Carleton and Hsiang (2016) analyze the broader social and economic impacts of climate change, demonstrating that precipitation and temperature variability can have wide-ranging consequences for societies.

A final theme in the literature involves methodological considerations and critiques of existing climate-conflict research. Adams et al. (2018) examine the role of precipitation in climate-conflict research, highlighting the importance of using appropriate sampling strategies and addressing potential biases. Buhaug (2015) provide a critical overview of the climate-conflict literature, emphasizing the need for a more nuanced understanding of the complex relationships between precipitation, temperature, and conflict. Burke, Hsiang and Miguel (2015) also call for a greater focus on the underlying mechanisms linking climate change and conflict, such as resource scarcity or economic shocks.

The climate change and political science literature has provided valuable insights into the relationships between precipitation, drought, temperature, and various dependent variables such as conflict, migration, and human security. While this body of research has made significant progress in understanding these complex relationships, there is still much to learn. Generally speaking, the literature has failed to find a link between climate change and civil war. However, I posit that this is because of the heavy reliance on Rainfall as a proxy of climate change, whereas it is variable better associated with the weather than climate. In the following sections, I will explain the logic regarding why Rainfall is a poor measure of climate change and propose that researchers use a new and more robust variable.

3 Theory: Carrying Capacity, Conflict, and Climate Change

3.1 Human and Economic Carrying Capacity as a Catalyst for Conflict

In rural agrarian societies, land serves as a physical space and an economic asset critical for livelihoods and social structures. A robust carrying capacity enables the land to support larger populations and a wide range of socio-economic activities. The civil war Literature shows that in developing countries, a weakened economy increases susceptibility to conflict (Fearon and Laitin 2003; Cederman, Weidmann and Gleditsch 2011; Mach et al. 2019).

However, environmental factors like climate change can drastically reduce this carrying capacity. For farmers and herders who make up a significant share of the economy in developing countries, diminished carrying capacity can lead to reduced agricultural yields and less fertile grazing lands. This economic downturn, characterized by reduced income and increased unemployment, exacerbates social tensions and can be a precursor to conflict and civil war.

The insidious nature of climate-induced changes lies in their gradual onset, which can slowly strain social and economic systems until they reach a tipping point. When these strains become overt, the social fabric may be too frayed to prevent conflict, positioning climate change as a "threat multiplier" in vulnerable regions.

3.2 Herders vs. Farmers: A Case Study in Resource Conflict

One specific form of this escalating tension may be the increasing conflicts between herders and farmers. By reducing the availability and quality of fertile lands and pastures, climate change can cause herders to encroach on traditionally used farming lands. Such encroachments can lead to confrontations, legal disputes, and social unrest, adding another layer of instability to already stressed environments. Implications

Understanding the relationship between carrying capacity and conflict provides a valuable framework for both academic inquiry and policy formulation. It offers a concrete mechanism through which climate change can heighten social tensions and lead to political violence, making it an essential consideration for conflict prevention and climate adaptation strategies.

3.3 Why Albedo Over Rainfall: A Compelling Alternative

In this context, Albedo serves not just as an environmental indicator but also as an economic one. Changes in Albedo can reflect agricultural productivity and, by extension, the economic well-being of communities. Unlike rainfall, Albedo provides a comprehensive understanding of land degradation and its economic implications, making it a politically relevant variable for conflict prediction.

4 Albedo: A More Robust Indicator for Climate Change Assessment

Understanding the dynamics of climate change is fraught with complexities, often involving a convoluted interplay between temperature, saturation vapor pressure, and topography in influencing Rainfall patterns. These multifaceted interactions make it challenging to find reliable indicators that not only capture the nuanced changes in the Earth's carrying capacity at a sub-national level, but also correlate strongly with political, economic, and societal variables.

Albedo, a measure of surface reflectivity, presents a potential alternative for assessing climate change more reliably. Unlike traditional indicators such as Rainfall, Albedo has several potential advantages. Firstly, its values are already well-established for various types of terrain and are easily measurable, thus facilitating empirical analysis. Secondly, variations in Albedo could serve as direct markers for changes in land cover, ice melt, and sea level rise. Furthermore, Albedo can be accurately quantified through satellite imagery, lending credibility to its potential as a robust and reliable indicator of climate change.

This section delves into the argument for replacing Rainfall with Albedo as the go-to metric for climate change assessment. It explores the rationale behind this proposed shift, and discusses the potential advantages and limitations of adopting Albedo as a primary climate change indicator.

4.1 Measuring Albedo

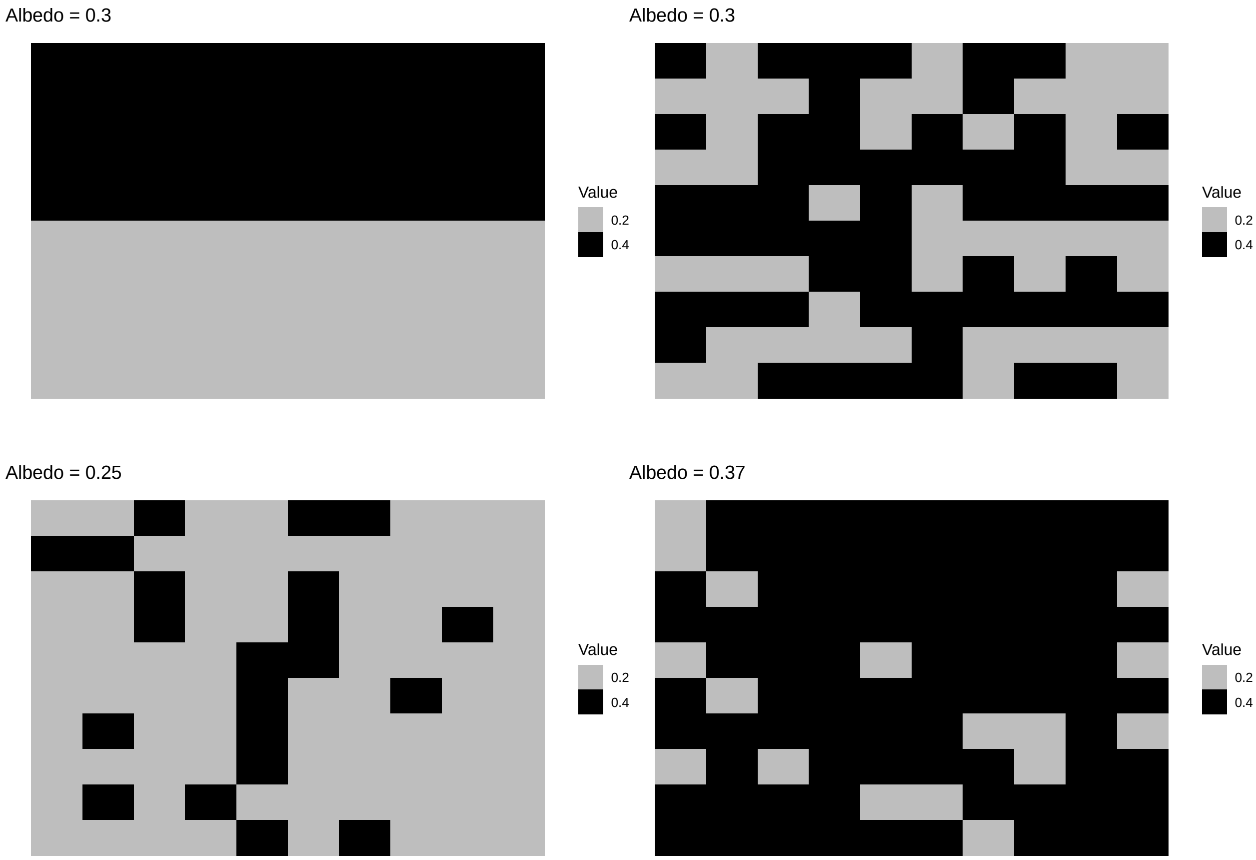
Albedo is a measure of the reflectivity of a surface, expressed as the ratio of light reflected by the surface to the light received. Absorption of light, therefore, is 1 - Albedo. This value can vary depending on color, texture, and composition. For instance, surfaces that are lighter in color, such as snow and ice, tend to have a higher Albedo (0.7 - 0.9), reflecting more light and absorbing less heat. On the other hand, darker surfaces, such as soil or vegetation(0.2), have a lower Albedo, reflecting less light and absorbing more heat. Water absorbs nearly all light that strikes it and has an Albedo approaching 0.1, while sand ranges between 0.35- 0.4.

To measure the Albedo of a surface is just a case of finding the average Albedo of a given area. Using a chessboard as an example, let's assign the black spaces to have an Albedo of 0.1 and the white spaces to have an Albedo of 0.9. In this case, the average Albedo of the board would be 0.5. An increase in the number of white spaces and a decrease in black spaces would increase the overall Albedo, while an increase in black spaces and a decrease in white spaces would decrease the overall Albedo.

Figure 1 demonstrates the Albedo measurement for each pixel. By calculating the average Albedo within a 50 x 50 km region, it is possible to determine the Albedo for a single pixel. For example, if there is an equal mixture of desert and grassland, the Albedo will be approximately 0.3 for that one pixel, regardless of the terrain arrangement.

After calculating the cell, the pixels are arranged to match their latitudes and longitudes. This process allows researchers to study the distribution of Albedo across the Earth's surface and better understand its role in the global climate system.

Figure 1: How Albedo is Calculated:



4.2 Using Albedo in the Field

The geographic representation of Albedo has vast implications, observed at both a global and a more localized scale. In effect, it is akin to using a black-and-white photo for analysis. However, unlike a black-and-white photo, each pixel has been calibrated in this case to ensure that lighting conditions do not alter the measurements. It presents a valuable means of understanding and monitoring how environmental events and anthropogenic activities, such as human-induced land use change, natural disasters, and desertification, influence the Earth's surface reflectivity.

This section uses examples involving changes to the Aral Sea, California's Sacramento Valley drought, the aftermath of Hurricane Katrina, and North-East Nigeria's desertification to demonstrate Albedo's usage and utility. Each case reveals the intricate connections between land use, natural disasters, and the observed alterations in Albedo, thereby illustrating how Albedo serves as a crucial variable in assessing environmental change. The following section discusses these real-world cases, demonstrating how researchers utilize Albedo in field investigations to analyze the effects of environmental changes and validate satellite-based measurements.

Figure 2 showcases Albedo's application in measuring terrain changes. The figure illustrates changes in the Aral Sea, Sacramento Valley, Hurricane Katrina's aftermath, and North Eastern Nigeria's desertification.

The Aral Sea is a famous example of land use change caused by human activity. Figure 2 (a,b, and c) displays the sea's transformation, highlighting the increased Albedo from the water-covered surface to a barren, dry landscape.

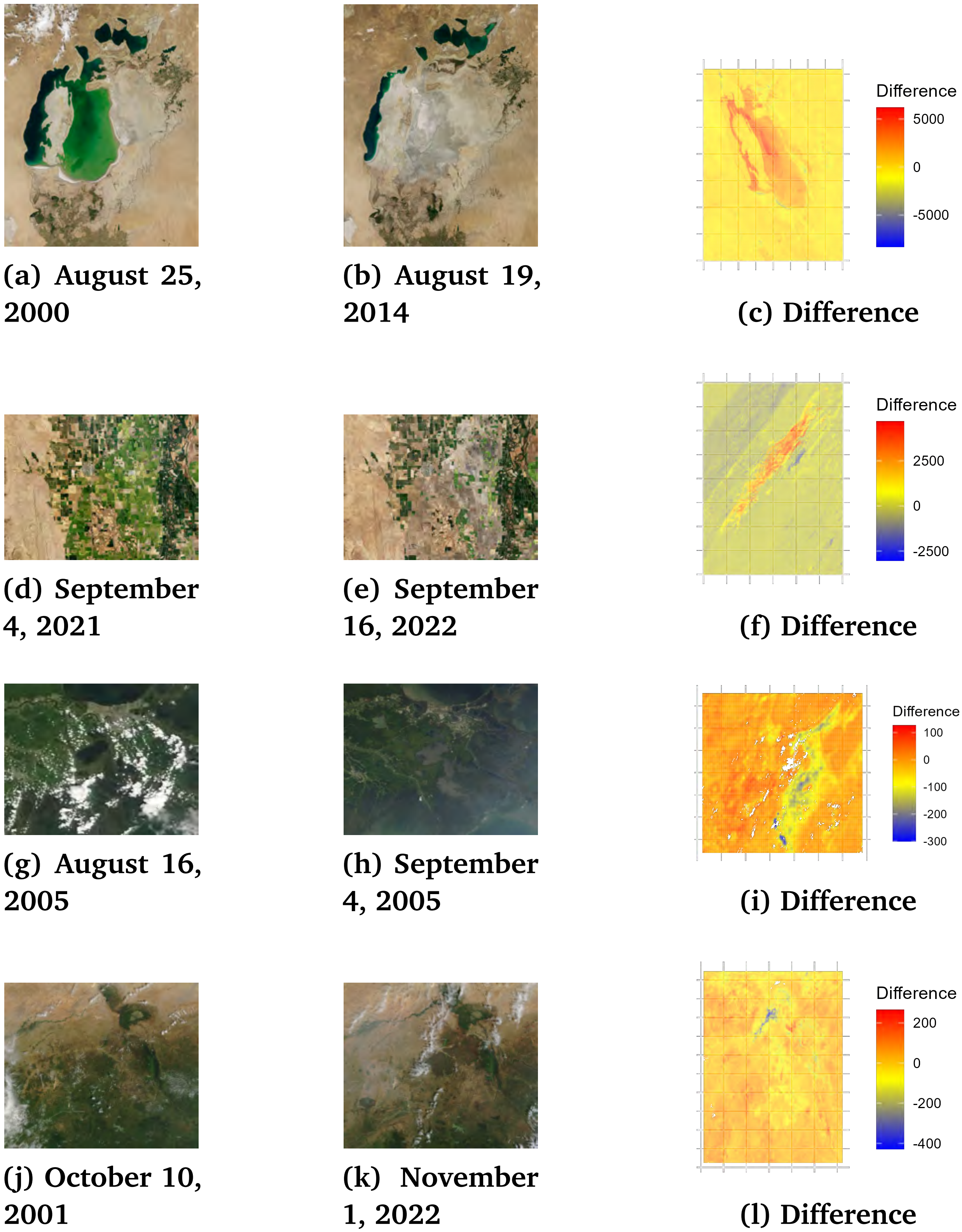
California's Sacramento Valley experienced a severe drought since 2020, impacting agriculture. Low reservoir storage levels caused reduced water deliveries [2] to the Central Valley by 43% in 2022. Consequently, rice growers planted less grain than usual. Figure 2 (d,e, and f) displays the Central Valley's increased Albedo due to the reduced water supply for agriculture.

Figure 2 (g,h, and i) also presents images of New Orleans surrounding Hurricane Katrina's period. The right-side raster image demonstrates the difference in Albedo before and after the flood, revealing how effectively Albedo represents the extent and location of the flooding.

North-East Nigeria has been affected by desertification, with Figure 2(j,k, and l) displaying the region's transformation over time. The right-side image of Figure 2 shows the area's alarming rate of desertification. The increasing Albedo contributes to a cycle of warming and drying, intensifying the desertification process.

By examining these cases, I demonstrate that Albedo measurements provide accurate insights into the consequences of desertification, drought, and flooding on ecosystems, economies, and communities. The ability to remotely obtain Albedo data through satellite imagery enhances its

[2] https://www.latimes.com/environment/story/2022-11-23/drought-cost-california-agriculture-1-7-billion-this-year



(a) August 25, 2000
(b) August 19, 2014
(c) Difference
(d) September 4, 2021
(e) September 16, 2022
(f) Difference
(g) August 16, 2005
(h) September 4, 2005
(i) Difference
(j) October 10, 2001
(k) November 1, 2022
(l) Difference

Figure 2: Comparison of the Aral Sea (a,b, and c), California Drought (d,e, and f), Hurricane Katrina (g,h, and i), and Desertification Nigeria images (j,k, and l).

utility, allowing researchers to track changes over time on a global or subnational scale. For the purposes of desertification and its effects on the likelihood of civil war, this paper will focus on long-term changes in Albedo.

This means that an increase in Albedo should correspond with a decrease in the land's carrying capacity.

H1: An increase in Albedo should result in a decrease in vegetative health

4.3 Albedo and Climate

The Albedo of the Earth's surface is a key factor influencing the planet's climate, with Albedo being the proportion of incoming solar radiation that is reflected back into space by a surface. Different surfaces have different Albedos based on their characteristics. For example, fresh snow has a high Albedo of up to 0.9, meaning it reflects 90% of incoming sunlight. In contrast, the ocean has a lower Albedo.

The higher the Albedo of the Earth's surface, the more sunlight it reflects, resulting in less solar energy being absorbed. This has a cooling effect on the climate. Conversely, lower Albedo surfaces absorb more radiation, heating the planet. Even small changes in Earth's average Albedo can have significant climate impacts. This is because the energy from the sun that is not reflected back into space get absorbed by the Earth. The Earth's surface then re-emits the energy in the infrared wavelengths. For a greater discussion on why this is, please see the Appendix.

Greenhouse gases absorb specific wavelengths of infrared radiation based on their molecular structure and vibrational modes described using absorption cross-sections (Herzberg 1953). The excited greenhouse gas molecules then re-emit the absorbed radiation in all directions, with a portion directed back towards Earth's surface. Greenhouse gases contribute to radiative forcing by absorbing and re-emitting infrared radiation, which alters the Earth's energy balance. As greenhouse gas concentrations increase, more infrared radiation is absorbed by these gases. With the gases now warmed, a fraction of the energy is returned to the Earth's surface. This causes an increase in the net downward radiation, leading to the subsequent warming of the Earth's surface and lower atmosphere (**?**).

Climate change is expected to significantly alter the Earth's Albedo through several mechanisms. Rising global temperatures are melting sea ice, glaciers, and ice sheets, exposing more low-Albedo ocean and land. This melting exposes darker surfaces that absorb more heat, causing a positive feedback loop of further warming. In addition, increased wildfires triggered by climate change will convert reflective snowy forests into darker charred landscapes that absorb more sunlight. Changing cloud patterns and atmospheric particle concentrations will also impact Albedo. Scientists estimate that the net effect of climate change will be to decrease the Earth's Albedo by several percentage points over this century.

The Ice-Albedo feedback loop is another aspect of Earth's climate system (Stroeve et al. 2007). It is a positive feedback mechanism that begins with initial warming caused by increased greenhouse gas concentrations or changes in solar irradiance. This warming leads to the melting of ice and snow, which reduces Earth's overall Albedo and increases the absorption of solar radiation. The subsequent warming further melts ice and snow, amplifying the initial warming and causing increases in global temperature. This feedback loop has significant implications for Earth's climate system, including accelerating polar ice melt, rising sea levels, and altering global ocean circulation patterns (Serreze and Barry 2011). The Albedo feedback loop can also exacerbate the effects of global warming on ecosystems and human societies, leading to increased frequency and intensity of extreme weather events that can impact agriculture, infrastructure, and human health. Moreover, we should expect that on a global level, as climate change increases, we should expect to see the Earth's Albedo should decrease.

H2: Earth's Albedo should decrease over time due to climate change.

4.4 Climate Change, Albedo, and the "Winner" and "Loser" Effects: Understanding the Pathways to Conflict

Climate change continues to reshape our world, manifesting in various ways that can have profound impacts on societies and political landscapes. A critical examination of Albedo changes in Nigeria and Russia, as depicted in Figure 3, reveals how the nuanced "winner" and "loser" effects of climate change can create complex pathways to conflict.

4.4.1 The "winner" and "loser" Effects: A Conceptual Framework

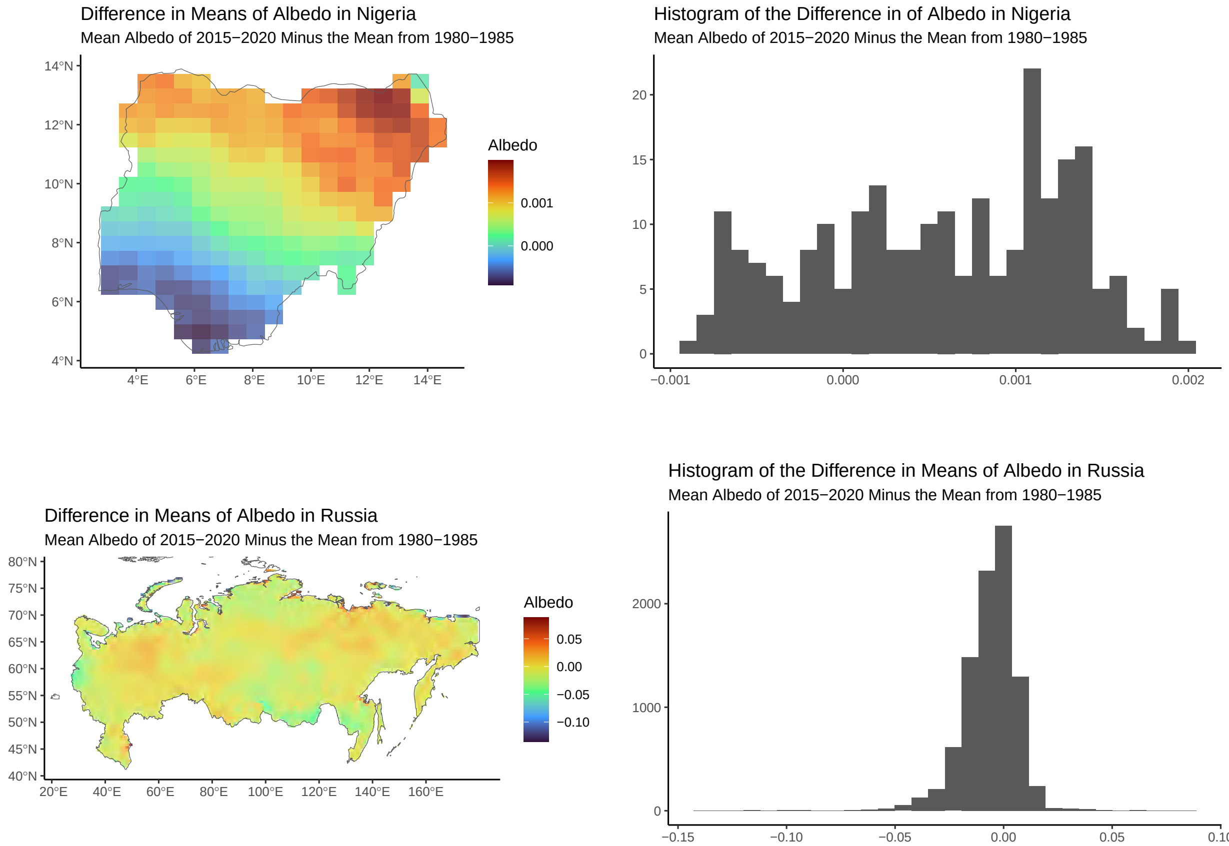
The terms "winner" and "loser" refer to the differential impacts of climate change, creating regions or communities that either benefit from or are adversely affected by environmental changes. Often researchers think of the areas which will be harmed by climate change. However, increased Rainfall and thawing of permafrost will open up new opportunities for some, while others struggle with the harsh realities of desertification and drought. These effects can be observed in the context of desertification in Nigeria and warming in Russia.

Areas negatively affected by desertification or other environmental changes may face scarcity of vital resources, such as water and arable land. This scarcity can lead to intense competition and heightened tensions, providing fertile ground for conflict. Drawing from the theoretical insights from Roche et al. (2020) it is important to recognize that climate anomalies, such as desertification, can create "winners" and "losers" at the subnational level, depending on the opportunity cost of labor and local economic conditions.

The disparities between "winners" and "losers" may create economic imbalances, fostering resentment and social unrest. Regions that benefit due to changes in their environments may flourish, while others may languish, creating friction and potential conflict (Cederman, Weidmann and Gleditsch 2011; Houle 2015).

Figure 3 displays the difference in Albedo between 1980-1985 and 2015-2020 in Nigeria and

Figure 3: Measuring Sub-national Climate Change using Albedo



Russia, showcasing opposite ends of climate change, with Nigeria experiencing desertification and Russia experiencing warming.

The top left of Figure 3 shows the change in Albedo in Nigeria. The results indicate that desertification is ongoing in Northern Nigeria, with the highest rate of change in the North East. This aligns with the ground truth and supports the view that the Sahara Desert is expanding into Northern Nigeria.

Desertification is most severe in the area near Jimeta, located near Nigeria's eastern border with Cameroon, which has experienced significant desertification despite being approximately 300 km south of the Sahara. Moving west towards the border with Benin, the rate of desertification decreases until it reaches approximately zero, likely due to the presence of a national park and a nearby forestry reserve that serve as barriers to desertification (Sagan, Toon and Pollack 1979; Otterman 1974; Schlesinger et al. 1990). A similar pattern occurs along the eastern border south of Jimeta, where there is also a lush national park. The southern area of Nigeria remains lush and appears slightly darker.

In Nigeria, desertification is most severe near Jimeta, leading to increased competition for resources. This can be seen as a "loser" effect, where environmental changes lead to scarcity and potential conflict. Conversely, the areas to the south, which are becoming more lush represent a "winner" effect where environmental preservation mitigates the negative impacts.

The histogram in the top right of Figure 3 shows the average change in Albedo from 1980-1985 to 2015-2020. The data suggests that, on average, there has been an increase in Albedo, indicating the spread of desertification. However, the histogram also suggests that climate change does not affect all areas equally, with some regions in the south becoming darker and potentially lusher.

The bottom left map in Figure 3 shows the difference in mean values of Albedo between 1980-1985 and 2015-2020 in Russia. The map indicates that the land in Russia is becoming slightly darker on average, suggesting a decrease in snow or ice. A few areas have become slightly brighter, which is difficult to interpret because of Russia's proximity to the North Pole. It could be due to increased snow, a single large storm, or drying out of an area. This highlights one of the limitations of using Albedo as a measure in cold regions. However, the histogram on the right provides more insight. It shows that, on average, the Albedo of Russian land is decreasing, which is consistent with the observed changes in Russia.

These data highlight the nuanced relationship between climate change and societal stability. Rather than a uniform increase in risk, climate change produces differential impacts that can either increase or decrease the risk of conflict, depending on local economic conditions and the specific nature of the environmental changes.

These data suggest that climate change produces subnational "winner" and "loser" effects that have been found to promote conflict and civil war (Cederman, Weidmann and Gleditsch 2011). Countries whose average Albedo is increasing, indicating a drying environment, should be more prone to violent conflict as a result of a shift in the opportunity cost of labor (Roche et al. 2020).

Given these insights, we can derive the following hypotheses:

H3: As the average Albedo of a country increases, the probability of civil war will increase.

H4: As the average Albedo of a country increases, the number of civil wars it will face will also increase.

5 Deconstructing the Rainfall-Climate Change Nexus

Numerous studies have constructed links between Rainfall, agriculture, and climate change. Recognizing the complex relationship between precipitation and the environment leads us to reexamine our assumptions about Rainfall's influence on agriculture and political stability. This section explores the various factors that modulate Rainfall, such as temperature, orographic lift, rain shadow effect, aspect, elevation, local convection, and wind channeling. Furthermore, I discuss the constraints and potential fallacies of using Rainfall as a measure for climate change, especially highlighting the possibility of limited variation due to climate change.

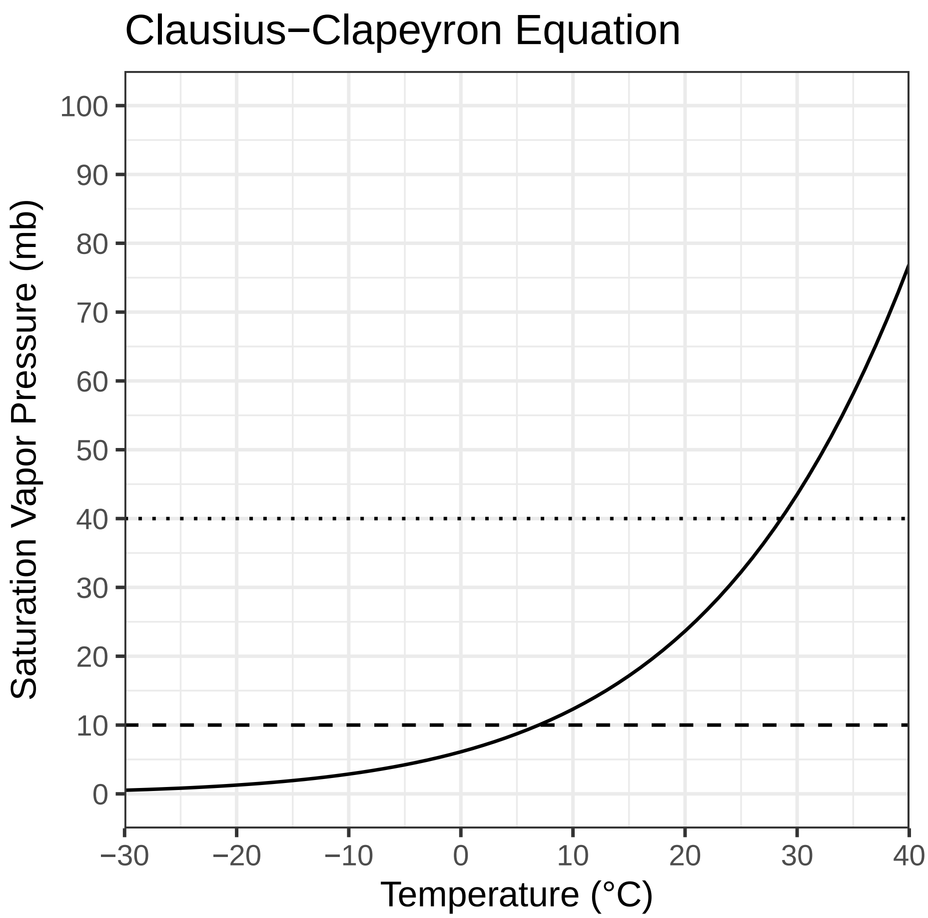
5.1 Decoupling Precipitation and Thermal Conditions

The Clausius-Clapeyron equation, a fundamental thermodynamic principle, models the relationship between temperature and saturation vapor pressure. It provides a theoretical understanding of the atmosphere's water vapor capacity at different temperatures and the conditions leading to precipitation.

Figure 4 demonstrates the Clausius-Clapeyron equation's application, illustrating the relationship between temperature and atmospheric water-carrying capacity. Given the roughly

7% increase in the atmosphere's water-carrying capacity per degree Celsius, modest changes in global Rainfall to date are expected.

Figure 4: Vapor Pressure: The Relationship Between Temperature and Atmospheric Water Carrying Capacity



This increase might intensify aridity in dry regions, supporting the notion that "wet areas get wetter" and "dry areas get drier." However, the actual variation in Rainfall due to climate change may be less significant than these phrases suggest. Researchers should be cautious when examining climate change's impacts on Rainfall, especially in retrospective studies. Some evidence also suggests overestimation of actual Rainfall overland using this equation.

5.2 Topography and Precipitation: A Complex Interplay

Topography significantly influences precipitation through mechanisms like orographic lift, aspect, elevation, local convection, and wind channeling. These factors demonstrate that increased temperature and saturation vapor pressure do not necessarily guarantee increased Rainfall. Thus, caution is required when attributing Rainfall patterns to climate change.

Given this intricate relationship, I hypothesize:

H5: Rainfall will have remained roughly constant from 1980 through 2019 globally over land with negligible substantive changes over that time period.

5.3 Variables

The primary dependent variable, conflict, is measured using the binary variable $onset_{ko}flag$ from the Geographical Research On War, Unified Platform (GROWUP) dataset from the PRIO group, indicating the start of a group-level conflict (Fearon and Laitin 2003; Collier and Hoeffler 2004; Fearon, Kasara and Laitin 2007; Cederman and Girardin 2007; Blair and Sambanis 2020). As a robustness check, the number of onsets per country from 1980-2019 is summed, serving as the second dependent variable in the analysis. This measure allows for a straightforward assessment of conflict occurrence while acknowledging that other civil war outcome measures may provide additional insights.

Data from the Armed Conflict Location & Event Data Project (ACLED) is used for further robustness checks, providing additional insight into the degree of conflict in a region(Hegre, Østby and Raleigh 2009; Schutte and Weidmann 2011; Abay et al. 2022; Guha Sapir et al. 2022). Events are Geo-located and matched to countries. Then the number of events between 1980 and 2019 is summed for each country to serve as a further robustness check.

The main explanatory variable is clear sky Albedo, where clouds are NAs, and the data is averaged across 14 days, and Coeficient of Variation in Rainfall, both drawn from NASA's

MERRA-2 dataset. Because the unit of analysis is at the country level, the change in Albedo is calculated by taking the difference between the mean annual Albedo of 2015-2020 and the Albedo between 1980-1985. Then the mean value for each country is used.

Figure 5 displays the average Albedo for land and water across the Earth from 1980 to 1985. Areas with high Albedo, such as Greenland and Antarctica, are due to the presence of ice and snow. The Sahel region also has a noticeable average Albedo of around 0.4. In contrast, Central Africa and Southern Canada have a relatively low Albedo, with values below 0.2. The drastic change in Albedo is evident when comparing the Sahel in North Africa to the rainforests of Central Africa or the Great Planes of the Mid-Western United States to the forests of Canada.

Figure 5: Global Albedo:

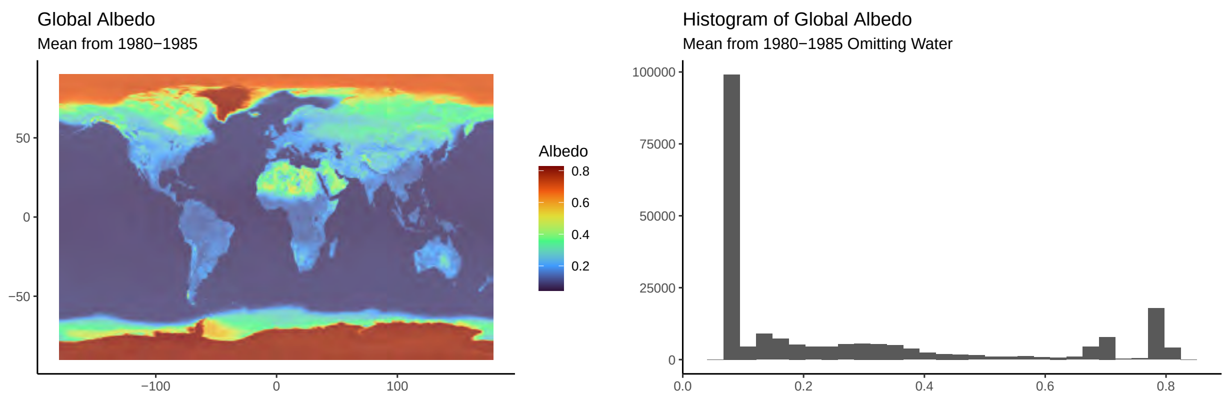
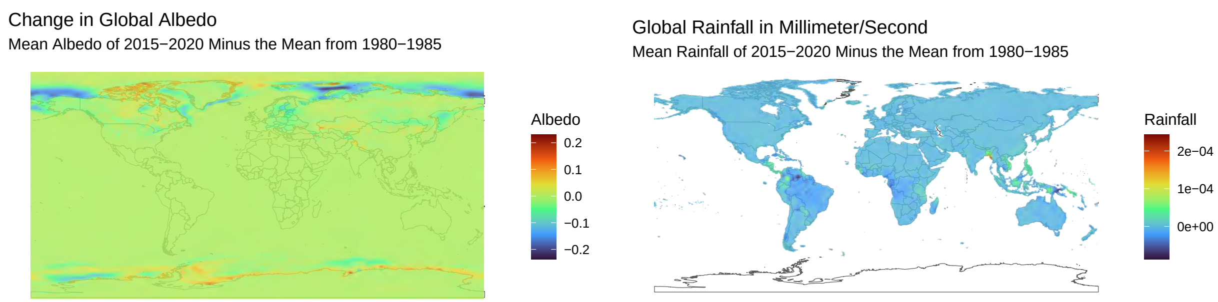


Figure 5 displays the distribution of mean Albedo measurements on the right. The large vertical column at around 0.09 represents the majority of the Earth's surface, which is water. Another peek at approximately 0.15 represents lush vegetation, such as forests, as confirmed by the map on the left. Rainforests in Africa, South America, and Southeast Asia are close to an Albedo of 0.15. There is a range of Albedo estimates between 0.2 and 0.35.

It is important to interpret this data cautiously, as it reflects average Albedo across multiple seasons. A high Albedo indicates desert in areas where snow is uncommon, such as much of Africa and the Middle East. Closer to the poles, the average Albedo is often a combination of snow and land, explaining the higher average Albedo than grassland and a lower average Albedo than a snowy landscape. The far right of the histogram displays two final peaks, one for snow and the other for ice.

Figure 6: Measuring Climate Change: Rainfall and Albedo



Note: Both figures here are differences in means between the Albedo or Rainfall and the 1980s average. Both variables have the same spatial resolution, but Rainfall is limited to overland usage.

The Clausius-Clapeyron equation, which describes the amount of water vapor that air can hold as a function of temperature, suggests a limit on the expected change in Rainfall due to climate change. This is because the temperature increase due to climate change is often relatively small on a global scale, leading to limited changes in Rainfall. Accordingly, while certain regions might see more substantial alterations in precipitation patterns due to localized warming, the global average Rainfall is unlikely to change dramatically.

In addition to Albedo and CV, total precipitation to land is used as a control variable, with data obtained from MERRA-2's *Prectotland* variable, measuring Rainfall and converted into millimeters of rain per day.

The data from Figure 6 using NASA's MERRA-2 dataset displays the difference in means from 1980-1985 to 2015-2020 for Albedo and Rainfall. The Albedo map shows a clear reduction in Albedo in the northern hemisphere and along Antarctica. This is in line with the polar ice melting less snow during winters.

The Rainfall map shows very little change for most of the world, except for a few localized areas. This makes intuitive sense considering the Clausius-Clapeyron equation. Given the slow rate of temperature increase and the less dramatic changes in Rainfall, the variations in Albedo provide a more apparent and reliable marker of the long-term climate transformations taking place.

Vegetation Condition Index (VCI) (NOAA 2018) serves as the primary independent variable in this study and has been validated on a global scale. The index is computed with a spatial resolution of 4 km and a 7-day composite temporal resolution. VCI is derived from remote-sensing technology and is calculated based on the Normalized Difference Vegetation Index (NDVI). It serves as a valuable proxy for moisture conditions and overall vegetation health in a given area. Elevated VCI values are typically associated with healthy, robust vegetation and sufficient soil moisture, making the index a crucial metric for assessing land suitability for agriculture and other human activities. Given its high sensitivity to vegetation changes, VCI is an effective indicator for monitoring ecological health and potential desertification trends.

Temperature Condition Index (TCI) (NOAA 2018) is included as a control variable to isolate the effects of temperature on the dependent variable, Albedo. Like VCI, TCI also has a 4 km spatial resolution and a 7-day composite temporal resolution. It is computed using measurements in the 10.3–11.3 μm wavelength range from the Advanced Very High Resolution Radiometer (AVHRR). TCI serves as a proxy for thermal conditions, capturing variations in land surface temperature that could impact vegetation health and, consequently, Albedo. By including TCI in the model, we control for the influence of temperature, allowing for a more nuanced understanding of the relationship between VCI and Albedo.

Vegetation Health Index (VHI) (NOAA 2018) is another control variable in the model and is particularly useful for providing a comprehensive view of vegetation health. It is a composite index formulated as $\text{VHI} = a \times \text{VCI} + (1 - a) \times \text{TCI}$, where a is a coefficient that determines the contribution of VCI and TCI to the index. VHI integrates both moisture and thermal conditions, offering a more holistic assessment of environmental health. This index is valuable for capturing the combined effects of moisture and temperature, which are critical factors for vegetation vitality and, by extension, Albedo.

GDP per capita from the World Bank is included as a control for economic development because economic development has been a fundamental variable in the civil war literature (Collier and Hoeffler 2002; Fearon and Laitin 2003; DeRouen Jr, Lea and Wallensteen 2009; Gurses and Mason 2010). Another variable that has been the cornerstone of the civil war literature is ethnic fractionalization or ethnic politics. This paper will employ the N^* variable to capture the effect of ethnic power relations within countries (Cederman and Girardin 2007; Fearon 2003).

Another standard variable in the civil war literature is the ruggedness of the terrain. The mean elevation of countries is used as a proxy for mountainous terrain, following the theoretical concept proposed by Fearon and Laitin (2003). Higher Mean Elevation indicates more rugged terrain, which can provide a secure refuge for rebel groups and hinder the reach of government forces (Carter, Shaver and Wright 2019). To control for the oil curse, the number of oil fields within a country's boundaries is counted as a variable (Ross 2004, 2006, 2012).

Researchers have found that past violence predicts future violence through grievances or other mechanisms (Collier and Hoeffler 2004; Fearon and Laitin 2003). Therefore, the sum of the number of peace years (representing the years since the last civil war) is a control variable for the models. The log of the population of a country is added as a control variable as is common practice in the civil war literature (Fearon and Laitin 2003; Raleigh and Hegre 2009; Acemoglu, Fergusson and Johnson 2017).

5.4 Models

The expectation from the Clausius-Clapeyron equation is that the effects of global warming should not impact Rainfall much in retrospective analyses, and some researchers (O'Gorman and

Muller 2010; Skliris et al. 2016) have found that the Clausius-Clapeyron equation overestimates the increase in global Rainfall. Therefore, the first model will test whether global Rainfall has changed since the 1980s.

If Rainfall has not changed by a substantively significant amount, then it would be illogical to continue using Rainfall as a measure of climate change because researchers would be using a constant to measure change over time. The same logic holds for Albedo. Albedo is expected to decline globally as part of the Albedo-climate feedback loop. Therefore, on average, Albedo is expected to decline with both substantive and statistical significance.[3]

The study then employs four models to illustrate the usage of Albedo and CV to measure the impact of climate change on conflict. The first model uses logistic regression to model the effect of climate change on the likelihood of conflict at the state level, with the binary onset variable for civil wars serving as the primary dependent variable.

The second and third models use negative binomial regressions due to the count nature of their dependent variables. The second model transforms the civil war onset variable from a binary variable to a count variable, with the dependent variable being the sum of all civil war onsets for each country. This model specification suggests that an increase in Albedo should result in increased civil wars in a country, thereby improving the signal-to-noise ratio from the first model.

The third model focuses on the number of events recorded by the Armed Conflict Location & Event Data Project (ACLED) from 1980-2020 as the dependent variable. This model captures a broader range of events[4] than the civil war onset variable and includes several forms of political violence, serving as a robustness check. Again, an increase in the number of events is expected to correspond with an increase in Albedo over time.

The final model will utilize Bayesian Additive Regression Trees with Cross-Validation

[3]Note: Albedo should increase as desertification increases. However, the volume of melting ice and snow and their much higher reflectivity should greatly outweigh the increase in desertification by global surface area.

[4]The events selected are: Bombing/Explosion, Armed Assault, Facility/Infrastructure Attack, and Hijacking.

(BARTcv) to assess the effects of Albedo and CV on civil war onset (Chipman et al. 2010; Montgomery and Olivella 2018). Climate change and civil war are multifaceted phenomena characterized by numerous interacting variables. BARTcv is adept at modeling these complex, nonlinear relationships without imposing restrictive assumptions about the underlying data structure. By incorporating cross-validation, BARTcv enhances the robustness of the model's predictive performance estimation, mitigating overfitting and ensuring generalizability to unseen data. Furthermore, BARTcv's allowance for uninformed priors ensures that the analysis does not require specific prior knowledge about the relationships between variables, leading to an unbiased examination guided solely by the data.

Bayesian Additive Regression Trees (BART) is a non-parametric Bayesian method designed to unravel complex, multifaceted relationships. It operates by constructing a series of decision trees, where each internal node represents a test on an attribute, and each leaf node signifies a class label or value. This structure enables the capture of intricate interactions between variables, facilitating a nuanced understanding of underlying relationships.

Unlike traditional decision trees, BART combines multiple trees additively. The final prediction is derived from the sum of individual trees' predictions, allowing for the modeling of more complex relationships and a reduction in overfitting. BART's incorporation of Bayesian principles, along with the use of uninformed priors, ensures an unbiased analysis. This approach provides a means to quantify uncertainty in predictions, allowing for more robust and reliable conclusions.

The cross-validated version of BART, known as BARTcv, further enhances this approach by employing cross-validation. By dividing the data into subsets and testing the model on different combinations of these subsets, BARTcv provides a more robust estimation of the model's predictive performance. This method aids in the avoidance of overfitting and ensures that the model is applicable to unseen data, enhancing its generalizability.

BARTcv's non-parametric nature enables the flexible modeling of complex nonlinear relationships between variables. In the context of this study, such as the relationship between Albedo, CV, and civil war onset, BARTcv's capabilities are particularly pertinent. The utilization of uninformed priors and cross-validation ensures an unbiased and robust analysis of these multifaceted phenomena.

Bayesian Additive Regression Trees with Cross-Validation (BARTcv) offers a sophisticated and robust non-parametric method for modeling complex relationships. Its application to the relationship between climate change factors (Albedo and CV) and civil war onset can yield valuable insights, providing a nuanced and data-driven approach to understanding these intricate interactions.

6 Albedo the Better Measure of Climate Change

This research explores climate change as a catalyst for violent conflict, showcasing Albedo as a key measure in tracking these transformations. Using NASA's MERRA-2 dataset, this paper finds evidence supporting the hypothesis that Albedo is a superior and more intuitive long-term climate marker than Rainfall. This finding correlates with expectations from the Clausius-Clapeyron equation, where a gradual temperature rise will result in negligible changes in precipitation. In sharp contrast, Albedo changes, closely linked to ice sheet melting rates and desertification, offer a more vivid picture of climate fluctuations.

Table 2 tests whether Albedo has indeed changed as expected by the climate change model and the Clausius-Clapeyron equation's expectation of minimal changes in Rainfall globally.

Here the effect for Albedo is negative and statistically significant at the 0.001 level, as expected by the results from Figure 6. This means that, on average, the Earth has become darker since 1980, as expected given the melting of the ice sheets. The Rainfall variable has less statistical power than the Albedo regression since it can only be accurately measured over land but has the same resolution. The global estimated change in Rainfall in the simple regression was 0.002 millimeters of rain per day on average. However, the estimate failed to reach any level conventional level of statistical significance.

Controls for the month of the year are included in the final two models to account for the possibility that monthly variation might exaggerate the changes in Albedo or wash out the estimate for Rainfall. Again, Albedo decreases over time and is significant at the 0.001 level. Now we see a larger increase in the change in Rainfall per year, though it is still not statistically significant.

The analysis of the data reveals that the total Rainfall is not a reliable indicator of climate trends. However, the coefficient of variation (CV) in Rainfall presents a more nuanced picture and is found to be statistically significant. This significance in Rainfall CV reflects an increase in Rainfall variability over the time span considered in the study.

The high degree of statistical significance in the Rainfall CV supports the notion that the variability, rather than the average amount of Rainfall, is increasing. This finding aligns with the predictions made using atmospheric chemistry models, such as the Clausius-Clapeyron equation. It suggests that the climate is not necessarily experiencing an increase in total Rainfall, but rather a growing frequency of extreme weather events. This trend indicates a shift in weather patterns, potentially leading to more unpredictable and severe weather conditions.

Figure 7 presents the outcomes of the regression analysis. The Earth's surface Albedo was approximately 0.221 in 1980 and decreased to 0.218 in 2020. Accordingly, the average location on Earth's surface now absorbs 0.003 more energy. While this might not appear significant, it is essential to consider that the Sun produces approximately 340 watts per square meter[5], with about 1,000,000 square meters in a square kilometer and each pixel measuring approximately 2,500 square kilometers. This implies that each pixel now absorbs an additional 2,550,000,000 watts annually. In contrast, the Rainfall variable remained relatively stable at approximately 780.4 millimeters per year, marginally lower than the average annual precipitation in Italy

[5]https://earthobservatory.nasa.gov/features/EnergyBalance/page2.php

Table 2: Albedo The Better Measure of Climate Change

	Albedo %	Rainfall MM per Day	Albedo %	Rainfall MM per Day	CV Rainfall
Year	-0.008***	0.002	-0.007***	0.023	0.109***
February			1.212***	-5.761***	
March			6.721***	-16.154***	
April			1.521***	-7.073***	
May			-1.532***	47.184***	
June			-3.284***	165.552***	
July			-6.299***	217.728***	
August			-5.332***	199.165***	
September			0.830***	123.741***	
October			1.143***	55.863***	
November			0.533***	13.615***	
December			0.139***	-0.079	
Intercept	37.801***	776.656***	36.042***	668.615***	
N	93,525,124	28,319,356	93,525,124	28,319,356	2,355,040
R2	0.00002	5e-10	0.021	0.007	0.001

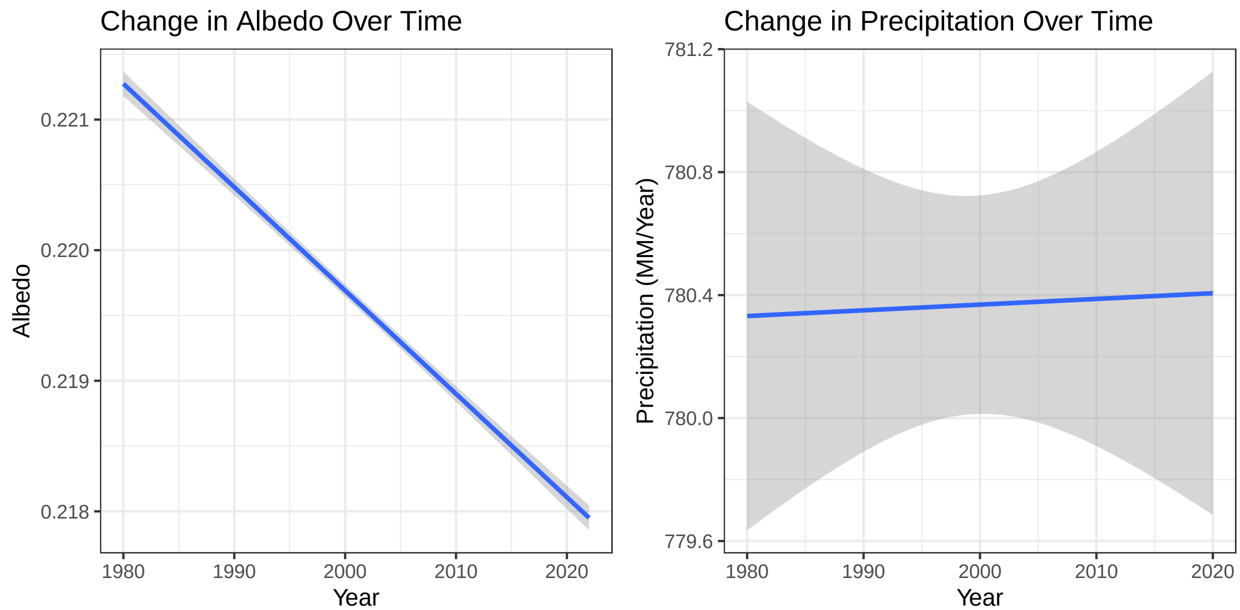
+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(811.22 mm)[6].

These findings suggest that the lack of discernible links between climate change and conflict in most empirical research to date is unsurprising. Given the limited theoretical expectation of significant Rainfall changes based on the Clausius-Clapeyron equation, using Rainfall as an indicator for variations in conflict is akin to employing a constant to measure variation.

Future research should adopt a variable that more accurately reflects climate change. As demonstrated, Albedo and Precipitation CV can be employed as a measure of climate change. The remainder of this paper will illustrate the application of Albedo and CV in predicting civil war and violent conflicts.

Figure 7: Albedo, the Better Measure of Climate Change



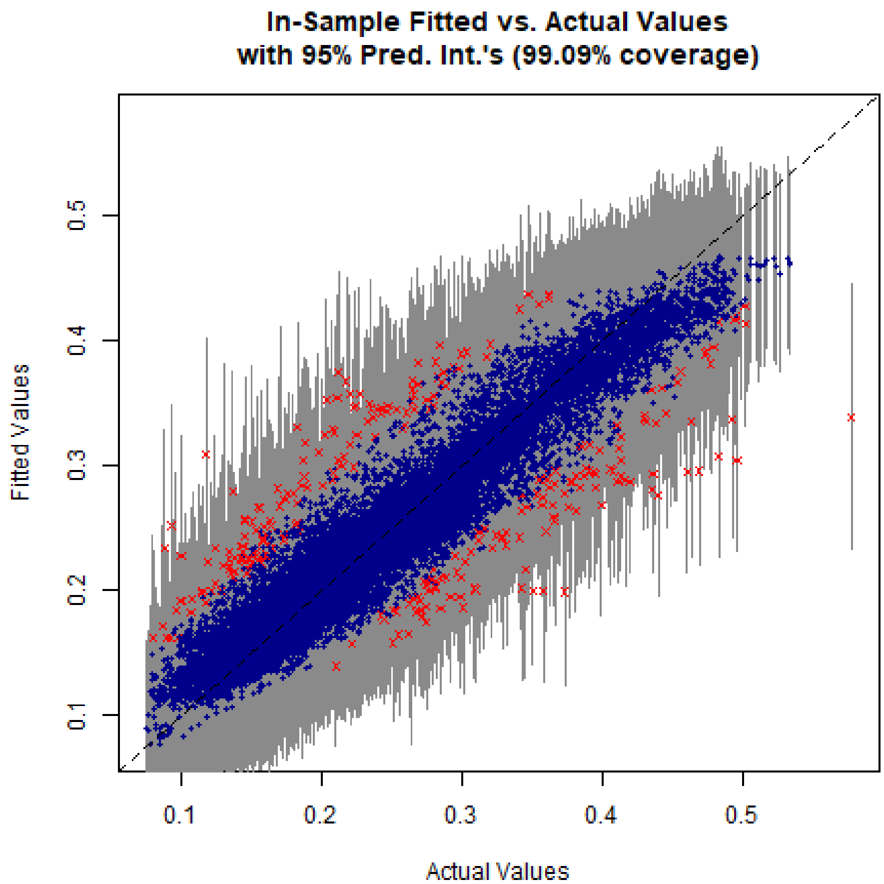
6.1 Carrying Capacity Model

Utilizing BART as the statistical model, this section offers a comprehensive analysis of how key environmental indices—namely Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Vegetation Health Index (VHI)—interact with Albedo. The section incorporates graphical representations to visualize these relationships and to substantiate the model's high explanatory power and predictive accuracy. Detailed discussions follow on the significance of controlling for specific variables, the theoretical implications of the observed relationships, and the broader policy implications for areas vulnerable to desertification and ecological degradation.

The Bayesian Additive Regression Trees (BART) model demonstrated exceptional performance in capturing the relationship between the dependent and independent variables. The model with the hyperparameter with k = 2 yielded a high Pseudo-R^2 value of 0.9306, indicating that approximately 93% of the variance in the Albedo can be explained by the included

[6] https://climateknowledgeportal.worldbank.org/country/italy/climate-data-historical

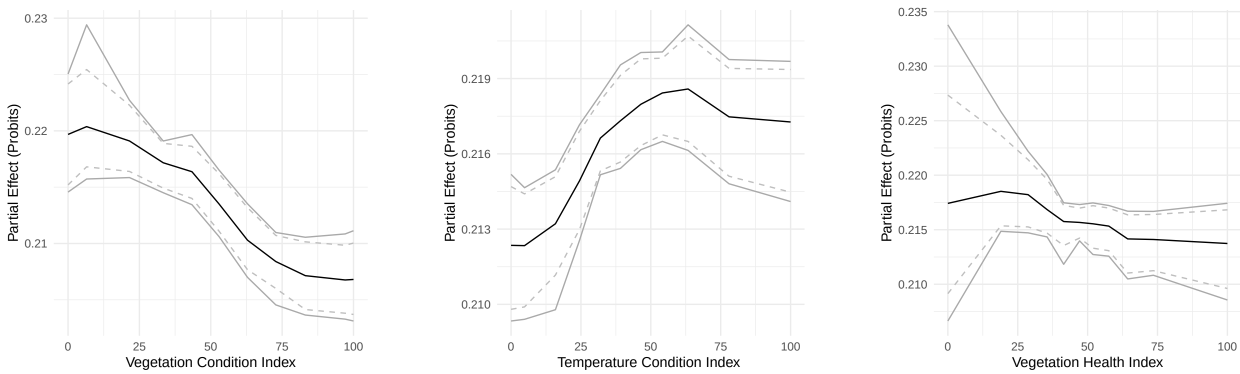
Figure 8: BART Model Fit



variables (VCI, TCI, VHI). Furthermore, the in-sample fitted vs. actual values, along with a 95% prediction interval, covered over 99% of the observations as demonstrated by Figure 14. This high coverage rate underscores the model's predictive accuracy and reliability.

Figure 9 illustrates the partial dependence plots along with 95% credible intervals, clearly demonstrating the inverse relationship between Vegetation Condition Index (VCI) and Albedo. As VCI increases, indicating healthier vegetation, Albedo correspondingly decreases. This trend holds true even when the effects of Temperature Condition Index (TCI) and Vegetation Health Index (VHI) are controlled for in the model. See the Appendix for the Effect of VHI without the confounding VCI.

Figure 9: Albedo and Human Carrying Capacity



Note: This figure depicts the partial dependence plots for the BART model estimating the relationship between VCI and Albedo controlling for TCI, and VHI. 95% CIs are the solid lines, and 90% CIs are the hashed lines. The relationship between Albedo and VCI is negative and significant as expected. This means an increase in Albedo strongly corresponds with a reduction in the land's carrying capacity. The northern latitudes were removed for this analysis. This means that an increase in Albedo corresponds to an average drying of the land.

Controlling for TCI and VHI is crucial for isolating the unique effect of VCI on Albedo. TCI serves as a proxy for thermal conditions, while VHI offers a composite measure of both moisture and thermal conditions affecting vegetation health. By keeping the impacts of these variables constant, the model effectively isolates the relationship between VCI and Albedo, ensuring that it is not confounded by other environmental factors.

The observed inverse relationship between VCI and Albedo is consistent with theoretical expectations. A decline in VCI, which signals deteriorating vegetation, is associated with an increase in Albedo—likely due to increased surface reflectivity often seen in desertifying landscapes.

These findings have significant implications, particularly for policy evaluation and decision-making in areas susceptible to desertification and ecological degradation. They establish Albedo as a scientifically rigorous and politically relevant measure, serving as a reliable alternative to more commonly used environmental variables like Rainfall. The model's high explanatory power further substantiates Albedo's utility for assessing both ecological shifts and their broader socio-political impacts.

6.2 Onset Model

The Conflict Initiation Model explores variations in Albedo and its relationship with conflict onset, showing a clear link between changes in Albedo—often due to factors like increasing desertification or long-lasting dry spells—and the start of conflicts. Table 3 displays the models, with five different onset models providing various perspectives on the relationship between Albedo, Rainfall, CV Rainfall, and conflict onset.

The Onset Models reveal a strong connection between changes in Albedo and the start of conflicts. The effect of Albedo Difference is large and statistically significant across models, with coefficients ranging from 16.216 to 24.454, and significance levels at 0.05 and 0.01. This suggests that areas witnessing an increase in Albedo, generally due to worsening desertification or extended dry spells, are more likely to experience the start of civil conflict.

These findings can be connected back to the theoretical framework introduced earlier in the paper, particularly the "winner" and "loser" effects. Regions experiencing increased Albedo might be categorized as "losers" in the context of climate change, facing worsening desertification. Conversely, areas with stable or increased Rainfall might be seen as "winners," benefiting from water stability and reduced conflict likelihood. This dynamic creates a landscape where environmental changes determine winners and losers, potentially escalating tensions and competition over resources.

A notable addition to the analysis is the CV Rainfall variable, representing the coefficient of variation in Rainfall. Its positive coefficients in Onset 2 and Onset 3 models (0.340 and 0.419, respectively, with $p < 0.1$ and $p < 0.05$) suggest that areas with higher variability in Rainfall patterns may have an increased likelihood of conflict onset. This variability, combined with Albedo changes, may create a multifaceted environmental stressor, exacerbating tensions and competition over increasingly scarce and unpredictable resources.

In addition to the significant variables, some variables, such as Mean Elevation andN^*, do not exhibit significant relationships with conflict onset in the models. Mean Elevation, captures the mountainous terrain, and its non-significance may suggest that geographical features like mountains may not be directly influencing the conflict in the context of this analysis (Fearon and Laitin, 2003). N^*, capturing ethnic power relations (Cederman), may not have shown significance due to other prevailing factors in the data, reflecting the complex interplay of socio-political structures and environmental changes.

The model also considers the Rainfall variable, showing a significant inverse correlation in Onset model (coefficient = -0.092, $p < 0.1$), meaning that areas with more Rainfall are associated with a lower average chance of conflict breaking out. This variable, along with CV Rainfall, provides a more nuanced understanding of how Rainfall patterns, including both mean levels and variability, interact with Albedo changes in influencing conflict onset. Stable water availability might reduce conflicts over scarce resources, while unpredictable Rainfall could create additional stressors leading to conflict.

One point to consider is potential post-treatment bias in measurements of Albedo and Rainfall, as they were measured simultaneously or by the same methods. While it is not possible to completely prevent this form of post-treatment bias, Rainfall was excluded from some models to mitigate the effect. As a result, the effect of Albedo remained statistically significant, exceeding the 0.05 level.

6.3 Conflict Count Model

The Conflict Count Model further investigates the relationship between changes in Albedo, Rainfall, and other socio-economic factors with the number of civil conflicts within a State, as detailed in Table 3.

Mirroring the findings from the Onset Models, the Albedo Difference variable again achieves

Table 3: Albedo Predicts Climate Conflicts

	Dependent variable:				
	Onset	Onset 2	Onset 3	Onset Count	Onset Count 2
	(1)	(2)	(3)	(4)	(5)
Albedo Difference	19.912**	16.216*		24.454**	21.657**
CV Rainfall	0.244	0.340*	0.419**		
Rainfall	-0.092*			-0.181	
Mean Elev	-0.012	-0.006	-0.008	-0.028	-0.028
N^*	-0.306	-0.321	-0.236	0.029	0.018
Peace Years	-0.039***	-0.040***	-0.040***	-0.098***	-0.095***
Log Pop	0.273	0.447	0.410	0.803	0.698
GDP Per Capita	-0.069***	-0.063***	-0.067***		
Year	0.016**	0.016**	0.015*		
Oil Field Count	0.042**	0.041**	0.045**	0.034*	0.032*
Polity	-0.016	-0.024*	-0.022	-0.023	-0.024
Mean GDP(1000s)				-0.031*	-0.030
Constant	-33.964**	-34.722**	-32.265**	1.199**	1.278**
N	3699	3699	3699	125	125
AIC	1229.1	1230.6	1232.0	348.2	348.2
BIC	1303.7	1299.0	1294.1	379.3	376.5
Log.Lik.	-602.552		-605.983	-163.108	-164.122
F	6.866	7.117	7.560	8.261	9.086
RMSE	0.20	0.20	0.20	1.90	1.99

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

statistical significance (coefficient = 24.5, $p < 0.05$) and exhibits a positive relationship with conflict count. This evidence builds on the earlier analysis, reinforcing the hypothesis that increases in Albedo—often reflective of changes in soil aridity and desertification—can potentially intensify the number of civil conflicts. This association between Albedo and conflict underscores the role of environmental changes in shaping conflict dynamics, particularly in regions prone to desertification.

Conversely, the Rainfall Difference variable does not demonstrate statistical significance in this model. While the Onset Models revealed some nuanced relationships between Rainfall patterns and conflict onset, the lack of significance in the Conflict Count Model may suggest that Rainfall Difference has a less direct impact on the number of conflicts. This discrepancy warrants further exploration and may highlight the complex interplay between different environmental factors and conflict dynamics.

The model also reveals significant relationships with other socio-economic variables. There is an inverse relationship between 'Mean Peace Years' and the number of conflict onsets (coefficient = -0.099, $p < 0.05$). This finding is intuitive and supports the notion that a more protracted duration of peace within a nation correlates with fewer instances of conflict, emphasizing the importance of sustained peace efforts. Additionally, 'Mean GDP' exhibits a significant inverse relationship with the number of conflicts (coefficient = -0.00004, $p < 0.1$), and the 'Num Oil Fields' variable presents a positive correlation, aligning with prior expectations.

In Model 5, where Rainfall is omitted as a variable, the effect of Albedo remains largely consistent, underscoring its persistent significance in conflict prediction. The significant role of Albedo in predicting conflict aligns with global concerns about climate change and environmental degradation. These results also reinforce the importance of socio-economic stability, symbolized by variables such as 'Mean Peace Years' and 'Mean GDP,' in maintaining peace.

Table 4: Albedo Predicts Violent Events

	Number of Events	Number of Events2
Constant	5.499***	5.484***
Albedo Difference	42.810***	43.309***
Rainfall Difference	0.033	
Mean Elev/100)	-0.018	-0.018
Mean Log Pop	2.622***	2.637***
Mean Peace Years	-0.067***	-0.067***
Oil Field Count (100s)	-0.009	-0.009
Mean N^*	-0.571	-0.577
Mean GDP (1000s)	0.027*	0.028*
Mean Polity	0.028	0.028
Num.Obs.	122	122
AIC	1754.4	1752.4
BIC	1785.3	1780.5
Log.Lik.	-866.214	-866.222
RMSE	2618.81	2621.12

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

6.4 Conflict Event Frequency Model

The Conflict Event Frequency Model, summarized in Table 4, reveals the complex interplay between environmental change and conflict events, reflecting the concept of winners and losers in the context of climate change. The strong positive correlation between Albedo Difference and the frequency of conflict events (coefficients of 42.810 and 43.309, $p < 0.01$) illustrates how areas experiencing an increase in Albedo, often due to desertification, are more prone to violent events. This can be understood in terms of climate change's differential impacts, creating "winners" and "losers." Regions suffering from increased Albedo become the "losers," facing environmental degradation that potentially escalates conflicts. In contrast, Rainfall Difference does not show statistical significance, possibly reflecting the nuanced nature of Rainfall's impact.

Moving to the socio-economic variables, the negative correlation with Mean Peace Years (coefficient = -0.067, $p < 0.01$) and the positive association with Mean Log Population (coefficient = 2.622 and 2.637, $p < 0.01$) highlight how social stability and population dynamics intersect with environmental change, influencing conflict outcomes.

These findings underscore the multifaceted nature of climate change's impact on conflict. The notion of winners and losers illuminates how climate change exacerbates existing vulnerabilities, intensifying conflicts in areas already struggling with environmental degradation. It calls for tailored interventions that recognize the differential impacts of climate change and address the unique challenges faced by the "losers."

By examining the relationship between Albedo and conflict events, this analysis offers a nuanced understanding of how climate change creates winners and losers, accentuating conflicts in environmentally fragile regions. It underscores the need for holistic approaches that consider the intersecting environmental, social, and economic factors shaping conflict dynamics. The analysis strengthens our understanding and suggests the need for future research to explore regional variations and the mechanisms through which climate change contributes to the unequal distribution of conflict risks.

6.5 BART Model

The BART model was fitted to the data much like the logits, however, in this case Rainfall was dropped from the BART model because of its theoretical relations with CV and relationship with Albedo. The cross-validation procedure selected k = 5 and 200 trees. Overall, the model correctly classified 91% of cases as civil war years or no conflict years. Given the sparse data, it is unsurprising that the model struggled with conflicts, resulting in a 50% accuracy.

The cross-validation procedure in the BART model selected specific parameters to optimize the model's performance. The parameter $k = 5$ represents the number of subsets into which the data is divided for cross-validation, allowing for a rigorous assessment of the model's predictive accuracy on unseen data. The choice of 200 trees reflects the complexity of the model, with more trees allowing for a richer capture of underlying patterns and relationships. These parameters were selected to balance the need for model flexibility with the risk of overfitting, ensuring a robust and generalizable analysis.

Rainfall was intentionally excluded from the BART model due to its theoretical relations with CV and relationship with Albedo. Including Rainfall could have introduced multicollinearity, where variables are highly correlated, potentially leading to unstable estimates. By excluding Rainfall, the model focuses on the more direct and meaningful relationships between Albedo, CV, and civil war onset, reducing the risk of spurious correlations and enhancing the interpretability of the results.

The BART model's performance can be assessed through different metrics. The overall correct classification rate of approximately 91% indicates the model's effectiveness in distinguishing between civil war years and no conflict years. However, a closer examination reveals a 50% accuracy rate for conflicts specifically. This discrepancy highlights the challenges in modeling rare events like civil wars, where the data is sparse and imbalanced.

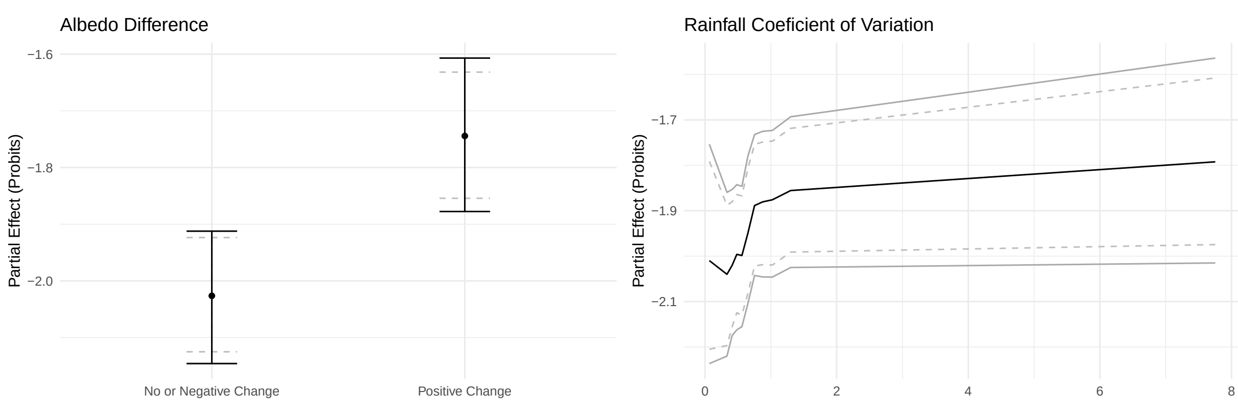
Table 5: BART Model Fit

	model errors
actual 1	0.509
actual 0	0.073
use errors	0.092
Number of Trees	200
k	5

Figure 10 displays the BART model estimates for the Albedo Difference variable and the CV variable. Here we can see that both variables are pointing in the expected direction, but only the Albedo Difference variable is statistically significant. This implies that given the maximum amount of flexability, desertification increases the probabilty of civil war. It should be noted, however, that while CV failed to reach statistical significance here. It may be due to the fact that the BART model is less efficient than some MLE models and so it may be the case that more observations were needed.

The BART model's estimates for the Albedo Difference variable and the CV variable provide valuable insights into the complex relationship between environmental factors and civil war onset. The statistical significance of the Albedo Difference variable implies that desertification, as measured by changes in Albedo, plays a crucial role in increasing the probability of civil war. This finding aligns with theoretical expectations and contributes to the growing body of evidence linking environmental degradation to conflict. Conversely, the lack of statistical significance for CV may reflect the model's limitations or the need for more observations, rather than a definitive absence of a relationship. These results, taken together, underscore the multifaceted nature of civil war onset and the importance of considering both direct and indirect environmental factors in understanding and predicting conflict.

Figure 10: Albedo Predicts Civil War Onset



6.6 Mediation Analysis

Arid regions produce less evapotranspiration and, thus, less moisture for precipitation, so some might argue that Albedo might indirectly impact the start of civil wars through its effect on Rainfall.

To explore this theory, mediation analysis was employed using the binary onset variable as the main dependent variable. The results, presented in Table 6, show that differences in Albedo

Table 6: Mediation Analysis Results

	Estimate
ACME (control)	-0.041**
ACME (treated)	-0.021**
ADE (control)	0.923**
ADE (treated)	0.942**
Total Effect	0.901**
Prop. Mediated (control)	-0.046*
Prop. Mediated (treated)	-0.000*
ACME (average)	-0.031**
ADE (average)	0.933**
Prop. Mediated (average)	-0.023*

can directly influence the start of a conflict, as well as indirectly, through its effects on Rainfall.

Interestingly, the direct impact of Albedo changes on conflict onset was significant (average direct effect = 0.933, p = 0.010), suggesting a strong connection between changes in Albedo and the likelihood of a conflict breaking out, regardless of Rainfall.

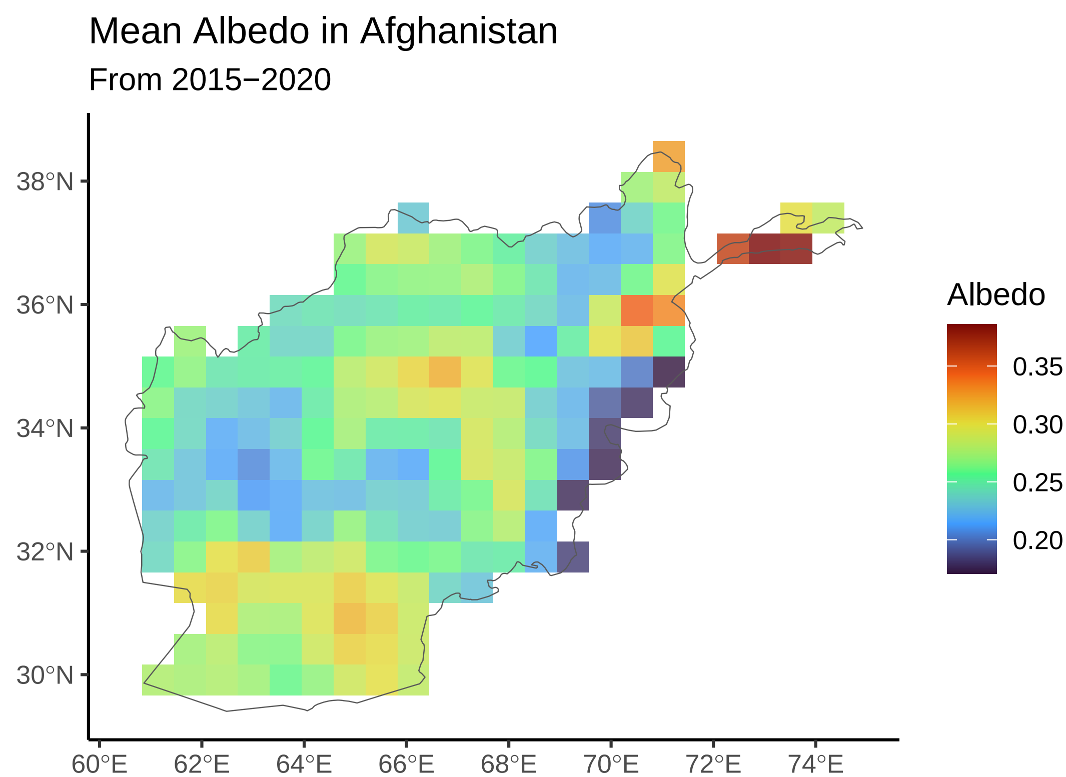
In addition, the analysis found a significant indirect effect of Albedo changes on conflict onset through Rainfall (average causal mediation effect = -0.031, p = 0.022). This suggests that changes in Albedo can influence the onset of conflicts by altering Rainfall levels which is not too surprising.

However, it is worth noting that the percentage of the total effect mediated through Rainfall, while not negligible, was quite small and did not meet any standard level of statistical significance (average proportion mediated = -0.0228, p = 0.062). This implies that while Rainfall affects how Albedo changes affect conflict onset, the bulk of the effect appears to be directly from Albedo onto Civil War.

7 Discussion

The results from all three models consistently indicate a positive and significant relationship between carrying capacity as measured by Albedo Difference and conflict, whether it is conflict onset, the number of conflicts, or the overall number of events. These findings show that climate change, as measured by Albedo change, is important in predicting political violence. The analysis also highlights the importance of considering other relevant factors, such as Rainfall, GDP per capita, peace years, and population size, in understanding the complex dynamics of conflict.

Figure 11: Afghanistan Albedo



By examining the relationship between carrying capacity change and conflict through multiple models, this study contributes to the growing body of literature on the role of climate-related factors in predicting political violence.

Another interesting finding from these models is that elevation is not statistically significant at conventional levels. Albedo and mountainous terrain are closely correlated. Mountains often experience extreme wind and rain erosion, inhibiting vegetation growth. Although these harsh conditions may offer cover for guerillas, they also reduce local inhabitants' ability to farm and be self-sufficient. A lack of self-sufficiency can lead to food scarcity and limited agricultural job opportunities. For example, Afghanistan, a mountainous nation, has been embroiled in conflict for decades. Figure 11 depicts the mean Albedo across Afghanistan. The country lies in a region where the carrying capacity of the land is low. Some of the fiercest fighting during the US occupation occurred in southern Afghanistan, where the Albedo suggests that agriculture is nearly impossible. Therefore, the lack of significance for mean elevation might not be attributable to the US military's inability to operate in rugged terrain but rather a consequence of general economic scarcity and food insecurity brought about by a diminished carrying capacity. Future research could further explore this relationship to better understand the connections between elevation, carrying capacity, and conflict.

8 Conclusion

This paper has contributed to the climate change and conflict literature by demonstrating the importance of Albedo as a more accurate and reliable measure of climate change than Rainfall. The results from the models found that the physics undergirding Rainfall are complex and that climate researchers should refrain from using Rainfall as a measure of climate change. These findings also shed light on the mixed results from the climate and conflict literature. In short, using Rainfall as a measure of climate change is akin to using a constant to measure variation.

On the other hand, Albedo links theoretically and empirically as a measure of climate change. Albedo is easy to measure, easy to interpret, and available globally at a subnational level making it an ideal variable for climate and conflict researchers.

The analyses conducted across multiple regression models consistently show that Albedo Difference is positively and significantly related to conflict onset, the number of conflicts, and the overall number of events, highlighting the critical role of climate change in predicting political violence.

The findings underscore the importance of accounting for climate change in understanding conflict dynamics and emphasize the need for policies and interventions addressing climate change's consequences on conflict.

The Albedo data used in this study opens up new avenues for future research, allowing for the exploration of sub-national trends in climate change and civil war. This can lead to more targeted research that can enable policymakers to implement strategies with greater precision, focusing on the areas and communities worst affected by climate change and related disasters.

One interesting observation from the analysis is that elevation does not have a statistically significant relationship with conflict when controlling for Albedo. Given the close correlation between Albedo and denuded mountainous terrain, this result suggests that further research should explore the connections between topography, agriculture, and conflict to gain deeper insights into the role of geographical factors in conflict dynamics. These findings indicate that mountainous terrain may play a more complex role in civil war dynamics than initially theorized.

By establishing Albedo as a measure of climate change and its relationship with conflict, this study opens new avenues for future research in the field of political science. It encourages scholars to adopt Albedo as a measure of climate change and explore its potential applications in predicting other forms of political violence, such as terrorism, civil unrest, and climate migration. Ultimately, understanding the interplay between climate change and conflict can help policymakers design more effective strategies to mitigate the risk of political violence in the face of a changing global environment.

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A Appendix

A.1 Clausius-Clapeyron equation derivation

This segment introduces the Clausius-Clapeyron equation, derived from first principles using the concept of a reversible phase transition between a liquid and its vapor. The Clausius-Clapeyron equation characterizes the association between a material's vapor pressure and its thermal state, originating from the core tenets of thermodynamics.

Consider a reversible phase transition between the liquid and vapor phases of a substance, where a small amount of liquid (dm) gets converted to vapor at constant temperature (T) and pressure (p). The enthalpy change (ΔH) during this transition is equal to the latent heat of vaporization (L) (Schroeder 2000).

For this process, we can apply the first law of thermodynamics, which states that the change in internal energy (ΔU) is equal to the heat added to the system (q) plus the work done by the system (W):

$$\Delta U = q + W \tag{1}$$

For a reversible process, the work done can be represented as the product of pressure (p) and the volume change during the transition (ΔV):

$$W = p\Delta V \tag{2}$$

The heat added (q) can be expressed in terms of the latent heat of vaporization (L) and the mass of the substance that undergoes a phase transition (dm):

$$q = L \cdot dm \tag{3}$$

During the phase transition, the internal energy change (ΔU) is zero because the process is isothermal (constant temperature) (Schroeder 2000). Therefore, we have:

$$0 = L \cdot dm + p\Delta V \tag{4}$$

Divide both sides by dm and rearrange the equation:

$$\frac{L}{\Delta V} = -p \tag{5}$$

Now, apply the ideal gas law to the vapor phase:

$$pV = nRT \tag{6}$$

where n is the number of moles, R is the ideal gas constant, and T is the temperature. Express the number of moles (n) in terms of the mass (m) and molar mass (M):

$$n = \frac{m}{M} \tag{7}$$

Substitute this expression for n into the ideal gas law:

$$pV = \frac{m}{M}RT \tag{8}$$

Rearrange the equation to express the pressure (p):

$$p = \frac{m}{V} \cdot \frac{RT}{M} \tag{9}$$

Recognize that the term $\frac{m}{V}$ represents the density (ρ) of the vapor phase:

$$p = \rho \cdot \frac{RT}{M} \tag{10}$$

Take the natural logarithm of this expression:

$$\ln(p) = \ln(\rho) + \ln\left(\frac{RT}{M}\right) \tag{11}$$

Differentiate both sides with respect to temperature (T):

$$\frac{d[\ln(p)]}{dT} = \frac{d[\ln(\rho)]}{dT} + \frac{d[\ln\left(\frac{RT}{M}\right)]}{dT} \tag{12}$$

Recognize that $\frac{d[\ln\left(\frac{RT}{M}\right)]}{dT} = \frac{R}{RT} = \frac{1}{T}$:

$$\frac{d[\ln(p)]}{dT} = \frac{d[\ln(\rho)]}{dT} + \frac{1}{T} \tag{13}$$

Recall the expression derived from the first law of thermodynamics (Step 5):

$$\frac{L}{\Delta V} = -p \tag{14}$$

Differentiate both sides with respect to temperature (T):

$$\frac{d\left(\frac{L}{\Delta V}\right)}{dT} = -\frac{dp}{dT} \tag{15}$$

Substitute the expression from Step 9 into this equation:

$$\frac{d[\ln(p)]}{dT} = \frac{1}{T} - \frac{d\left(\frac{L}{\Delta V}\right)}{dT} \tag{16}$$

Rearrange the equation to get the Clausius-Clapeyron equation:

$$\frac{dp}{p} = \frac{L}{RT^2} dT \tag{17}$$

This equation relates the change in vapor pressure (dp) with the change in temperature (dT) for a substance undergoing a phase transition. The Clausius-Clapeyron equation can be further simplified or integrated as needed.

The dew point is the temperature at which air becomes saturated with water vapor and condensation occurs. We must consider the relationship between the saturation vapor pressure and temperature to determine the dew point. The Clausius-Clapeyron equation can help us derive this relationship.

Starting with the Clausius-Clapeyron equation in the differential form:

$$\frac{dp}{p} = \frac{L}{RT^2} dT \tag{18}$$

Integrate both sides of the equation with respect to temperature, considering that the saturation vapor pressure p_s depends on the temperature T:

$$\int_{p_1}^{p_s} \frac{dp}{p} = \int_{T_1}^{T} \frac{L}{RT^2} dT \tag{19}$$

Assuming that the latent heat of vaporization (L) is constant over the relevant temperature range, we can integrate both sides:

$$\ln\left(\frac{p_s}{p_1}\right) = \frac{L}{R}\left(\frac{1}{T_1} - \frac{1}{T}\right) \tag{20}$$

Now, let's introduce the concept of relative humidity (RH), which is the ratio of the partial pressure of water vapor in the air (p_v) to the saturation vapor pressure at the given temperature (p_s):

$$RH = \frac{p_v}{p_s} \tag{21}$$

At the dew point temperature (T_d), the air becomes saturated, and the relative humidity is 100%:

$$\frac{p_v}{p_{s,d}} = 1 \tag{22}$$

Using the Clausius-Clapeyron equation, we can relate the saturation vapor pressures at the dew point temperature (T_d) and the actual temperature (T):

$$\ln\left(\frac{p_{s,d}}{p_s}\right) = \frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_d}\right) \tag{23}$$

Now, we can use the relationship between p_v and p_s:

$$p_v = RH \cdot p_s \tag{24}$$

At the dew point, $p_v = p_{s,d}$, so we can write:

$$RH \cdot p_s = p_{s,d} \tag{25}$$

Substitute this expression into the equation relating the saturation vapor pressures at T and T_d:

$$\ln\left(\frac{RH \cdot p_s}{p_s}\right) = \frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_d}\right) \tag{26}$$

Simplify the equation:

$$\ln(RH) = \frac{L}{R}\left(\frac{1}{T} - \frac{1}{T_d}\right) \tag{27}$$

Finally, rearrange the equation to solve for the dew point temperature (T_d):

$$\frac{1}{T_d} = \frac{1}{T} - \frac{R}{L}\ln(RH) \tag{28}$$

$$T_d = \left(\frac{1}{T} - \frac{R}{L}\ln(RH)\right)^{-1} \tag{29}$$

This equation allows us to calculate the dew point temperature (T_d) based on the actual air temperature (T) and the relative humidity (RH).

A.2 Clausius-Clapeyron equation derivation

To calculate the Earth's surface temperature, we can use the Stefan-Boltzmann law to estimate the Earth's blackbody radiation. The Stefan-Boltzmann law states that the thermal energy radiated by a blackbody per second per unit area (j^*) is proportional to the fourth power of the temperature (T), with the proportionality constant σ known as the Stefan-Boltzmann constant:

$$j^* = \sigma T^4 \tag{30}$$

Since the Earth is mostly spherical, the surface area of the Earth is $4\pi r^2$. To represent the Earth, we can rearrange Equation 30 to:

$$E_{output} = \sigma T^4 \times 4\pi r^2 \tag{31}$$

The Earth's surface receives its heat from the Sun, so we can estimate the Earth's radiant thermal energy output using the Sun's thermal energy input to the Earth's surface and the Law of Conservation of Energy, which states that these must be equal.

The energy the Earth receives is equal to the solar energy output in watts per square meter, or solar flux (K_s), multiplied by the footprint of the area of the Earth receiving sunlight at any given point in time. Since the Earth is spherical, the footprint of energy absorbed is circular, which means that the surface area receiving solar energy is πr^2, where r is the radius of the Earth in meters. Therefore, if the Earth were a perfect blackbody absorber, the equation for energy input would be:

$$E_{input} = K_s \pi r^2 \tag{32}$$

However, since the Earth is not a perfect blackbody absorber and absorbs only a percentage of the energy it receives (Albedo), the energy input equation becomes:

$$E_{input} = K_s \times (1-\alpha) \times \pi r^2 \tag{33}$$

where α is the Albedo of Earth.

Using the Law of conservation of energy, $E_{input} = E_{output}$ we can set Equation 31 equal to Equation 33 to solve for the energy emitted by the surface of the Earth, which gives us:

$$K_s \times (1-\alpha) \times \pi r^2 = \sigma T^4 \times 4\pi r^2. \tag{34}$$

This simplifies to the equation for the Earth's energy balance:

$$\frac{K_s \times (1-\alpha)}{4} = \sigma T^4. \tag{35}$$

Since climate researchers are interested in changes to the Earth's temperature, we can solve for T. After some basic algebra, we have the following:

$$T = \sqrt[4]{\frac{K_s \times (1 - \alpha)}{4\sigma}} \tag{36}$$

This means that temperature is directly related to the Albedo of a surface. Plugging in for K_s, which is known, and σ, which is a constant, we can estimate the temperature radiated from the surface of the Earth given different Albedos.

Figure 12: Albedo and Temperature Relationship

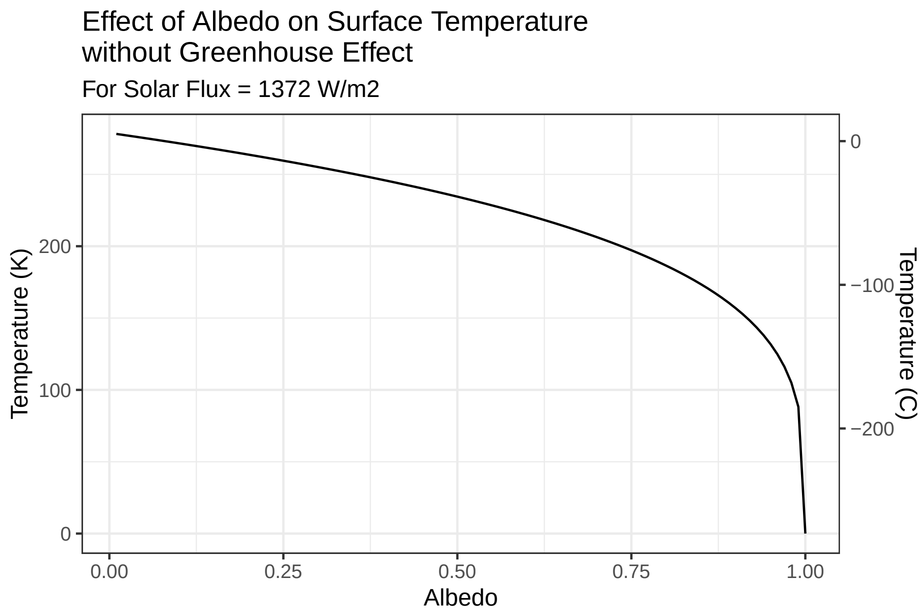


Figure 12 depicts the relationship between Albedo and temperature. Here, we can see that a change in Albedo can greatly affect the Earth's surface temperature, assuming that the Sun's solar flux stays constant. Satellites have estimated Earth's average Albedo, including clouds, to be approximately 0.3.[7] This means a 3% reduction in Earth's Albedo (from 0.3 to 0.29), for example, from the melting of polar ice or a decrease in snowfall globally, would result in a 1 degree Celsius increase in global temperatures. On the other hand, if the Earth were completely covered in ice the temperature would drop by 100 degrees Celsius. This model assumes there are no greenhouse gases, however.

To account for the role of greenhouse gases, we can improve this model by adding an atmospheric layer that is transparent to incoming solar flux and absorbs a percentage of surface radiation (f). Let T_s equal the temperature of the surface of the Earth and T_a equal the temperature of the atmospheric layer. The atmospheric layer will have to emit energy toward the surface to increase the surface temperature. It will need to radiate some fraction of the energy into space, or the Earth will continue to warm until it stops receiving heat from the Sun.

[7] https://earthobservatory.nasa.gov/images/84499/measuring-earths-Albedo

We can model the emitted radiation flux from the atmosphere with Kirchhoff's Law ($f\sigma T_a^4$).

The Earth's energy balance would now equal the energy of the surface plus that of the atmosphere. This results in adding the atmospheric layer to Equation 35, resulting in:

$$\frac{K_s \times (1-\alpha)}{4} = (1-f)\sigma T_s^4 + f\sigma T_a^4. \tag{37}$$

The energy in the atmosphere needs to balance the energy from the surface. This yields:

$$f\sigma T_s^4 = 2f\sigma T_a^4 \tag{38}$$

Solving for $f\sigma T_a^4$ leads to:

$$\frac{f}{2}\sigma T_s^4 = f\sigma T_a^4 \tag{39}$$

We can now plug Equation 39 into Equation 37, which results in:

$$\frac{K_s \times (1-\alpha)}{4} = (1-f)\sigma T_s^4 + \frac{f}{2}\sigma T_s^4 = \left(1-\frac{f}{2}\right)\sigma T_s^4 \tag{40}$$

Solving for T_s produces:

$$T_s = \sqrt[4]{\frac{K_s \times (1-\alpha)}{4\sigma\left(1-\frac{f}{2}\right)}}. \tag{41}$$

A.3 Albedo and Climate

Albedo, the proportion of incoming solar radiation reflected by a surface, is critical in determining the Earth's climate. Varying surface characteristics, such as ice cover, vegetation, and urban development, directly influence the Earth's Albedo, affecting the absorption and distribution of solar energy across the globe. Consequently, fluctuations in Albedo can lead to a cascade of climatic changes, such as altered ocean currents, increased heat waves, and shifting Rainfall patterns. Understanding the relationship between Albedo and climate requires examining how the Earth's surface temperature, a primary driver of climatic processes, is influenced by Albedo.

For the complete derivation using the Stefan-Boltzmann law to measure the effect Albedo has on climate and climate change, see Appendix A.2.

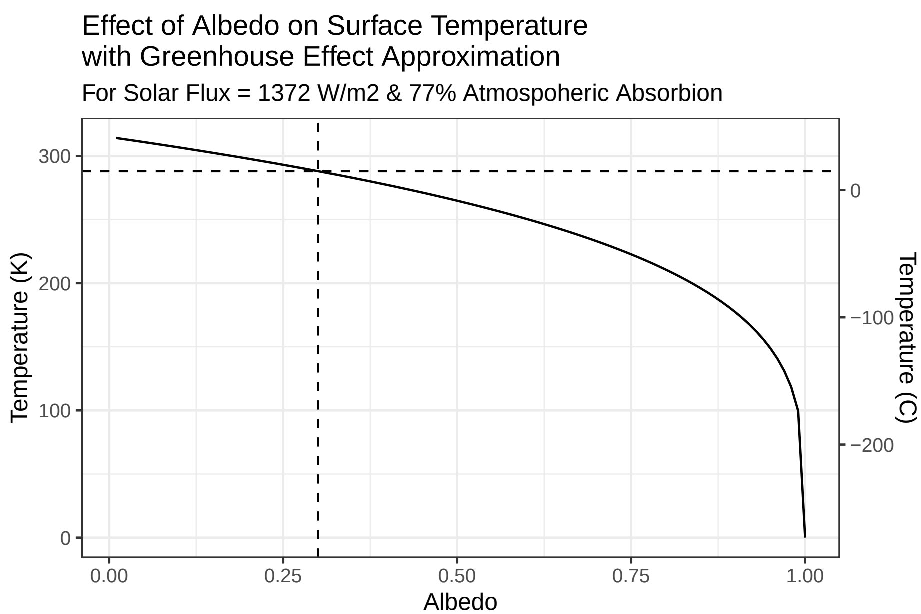
Figure 13 displays the relationship between temperature and Albedo, assuming that the atmosphere absorbs 77% of Earth's thermal radiation.[8] The hashed lines represent the Earth's average Albedo and average annual temperature. A 3% reduction in Earth's Albedo, equivalent to going from 0.3 to 0.29, would result in a 1-degree Celsius temperature increase.

Here we can see that the surface temperature is highly dependent on the Albedo of the surface, even when including the greenhouse effect. We can observe that temperature is a function of Albedo and atmospheric absorption. Due to the Law of Conservation of Energy

[8] See Appendix A.2 for derivation explaining why this is the case

and the Earth's surface receiving its thermal energy from the Sun, the climate is a function of Albedo, holding all else constant. Plugging in the average Albedo for Earth and the average global temperature of approximately 15 degrees Celsius,[9] into the equation results in about 77% of the Earth's thermal energy being absorbed by the atmosphere.

Figure 13: Albedo is Fundamental to Climate



While this model helps us understand the overall mechanism by Albedo greenhouse gasses work to warm the Earth and create the climate, it assumes 1) that the atmosphere is homogeneous and 2) that the atmosphere is transparent to incoming solar radiation. Both assumptions are false. We can further refine this model to better analyze the effects of greenhouse gases. To do so, we need to consider the wavelengths of light emitted by the Sun and the Earth.

Wien's Law governs the relationship between the temperature of an object and the wavelength of light that it emits due to blackbody radiation. Blackbody radiation is the emission of electromagnetic radiation by an idealized body that absorbs all incident radiation, regardless of frequency or angle of incidence. The blackbody emits a characteristic radiation spectrum, determined only by its temperature (Planck 1901).

Wien's Law states that the wavelength at which the intensity of radiation is at its peak (the peak wavelength) is inversely proportional to the temperature of the blackbody. Mathematically, we can express it as

$$\lambda_{max} = b/T, \tag{42}$$

where λ_{max} is the peak wavelength, T is the temperature of the blackbody in Kelvin, and b

[9] https://solarsystem.nasa.gov/resources/681/solar-system-temperatures/

is Wien's displacement constant, approximately equal to $2.898x10^(-3)mK$ (Planck 1901).

The Sun and the Earth emit radiation as blackbodies(Planck 1901), albeit imperfectly. To calculate their peak emission wavelengths, we need to know their temperatures.

The Sun's effective temperature is about 5,778 K (Bahcall, Pinsonneault Basu, 2001). Applying Wien's Law gives us the following:

$$\lambda_{max}(Sun) = (2.898x10^(-3)mK)/(5,778K)5.02x10^(-7)mor502nm. \quad (43)$$

This wavelength is in the visible range, which explains why sunlight appears predominantly yellow-white. Greenhouse gasses absorb energy mainly in the infrared spectrum, allowing much of the sunlight not reflected into space by high Albedo clouds or aerosols or absorbed by the ozone layer to pass through the atmosphere before striking the Earth.

The Earth's average temperature is around 288 K (Hartmann, 1994). Applying Wien's Law:

$$\lambda_{max}(Earth) = (2.898x10^(-3)mK)/(288K)1.007x10^(-5)mor10.07m \quad (44)$$

This wavelength is in the infrared range, so the Earth emits predominantly infrared radiation. This means that the energy absorbed by the Earth, 1 - Albedo, is radiated back into the atmosphere as infrared radiation. The leading greenhouse gases are Water vapor (H2O), Carbon dioxide (CO2), and Methane (CH4) where all three have absorption bands in the infrared spectrum (Herzberg and Herzberg 1953; Rothman et al. 2005, 2009). This means that climate change is when the Sun's energy strikes the planet, and part of it is absorbed by the Earth and then transmited into the Atmosphere as infrared radiation. As the Greenhouse gasses increase, the total absorption of infrared radiation also increases.

From here, we can derive the current model of the greenhouse effect, radiative forcing (RF). RF is a measure of the change in the balance between incoming solar radiation and outgoing terrestrial radiation in the Earth's atmosphere due to a change in atmospheric composition, such as an increase in greenhouse gas concentrations or other factors like aerosols and solar irradiance. It is expressed in watts per square meter (W/m^2) and is used to quantify the effect of various factors on the Earth's energy budget and temperature.

$$RF = \Delta(E_{in} - E_{out}) = \Delta E_{in} - \Delta E_{out} \quad (45)$$

Greenhouse gases contribute to radiative forcing by absorbing and re-emitting infrared radiation, which alters the Earth's energy balance. As greenhouse gas concentrations increase, more infrared radiation is absorbed by these gases. With the gases now warmed, a fraction of the energy is returned to the Earth's surface. This causes an increase in the net downward longwave radiation, leading to a positive radiative forcing and the subsequent warming of the Earth's surface and lower atmosphere (**?**).

Greenhouse gases absorb specific wavelengths of infrared radiation based on their molecular structure and vibrational modes described using absorption cross-sections (Herzberg 1953). The excited greenhouse gas molecules then re-emit the absorbed radiation in all directions, with a portion directed back towards Earth's surface. To calculate radiative forcing, we must solve the radiative transfer equation (RTE) for Earth's atmosphere, which accounts for absorption, emission, and scattering by gases, aerosols, and clouds. Radiative forcing is the difference in net downward longwave radiation at the tropopause between perturbed and unperturbed atmospheres (Schimel et al. 1996; Schulz et al. 2006; Van Vuuren et al. 2011). Climate sensitivity, influenced by various feedback processes such as water vapor, cloud, and ice-Albedo feedback, determines the impact of radiative forcing on Earth's temperature (Hansen et al. 1984).

The ice-Albedo feedback loop is another aspect of Earth's climate system (Stroeve et al. 2007). It is a positive feedback mechanism that begins with initial warming caused by increased greenhouse gas concentrations or changes in solar irradiance. This warming leads to the melting of ice and snow, which reduces Earth's overall Albedo and increases the absorption of solar radiation. The subsequent warming further melts ice and snow, amplifying the initial warming and causing increases in global temperature. This feedback loop has significant implications for Earth's climate system, including accelerating polar ice melt, rising sea levels, and altering global ocean circulation patterns (Serreze and Barry 2011). The Albedo feedback loop can also exacerbate the effects of global warming on ecosystems and human societies, leading to increased frequency and intensity of extreme weather events that can impact agriculture, infrastructure, and human health. Moreover, researchers should expect that on a global level, as climate change increases, we should expect to see the Earth's Albedo should decrease.

Taken together, the Law of Conservation of Energy, the Stefan-Boltzmann law, and Kirchhoff's Law show that only two terrestrial variables determine climate: 1) Albedo and 2) atmospheric absorption. Therefore, a change in Albedo will change the climate.

A.4 Albedo and VHI

Figure 14: BART Model Fit