



# Climate Models as a Retroactive and Exploratory World-building Tool

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*Abstract:* Literary world-building allows authors to experiment with their creation, changing features of imaginary worlds to contrast with the real world. In this sense, fictional world-building is a literary analogue to scientific models – simplified representations of the world. Merging the disparate disciplines of literary world-building and climate modelling, we present case studies of participatory culture, simulating the imaginary worlds of J.R.R. Tolkien, George R. R. Martin, and Robert Jordan, comparing our simulations to the original authors’ depictions. We also show how a climate model of an in-development fantasy world can guide world-building of new imaginary worlds, facilitating narrative immersion. Combining fantasy world-building and climate modeling offers the opportunity to fill gaps in imaginary worlds and draw pedagogical attention to the science of climate models, particularly in a classroom setting.

*Keywords:* world-building, climate models, fantasy, J.R.R. Tolkien, George R. R. Martin, Robert Jordan

## 1. Introduction

Epic fantasy has been defined as constituting “a story writ continentally” with the fantasy world itself as a protagonist (Attebery 1). The quest nature of epic fantasy lends itself to *world-building*, with characters traversing strange, new lands and overcoming trials and hardships that are part of the world (Presley 28). World-building – involving the development of geography, climate, society, history, magic systems, and theology in imaginary worlds – is thus

particularly associated with fantasy fiction. Often these imaginary worlds take inspiration from historical events, climatic change, or geographical locations.

This article presents four case studies of climate models developed from fictional fantasy worlds. The first three are from the existing worlds: J.R.R. Tolkien's Middle-earth (a part of Arda), George R. R. Martin's world from *A Song of Ice and Fire* (1996–) and its tv adaptation *Game of Thrones* (2011–2019), and Robert Jordan's world from *The Wheel of Time* series (1990–2013). The fourth models a fictional world of Terrios for an in-development climate fiction story by John Cook. We explore how this exercise is an active and sophisticated form of participatory culture that can enhance readers' engagement with and immersion into the imaginary worlds. We recognize that using climate models to explore imaginary worlds does make the assumption that such worlds adhere to "real-world" scientific framework, an assumption that may not have been intended by the original authors. However, climate models like our case studies can function as paratexts, defined by Gérard Genette as extra materials surrounding a text that help the audience engage with the main work (2). Non-authorial, fan-created paratexts like our climate models extend beyond Genette's original formulation, which restricted its scope to author and publisher intent to guide reader reception of the main text.

## 2. Fantasy world-building and participatory culture

When coining the terms *primary world* (the real world) and *secondary worlds* (imaginary worlds created by the author), Tolkien argued that storytellers are *sub-creators*, constructing worlds with internally consistent laws that readers can believe (*Fairy Stories* 18). An immersive experience is established if sufficient details and description are supplied for the reader to vicariously enter the imaginary world (Wolf, 48). The author's goal is for the reader to suspend their disbelief, a state which Tolkien described as *secondary belief*.

Fantasy has been critiqued as a form of escapism (Tally 43) that potentially causes audiences to disengage from societal issues (Suvin 392). Tolkien rejected this criticism, arguing that fantasy stories are not an escape from reality but a "revolt against the apparent inevitability of the modern, urban, industrial world" (Bal 1287). World-building has the potential to serve a critical purpose (Kraatila, "World-Building" 30), with imaginary worlds being used as satirical or social thought experiments dating back to antiquity (Wolf 148). Early imaginary worlds provided commentary on society, such as Thomas More's *Utopia*, an idealistic island operating on principles of communal living and social equality, which served to highlight flaws and injustices in the real world (Padrón 267). An imaginary world can offer a fresh perspective through which to view our own reality.

On occasion, world-building extends beyond the creation of the original author. Much of Tolkien's *legendarium* was published posthumously by his son Christopher Tolkien through careful curation of copious and sometimes contradictory drafts. Sanctioned by the wife of the late Robert Jordan and his editor, Brandon Sanderson completed *The Wheel of Time* series (Livingston 35–41). A "closed" world is one where the author has declared it finished with no more canonical material to be added to it. However, even in the case of some

closed worlds such as Tolkien's Middle-earth, the author wished to "leave scope for other minds and hands, wielding paint and music and drama" (Wolf 270).

A non-canonical form of additive world-building is practiced in participatory fan culture, where fans act not just as passive consumers but also active creative producers (Jenkins, "Fandom" 18). Henry Jenkins introduces concepts such as textual poaching – the act of fans re-purposing materials from a commercial text in their own creative works for various purposes, such as filling gaps in the original work (*Textual Poachers* 53) – and collective intelligence, where readers as a community pool resources and combine skills in a process of shared meaning-making ("Collective"). Jenkins also draws upon the concept of oppositional reading, developed by Stuart Hall, to describe when readers reject the author's intended meaning in favor of a different interpretation (Hall 54). A prominent activity in participatory culture is fan fiction, defined as "fiction written by a 'fan' or reader, without the consent of the original author, yet using that author's characters and world" (Hobb 2005). While most fan fiction focuses on expanding the narratives of characters, it can also expand the world-building, satisfying the reader's desire to fill in gaps left by the author (Wolf 279). M. D. Presley refers to "inspired worldbuilding" that invites the audience to take an active part in the world, exercising their imagination after the story has concluded (88).

To fill those gaps, according to Presley, readers rely on "Primary World defaults" – the expectation that the laws of physics in the imaginary world are largely the same as in our world. This aspect of gap-filling is what Marie-Laure Ryan calls "the principle of minimal departure" (406), asserting that when readers interpret an imaginary world, they automatically assume the world operates similarly to our reality, except where the text explicitly dictates otherwise. Presley refers to it as "terra de facto" – the belief that any detail that is not an output of a fantasy conceit (like magic) must abide by the laws and constraints of the real world (232). This approach minimizes the cognitive labor required to believe the story, facilitating readerly immersion (Gerrig 279). Tolkien similarly argued that a secondary world should be credible in order to command secondary belief and always sought to maintain a finely-tuned balance between familiar realism and the fantastic. The elements of Middle-earth fit into "a framework of climate and geography, familiar skies by night, familiar shrubs and trees" (Kocher 147). This was a hallmark of Tolkien's style, describing familiar, homely things such as weather, the quality of sunlight, the hues of each sunset, all designed to bolster the reader's secondary belief (Kocher 154). Readers assess the created world in terms of the real world, understanding implicitly that anything that does not obviously deviate from the primary world (like dragons or magic) must adhere to our understanding of reality (Presley 80).

While simplified and imperfect, imaginary worlds must still be inherently consistent to provide verisimilitude for readers. In this sense, such worlds can be understood as analogous to scientific models – imperfect but useful representations of the real world (Kraatila, "World-Building" 33). Just as scientific models simplify and omit confounding factors to focus on specific properties, world-building pares away unnecessary details, providing "epistemic access" to phenomena that are otherwise difficult to comprehend (Elgin 8). For example, climate models – complex computer programs that represent our best theoretical understanding of fluid motions, physics,

chemistry, radiation, and biology – are often used as “digital twins” for the real world, where, for instance, an adaptation strategy can be tested in climate models, then fed back into the real world if proven fruitful. Future predictions from climate models play an important role in societal planning, with model results featuring in the Intergovernmental Panel on Climate Change reports (IPCC).

Because climate models are based on fundamental physical laws, they can be applied to a variety of situations. Their chief use is simulating the Earth’s climate in modern times and the near future, but because the laws of physics are equally applicable at any time, the same models can be applied to any period in Earth’s history, going back many millions of years to when the planet looked very different and, similarly, millions of years into the future. As the laws of physics apply across the universe, climate models can also simulate other planetary bodies both inside and outside our solar system, as well as imaginary worlds. To simulate other worlds, a climate model requires maps specifying the height of the terrain (topography) and ocean depth (bathymetry), along with the type of land or oceans, the concentrations of different gases making up the atmosphere, especially those relevant for mediating temperatures (like ozone and carbon dioxide), and the amount of energy received from a parent star or stars. Further, the model needs parameters such as the radius and rotation rate of the planet.

Farah Mendlesohn argues that in a well-built imaginary world, if one turns the corner of the street, one will not run off the page of the author’s speculation because the coherence of the world is such that out of sight of the author, it forms itself (104). It is in this spirit of emergent imaginary world properties that climate scientists have developed climate models of several fantasy worlds. In some works of fantasy, like the case studies of Tolkien, Martin, and Jordan we present here, the maps and world-building are so detailed that development of a climate model of the imaginary world is possible. The aim of these case studies is to use the medium of fantasy fiction to communicate fundamental aspects of climate science to a broad audience, although they also provide external devices to reflect on the authors’ original worlds.

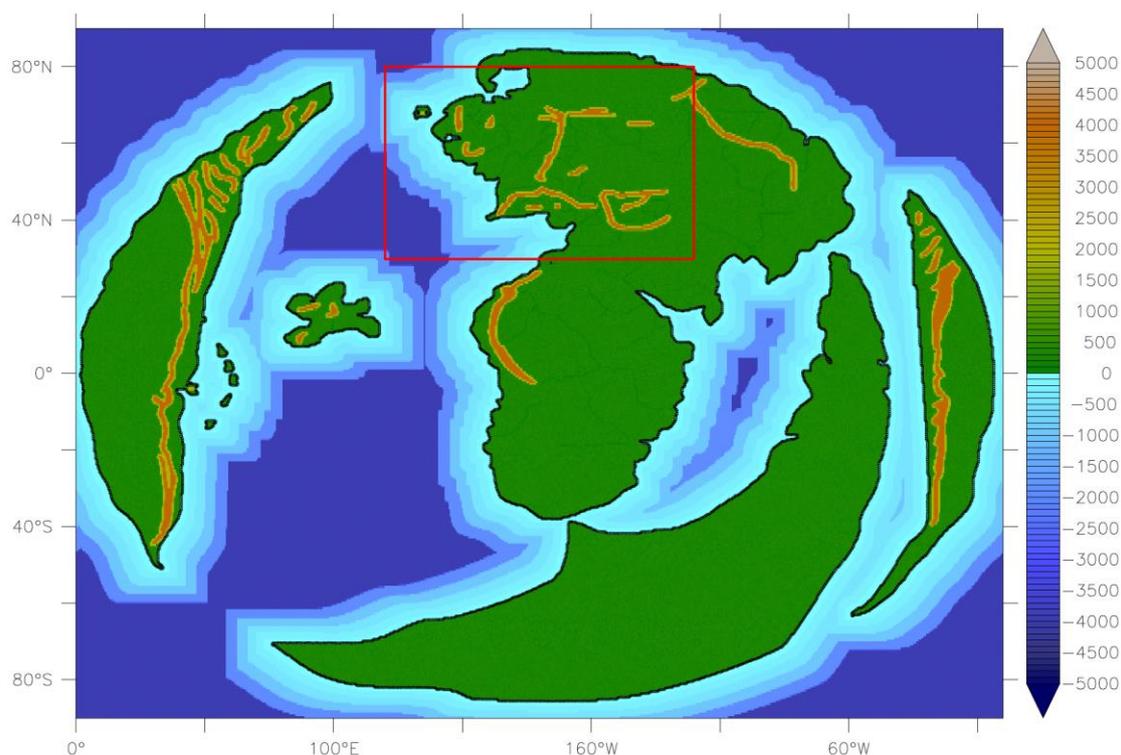
### **3. The Climate of Tolkien’s Middle-earth**

J.R.R. Tolkien has been highly influential on the fantasy genre, being the first “great world-builder” and a model for modern fantasy authors (Dwyer 3). Tolkien displayed extraordinary attention to detail, drawing up elaborate charts to calculate times and distances that sometimes even included the direction of the wind and the phase of the moon (Carpenter, *Letters* 194). He drew upon his thorough and impressive knowledge of natural history and horticultural lore to develop realistic depictions of nature, helping readers transition from the real to the imaginary (Brisbois 198). The detailed nature of Tolkien’s world has inspired a diverse range of participatory fandom, including a number of books on the invented flora and fauna in Middle-earth (Wolf 173). His maps have inspired mapmaking of Middle-earth by others, like the unauthorized book *The Atlas of Middle-earth* (Wolf 162). In that book, explanations of Middle-earth’s

climate were attempted, such as the grasslands of Rohan resulting from the rain shadow of the Misty Mountains (Fonstad 182).

A radical example of textual poaching, where the author's original creation was repurposed to fill in gaps in worldbuilding, was a comprehensive simulation of the climate of Arda (of which Middle-earth is a relatively small region), described in a non-peer-reviewed mock paper by Radagast the Brown (2013) and expanded upon here. To build a climate model of Arda, first a map of topography and bathymetry was constructed using canonical maps published by Tolkien (*Lord of the Rings*, *Shaping of Middle-earth*) and unauthorized maps (Fonstad). The starting point was a map of the Northern Hemisphere during the Second Age of the world of Arda. The apparently flat world of Arda was mapped onto a sphere by the straightforward mapping of the circular Arda onto an equal-latitude/longitude grid. The missing corner regions were set to be oceans.

Tolkien specified that Middle-earth was our Earth at some distant past (*Lord of the Rings* 2) with the same year-length as ours (1107). In a 1958 letter, Tolkien suggested the fall of Barad-dûr occurred around 6000 years ago (Carpenter, *Letters* 283). Consequently, the radius of Earth and Arda were assumed to be the same, spinning at the same rate in the same direction. Similarly, the strength of the sun, the distance from the Sun to the Earth, and the tilt of the Earth on its spin axis, were assumed to be identical. The resulting global map, at a resolution of  $0.5^\circ$  longitude by  $0.5^\circ$  latitude, is shown in Figure 1.



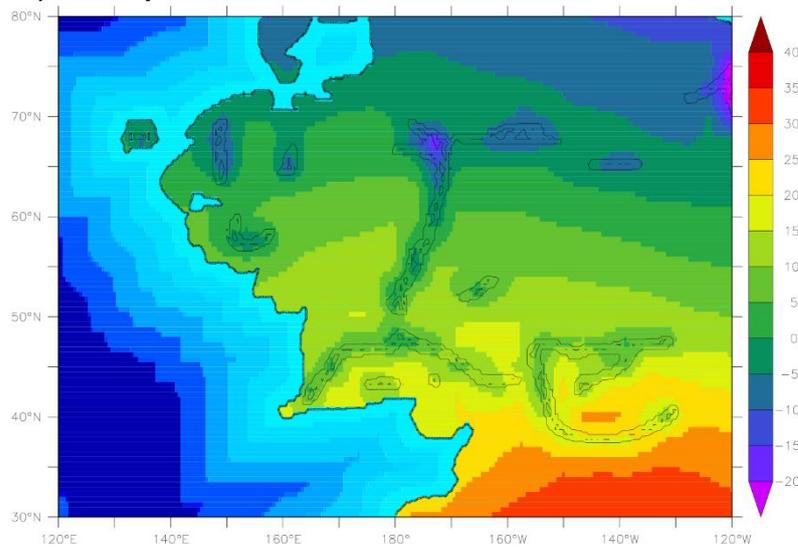
**Figure 1.** Map of topography and bathymetry for the Arda simulation, shown in units of metres. This world is known as “The Second Age of Arda.” The red rectangle shows the position of Middle-earth.

The climate model simulates temperature over the region of Middle-earth, shown below in Figure 2a. The relationship between temperature and latitude is clear, with cooler poleward regions (for instance, the annual average temperature is below freezing in the far Northern Kingdom of Forodwaith), and warmer equatorward regions (for instance, the annual average temperature is higher than 30°C in Haradwaith). In this respect, the climate of Middle-earth is similar to Western Europe and North Africa, which is unsurprising given that Tolkien was inspired by these regions. High-altitude mountainous regions such as the Misty Mountains are colder than the surrounding low-lying regions. This is because air temperatures cool with increasing altitude, as rising air gives up heat energy in order to expand as it rises. The temperature decreases east of the Misty Mountains, similar to Europe, because seasonality increases farther from the ocean. Winters become colder and summers become warmer, but winters cool more than summers warm, and so annual average temperatures fall away from the ocean.

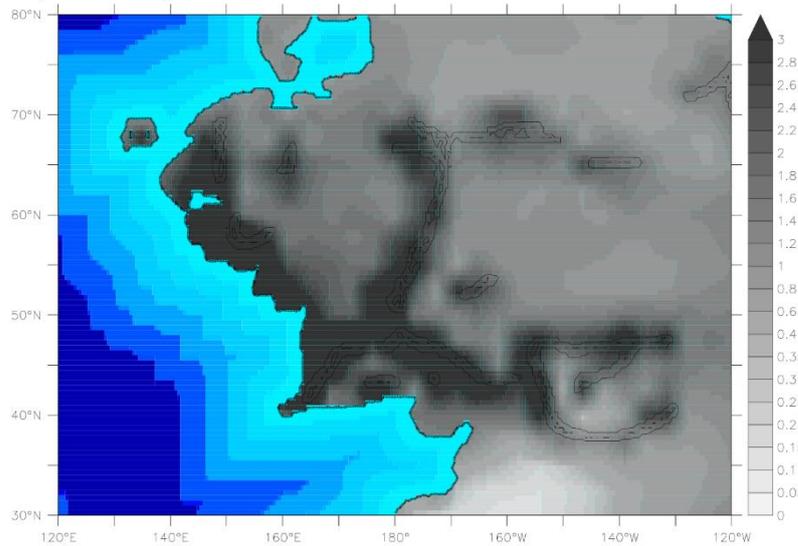
The model-predicted precipitation (rain and snow) over Middle-earth is shown in Figure 2b. The most striking effect is that the highest precipitation occurs over and to the west of mountainous regions, with a drier rain-shadow to the east of the mountains (for example, east of the Misty Mountains). This is because prevailing winds bring moist air from the western ocean onto the lands of Middle-earth. The air cools as it rises over the mountains, causing its moisture to condense from vapor into liquid, forming clouds and falling as rain or snow. On the eastern side of the mountains, the air has lost much of its moisture resulting in less precipitation. The regions in the far South of Middle-earth, in southern Mordor and Haradwaith, are dry, because these are “subtropical” regions, similar to the Sahara desert where dry air descends towards the planet’s surface.

Surface wind speed and direction, and mid-atmospheric pressure over the land of Middle-earth, are shown in Figure 2c. Strong westerly winds blow in the coastal southern regions of Middle-earth, such as the Bay of Belfalas, while easterly winds blow in the north.

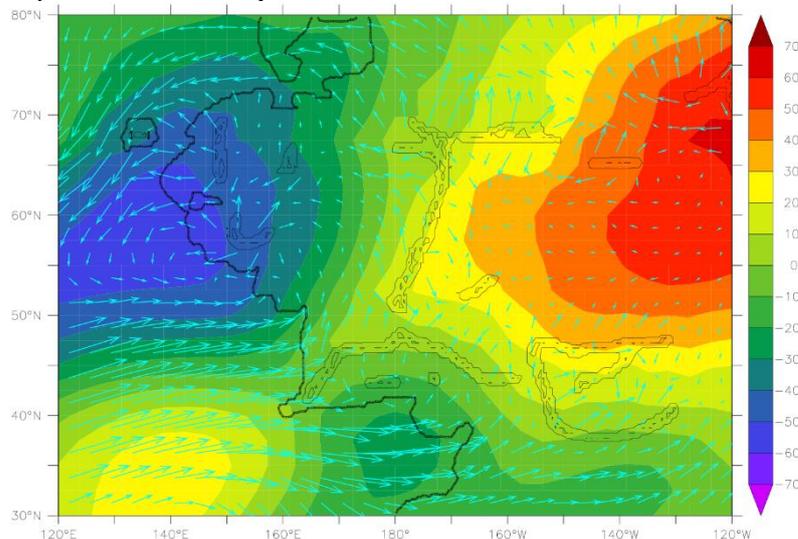
### a) Temperature



### b) Precipitation

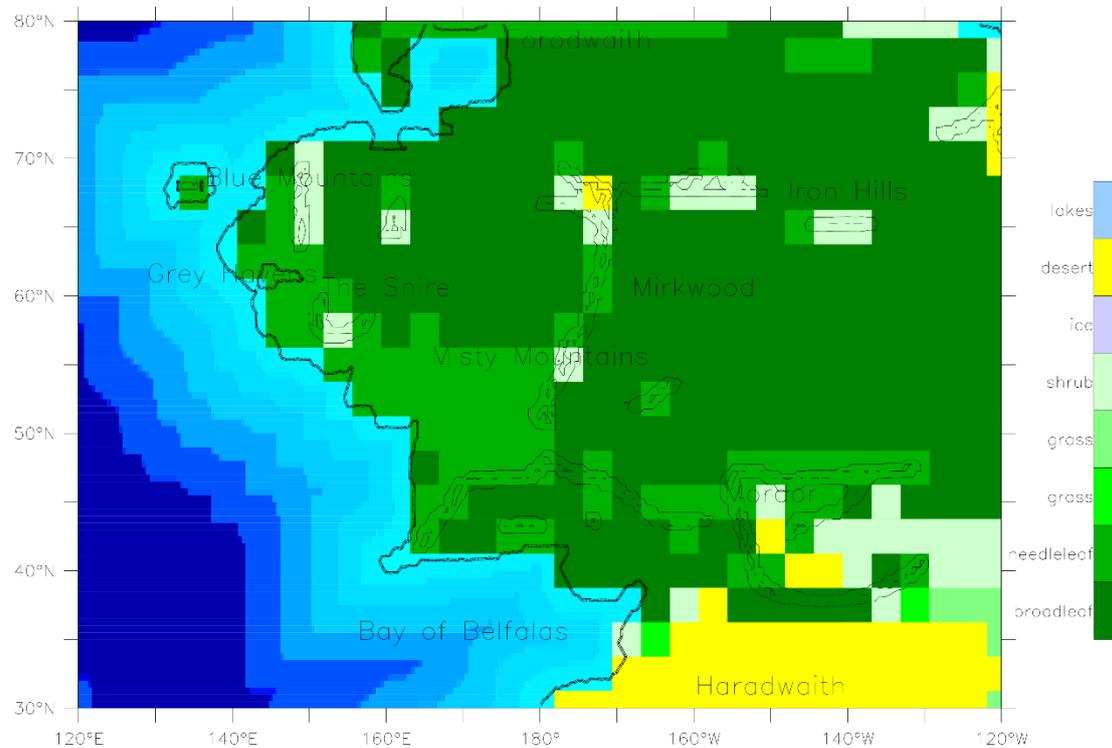


### c) Wind and pressure



**Figure 2.**  
a) Annual-average modelled temperature (units of °C), b) precipitation (units of mm/day), and c) surface winds and mid-atmosphere pressure (geopotential height at 500 mbar, geopotential height in units of metres) in Middle-earth. Thick black lines show the continent outlines; thin black lines show topographic contours. In Figures a and b, the ocean is shown in shades of blue which represent depth.

The vegetation component of the model allowed us to examine the model-predicted vegetation of Middle-earth, shown in Figure 3. Vegetation depends strongly on rainfall and temperature. Deserts are found in the warm, dry regions of the far South, and low-lying shrubs are found over much of Mordor. Shrub and cold desert are found on the peaks of the Misty Mountains, the Iron Hills in the north, and Blue Mountains in the west.



**Figure 3.** Model-predicted vegetation for the Middle-earth simulation. The approximate positions of places discussed in *Lord of the Rings* are also shown for reference.

The model simulations offer interesting insights into Middle-earth's climate. The easterly winds in the north (Figure 2c) may explain why ships sailing to the Undying Lands to the West depart from the Grey Havens, situated in the region of these easterly winds. The vegetation simulation, with much of Middle-earth covered with forests, is consistent with Elrond's claim that squirrels "could go from tree to tree from what is now the Shire to Dunland west of Isengard" (Tolkien, *Lord of the Rings* 265). Of course, the vegetation model does not account for disturbance of vegetation from its "natural" state, such as forest fires caused by dragons, deforestation by dwarves, or growing of pipe-weed by hobbits.

When the Middle-earth climate simulation was first released (Brown 2013), the research was used to educate the public, explaining how models based on fundamental laws of physics could be applied to other worlds, even imaginary ones. The author was contacted by many educators, who reported that they were using the work as a teaching tool. For example, in a first years' course on marine science, students were instructed to draw prevailing Middle-earth surface winds, ocean circulation and regions of oceanic upwelling. The work has been translated into multiple languages, including chapters in

“Tolkien et les sciences” and “Le Trône de fer et les sciences”, both of which were nominated for the coveted “Grand Prix de l’Imaginaire” prize. The research received significant media attention with coverage in the *Guardian*, *Scientific American*, and PBS.

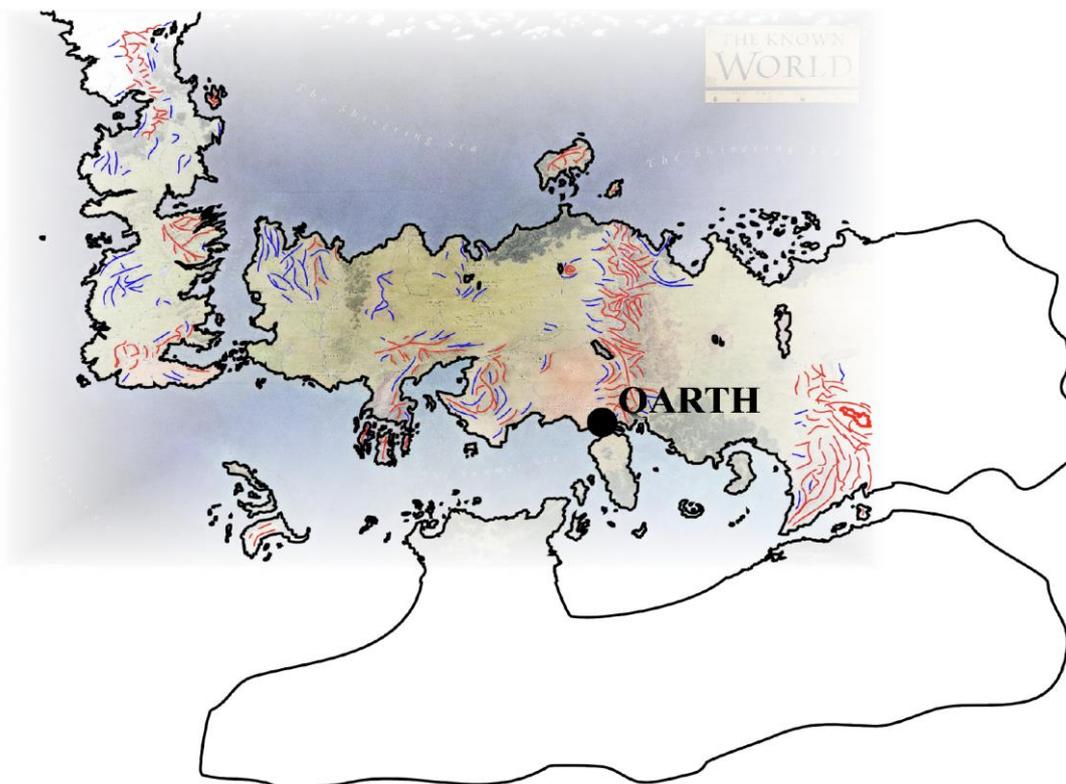
In 2014, Brown’s work was presented at fantasy fiction events, including BristolCon, a science fiction and fantasy convention. The newly “poached” reality created by the climate model was able to deepen narrative immersion for fantasy readers by supplementing the author’s original material with empirically driven plausibility. The model simulation did not merely fill in geographic blanks, but imposed a complex real-world logic onto the fantasy world, making the landscape a knowable character in the narrative. This activity moves beyond simple acceptance of the text’s geography to a moment of negotiation – the fans’ contribution is a response to the text’s lack of environmental detail. The fan response to the Middle-earth climate model was followed by strong public demand for similar climate simulations of other imaginary worlds such as the continent of Westeros from *Game of Thrones* (Nuccitelli).

#### **4. Explaining the Climate of Game of Thrones**

A distinguishing feature of the world from Martin’s A Song of Ice and Fire series is its unpredictable seasons, an iconic example of climatic world-building influencing the story (Moser 61). The length of these seasons serves as a plot device whereby a long-lasting winter creates a “land bridge” of snow and ice that allows a catastrophic plague of the undead known as White Walkers to move southward. The puzzle of these unpredictable seasons has inspired much activity within participatory culture, drawing on the collective intelligence of the fan community. A number of hypotheses have postulated various causes for the errant seasons. These include reduced carbon dioxide concentration (Mera), decreased sunspot activity (*New York Post*), decreased ocean circulation strength (Farnsworth and Stone), changes to the planet’s orbit around the Sun (e.g. Laughlin; Delcke), or magic (illuminatus235).

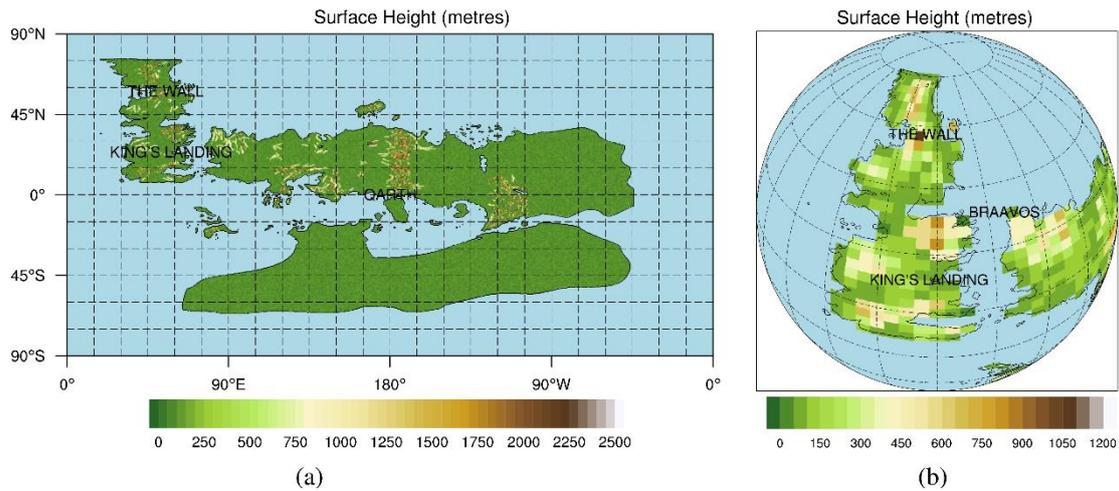
Astronomers have also proposed their own explanations for the unpredictable seasons. Veselin Kostov led a team of scientists simulating the orbit of a planet orbiting around a binary star system composed of two sun-like stars. Such a three-bodied system is unpredictable, and they found chaotically varying years spanning from 600 to 850 days. However, Florian Freistetter and Ruth Grützbauch argued that Kostov’s binary star system was dynamically unstable. They proposed an alternative binary star system, where the planet moved perpendicular to the plane of the orbiting stars like a yo-yo – a configuration known as a Sitnikov orbit. Simulating such an orbit, Freistetter and Grützbauch reproduced the seasons resembling those described in A Song of Ice and Fire. A team of astrophysicists led by Adiv Paradise, who researches the climate of cold Earth-like planets, extended this research by simulating the climate of a world in a Sitnikov orbit. They found that when the planet passed closest to the binary stars, the sunlight would be so bright that the planet’s surface temperatures would reach over 100 °C. They concluded that the unpredictable seasons must be caused by some other factor, such as a chaotically varying axial tilt.

Incorporating rigorous, system-level modelling to this wide array of collective intelligence activity, we used the “CitCM3” climate model (Valdes et al.) to simulate the seasonality of Martin’s world. Climate models are typically used to manipulate different factors such as the amount of carbon dioxide (CO<sub>2</sub>) in the atmosphere or changing mountain or ice sheet heights and extent, to understand their impact on atmosphere and ocean circulation (Farnsworth et al.). However, they can also be used to explore the impact on climate if the planet’s axial tilt varies. Many of the model’s boundary conditions were created using a map of the “Known World” (Martin, *The Lands*). As the city of Qarth is described as “the center of the world, the gate between north and south, the bridge between east and west ...” (Martin, *Clash* 383), it was placed at the center of the planet. Continental outlines, mountains, and hills were traced from the published map, and continents outside the Known World were invented (Figure 4).



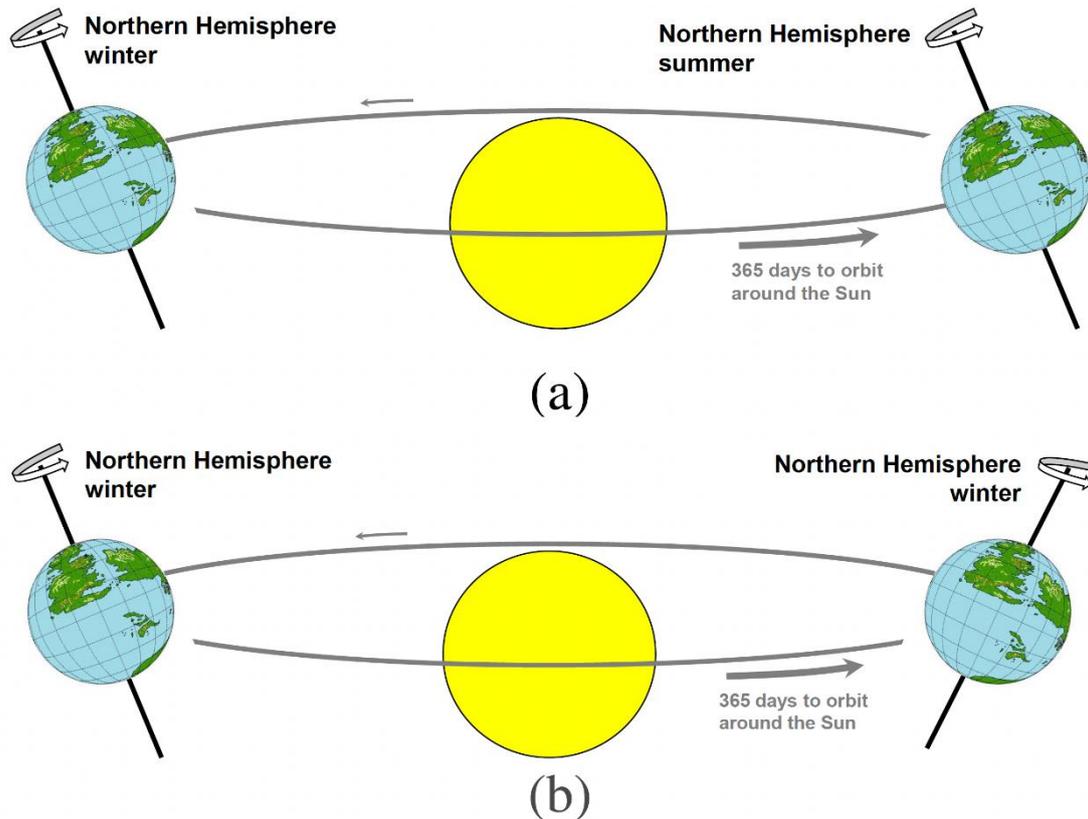
**Figure 4.** The map of the Known World overlaid with tracing of continental outline (black lines), mountains (red regions) and hills (blue regions).

The map was then converted into a digital form to be input into the climate model, as a series of grid boxes of resolution 0.5° longitude by 0.5° latitude. Mountains were assumed to have an average height of 2000 meters, hills an average height of 1000 meters, coastal regions a height of 20 meters, and all other land an average height of 100 meters. The resulting digital elevation map is shown in Figure 5a. This was interpolated to the same resolution as the climate model, resulting in the geography shown in Figure 5b.



**Figure 5.** a) High-resolution ( $0.5^\circ$  longitude x  $0.5^\circ$  latitude) mountain height for the whole planet. b) Model-resolution ( $3.75^\circ$  longitude x  $2.5^\circ$  latitude) mountain height for the region of Westeros and western Essos. Note the difference in color scale between a and b.

Initially, the model was set up for a world with similar seasons as the real Earth, with four seasons in a single year. The tilt of the spinning axis of the planet was set at a fixed angle throughout the year, as is the case with the 'real' Earth shown in Figure 6a. The tilt of the Earth's axis is the cause of seasons, and one way that seasons can be made to last longer is to allow this tilt to change throughout the year, so that the Earth "tumbles" on its axis like a wobbly spinning top. If the Earth tumbled exactly once a year, the spin axis would always point toward or away from the Sun, shown in Figure 6b, and the seasons would thus remain fixed at Northern/Southern Hemisphere summer or winter. This extended winter or summer would end if the tilt suddenly flipped so that the opposite hemisphere pointed toward the sun.



**Figure 6.** Configuration of Earth's orbit for a) Earth, where the angle of tilt of the spinning axis stays constant, and b) the world of *A Song of Ice and Fire*, where the tilt tumbles as the planet rotates around the Sun.

To simulate this kind of unchanging seasonality, a model was set up with the planet tumbling on its axis, resulting in a permanent Northern Hemisphere winter and Southern Hemisphere summer. To reduce the temperature difference between the winter and summer hemispheres (as the climate model became unstable if the temperature difference was too great), the tilt of the spinning axis was decreased from  $23.5^\circ$  (Earth's value) to  $10^\circ$ . This gave a less extreme winter in the Northern Hemisphere and less extreme summer in the Southern Hemisphere, and the model ran happily for at least 10 years. To ensure that a permanent winter is feasible Westeros must occupy relatively northern latitudes.

The climate model results show that a tumbling axis with an angle of tilt of about  $10^\circ$ , results in permanent seasons in broad agreement with the described climate of Westeros. To transition between the two seasons, the tilt would have to flip every few years. The reason for this flip is unclear. The tilt of the real Earth is stable because of the presence of the moon; if the moon was removed, the tilt would become unstable, which could result in unpredictable seasons. Could a similar phenomenon explain the seasons of Westeros? The world has one moon but according to legend, used to have a second moon until it "wandered too close to the sun and it cracked from the heat" (Martin, 1996, 288). Might the loss of a second moon have caused a chaotically tilting axis? This question seems suited for the astronomy community to explore.

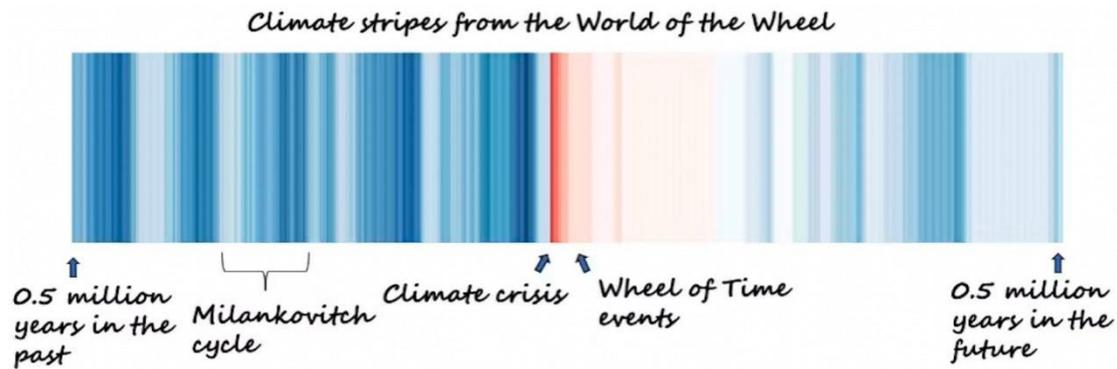
Fandom's aggregated expertise – blending climatology, astronomy, coding, and lore knowledge – has aimed at achieving mastery over the text's reality. By attempting to solve the narrative mystery of a plausible mechanism of the seasons, it elevates the setting from a mere backdrop to a complex, internally consistent, and thus more believably real place. The pleasure of fan immersion comes from understanding the system that dictates the narrative.

## 5. Glimpsing Earth's future in the World of the Wheel

The story of *The Wheel of Time*, the 14-book epic fantasy series, is set in the Third Age of what we call the "World of the Wheel." While it is not explicit in the storyline, Jordan has confirmed that the First Age was actually modern-day Earth, which ends with a dramatic event – perhaps climate change (Theoryland). From his remarks, we estimate that the books take place around 18 000 years from today. By poaching from these remarks, we may pose an interesting question bridging the scientific and the literary: would today's climate change still be experienced in the World of the Wheel after all those centuries? Imposing real-world climate data and simulated history onto the fictional geography of *The Wheel of Time*, our model here explores the environmental legacy of the "First Age" (our current age) on the fictional "Third Age." The model's output thus becomes a fan-generated backstory of sorts.

About a quarter of carbon dioxide emitted today will remain in the atmosphere even 18 000 years from now. According to biogeochemistry models, carbon dioxide levels could be as high as 1100 parts per million (ppm) at that point (Lord et al. 8), much higher than the present-day value of 422 ppm, although reaching levels this high is highly unlikely (Hausfather and Peters 620). This high value assumes that the Paris climate goals will be exceeded and that many natural stores of carbon will also be released into the atmosphere (such as melting permafrost).

However, high carbon dioxide concentrations do not necessarily mean a warmer climate. On geologic timescales, the amount of energy from the Sun has slowly increased by around 1% every 110 million years. This is why hundreds of millions of years ago, more atmospheric carbon dioxide was needed to balance the lesser amount of energy received from the sun. Over shorter timescales, such as the last hundreds of thousands of years, slow changes in the orbit and tilt of the planet have been important factors. These cause Milankovitch Cycles, where the Earth transitions from ice ages to warmer periods around every 100 000 years. Given that we are currently at the peak of such a cycle, the planet will naturally cool over the next 50 000 years, which is why in the 1970s, some scientists were worried about a new ice age (Maslin). But will cooling from the Milankovitch cycle be enough to offset warming from the remaining carbon dioxide in the atmosphere? Figure 7 shows a million-year version of the classic warming stripes graphic, a visualization of climate where blue stripes represent cooler periods and red stripes represent warmer periods (data from Lord et al. 8; climate stripes inspired by <https://showyourstripes.info>).



**Figure 7.** Warming stripes of Earth (and the World of the Wheel) for a million years.

The recurring blue bands are the 100 000 year Milankovitch cycles, clearly visible in the first half of the million-year period. Anything red can be considered human-caused climate change, and the events of The Wheel of Time are well within this period. Even the descending Milankovitch cycle won't be enough to counteract the increased warming from carbon dioxide, and so the inhabitants of the World of the Wheel would still experience elevated temperatures from a climate crisis that occurred 18 000 years earlier. While most (80%) emitted carbon dioxide is drawn back out of the atmosphere on short timescales (<200 years) by the carbon cycle, 20% remains on longer timescales (thousands of years). However, some of the weather changes from the still elevated temperatures could be offset by other factors. From a geological perspective, 18 000 years is not a long time, and landmasses would not change significantly, but in this fantasy future magical channelers "broke" the world at the end of the Second Age, creating several new supercontinents.

To find out how the climate would work in the World of the Wheel, we used an exoplanet climate model (Ball et al.), feeding in a topography based on hand-drawn maps of the world and carbon dioxide levels of 830 ppm based on one of the high potential future carbon pathways (Lord et al.). According to our model, the World of the Wheel would be warm all over the surface, with temperatures over land never cold enough for snow apart from on the mountains.

The World of the Wheel likely has stronger and wavier high-altitude jet streams – fast-moving currents of air high in the atmosphere – than modern-day Earth, because it has more mountain ranges, which generate atmospheric waves called Rossby waves, causing oscillations in the jet stream. There is limited evidence that the jet stream also gets wavier due to climate change (Mann et al.), although this influence is a much smaller factor than the introduction of new mountain ranges. According to our climate model, the jet streams would bring moisture from the western ocean onto land, and deposit it north of the Mountains of Dhoom. Surprisingly, this region (The Great Blight) is described as desert-like in the books, although the cause is suggested by the author to be due to metaphysical corruption, not physical (Jordan 585).



**Figure 8.** Simulation of the World of the Wheel, with red and yellow arrows showing the jet stream (Steinig).

Winds often revolve around two particularly enormous mountains, Dragonmount and Shayol Ghul, before blowing downslope and reaching far across the land masses. The peak of Dragonmount itself is nearly always surrounded by clouds, because the mountain is so large that winds travelling up its slopes force surface moisture to higher altitudes, cooling it and causing water vapor to condense into clouds. The fact that winds would be so different from modern-day Earth is predominantly due to topography, not increased temperatures from climate change.

Nevertheless, in the World of the Wheel, despite the extremely long time since carbon polluted the atmosphere, the inhabitants would still be exposed to warmer-than-usual temperatures. Here the story and the science diverge, as at times snow is mentioned in *The Wheel of Time*. Our finding that the simulated Earth 18 000 years in the future is hotter than the temperate, snow-prone world described in *The Wheel of Time* – a familiar, quasi-European fantasy setting – represents a significant act of oppositional reading realized through data, forcing a new critical interpretation of *The Wheel of Time*. The pervasive presence of snow in the narrative might be interpreted as denying the environmental legacy of the First Age (our world's climate change), while our application of climate science re-injects this lost history into the world, striving to achieve a deeper form of narrative immersion that feels causally linked to the reader's own reality.

## 6. Using a climate model to world-build “climate fantasy”

The three previous case studies demonstrate the retroactive benefits offered by climate science to the fantasy genre, enabling readers to engage in participatory acts such as textual poaching, collective intelligence, and oppositional reading. Climate models also offer an exploratory tool that can aid immersive world-building and potentially enhance the exploration of climate change themes in fantasy fiction. The battle for our planet's future is first and foremost a battle of

imagination – conceptualizing the scope of climate change and imagining a sustainable future (Oziewicz, “Planetarianism” 242). Fiction is a powerful tool for communicating the impacts of climate change, which are more emotionally compelling when told as a story compared to dry graphs and numbers (Oziewicz, “It Wasn’t Us” 23). In particular, fantasy is uniquely positioned as a literary genre to address climate change themes (Fetherston 463).

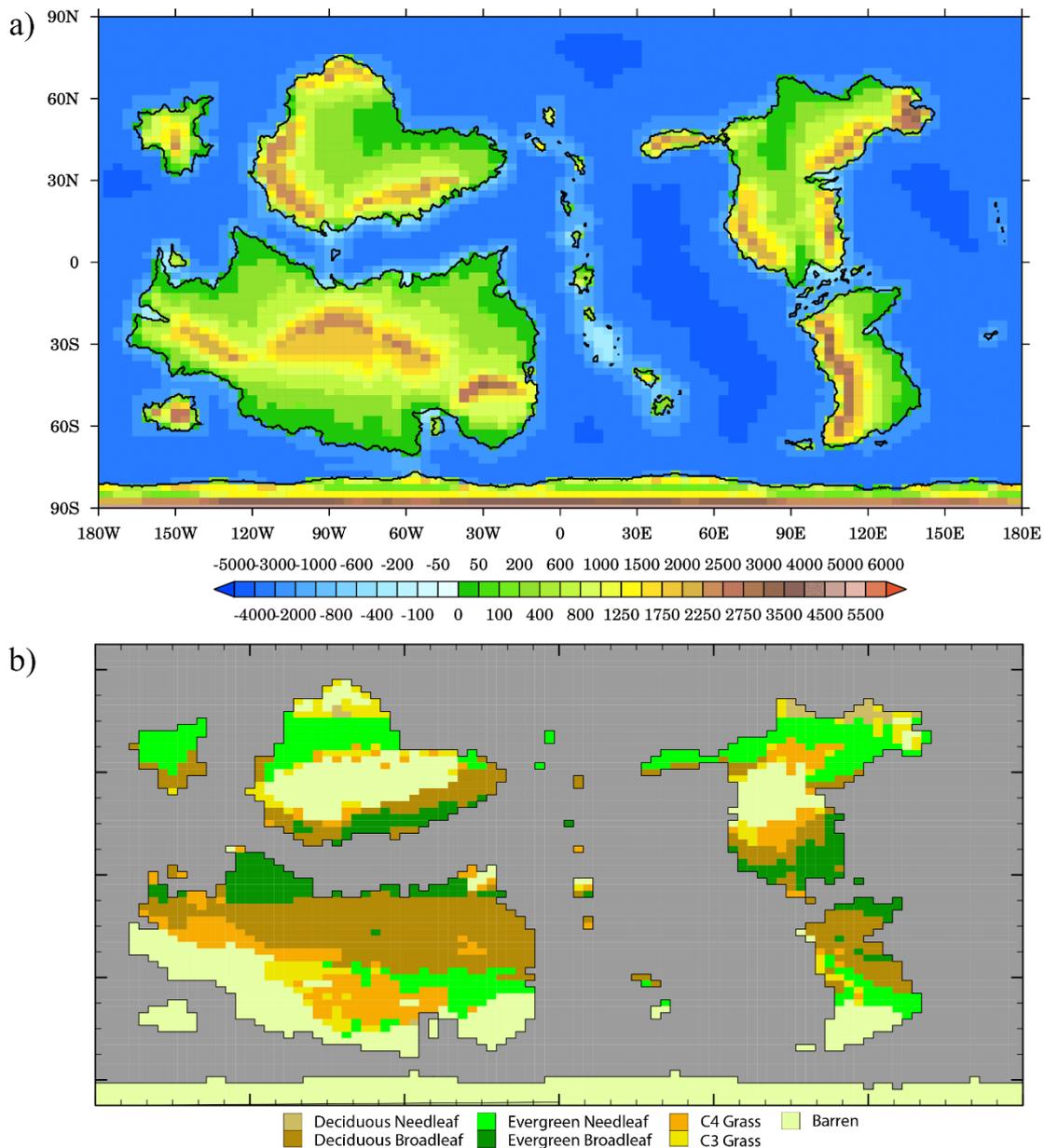
Marek Oziewicz argues that fantasy can challenge two underlying ideologies that obstruct progress on climate change. The first is anthropocentrism, the belief that humans are separate to and masters of the natural world. More than other literary genres, fantasy includes the nonhuman perspective, encouraging a shift from anthropocentric to ecocentric thinking (Le Guin 38). Fantasy can help readers abandon the illusion of mastery over nature and imagine a more ecocentric future (Oziewicz, “Fantasy” 68). The second ideology is neoliberalism, which fuels the belief in unlimited economic growth on a finite world (Oziewicz, “Planetarianism” 243). These societal systems can be interrogated through materialist fantasy, which explores how the physical environment and economic systems within an imaginary world influence its societies and characters. Such narratives can critique real-world issues such as extractivism, oppression, and environmental degradation. In science fiction, realistic alternative worlds are depicted through physics, chemistry, etc, while in fantasy, realism is constructed through detailed worldbuilding (Grifka-Wander 73). Immersing readers into materialist, internally consistent worlds can challenge them to contrast the imagined world with their own world and critically examine their own thinking and practices (Brochu 128).

In pursuit of the goal of creating an immersive reading experience, John Cook has developed an allegorical fantasy story exploring the denialist response to environmental damage. This theme was previously explored in the film *Don’t Look Up* (2021), which uses an asteroid as an allegory for climate change to explore irrational societal responses to an existential threat. However, a contemporary story satirizing a segment of the population can alienate that particular audience (Little 5). In contrast, locating a story in a fantasy world removes the connection to a specific nation or community, making it “about all of them at once, yet determined by none of them” (Kraatila, “Conspicuous Fabrications” 424).

To enhance the verisimilitude and immersive nature of the story, Cook integrated a climate model into the world-building process. In contrast to the retrospective case studies previously presented, he used climate modelling early in the world-building process. Presley argues that world-building should start with geography given the environment affects the individuals inhabiting the world, then continue through biology, physics, metaphysics, technology, and finally culture (172). A believable and engaging imaginary world requires three elements: invention, completeness, and consistency (Wolf 33). Incorporating a climate model in the world-building process contributes to all three attributes, with invention of landscapes, comprehensive simulation of biomes and climate across the entire planet, and consistency with the laws of nature.

Cook created a digital elevation map, specifying heights on land and in the ocean depths (Figure 9a), and used this map to develop a climate model which predicted climate behavior and the distribution of biomes (Figure 9b).

The digital elevation map and biomes map informed the design of the fantasy map and subsequent storytelling (Figure 9c).



**Figure 9.** a) Digital Elevation Map; b) Sheffield Dynamic Global Vegetation Model (SDGVM) output, c) fantasy map for the imaginary world Terrios.



The model output provides concrete details such as temperature, precipitation (rain or snow), and wind conditions at every step along the characters' journey through a variety of biomes. This emulated and expanded on Tolkien's meticulous use of "endless calculations of time and distance, drawing up elaborate charts concerning events in the story, showing dates, the days of the week, the hours, and sometimes even the direction of the wind and the phase of the moon" (Carpenter, *Biography* 220). Tolkien used seasons to add subtextual depth to *Lord of the Rings*, specifying that "[t]he main action begins in autumn and passes through winter to a brilliant spring: this is basic to the purport and tone of the tale" (Carpenter, *Letters* 272).

Integrating insights from climate modelling offers a powerful new tool to help fantasy authors build a rich, detailed imaginary world. Creating an immersive experience can contribute to connecting readers to the natural world, thus taking advantage of the genre's inherent capacity to engage readers with ecocritical ideas (Ulstein 15). Further, such work can act as authorial paratext, with the model's outputs strategically deployed as both peritext – inside the book – and epitext – outside the book (Genette 5). An example of peritext might be maps based on simulated biomes, visually verifying the world's consistency (e.g., Figure 9c). Epitext could be release of the model code, its data, or commentary on its creation outside the book (such as this article). The model does not just describe the climate; it attempts to justify the world's ecological details, grounding the fantastical world in real-world physics. Climate models, existing as code or scientific output, are a sophisticated form of public paratext which use scientific insights to mediate and enrich readers' understanding of the original text's world.

A comprehensive, internally consistent world can also lay the foundation for constructing a materialist fantasy which explores how the physical environment influences the development of societies and culture. Of course, detailed climate simulations are only one aspect of an immersive imaginary world, which also requires societies and cultures, governance structures, histories and mythologies, genealogical relationships, magic systems, theologies, and more (Wolf 53). If the fantastic elements are the vibrant paints to splash across a new world, then geography is the canvas (Presley 231).

## 7. Discussion

A well-developed imaginary world extends beyond the canonical stories told within them, inviting imaginative readers to speculate and explore in creative and innovative acts of participatory culture (Wolf 17). A subset of this phenomenon is "scientific fan fiction," where scientists apply scientific concepts to an imaginary world, encouraging fans to engage more deeply with both the original works and the science involved (Larsen 2). When the climate model is created by a reader, the model's function is one of critical confirmation or challenge, serving as an external, analytical tool to test the coherence that the narrative was already implicitly promising. If the model confirms the text, it validates the reader's original act of secondary belief, strengthening the overall sense of immersion and realism for the entire reading community (like in the case of easterly winds blowing near Middle-earth's Grey Havens).

Thus climate models offer a new, modern tool for exploring imaginary worlds in both the conventional digital twin way, and the reverse way. The reverse way is retrospective, where readers use climate models to fill in the gaps of pre-existing imaginary worlds, like we do in our first three case studies. The conventional way is exploratory, where the author uses the climate model to “discover” the imaginary world and incorporate insights into world-building, as illustrated in our fourth case study.

The fantasy world climate model serves as a powerful mechanism for constructing and maintaining secondary belief. Gerrig argues that the best narratives minimize the cognitive labor required to believe the story (279). Successful immersion relies on the ability of the narrative to maintain the reader’s secondary belief. The climate model, and its paratextual presentation, provides this assurance. It offloads the cognitive check on environmental physics from the reader’s mind to a validated, rigorous system. The model’s successful output functions as paratextual support, confirming to the reader that their innate cognitive schemata about how weather and ecology work are still valid in the imaginary world. It provides a formal, data-driven validation that the world is built on a coherent, minimally-departed foundation.

Hence it is worth considering how and when it is appropriate to develop climate models of an author’s work. For example, caution should be exercised before climate modeling the imaginary worlds created by Robin Hobb, given her staunch opposition to fan fiction based on her work. N. K. Jemisin expressed an ambivalence for fantasy maps, with her book *The Hundred Thousand Kingdoms* critiquing cartography as a colonizing tool (Melville 16), emphasising the need for more Global South perspectives in epic fantasy such as the work of epic world-builders such as R. F. Kuang and Tomi Adeyemi. In some fantasy worlds, the magic system clearly works against natural laws, such as Sanderson’s *Stormlight Archives*, which features global-scale storms that behave counter to the physical processes governing storms. A climate model based on the laws of physics would fail to represent such a world as presented by the author. Along these lines, Tolkien expressed a strong dislike of “scientification” of his writing, objecting to the changing of the Elvish bread lembas to a “food concentrate” (Carpenter, *Letters* 293).

However, while many fantasy series require suspension of disbelief, integrating real-world physics into the narrative helps ground readers in the world. In this spirit, our climate modeling of Middle-earth, Westeros, and the World of the Wheel represents the highest order of engagement with Ryan’s principle of minimal departure. In the cases of Middle-earth and Westeros, the models fill gaps in the texts, providing a scientific and climatically plausible realism that reinforces narrative immersion. The models ensures the fantastic setting remains tethered to a stable, understandable physical reality. However, in the case of *The Wheel of Time*, when the simulated deep-future climate is significantly hotter than the temperate, snowy world described by Jordan, the model output becomes a form of oppositional reading. Armed with physics-based science, we discover that the text itself is in violation of the principle of minimal departure by neglecting the environmental legacy of the First Age (our time). In this scenario, the participatory community negotiates a new understanding, using real-world physics to establish a deeper, more rigorous narrative. The modeling process thus transforms the principle of minimal

departure from a reading rule into a dynamic, critical tool for world-building mastery.

Despite the fascinating insights that can be gained from using climate models to explore the weather and climate of imaginary worlds, there is a cost (computational, time, and, ironically carbon dioxide) associated with such processes. Such advanced activity will be beyond the resources of many fans and authors, who may prefer to stick to traditional world-building. However, simpler global climate models such as ExoPlaSim do not require supercomputers, but allow world-builders to input custom geography and generate realistic climate data on a laptop within hours; this is the model Paradise and colleagues used to simulate Westeros climate. Thus, climate models offer a powerful exploratory tool for worldbuilders – not only book authors but also game developers and screenwriters. During the Age of Exploration at the end of medieval times, as audiences began reading about explorers' journeys into new worlds, fictional creation of imaginary worlds became more detailed and comprehensive in response to reader demand (Wolf 72). In the same way, the modern ability to simulate detailed climates and biomes might inspire today's world-builders to make use of climate models to build comprehensive, accurate, and consistent environments. Lin Carter argues that world-builders should consider geography when sketching out their map – lush rainforests should not lie against a burning desert, and it pays to “do a bit of reading into climatology” (180). Climate models offer a more systematic and comprehensive approach to world-building.

That said, a limitation in our approach is that only a single climate model was used to explore the weather and climate of each imaginary world. This results in considerable uncertainty in our findings, because any single model has biases due to the finite resolution of the model used. The IPCC attempts to minimize (or at least, characterize) these uncertainties by using multiple models developed at a number of international climate modelling institutions, and present averages (with ranges of possible values) of the results. Furthermore, the boundary conditions implemented in fantasy models are more uncertain than those used by the IPCC, because conditions such as global topography and greenhouse gases are not always straightforward to determine accurately from the underlying fictional texts; for example, just how high was Mount Doom, or Dragonmount? Therefore, other researchers may equally validly implement quite different boundary conditions, in a different model, and end up with a considerably different representation of climate. In addition, even though climate models aim to represent our best possible understanding of scientific processes, this understanding has different levels of maturity for different aspects of the Earth system. For example, although the underlying fluid dynamics of the atmosphere and ocean are well understood (the well-known Navier-Stokes equations), other aspects such as the influence of evolutionary biology and long-term changes in vegetation-climate interactions, are still relatively poorly represented in models of Earth's past climate.

Building climate models, nevertheless, introduces a fan-generated epistemology, shifting the source of fictional truth from authorial fiat to systemic plausibility. The model asserts that Middle-earth's weather or Westeros's seasons are not determined by mere description, but by real-world physical laws, pushing the principle of minimal departure to its extreme. This creates a bifurcated knowledge system where the canonical truth is the text,

while the modeled truth is the physical mechanism underpinning the text. Cases where the model conflicts with the text force an oppositional reading, asserting that the text's environmental knowledge is incorrect and thereby claiming a higher, scientifically validated form of reality.

To “scientific” imaginative creation is to treat the fantasy world not just as a backdrop, but as a complex, self-contained system capable of being studied, tested, and predicted. This act is the ultimate expression of the fan mastery over the material described by Jenkins (*Textual* 74). Successfully modeling climate systems on an imaginary planet demonstrates a level of mastery over the system's structure that can surpass the author's own world-building needs. Scientifying fantastic works risks demystification, but in the participatory context, it can also offer a compensatory gain. In the Wheel of Time case study, for instance, the model injects a new moral dimension of environmental inheritance. It suggested that the trauma of the First Age (our current age of climate crisis) is a persistent, tangible reality that persists in the future world, making the fantasy world a powerful reflection of our own reality.

## 8. Conclusion

Coupling climate models with the fantasy genre offers a variety of educational opportunities. Retroactive modeling of existing worlds like Middle-earth have already proved to be a useful teaching tool for educators seeking to engage students about climate science, exploring the concepts of prevailing surface winds and ocean circulation. Exploratory climate models also offer the potential to enhance new fantasy stories, such as those that address climate change themes. The ability of modern climate models to project future scenarios is incredibly sophisticated and yet Marek Oziwicz argues that our most advanced technology for imagining the future is the story (“Planetarianism” 254). Fantasy stories can not only use allegory to help readers conceptualize the threat of climate change, they can also incorporate narratives of collective action that help readers imagine futures where our current destructive practices are replaced with sustainable ones (Oziwicz, “Fantasy” 68).

In summary, climate modeling of fantasy worlds is a happy collision between the dual thought experiments of fantasy world-building and climate modeling, offering opportunities for both the fantasy genre and climate science. The simulated precipitation maps and pressure systems are not just scientific curiosities, but represent the community's creative negotiation with the text. This scientific “poaching” transforms the map from a static, descriptive element into an active, knowable character in the narrative, thereby fundamentally shifting the terms of narrative immersion for the engaged fan. Climate models can deepen our understanding of fantasy worlds, enrich the world-building process leading to more immersive reading experiences, and draw pedagogical attention to the science of climate models.

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