

The Climate of Middle Earth

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Abstract. In this paper, I present and discuss results from a climate model simulation of the ‘Middle Earth’ of elves, dwarves, and hobbits (and not forgetting wizards such as myself). These are put into context by also presenting simulations of the climate of the ‘Modern Earth’ of humans, and of the ‘Dinosaur Earth’, when dinosaurs ruled the Earth 65 million years ago.

Several aspects of the Middle Earth simulation are discussed, including the importance of prevailing wind direction for elvish sailing boats, the effect of heat and drought on the vegetation of Mordor, and the rain-shadow effects of the Misty Mountains. I also identify those places in the Modern Earth which have the most similar climate to the regions of The Shire and Mordor.

The importance of assessing ‘climate sensitivity’ (the response of the Earth to a doubling of atmospheric carbon dioxide concentrations) is discussed, including the utility of modelling and reconstructing past climate change over timescales of millions of years. I also discuss the role of the Intergovernmental/Interkingdom Panel on Climate Change (IPCC) in assessing climate change, and the responsibilities placed on policymakers.

1 Introduction

Computer models of the atmosphere, land surface, and ocean are routinely used to provide forecasts of the weather and climate of the Earth. They are based on our best theoretical understanding of fluid motion, physics, chemistry, and biology, written in the form of equations, and then converted into a form which can be solved by a computer.

Climate models and models used to make weather forecasts are very similar to each other, except that climate models typically simulate longer periods of time than weather models (years to centuries as opposed to days to weeks), and therefore, due to limits on computer time and power, make

predictions at a lower spatial resolution (typical scale of hundreds of kilometers as opposed to kilometers). Climate model predictions are an integral part of political and societal planning for the coming decades to centuries, and the recent report from the Intergovernmental Panel on Climate Change (IPCC) summarises many of these future predictions (IPCC, 2013a).

Because climate models are based on fundamental scientific understanding, they can be applied to many situations. They are not designed solely for simulating the climate of the modern Earth, and, in theory, the same underlying science should apply to any time period in the past. The only caveat is that in order to simulate climates different from modern, the user must provide some ‘boundary conditions’ - maps or variables which are not predicted by the model. Examples include spatial maps of the height of the global terrain (topography) and ocean depth (bathymetry), characteristics of rocks and soils, and concentrations of key atmospheric constituents, such as ozone and carbon dioxide (CO₂). In addition, key parameters such as the strength of the sun, and the radius and the rotation rate of the planet, also need to be provided to the model.

Adapting the model to simulate past time periods is potentially very powerful because, in theory, we can know the ‘right’ answer from observations, and test the performance of the models by comparing their results with these observations. For time periods prior to humans making careful observations of the weather, we rely on indirect observations of many aspects of past climates, such as information from tree rings and ice cores, and fossils of plants and animals. However, provided that we understand the uncertainties and errors in these ‘proxy’ records of past climate change, and provided we also understand and account for uncertainties in the boundary conditions we apply to the model, we can make use of past periods going back millions of years, to time periods when the Earth looked very different from the modern.

In addition, by varying the topography/bathymetry, the rotation rate and radius of the planet, and density of the atmosphere, we can, in theory, use climate models to simulate any planet, real or imagined.

In this paper I present three climate model simulations, of the Modern (pre-industrialised) Earth, of the Dinosaur Earth (a time period called the Late Cretaceous, about 65 million years ago, just prior to the extinction event which killed off the dinosaurs), and Middle Earth - the land of hobbits, elves, dwarves, wizards, and orcs.

The aims of this paper are threefold:

- (1) To demonstrate the flexibility of climate models, arising from their basis in fundamental science.
- (2) To present the modelled climate of Middle Earth, and provide some lighthearted discussion and interpretations.
- (3) To discuss the strengths and limitations of climate models in general, by discussing ways in which the Middle Earth simulations could be improved.

2 Model description

I use a climate model developed at the UK Met Office, 'HadCM3L', which is capable of simulating the atmosphere, ocean, and land surface. In common with most climate models, HadCM3L represents the world in 'gridbox' form, with a 3-dimensional network of boxes covering the surface and layered to extend up to the top of the atmosphere and down to the bottom of the ocean depths. The size of each box is 3.75 degrees of longitude by 2.5 degrees of latitude, with a height dependent on the distance from the Earth's surface - boxes situated near the surface of the Earth have a smaller height than those at the top of the atmosphere or bottom of the ocean. This results in a 'matrix' of boxes covering the world, with 96 boxes in the West-East direction, 73 boxes in North-South direction, 20 boxes deep in the ocean, and 19 high in the atmosphere (a total of more than a quarter of a million boxes, although not all are used as some are effectively below the sea floor).

In this matrix, the fundamental equations of fluid motion in the atmosphere and ocean are formulated and solved, with the additional complication that the Earth is spinning on its axis. Energy is added to the system due to absorption of light and heat radiation emitted by the Sun, and energy leaves the system through emission of heat or reflection of light radiation into space. All variables in the model can be considered as average values over the volume of each gridbox, and so the climate model can not provide any information at a spatial scale smaller than one gridbox (so, for example, although it makes sense to talk about the modelled climate of the UK, or Mordor, the model can not give information about Bristol, or Bree). However, in reality there are many processes which occur at a finer spatial scale than that of a single gridbox. As such, models include 'parameterisations' of sub-gridscale processes, such as cloud formation, and small-scale atmo-

spheric turbulence, or eddies in the ocean. It is the representation of these sub-gridscale processes which brings uncertainty into climate modelling (the equations of fluid motion and thermodynamics themselves have been known and understood for several centuries). As well as the atmosphere and ocean, the model includes a representation of the land and ocean surface, including processes associated with sea-ice, soil moisture, and, in our particular version of the model, the growth and distribution of vegetation.

The model is given an initial state of all the variables which it predicts (for example temperature, pressure, wind speed, snow cover, ocean density), and then the model is 'run' forward in time, in steps of typically 10 to 30 minutes. Weather systems develop and evolve, rain falls, the seasons come and go, and years of 'model-time' pass (for my model, one year of model-time typically takes about 2 hours of 'real-time'). Finally, the weather predicted by the model in the final years or decades of the simulation are averaged, resulting in a model-predicted 'climatology' - the climate, or average weather, predicted by the model.

HadCM3L is a relatively complex model, known as a 'General Circulation Model', or GCM. However, it is not a state-of-the-art model, and includes less processes and has fewer gridboxes (*i.e.* runs at lower resolution) than more recent models, such as those used in the most recent IPCC report (IPCC, 2013a). However, it is useful for my purposes, as its relative efficiency of computation means that it can be run for a sufficiently long time to reach an equilibrium, given that the initial state I put the model into may be quite different from the final predicted climate.

3 Experimental design

In this paper I present results from 3 climate model simulations using HadCM3L. The first is a simulation of the Earth during the period prior to large-scale industrialisation (for sake of argument, the period 1800-1850). I call this simulation 'Modern Earth'. The second simulation, 'Dinosaur Earth', is of the period just prior to the extinction of the dinosaurs (the Late Cretaceous, ~65 million years ago), and the third, 'Middle Earth', is of the climate of Middle Earth.

The model setups for these three simulations are very similar. The only important differences are the boundary conditions.

For Modern Earth, I use the standard pre-industrial global boundary conditions, provided by the UK Met Office, which are derived from observations of the modern continental configuration of the Earth, topography, bathymetry, and land-surface characteristics. This simulation uses a CO₂ concentration of 0.28% (280 parts per million, or '280 ppm') of the total atmosphere, a value which is obtained by extracting bubbles of pre-industrial atmosphere from 200-year-old ice below the surface in Antarctica. It is worth noting that 'ice-cores' (long tubes of ice extracted from kilometers into

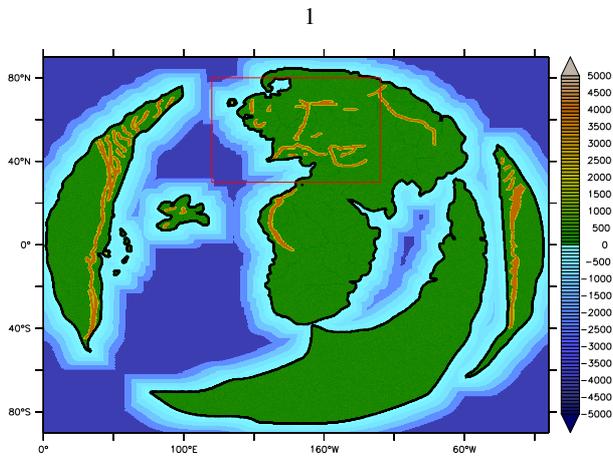


Fig. 1. High resolution map of topography and bathymetry for the ‘Middle Earth’ simulation, shown in units of metres. This world is known as ‘The Second Age of Arda’. The model runs over the whole world, but results are discussed only for the region known as ‘Middle Earth’ (shown with a red rectangle).

the ice) allow us to reconstruct the CO_2 concentration of the Earth back to 800,000 years ago. This shows that during ‘natural’ cycles of CO_2 and climate variation, between ice ages and warmer ‘interglacials’ such as the Earth has been in for the last ~ 6000 years, the CO_2 concentration varies between 180 and 280 ppm. The current CO_2 concentration on Earth is 397 ppm, which is well outside this natural range, a result of the burning of fossil fuels and deforestation by humans.

For Dinosaur Earth, the starting point is a relatively high-resolution (0.5 degrees of latitude by 0.5 degrees of longitude) map of the topography (mountain heights and positions) and bathymetry (ocean depths) of the Late Cretaceous (~ 65 million years ago), provided by the geological consultancy company, Getech (www.getech.com). They specialise in making detailed studies of the scientific literature, taking into account information from fossils, rocks, and ancient deep-sea sediments, in order to reconstruct many aspects of the past state of the Earth, including topography and bathymetry. From this basic topographic map, all necessary boundary conditions were created, at the spatial resolution of the model. As well as the topography and bathymetry, these include several land-surface characteristics such as the soil reflectivity (‘albedo’), the capacity of the soil to hold moisture, and the capacity of the soil and underlying rock to store heat. The land-surface characteristics for Dinosaur Earth were set to constant values over land points, typical of global-average modern values.

For Middle Earth, all the spatially varying boundary conditions are derived from maps and manuscripts from the extensive archives in Rivendell (Tolkien, 1954, 1986; Fonstad, 1991). The starting point is a map of topography and bathymetry, derived from a map of the Northern Hemisphere

during the Second Age of ‘Arda’ (of which Middle Earth is a relatively small region; henceforth, we use ‘Middle Earth’ interchangeably to mean the whole world of Arda, or the region of Arda known as Middle Earth). Considerably more effort could be made to faithfully reproduce the drawings in these manuscripts. Time constraints meant that this was not carried out as fastidiously as was perhaps required (and I had misplaced my spectacles that day...). In addition, there is a degree of uncertainty in the mapping of the original maps onto a spherical world, and it is likely that other equally-valid, or better solutions could be found, which could influence the results. Finally, many of the legends associated with Middle Earth (such as the discovery and final destruction of the One Ring) actually took place in the Third Age - here I assume that the climates of these two Ages were similar.

Each surface gridbox in the model is assigned a height above sea-level, calculated from the average topography within the region of that gridbox. The foothills of mountainous regions were assigned a height above sea-level of 2000 metres, the mountains themselves a height of 4000 metres, rivers a height of 100 metres, and all other continental regions a height of 300 metres. In addition, a small random value was added to the assigned height above sea-level of each surface gridbox, in order to represent small features not drawn in the original maps. The ocean depth was deepened progressively away from the coast, to a maximum depth below sea-level of 4000 metres. A decision had to be made of how to wrap the apparently flat, circular world of Middle Earth onto the sphere required by the climate model. I chose the relatively simple solution of a straightforward direct mapping of the circular Middle Earth onto an equal-latitude/longitude grid. The missing corner regions were set to be oceans. The resulting global map, at a resolution of 0.5 degrees longitude by 0.5 degrees latitude, is shown in Figure 1. I set the initial vegetation distribution to be shrubs everywhere on Middle Earth; this distribution evolved during the simulation (see Figure 4 for the final vegetation distribution in the simulation).

The global topography, at the resolution of the climate model, for all three simulations, is shown in Figure 2.

The Modern Earth simulation was run for more than 1000 years. The Dinosaur Earth simulation was run for ~ 500 years, which allows the surface climate to approach equilibrium. The Middle Earth simulation is likely to be relatively far from equilibrium, having been run for only 70 years.

In the Dinosaur Earth and Middle Earth simulations, the first 50 years of the simulation have a CO_2 concentration of 280 ppm, and the remaining years are at 1120 ppm ($4\times$ pre-industrial levels). The high CO_2 in Middle Earth could be interpreted as accounting for greenhouse gas emissions from Mount Doom.

Finally, it should also be noted that I assume that the radius of the Earth and Middle Earth are the same, that they spin at the same rate and thus have the same day-length, and that they spin in the same direction (from my window here in

Middle Earth I can see the sun setting over the mountains to the west, so this is a valid assumption). Also, I assume that the strength of the sun, combined with the distance from the Sun to the Earth, and the tilt of the Earth on its spin axis, results in an identical amount and seasonal variation of sunlight reaching the top of the atmosphere in Middle Earth as it does in Earth.

4 Results

The model-predicted annual-average temperature, precipitation (rain and snow), and winter wind speed/direction and pressure, in the region of Europe and the North Atlantic (for the Modern Earth and Dinosaur Earth simulations) and Middle Earth, are shown in Figure 3.

4.1 Pre-industrial Simulation, ‘Modern Earth’

The climate of the model of Modern Earth (see Figure 3(a,d,g) for the temperature, precipitation, and winds and pressure) has been compared to recent meteorological observations and to other models in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The model does a good job of simulating many aspects of climate, although compared to more recent models taking part in the latest IPCC report (IPCC, 2013a), its simulation of many aspects of climate is relatively poor. This is not surprising given its relatively low resolution compared to many models, and given recent improvements in the representation of sub-grid scale processes, such as those associated with clouds.

4.2 Late Cretaceous Simulation, ‘Dinosaur Earth’

The temperature, precipitation, and winds/pressure in the Cretaceous simulation is shown in Figures 3(b,e,h). There has been significant continental drift and reshaping of the ocean sea floor and other tectonic change since 65 million years ago, and so the continents in the region of the North Atlantic are only just recognisable. This simulation is just one in a series of simulations that scientists at the University of Bristol have carried out, covering the last 150 million years. There is a project, being led at the University of Bristol, and funded by the Natural Environment Research Council (NERC) to investigate these simulations in more detail, and carry out additional work to understand the confidence in their predictions, and how well they compare with the proxy climate data from the geological record that exists from this time period.

In particular, scientists at Bristol are interested in the relationship between past and future *climate sensitivity*. Climate sensitivity is a measure of how much the Earth warms given an increase in atmospheric CO₂ concentration. Climate sensitivity is a useful parameter to know because it summarises in simple terms the susceptibility of the Earth to global warming. Climate sensitivity is usually defined as

the global average surface temperature increase (in degrees Centigrade) that would occur if the atmospheric CO₂ concentration were doubled, and the Earth ‘equilibrated’ to a new temperature (the Earth may take many centuries or even millennia to fully equilibrate, but most of the warming is likely to occur in the first few decades following the CO₂ doubling). For more information on climate sensitivity, see Section 5.

4.3 Middle Earth Simulation

The temperature over the land of Middle Earth is shown in Figure 3c.

The relationship between temperature and latitude is clear, with the more northerly regions being relatively cold (*e.g.* the annual average temperature is below freezing in the far Northern Kingdom of Forodwaith), and the more southerly regions warm (*e.g.* the annual average temperature is higher than 30°C in Haradwaith). In this respect, to a first approximation, the climate of Middle Earth is similar to that of Western Europe and North Africa. This is unsurprising because I have assumed that Middle Earth is part of a spherical planet (Saruman tells me this is a ridiculous concept); regions near the equator on a spherical planet face directly towards the sun, whereas more poleward regions are tilted at an angle, and therefore receive less sunlight averaged over the year.

Middle Earth, just like Earth, spins on an axis which is tilted relative to the orbit of the Earth around the sun, so the land of Middle Earth also has seasons like the Earth.

High altitude mountainous regions (for example the Misty Mountains) are colder than the surrounding low-lying regions. This is because air temperatures reduce with increasing altitude, as rising air has to give up heat energy in order to expand as it rises.

East of the Misty Mountains, the temperature decreases the further eastwards one travels. This is because, just as in the European regions of the Earth, the further from the ocean the greater the ‘seasonality’ - *i.e.* winters become colder and summers become warmer. But winters cool more than summers warm, and so annual average temperatures in general decrease away from the ocean.

The model-predicted precipitation (rain and snow) over the land of Middle Earth is shown in Figure 3f.

The most striking effect is that the highest precipitation occurs over and to the west of the mountainous regions; *i.e.* there is a ‘rain-shadow’ to the east of the mountainous regions (for example, to the east of the Misty Mountains). This is because the prevailing wind brings moist air from the western oceans onto the continent of Middle Earth. As the air rises over the mountains it cools, causing the moisture it was carrying to condense from vapour into a liquid, to start forming clouds, and eventually fall as rain or snow. On the eastern side of the mountains the air has lost much of its moisture and there is less precipitation.

The regions in the far South of Middle Earth, in southern Mordor and Haradwaith, are very dry. This is because

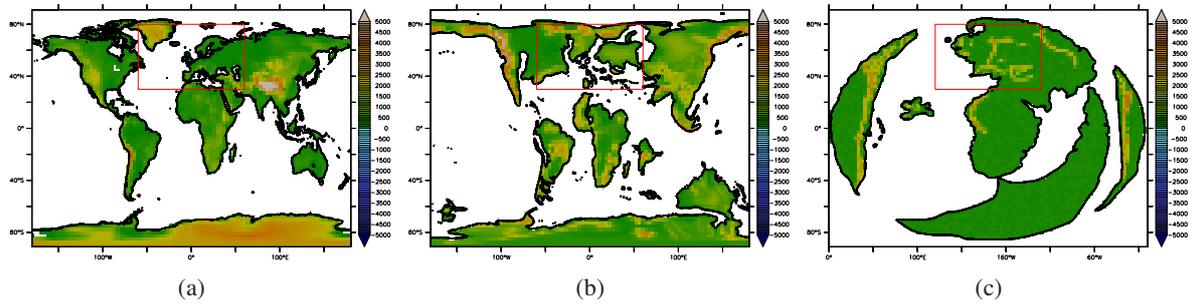


Fig. 2. Model resolution topography (in metres) for the simulations of (a) Modern Earth, (b) Dinosaur Earth, and (c) Middle Earth. The black lines show the outlines of the continents. White regions are ocean. The red rectangles show the position of the regions in Figure 3

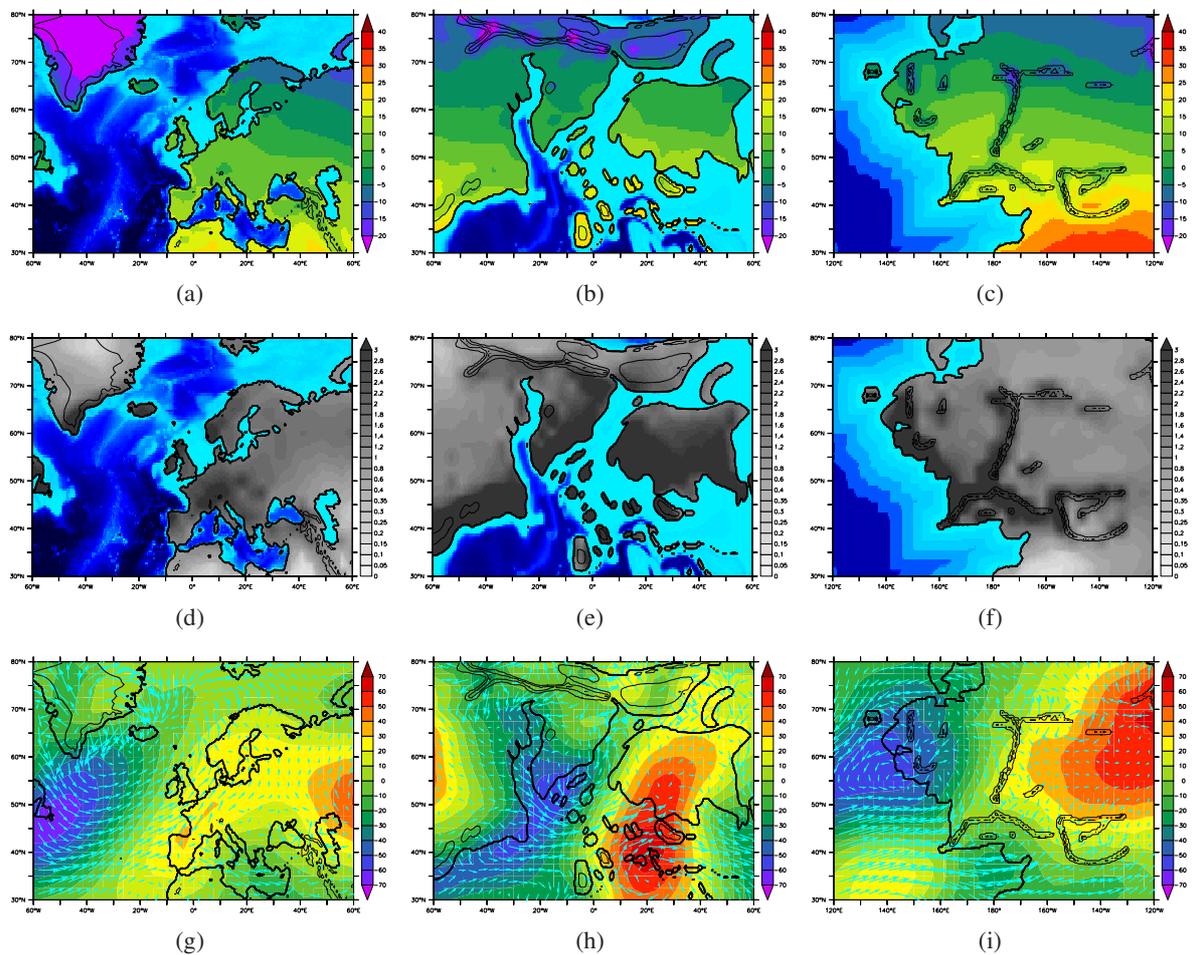


Fig. 3. Contours of annual-average modelled temperature (top, units of $^{\circ}\text{C}$), precipitation (middle, units of mm/day), and surface winds and mid-atmosphere pressure ('geopotential height' at 500 mbar, geopotential height in units of metres) in Western Europe (left), the Cretaceous North Atlantic (middle), and Middle Earth (right). The location of these regions in their respective worlds is shown in Figure 2. The annual-averages are calculated over the final 30 years of the Modern Earth simulation, the final 50 years of the Dinosaur Earth simulation and the final 10 years of the Middle Earth simulation. The different lengths of averaging periods should not greatly affect the results. The thick black lines show the outlines of the continents; thin black lines are contours of topography. In the top and middle plots, the ocean is shown in shades of blue which represent depth.

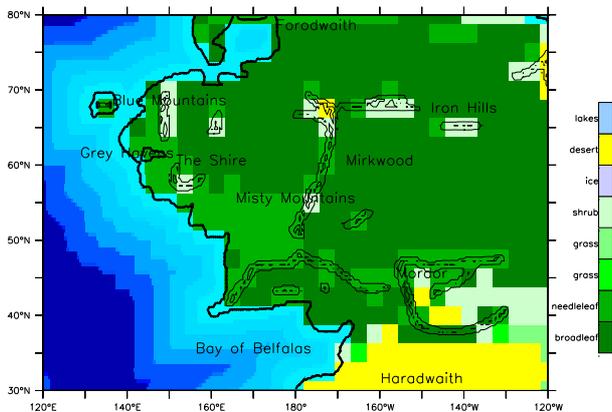


Fig. 4. Model-predicted vegetation for the Middle Earth simulation. The approximate position of places discussed in the text are also shown for reference.

these are ‘subtropical’ regions, similar to the desert region of the Sahara in the Earth. The subtropics are dry because they are in a region where air tends to descend from high altitudes, towards the surface. This is part of a large scale atmospheric circulation called the ‘Hadley Cell’, in which air rises in the equatorial regions, moves away from the equator, and descends again in the subtropics. The descending air suppresses rainfall for the same reason that rising air enhances rainfall - the descending air warms, and can hold more water in vapour form as opposed to liquid form.

The surface windspeed and direction, and mid-atmospheric pressure over the land of Middle Earth is shown in Figure 3i. It can be seen that there are strong westerly (*i.e.* coming from the west, towards the east) winds in the coastal southern regions of Middle Earth, in particular in the Bay of Belfalas. Conversely, there are easterly winds in the north of Middle Earth. This may explain why ships sailing to the Undying lands to the West tended to set sail from the Grey Havens, situated in the region of these easterly winds.

The vegetation component of the model allows us to examine the model-predicted vegetation of Middle Earth. It is important to realise that the vegetation model does not take account of disturbance of vegetation from its ‘natural’ state (such as forest fires caused (inadvertently or otherwise) by dragons, deforestation by dwarves, the growing of pipe-weed by hobbits, or the wanton destruction by orcs). This is the same for the simulation of the Earth, where the model does not take into account the activities of humans in modifying vegetation, such as the deforestation of the Amazon.

The model-predicted vegetation of Middle Earth, shown in Figure 4, depends strongly on the model-predicted rainfall and temperature. As a result, deserts are found in the warm dry regions of the far South, and low-lying shrub is found over much of Mordor. Shrub and cold desert is found on the

peaks of the Misty Mountains and the Iron Hills in the North, and Blue Mountains in the West. Much of the rest of Middle Earth is covered with forests. This is consistent with reports I have heard from Elrond that squirrels could once travel from the region of the Shire all the way to Isengard.

An interesting question in relation to these results is to ask where in the Earth is most like a certain place in Middle Earth. For example, one may be particularly interested in knowing where in the Earth is most like The Shire. The climate model predicts that the annual average temperature of The Shire is 7.0°C, and that the annual rainfall is 61 cm per year. Figure 5(a) shows the regions of the Earth which share this annual-average climate (regions in green have a temperature within 2°C of that of the Shire, regions in blue have a rainfall within 6 cm/year of the Shire, and regions in red are most Shire-like - matching both temperature and rainfall). By this metric, eastern Europe has the greatest concentration of Shire-like climate, in particular Belarus. It is interesting to note that in the UK (Figure 5(b)), the most Shire-like region is centered around Lincolnshire and Leicestershire. In New Zealand (Figure 5(c)), north of Dunedin in the South Island might be considered the ideal location to film a motion picture based in the Shire...

The same question can be asked about Mordor (Figure 5(d,e,f)). Los Angeles and western Texas are notable for being amongst the most Mordor-like regions in the USA, and in Australia, much of New South Wales, as well as Alice Springs, have an annual average climate very similar to that of Mordor.

5 More on the importance of climate sensitivity

The Intergovernmental Panel on Climate Change (IPCC) currently estimate, with ‘high confidence’, that climate sensitivity (the temperature response of the Earth to a doubling of atmospheric CO₂ concentrations, see Section 4.2) is in the range 1.5 to 4.5°C, with values less than 1°C being extremely unlikely. In reality, CO₂ concentrations are increasing over time, not instantaneously doubling, but to put the numbers in context, at current rates of human CO₂ emissions, the Earth could reach a doubling (560 ppm from a baseline of 280 ppm) by the year 2050.

The actual value of climate sensitivity is uncertain, because our climate models are not perfect representations of reality. In particular, the importance of many ‘feedbacks’, which can amplify or decrease the magnitude of climate change, are uncertain, because the processes which govern them are so complex, and involve the interactions of many parts of the whole ‘Earth system’. These interactions involve, for example, the biology of living plants and animals, the chemistry of atmospheric particles, the ice sheets of Greenland and Antarctica, and the complex circulation patterns of the atmosphere and ocean.

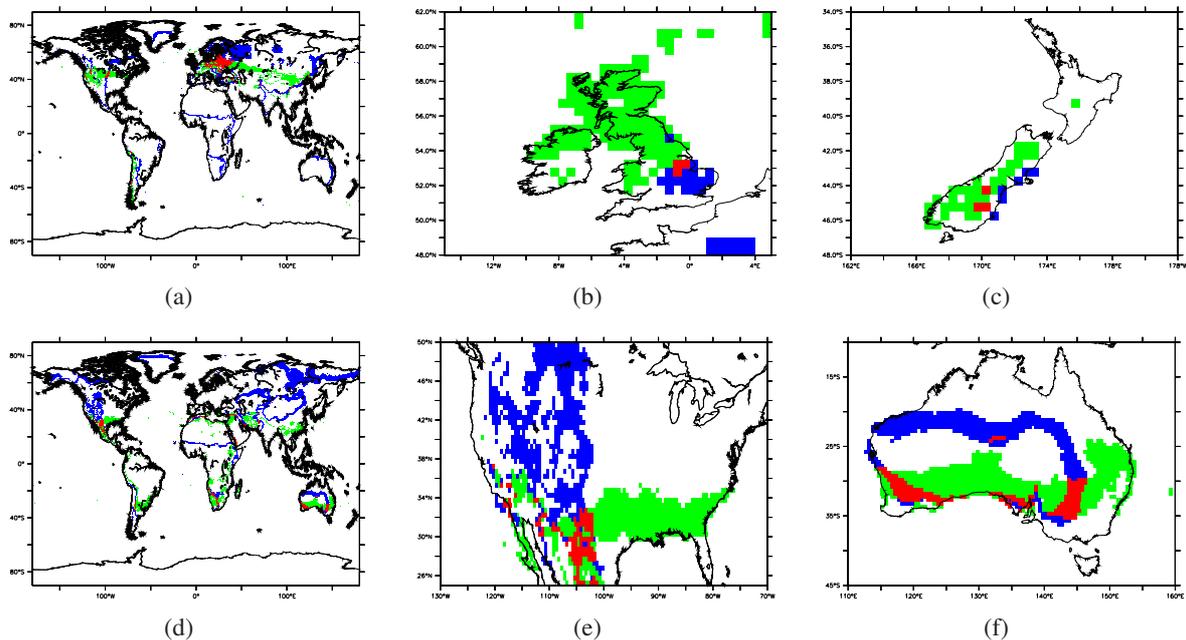


Fig. 5. (a,b,c) Blue regions show where on the Earth is most Shire-like in terms of rainfall; Green regions show where on the Earth is most Shire-like in terms of temperature; and Red regions show where on the Earth is most Shire-like in terms of both temperature and rainfall. (c,d,e) The same as (a,b,c), but for Mordor instead of The Shire.

However, it is possible to obtain information on climate sensitivity from studying past climates. In particular, if past CO_2 concentrations and past temperature changes can be estimated, in theory climate sensitivity can be estimated. Climate scientists at the University of Bristol are aiming to assess the utility of the past climates of the last 150 million years for estimating climate sensitivity. In particular they will investigate how climate sensitivity varies as the continents move, and tectonics change the height and shape of mountains and ocean floors. As well as allowing a better understanding of the workings of the planet that we (well, Earthlings at least!) live on, it will allow them to identify key time periods in which climate sensitivity was likely to be similar to that of modern, and allow new past-climate data to be collected for those time periods.

Knowledge of the value of climate sensitivity, and its associated confidence and uncertainty, can be a starting point for the assessment of the impacts of future climate change, for example the changing risk associated with heatwaves, flooding, droughts, and associated impacts on crops or spread of diseases. This then leads onto the assessment of the costs of climate change, on humanity and on ecosystems and the Earth as a whole, and also leads onto the costs of adapting to climate change (for example the building of flood defences, or migration of populations away from inhospitable regions). This then has to be weighed against the costs (or added to the benefits) of moving to a low-carbon economy and reducing emissions of greenhouse gases such as CO_2 . This whole

assessment process is handled in the Earth by the Intergovernmental Panel on Climate Change (IPCC), who produce reports every 5 years or so on all aspects of this problem (the Interkingdom Panel on Climate Change in Middle Earth was recently disbanded after a fight broke out in the final plenary session and several Coordinating Lead Authors were sadly beheaded). The reports are summarised in a series of very accessible summaries, freely available online IPCC (2013b). These are aimed at policymakers, because ultimately it is the policymakers who make the big decisions about when and how to act, and how to incentivise action by individuals, industry and commerce. Our future is in their hands.

6 Discussion

Here I discuss how the simulations of Middle Earth could be improved. The scientists at Bristol do not intend to make these improvements, but they are worth listing because they demonstrate techniques currently being used to better understand the past and future climate of the Earth.

The regional climate of Middle Earth would be better investigated with a higher resolution, nested or regional model. The gridboxes in these regional models are smaller than in a global model, and so more detail is obtained, and small-scale features of the atmosphere and ocean are better represented.

In this study I have only used one model, HadCM3L. This brings about uncertainties, because this model is only

one of many I could have used, which in general give different results, due to differing representation of key physical processes, in particular those which occur at a spatial scale smaller than one gridbox. There are two approaches commonly used to address this uncertainty: (1) ‘model inter-comparison projects (MIPs)’, and (2) ‘parameter perturbation studies (PPEs)’. MIPs are coordinated studies in which several modelling groups with different models all carry out an identical set of simulations. This allows model-model differences to be investigated. PPEs are similar, but a single model is used, and many simulations are carried out, each with different values of key uncertain parameters in the model. These parameters may be uncertain because there are not enough meteorological or oceanographic observations to properly constrain them, or they may be associated with ‘scaling-up’ small-scale processes to the scale of one gridbox. Both these approaches result in an ‘ensemble’ of results, which allow the uncertainty in our predictions of climate to be assessed.

This work could be developed by assessing the sensitivity of the Middle Earth climate to uncertainties in the applied boundary conditions. In particular, given the undoubted variations in CO₂ due to the nefarious activities of Sauron and Saruman, evaluating the climate sensitivity of Middle Earth would be an interesting exercise. Such activities also manifest themselves in terms of land-use change, and so imposing vegetation distributions from maps found in the libraries of Minas Tirith would also be an important piece of future work.

Climate models on Earth are routinely tested and evaluated by comparing results with the extensive global observational network of weather stations (*e.g.* rain gauges and thermometers) and satellite data. Due to time constraints (I am currently overwhelmed by petty administrative tasks placed on me by the White Council), I have not aimed to evaluate the simulations of Middle Earth with reference to meteorological records, such as the Red Book of Westmarch (known as ‘The Lord of the Rings’ and ‘The Hobbit’ by inhabitants of Earth). In any case, care must be taken if this approach were to be used, because the model results I have presented are climatological - *i.e.* averages over a long period of time, as opposed to instantaneous observations of, perhaps, snowstorms in the Misty Mountains. As discussed in Section 2, the model does predict ‘weather’. However, the modelled weather would very quickly diverge from any real weather because the atmosphere is ‘chaotic’, in that very small differences in prediction rapidly grow to cover the whole of Middle Earth - hence the proverb about the flapping of a butterfly’s wings in the Shire causing a hurricane in Mordor.

7 Conclusions

In this paper, I have presented climate model simulations of three time periods/worlds: The Modern Earth, Dinosaur Earth (~65 million years ago), and Middle Earth. The strengths and weaknesses of climate models have been dis-

cussed and illustrated through the examples. I have discussed the importance of assessing climate sensitivity in the context of current global warming, and highlighted the key role played by the IPCC, and the responsibility placed on policy-makers to act upon the information therein. I have introduced a NERC-funded project which will aim to increase our understanding of climate sensitivity in past climates.

The main findings concerning Middle Earth are that:

- The climate of Middle Earth has a similar distribution to that of Western Europe and North Africa.
- Mordor had an inhospitable climate, even ignoring the effects of Sauron - hot and dry with little vegetation.
- Ships sailing for the Undying Lands in the West set off from the Grey Havens due to the prevailing winds in that region.
- Much of Middle Earth would have been covered in dense forest if the landscape had not been altered by dragons, orcs, wizards *etc.*
- Lincolnshire or Leicestershire in the UK, or near Dunedin in the South Island of New Zealand, have an annual-average climate very similar to that of The Shire.
- Los Angeles and western Texas in the USA, and Alice Springs in Australia, have an annual-average climate very similar to that of Mordor.

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