A Simple Integrated Assessment Model (SIAM)

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PART 1 - Model description

1. Introduction

My aim here is to make the analysis of climate change more broadly accessible so that more of us can discuss and negotiate on the details that often sit hidden within the domain of the 'climate expert'. Experience has led me to conclude that this requires us to understand something of the workings of both the climate system and the economy, and when you start looking you quickly conclude not only does this require a joined up (integrated) modelling perspective, the complexity can become daunting. This complexity often draws us to believe our analysis needs to be similarly complex, and that certainly describes both the direction of travel of the climate-economy analysis community and the fact that the models they work on are often impenetrably complicated. Here I take the opposite view, that this extreme complexity means we are forced to work with simplifications of reality where you deliberately attempt to filter out as much distraction as possible so you can both get clarity and open up debate and discussion.

I find this a humbling endeavour given we know "all models are wrong" as George Box eloquently puts it. But Box also reassures us that some models are "useful", and I sincerely hope you find the wrong model I describe here to be so. After all, even its wrongness will shed some light for us. It is also worth pointing out this wrongness extends to the values we will necessarily weave in to our analysis. Often these will be the values of the economic orthodoxy, not because I too hold to them, I don't, but because we are attempting to understand and describe how things are currently done so that we are in better shape to foster change. I am of the opinion that it is through exposing those assumptions that we get to see where the real drivers of climate change reside and, as a result, where the more powerful prescriptions for avoiding climate change can be found.

There are many ways of viewing the climate change problem and its possible solutions, but the most commonly employed, and arguably the most influential, is through using a tool known as an Integrated Assessment Model (IAM)[1]. IAMs are important in the climate change debate because they attempt to specify economically optimal prescriptions for climate problems, and decision makers like to think their decisions are optimal. Despite their very significant failings, IAMs have become the most politically powerful decision support frameworks currently in play in the climate change space. For example, all the current set of climate scenarios used by the Intergovernmental Panel on Climate Change (IPCC), the Shared Socioeconomic Pathways (SSPs), are constructed using IAMs. Furthermore, the Obama administration used the 'DICE' IAM extensively to inform its policy on climate change[2] and the Stern Report (2006), which precipitated the 2008 UK Climate Act and its net-zero derivative, was based on the PAGE IAM developed in Cambridge by Chris Hope[3]. As a result, given climate

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1 see https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change for a useful introduction

2 Obama B (2017) https://science.sciencemag.org/content/355/6321/126

3 https://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm

change is one of the biggest issues facing contemporary society, the impetus for wanting to know what an IAM is and to appreciate how they work and are used should be obvious. This is my aim.

This is not the first attempt to communicate the detail of an IAM to a wider readership. Nordhaus and Boyer's seminal book, 'Warming the World'[4], is not only one of the first attempts, the Dynamic Integrated Climate-Economy (DICE) model it reports remains a benchmark to this day and earned Nordhaus the 2018 Nobel Prize for Economics. However, despite being classed as a wild oversimplification by today's IAM standards, unfortunately DICE and its relatives are still too complicated to be communicable to a wider non-economic audience. Perhaps this suggests the field is best left alone to the 'experts' as some argue (Tol, n.d)? I don't buy this. Not only do I believe it is important to try and lay bare some of the entrails of IAMs, I also believe it is possible to do this in such a way that is scientifically defensible. The trick will be to know where and how to take the necessary shortcuts, with a view to making the analysis as simple as possible, but no simpler. It often feels like in doing so I'm rowing in the opposite direction to everyone else given they appear to want to make their IAMs look more and more like the leviathan they are attempting to depict. For me that path leads only to perplexity.

In taking this journey hopefully the learning will be three-fold. First, and most important, I want you to gain some insight into the growth dynamics of the global economy and what determines this. Only when we appreciate this can we start to conceive of credible ways of addressing this central issue. Related to this, I want you to appreciate the temporal/intergenerational nature of the climate change problem and how current investment practices fail to address this. Secondly, I hope that in being able to develop and use an IAM you will understand something of the possible trade-offs that are thought to be important when deciding to exploit energy sources such as fossil fuels. It is undeniable that fossil fuels have done a lot of good for society, as well as a lot of bad, and so we must necessarily appreciate some of the important trade-offs in their future use. Finally, because you get to experience the process of IAM construction from the ground up you should feel empowered to engage in meaningful debate with anyone on interesting and important issues from across the climate change spectrum, ranging from orthodox economists at one extreme, through engineers, climate scientists and policy makers, and finally the unorthodox economists and sustainability scientists straddling this spectrum and the activists seeking system change.

The approach I have taken when writing this up parallels Nordhaus and Boyer in that it is really a tutorial in IAM construction in Excel. I am not a big fan of Excel, but it is a modelling lingua franca and the aim has to be to reach the widest possible audience. I am a fan of leading people through the actual model building though, rather than simply providing a handbook that describes how to press buttons within a finished product. This is because, like so many things, the deep learning is in the assembly process much more than it is in the end-use. Please do not be put off by the idea of constructing your own IAM. I have led many who would self-identify as modelling/math-phobes through a range of model building exercises in Excel. They invariably declare fear and trepidation from the outset when stood at the bottom of the mountain, but all invariably make it to the summit if they want to and appreciate both the journey and view from the top. The model itself is about as simple as you can possibly

4 http://www.econ.yale.edu/~nordhaus/homepage/homepage/documents/DICE_Manual_100413r1.pdf

conceive in this space (hence the name Simple Integrated Assessment Model - SIAM) whilst retaining some theoretical and empirical credibility, and we will take small steps. The aim is to educate and illuminate, not to obscure and confuse. That said, as with all mountain climbing, in addition to having the right equipment it requires some application. The climbing will also get progressively harder as your fitness and skill improve.

For those who do not wish to climb the mountain but would rather enjoy the view from some other vantage point, then I'm hoping this will still be an interesting read where you get to peer into the economic modellers mindset. I'm also hoping you will engage with the issues that strike at the very core of the current economic calculus and how it rubs up against the the climate change problem. I have tried to make your reading richer by flagging what I believe are relevant and interesting background issues that have led to the evolution of certain components of IAMs. Often this has involved some detours off into narratives where I am not expert and I apologies in advance for my ignorance. I also do not fully acknowledge all the shoulders I stand my construction on simply because there are too many, which I also apologies for.

2. What is Integrated Assessment?

The roots of IAMs can be traced back to at least the MIT World3 model that was used as the basis for the ground breaking and highly influential Limits to Growth book of Meadows et al., (1972)[5]. World3 was the forerunner of using global scale models to alert society to the risks of over exploitation of environmental resources and carrying capacities, a tradition on which IAMs are built. IAMs provide a means of exploring how one might think about trading the economic and social benefits of using fossil fuels (or other activities having a climate impact) against the net loss this use imposes on current and future generations through the effects of climate change. This is done by combining two different modelling paradigms, macro-economics and climate systems, to form an integrated climate-society system view.

The structure of IAMs is simple. The economy with its inputs and outputs interacts with the climate with its inputs and outputs via a climate-society feedback (see Figure 1). What Nordhaus did which was different to the World3 framework was to ask the following question: If using fossil fuels is both good and bad, how much fossil fuel should we use and when in order to get the trade-off of these goods and bads 'right'? Nordhaus is an orthodox economist working at Yale and so it is no surprise he frames this as an orthodox macroeconomic problem, where 'right' is defined as maximising consumption over some time frame. The framework implies a rational central planner attempting to judge what is best at the global scale for all concerned, controlling things through a carbon tax. I am not expecting you to agree with this framing, I certainly don't. The important thing is that you understand this framing so that you can critique its strengths and weaknesses and offer alternatives where necessary. We will certainly be trying to do that, in addition to developing some of those alternatives.

5 Meadows D, Meadows D, Randers J, and Behrens W. (1972) Limits to Growth. New York Universe Books

3. The Simple Integrated Assessment Model (SIAM)

Recent developments in the field have meant that we can specify a 'credible' simple IAM (let's call it the Simple Integrated Assessment Model - SIAM) at a level of detail that can be described and implemented in Excel in a small number of clear steps. In Part 1 we will lay out the model description, while Part 2 walks you through the construction process step-by-step with the aim that you follow this recipe in order to construct and run your own IAM. Once built, we will explore a Business-As-Usual (BAU), a decarbonisation and an adaptation scenario, but if you want to skip this building process and play with the finished product, this is available here[6].

Our analysis will necessarily be global for two reasons. Firstly, the climate system receiving greenhouse gas emissions has no regard for nation or individual given the atmosphere is so well mixed. Secondly, it is safe to say the global economy is the definition of a complex system, where the link between the actions of individuals, or even nation states, does not readily map to the behaviour at the global scale. Instead this behaviour is dominated by emergent phenomena arising from the network interactions of the now ~8 billion[7] agents within the global economy. Here again we depart from the economic orthodoxy, which appears obsessed with attempting to derive the marco from the micro.

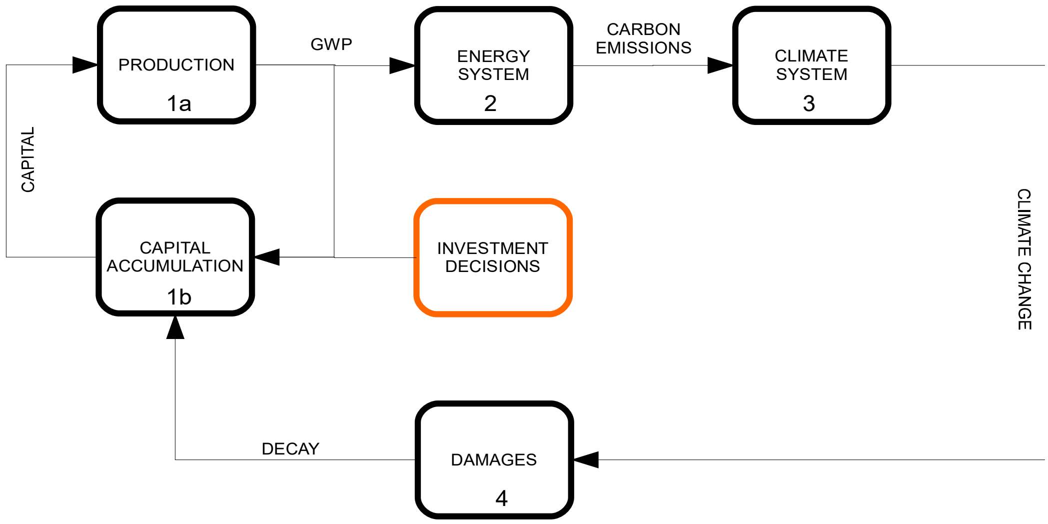

Figure 1. A schematic of the Simple Integrated Assessment Model (SIAM). Numbers denote which equations apply in the accompanying text below.

The key to not losing yourself in the detail of what follows is to have a map in mind as you work your way through the various steps. Study Figure 1 carefully and try and memorize its

6 https://www.lancaster.ac.uk/staff/bsaajj/SIAM.html

7 Throughout I will try and round numbers and use approximations in order to simplify the analysis still further. These approximations are carefully chosen in an attempt to not sacrifice accuracy unduly, whilst at the same time acknowledging how the considerable uncertainties we face in our analysis impact on the precision with which we can use quantities.

components and how they are arranged and connected relative to one another. Hopefully this should largely parallel your thinking if you are familiar with climate change. You should then be able to see where the specific components plug into this overall framework as you go. Maths is a necessary evil in this operation because we need to translate our conceptual pictures of the world into operational models that we can use to get the numbers out we need to put things like the Paris Agreement into context. I have made every effort to make this aspect as simple, transparent and accessible as possible, again with a view to widening access to these important concepts. You won't have to do any maths, just don't be put off when you see some, and believe you have the ability to translate it into Excel, which you do. Each step is itself relatively straightforward and you do not need to get the maths to be able to get what is going on in that step, although it does help. What is confusing here will be that there is a number of steps and that they are arranged in a feedback loop. This is why it is valuable having the map in Figure 1 in view throughout.

By way of warning Sections 3.1 to 3.4 provide an account of the global economy that parallels some elements of orthodox economic thinking. As I have said already, I think it is important you see this both because elements of that account provide a useful description of the status quo and hence why climate change is a wicked problem, and because I think it is useful to try and understand the economists mindset given they have the ear of power. That said, the orthodox economist would, in all likelihood, take great offence over my account of the global economy given it is so simple. They would also probably be offended by my drawing on a field know as ecological economics, which views the economy as a metabolic process akin to a biologists view of energy flows in the body or an ecologists in an ecosystem. Although an unfamiliar economic account, I am hoping that the body metaphor proves useful in helping you see through the complexities of the economy. So forgive me dwelling here a while, I believe it is necessary to create common understanding before drawing from this to develop prescriptions for the climate change problem. In contrast, the account of the climate system that follows this will be a walk in the park.

3.1 Metabolism

Because you are familiar with money as an economic measure I want to base SIAM in monetary units both to make it accessible and to allow you to draw the necessary parallels with wider discussions on climate change. However, this approach is problematic because the economics associated with a monetised view has a somewhat ethereal quality that I find particularly opaque. Furthermore, at their core IAMs describe the way energy is used in the global economy. The reason for this focus is because it is this energy use that is driving greenhouse gas emissions, either directly or indirectly, and these in turn drive the changes in climate that feedback and affect the economy (see Figure 1). To me these two observations suggest we would be better off recasting our economics as metabolism, adopting the mindset of the ecological economist. What this also affords us is biology and the body as a metaphor for the global economy, something I am hoping you feel more comfortable and familiar with. This is not a slight of hand. Orthodox economics missed a trick when it ignored the parallels between the behaviour of economic and biological systems, parallels that run deep and true given the thermodynamic roots underpinning both behaviours[8]. I certainly believe had

8 There is a large and developing literature on this but perhaps it is best to point you at possibly the most seminal work to date - Georgescu-Roegen, N (1971) The Entropy Law and the Economic Process.

economics aligned itself with biology rather than physics as a discipline we would have been in a far better position to accommodate the deep complexities economic systems present to us.

Your body is a very useful device when thinking about the economy because both bodies and economies are bewilderingly complex and yet share fundamental reliance on processing energy to maintain form and function. Your body takes in about 2000 kcal per day from the environment as food to satisfy your average power demand of around 100 W. The global economy takes in around 3.3×10^{14} kcal per day from its environment as primary energy to satisfy its current average power demand of around 20 TW (terra Watts). Given there are ~8 billion people on the planet, global per capita primary energy consumption is currently $(20 \times 10^{12})/(8 \times 10^{9}) = 2.5$ kW per person, although clearly this is very very unequally distributed. So, on average, we each consume 25 times more primary energy than we do food energy. Currently, ~80 % of this global primary energy use is derived from fossil fuels.

If this primary energy flow parallels the flow of food from the environment into your body via your mouth which is used to maintain you, then your body is your capital infrastructure both demanding this flow, being used to capture this flow, and being created through the incremental embodiment of some fraction of this flow of food into your soft and hard tissues. This parallels the capital creation and production processes we explore for the global economy in Sections 3.2 and 3.3. What doesn't get invested in making tissue is consumed in the running of those tissues, just like a significant proportion of global primary energy is taken up simply to run the global economy. The left over fraction is what we might call 'useful' energy[9], and I will assume this is what is being measured by GDP (see Section 3.2).

Your body is made up of ~30 trillion microscopic cells and yet you are comfortable backgrounding that detail when thinking about the macroscopic behaviour of your body. Similarly our account of the global economy will be monolithic and body-like, not because we don't care about it's individual members, but because the global economy is body-like and lends itself to a macroscopic analysis. So, just as the energy use of your cells vary by many orders of magnitude, so through huge inequalities, do the individuals in the global economy and it is our job to not loose sight of the individual and their diversity. This aggregation is not unique to our account of the economy. We will also only describe the global mean behaviour of the climate system. Again, let's not loose sight of the diversity of climate behaviour behind that global average too.

We will revisit this metaphor periodically, especially when thinking about growth, but there is one other feature of the body that is relevant here. All parts make up the whole, and it is wrong to view these parts as falling neatly into 'useful' and 'not useful' roles as is commonly done in energy economics; they all form an integrated whole which we call 'the body'. Although this sounds obvious when applied to the body, this is not how we have tended to view society. Traditionally we see human and non-human elements as distinct and separate. We also traditionally see different non-human parts as falling into similar classes. For example, the energy system is essentially seen as providing a service, with that service being useful, but the systems giving rise to the service as somehow an undesirable inefficiency. I

9 We will use the term 'useful' a lot as it is common in ecological and energy economics and derives from the engineers notion of work, but I appreciate it is a loaded one when discussing GDP. For example, GDP includes the revenue stream associated arms manufacturing, which is difficult to label 'useful' unless you see defence as an essential element of an economy or society.

argue this is simply wrong-headed and, like the body, we need to view all components of society as wildly interconnected such that they form an integrated whole, albeit a very unequal one.

If GDP 'measures' useful work[10], albeit imperfectly like most measurements, then we can weave waste into our story too because this relates to the portion of the primary energy use that is used but does not lead to anything useful. This is easy to conceive of as things like the steam pouring out of a cooling tower or the warmth of the brakes on a car. The growing use of Sankey diagrams nicely articulates this view[11]. Finally, every time we see energy flows we necessarily mustn't lose sight of the parallel flows of matter and information.

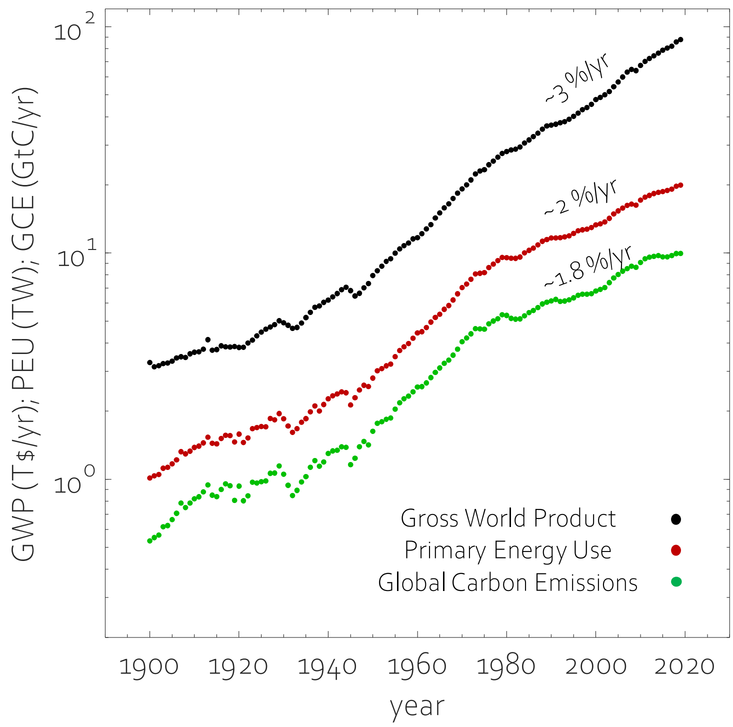

Figure 2. The evolution of Gross World Product (GWP), Primary Energy Use (PEU) and Global Carbon Emissions (CGE) 1900 - 2019. GWP and PEU are aggregates of 8 constant dollar and 4 thermal equivalent estimates compiled by Jarvis and King[12]. The CGE estimates are from the Global Carbon Project[13]. The estimated relative growth rates apply from 1980.

10 In Section 3.3 we will argue that what is useful is the creation of productive structure, something the economist calls capital.

11 http://www.sankey-diagrams.com

12 https://esd.copernicus.org/preprints/esd-2020-59/esd-2020-59.pdf

13 https://data.icos-cp.eu/licence_accept?ids=%5B%22xUUehljs1oTazlGlmigAhvfe%22%5D

3.2. Production

Given SIAM is circular (because of the feedback relationship between climate and society – see Figure 1) we can start anywhere in the loop when describing the economy-climate system. I have elected to start where most macro-economists would, with 'production', and specifically with what is traditionally referred to as the 'production function' (see box 1a in Figure 1). This is how annual flows like GDP (or its global counterpart Gross World Product, GWP) are 'produced'[14]. The orthodox view of production is where the flow of GDP depends on 'factors of production', most commonly conceived as technology, labour and capital. This appears set to change as the World Bank are now favouring a different perspective centred on labour being viewed as capital[15]. Immediately you can see these are not politically neutral positions as it is about how we represent people in our analysis and not surprisingly this has been a battleground for some of the great economic thinkers including Adam Smith and Karl Marx. I am going to go with the idea that people are capital because it provides far clearer and more accessible picture of the economics, is supported by data, and aligns with an ecological economics view of the world which I find useful when navigating the complexities. In previous iterations of this story I attempted to unpack both the difference between human capital and labour and why labour took hold of the orthodox view of production. I've since realised that really deserves a book to do the subject justice and hence have avoided that detour this time around. That said, we will revisit the significance of viewing people as capital at various points. It's a sometimes more liberating perspective than the name might imply, although it always begs questions over the investors ownership of that capital.

Having subsumed people into human capital our factors of production are now simply capital (both human made and humans) and 'technology', although we will not treat these as separate as we are about to see. To try and help you understand this framing I want to rethink what capital is because the orthodox view is far too slippery. I encourage you to view capital as complex intertwined networks of material objects, including people, structured in very particular and ingenious ways to process efficient flows of matter, energy and information. In this framing, a more accurate label for capital is 'productive structure' and I will use this term interchangeably with capital here on. Ecologists and biologists refer to productive structure as form and function, and this view of capital and production again aligns with that of the ecological economist. Here technology is any particular configuration of a network of productive structures and the subsequent efficiency that configuration confers on the ability of the whole to process flows of matter, energy and information. Those flows are valuable given they sustain the system, so it is not surprising that productive structures and hence capital are valued. Hopefully the biological parallels are becoming obvious. This framing allows us to link the economy directly to its energy use and hence CO_2 emissions in Section 3.6.

Having decided it is capital and its technological configuration that is doing the producing, it is useful to now reflect on what is being 'produced', which invariably is taken as GDP. There has

14 A group of economists called the post-Keynesian object to this 'supply' view of the economy, preferring to see it as the economy demanding something. The ecological economist is comfortable either way of seeing it given the networks supply what the cells demand. The issue really being raised by the post-Keynesian's is what is debt in the real world? Let's mark that up for discussion later.

15 https://openknowledge.worldbank.org/handle/10986/29001

been considerable backlash against GDP of late and understandably so given it in no way attempts to measure 'good' things[16]. As the analysis develops I will flag where I believe values come in and shape the direction we might want the economy to take, but I don't think this should be in how we measure the output of the economy. With our ecological economist hats on we should endeavour to keep such measures as objective as possible. Having tried to cast capital as productive structure, I want to also cast GDP as something physical and specifically the flow of what a physicist or engineer might call useful work[17]. This derives directly from the supply of primary energy to the economy (see Figure 2) and the efficiency of economic structures at translating this primary energy into useful work.

We will go into more detail on what this useful work does in Section 3.3 when we look at how productive structures are made and maintained, but first let's look at the conversion between the flow of money and the flow of useful work or power. I estimated that currently the global economy is about 5 % efficient at translating primary energy into useful work[18]. If so, each Joule of useful work done by the economy is equivalent to $(80 \times 10^{12})/(0.05 \times 500 \times 10^{18}) = 3.2 \times 10^{-6}$ dollars of value. So one dollar is equivalent to $1/3.2 \simeq 300$ kJ of useful work, and if the global economy was powered exclusively by human muscle power, a labourer would produce a little over one dollar of GWP per hour[19].

With technology and capital as the factors of the production and GDP as what is being usefully produced we are led to the AK model of production[20]. Here K is total capital (in our view produced, human and natural) while A represents the 'productivity' of this capital. By productivity we mean a measure of the efficiency of capital structures at harvesting primary energy from the environment and translating it into useful work, although that certainly is not how an orthodox economist would see it. The AK view of production was rejected by economists because it proved unable to successfully accommodate labour. Seeing labour as human capital in the vast web of productive structure comprising the economy helps resolve this and the latest available data for global GDP and total capital shown in Figure 3 appear to support our choice of the AK model.

So if y is the annual flow global GDP (or GWP, or something akin to useful work), then we

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16 see O'Neill DW, Fanning AL, Lamb WF and Steinberger JK (2018) A good life for all within planetary boundaries. Nature Sustainability, 1, 88–95

17 see Ayres W and Warr B (2010) The economic growth engine: how energy and work drive material prosperity. Edward Elgar.

18 Jarvis AJ (2018). Energy returns and the long-run growth of industrial society. Ecological Economics, 146:722-729.

19 People can sustain about 100 Watts of power output over the working day through their muscles. So if one dollar is equivalent to 300×10^3 J then it would take $300 \times 10^3/100/60 = 50$ minutes to output one dollars worth of useful work. That people earn much more than this reflects the fact they can use their energy wisely, and, more importantly, can use other machines to exploit other energy sources than food too.

20 This was originally proposed by Harrod and Dolmar over 70 years ago, although their view of production did include labour as a possible limiting factor, but reduced to the AK view of production when capital was a limiting.

simply relate this to capital K and productivity A,

$$y = AK \qquad (1a).$$

Figure 3 indicates global productivity has increased marginally over the last two decades, but we will initially treat this as a detail because nothing is ever truly constant, especially when we consider complex evolutionary beasts like the global economy. Our AK view of production is certainly a lot less messy than the Cobb-Douglas view of production most commonly employed in IAMs, and will make our subsequent analysis of economic growth in Section 3.4 far more transparent.

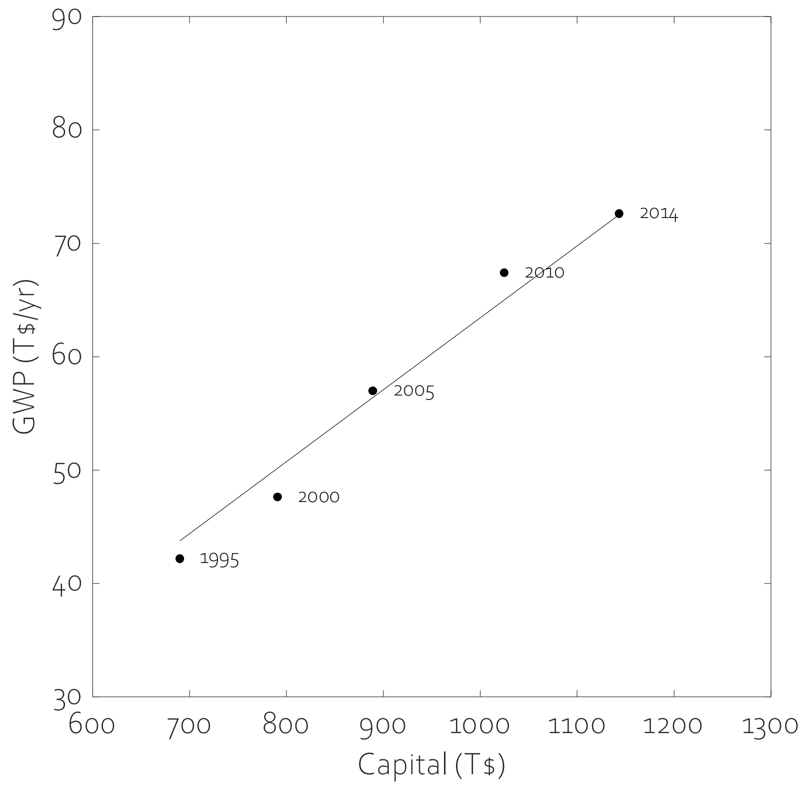

Figure 3. The relationship between World Bank estimates of total capital wealth[21] (K; produced + human + natural) and Gross World Product (y) 1990 - 2014 from Figure 2. Line is given by $y = 0.06K$.

3.3 Capital

So far we have described how GWP is 'produced' by the productive structures we call capital. That description required us knowing how big the accumulated stock of total capital, K, is. We create these structures through investing GWP to do the necessary useful work of productive structure making. It takes work to create these structures because you have to collect all the necessary materials together (the work of moving things) and then bake them into the appropriate configuration (the work of connecting and fixing), even if the structures are

21 https://datacatalog.worldbank.org/dataset/wealth-accounting

somewhat fluid. These structures can also feel somewhat ethereal simply because they contain far more information than they do materials, like the internet for example. However, this doesn't change the fact that vast quantities of useful energy are still being expended in creating these structures and significantly more primary energy is needed to provide this useful energy because the structures are never 100 % efficient at the conversion.

Like everything in the universe, once made structures will immediately start falling apart or decaying. Economist call that depreciation. Put simply, the increase (or decrease) in the total amount of capital, K, is the difference between investment of useful work (GWP) making productive structure and the inevitable effects of wear and tear, death, destruction and the related end-of-life decommissioning of 'stuff'. As a result, the accumulation of the stock of the capital of the global economy can be described by the balance between these creation and destruction processes.

We can state this balance in words as follows. The amount of capital we have this year is the amount we had last year, plus whatever additional capital we made from investing last years GWP to do the work of making more productive structure, minus any capital we lost last year through depreciation of the stock of last years capital. Let t be in annual time steps such that if t is 2020 then t - 1 = 2019, then the balance we have just described is given by,

$$K(t)=K(t-1)+iy(t-1)-dK(t-1) \qquad \text{(1b).}$$

Study this and you will quickly see it simply reflects the capital balance articulated in words above if we remember y is GWP and parallels the rate at which productive structure or capital is created through useful work. i is the portion of GWP that is invested in the capital creation process each year and d is the representative decay rate of all productive structures.

We could stop here and, as if by magic, simply offer 'suitable' values for i and d to use in our framework as would be the norm in IAM construction. However, there are some things we need to appreciate about investment and depreciation that have profound implications for both our understanding of the global economy, peoples relationship with it, and climate change. I want to start with depreciation and strongly encourage you to dwell here until you absorbed this as it bares heavily on everything that follows. We will discuss the value of i in Section 3.4 when looking at growth.

d has units of per year, so its inverse has units of years and hence $1/d$ is a timescale. Specifically, it can be seen as the average time a piece of representative capital resides in the pool of total capital. This is the expected or average design lifetime of capital and the reason why it is important to know its value is because it determines how quickly we can loose 'high-carbon' capital and replace it with its 'low-carbon' counterpart. In other words, it measures the inertia of the economy, which forms a critical component of the simulations we will look at later and, more importantly, how much of our current high carbon investments we would need to smash up and abandon if we want to meet the terms of the Paris Agreement.

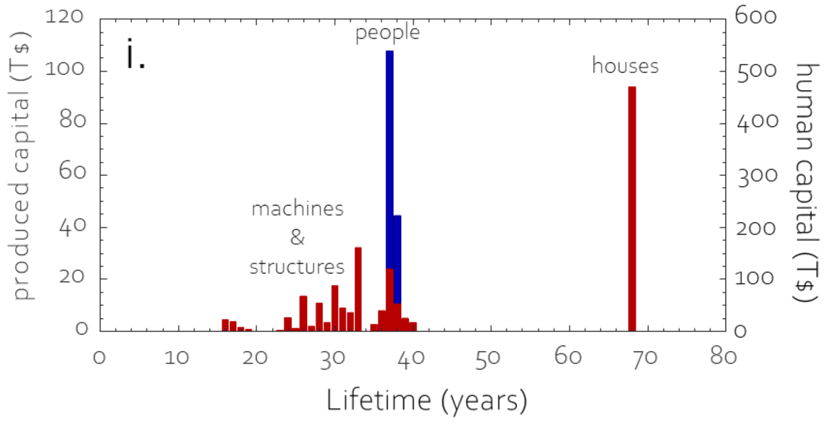

Figure 4. The relationship between capital value and turnover timescale for a 56 sector view of the global economy.

So what value should d take? People tend to think that modern society is characterised by ever more short-lived stuff. However, this view is biased by the fact that, in an exponentially growing system like the economy, the amount of new stuff always dominates, even if most of it goes on to live a long time. We also forget about the long-lived stuff too quickly even though it is part of everyday life (think bridges, roads, tunnels). A review of the IAM models out there would indicate d sits somewhere in the range 2 to 5 %/yr, suggesting a representative survival time for capital somewhere in the range of 20 to 50 years. Figure 4 shows how capital is distributed across timescales for the global economy. This confirms what we experience, that productive structures 'live' for a broad range of timescales. It also shows us that the average timescale is approximately 35 years and is dominated by human capital and hence the expected working lifetime of people. It is no accident that the two coincide because this highlights that current investment practices of people centre on making things that provide returns on investment within their working lifetime. Let's call this behaviour me-terialism, because it represents the individual working to invest in physical structures expecting the returns from these structures for themselves. In Part 2 we explore why this is a road block to sorting the climate change problem given 35 years is simply not a long enough perspective to fully embrace the downsides of climate change. This will lead us to the need to embrace some degree of we-terialsm in our investment practices, so look out for that in Part 2.

Capital turnover also tells us a lot about the risks of trying to change the economy too quickly. For example, if you had to change to a zero carbon economy in say 20 years in line with a 2040 net-zero objective and yet the economy can only evolve on a 35 year timescale, something has to fall off the lorry so to speak to allow it to go round the imposed 20 year bend. We will also explore this in Part 2 as it relates to the stranded asset problem[22].

It is vital to gain an appreciation of what equation (1b) is attempting to represent. If the fabric of the economy is being produced faster than it is decaying then $iy(t) > dK(t)$ and the capital stock and hence the economy is growing. Whereas if capital is decaying faster than it is being

22 Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. Nature Climate Change. https://doi.org/10.1038/s41558-018-0182-1

created then $iy(t) < dK(t)$ and the economy is shrinking. This is a critical aspect of the analysis that follows because we will assume that, prior to climate change becoming significant, $iy(t)$ is 3 % bigger than $dK(t)$ i.e. the economy is growing at 3 %/yr as it has approximately done for a long time now. However, as the climate changes the economy will experience ever increasing climate damages expressed through increases in the decay rate of infrastructure, d, so that ultimately $y(t) < dK(t)$ and the economy shrinks and dies if climate change is not addressed! We unpack this in more detail in Section 3.6 and PART 2.

Before moving on it is important to realise that the combination of the production function (equations (1a) or similar) and the capital balance (equation (1b) or similar) is the beating heart of orthodox economic growth models. Therefore, if you want to understand where the orthodoxy and its growth agenda is coming from, I strongly recommend you familiarise yourself with these two concepts and their feedback interaction. Simply put, capital liberates production[23] and production is invested to create capital, and so on and so on… It turns out it is no different for your body mass, or the growth of a forest, or the development of a river network. This is how things grow, or stop growing, or shrink and die, which leads nicely onto a consideration of growth.

3.4 Growth

You would have thought that because growth is so central to the wider economic discourse it would be the central focus of the orthodox tradition's analysis of the economy. Ironically it is not. Yes, the orthodoxy writes a lot about growth, but for them growth is a bi-product of the thing they think is more important to focus on, which is solving the age old problem of working out how much *you* consume now verses how much *you* save and invest to secure things *you* can consume in the future. Borrowing from microeconomics, this gives rise to the rational actor, a mythical person optimising their investment decisions in order to maximise *their* time discounted consumption. It would be interesting to dwell here a while and detour off into the historical roots of this view of human behaviour because it has had such a profound effect on shaping modern society. For now perhaps you might want to start your own research with googling Bernard Mandeville and tracing this philosophy through Leonhard Euler, Adam Smith and ultimately to Frank Ramsey's[24] seminal paper in 1928 which provides much of the foundation for the rational maximiser perspective in the present-day orthodox tradition.

The rational maximiser is a fiction. People, however clever and far sighted, can never predict how their investments will perform, so this type of behaviour is impossible to enact in the real world, even though it is mathematically elegant (though morally bankrupt). However, a good proportion of people do appear to be me-terialistic and I argue that fixating on growth of the

23 There is a school of economics called the post-Keynesian who abide the notion of a supply limited economy and instead would rather see it being demand led. Although there are very important methodological differences that flow from these differing perspectives, these are detail to the ecological economist easily reconciled by noting flows require both supply and demand potentials to drive them.

24 I recently discovered that, in addition to being a genius, Ramsey was somewhat of a left of centre radical, which is ironic given his most famous contribution to economics is foundational to the political right's view of and prescription for the economy.

macroeconomy substitutes for the rational maximiser myth in the current me-terialist system we experience. This is why growth, recession and bubbles are the stuff of the public discourse on the economy. We don't even discuss GDP, but rather its growth rate. For example, you are very unlikely to know how big global or national GDP is, yet you are much more likely to be able to say what their growth rates are or were.

However we view growth, it is a reality that has such profound effects on shaping the current climate change problem (and many other global issues) it must be a central component of our analysis, even if we intended to row away from it as an objective in the future. Not only does this allow us to explore the consequences of business-as-usual (BAU) behaviours, it also allows us to explore radical alternatives like degrowth, and everything in between, as we will in Part 2. So let's start by defining the relative growth rate, r, using equations 1a and 1b. It turns out because equation 1a an 1b are so simple it doesn't matter whether we look at either GWP or capital, so lets look at GWP given this is what we currently choose to measure and talk about so much. We get

$$r \simeq iA - d \qquad \text{(1c)}$$ [25].

Although growth rates can vary wildly year on year both nationally and globally reflecting the booms and busts we have become so familiar with, for as far back as we have decent data on GDP the global economy has grown at around 3 %/yr (Figure 2). I think this is the most important fact about the economy to have in view, not only because of the impacts of growth on people and the planet, but also because of what it tells you about human behaviour. Like the depreciation rate d, the relative growth rate is an inverse timescale and 3 %/yr equates to a timescale of 33 years i.e. very close to that of the turnover timescale of capital itself. This suggests we design capital to live (and die) at the same rate as the economy grows on average and I would argue this is is no accident.

Growth requires innovation and innovation requires replacing old less efficient productive structures with new ones. But you can't replace them too fast otherwise they never become profitable. Instead you have to replace them at just the right rate to counter the considerable downsides of growth. These downsides stem from the obvious fact that as all systems grow in size, the cost of distributing resources within them necessarily increases as everything tends to get further apart. This effect is what ultimately halts growth in our bodies and hence limits our size. Economies invest heavily on innovation to overcome this effect. Finally, the growth rate itself is reflecting that people are making investments of useful work over working lifetimes, expecting returns over these lifetimes to flow back to themselves, hence the tie up between working lifetimes, growth timescales and capital turnover timescales. Where this view agrees with the orthodoxy is that it too acknowledges that the current economic order is me-terialist given investments are me-focused rather than we-focused.

If $r \simeq 3$ %/yr, $d \simeq 3$ %/yr and, from Figure 3, $A \simeq 6$ %/yr, then from equation (1c) $i \simeq 1.0$ i.e. all of GWP is being invested in capital creation. That is more than four times higher than the orthodoxy currently believes is the case. This difference stems from having represented people as human capital[26], which from Figure 4 we can see is approximately three times larger than the capital invested in 'stuff' (produced capital). So a lot of what is called 'consumption'

25 The approximate symbol is important here because significant changes in i and A make things a little more complicated. Fortunately we won't have to worry about that.

by the orthodoxy is actually investments people make in themselves. This is a critical observation because it means people are no longer largely passive consumers attempting to maximise this consumption as the orthodoxy would have you believe, but rather they are habitual investors, even if they are able to only invest in the food that takes them from one day to the next.

The fraction of income allocated to transport becomes an interesting lens through which to view this investment take on consumption. You probably view transport as consumption, whereas an alternative view of transport is that it is the rearrangement of objects into spatially less likely but more productive configurations. That is, by definition, the creation of structure, even if this structure feels incredibly transient, and it is not surprising in hindsight that this activity both occurs on and reinforces the development of hierarchical networks just as it does in nature[27]. This transport activity involves dissipating energy as the economy does the useful work of moving things into these less likely configurations and this is why transport is so valuable. Perhaps that is also what we are enjoying when we travel, the shifting away from randomness. Hopefully that opens up a discussion for you as a minimum. It certainly links to the discipline of economic geography.

To conclude, I am going to argue there is no consumption, just investment of useful work made in creating productive structures with lifetimes ranging from hours (the cup of coffee you just drank) to centuries (the foundations of the building you drank it in) but with an average lifetime of ~35 years. If so, $i = 1$ and hence d is probably ~3 %/yr once we have properly accounted for all the short lived productive structure. If so, the growth rate of the global economy, which is clearly central to this entire debate, simply depends on the balance between the productivity, A, and the decay rate of capital structures, d. Also note how raising productivity through innovating on the efficiency of productive structure increases the growth rate of the system (which we look at in PART 2), which is not only central to the adaptive capacity of the economy, it should also immediately alert us to the potential rebound effects of increasing the energy efficiency of the economy (Brookes, 2000).

3.5 Emissions

We have spent a long time describing the economy, and rightly so, but now it is time to focus on the how this economic activity gives rise to greenhouse gas emissions. Again, it would be good to refer back to the map in Figure 1 to orientate yourself. Here we are going to use carbon and CO_2 as a representative for all greenhouse gas emissions both because carbon dominates our story and because the flows of other non-carbon greenhouse gas are somewhat correlated to fossil fuel use.

As a result of the growth in fossil fuel use, global carbon emissions have been growing at ~1.8 %/yr in since 1980 (Figure 2). We have come to conceptualise the drivers for emissions through the Kaya identity[28] which states the emissions rate as the product of factors including

26 This critically important observation was first made by Jorgenson & Fraumeni, (1989) who pioneered the human capital valuation methodology (https://www.nber.org/system/files/chapters/c8121/c8121.pdf)

27 https://www.move-lab.com/project/roadstorome/

28 https://en.wikipedia.org/wiki/Kaya_identity

GDP, energy intensity and carbon intensity. We can understand this in the context of growth analysis which states that if variables are multiplied together their growth rates are added. Since 1980 GWP has been growing at ~3 %/yr while PEU has grown at ~2.0 %/yr (Figure 2). The difference between the two is because the energy intensity of GWP has been falling, or put another way, the efficiency of the economy at translating PEU into the useful work and GWP has been increasing at 3.0 – 2.0 = 1.0 %/yr. Again note how these efficiency improvements are associated with growth in PEU, GWP and CO_2 emissions, not their reduction, again alerting us to the risks of using efficiency improvements to drive down emissions. It is also important to realise that the efficiency of the economy at translating primary energy flow into useful work has a thermodynamic limit that is significantly less than 100% and so this growth in efficiency has limits too.

If PEU has been growing at ~2 %/yr, CO_2 emissions have been growing a little slower at 1.8 %/yr because the carbon intensity of primary energy has been growing at 1.8 – 2.0 = -0.2 %/yr. This tells us that the global economy has been slowly decarbonising its primary energy supply for at least the last 40 years as we have switched from coal to oil to gas and nuclear and, more recently, renewables. The fact that both energy intensity and carbon intensity decline at these rates is no accident[29] and without any changes to this pattern, annual global carbon emissions, u, will follow a business-as-usual trajectory defined by,

$$u = 0.7\, y^{0.6} \qquad (2)$$

where 0.6 is the ratio of the growth rates of GWP and CO_2 emissions, or 1.8/3.0. Clearly a rate of decarbonisation of just 0.2 %/yr is too slow to do anything about sorting the climate change problem because ~3 %/yr growth in the economy swamps this decarbonisation. In fact, the decarbonisation rate of GWP would have to be >3 %/yr for emissions to decrease if the economy carried on growing as it has. In PART 2 we will address this by growing a parallel (alternative) economy which uses only carbon-free energy.

3.6 Climate

There are two elements to the global climate system relevant to our IAM; the global carbon cycle and the global energy balance. Like the global economy, both are highly complex and complicated systems in their own right and modelling them 'accurately' remains a fundamental challenge in the climate sciences. Fortunately for us, Allen et al.,[30] noted that the cumulative total of carbon emissions scales approximately linearly with Global Mean Surface Temperature Change (GMSTC; ΔT) both in the observations and in fully coupled Earth system models. The reasons for this are interesting but complicated, but in essence it boils down to two things. First and foremost the global carbon cycle is conservative with respect to CO_2 emissions on all geopolitical timescales. So if you put some CO_2 into the atmosphere a significant fraction of it stays there in effect permanently, and if it stays there it has a persistent radiative effect leading to temperature change. The result of this is that the cumulative sum of CO_2 emissions is what is important for determining the relationship

29 Jarvis AJ, Jarvis SJ, Hewitt CN (2015). Resource acquisition, distribution and end-use efficiency and the growth of industrial society. Earth System Dynamics, 6, 1-14.

30 Allen et al., (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature, 458, 1163.

between emissions and temperature change, not the emissions rate, which simply determines how quickly the temperature changes. The second effect of relevance is that the potency of the greenhouse effects of CO_2 decreases as atmospheric concentrations increase. However, this appears to be largely offset by the decreasing efficiency of the oceans to absorb CO_2 as global temperatures rise. These two effects appears to cancel each other out to gives rise to the linearity we observe between cumulative emissions and GMSTC (Figure 5).

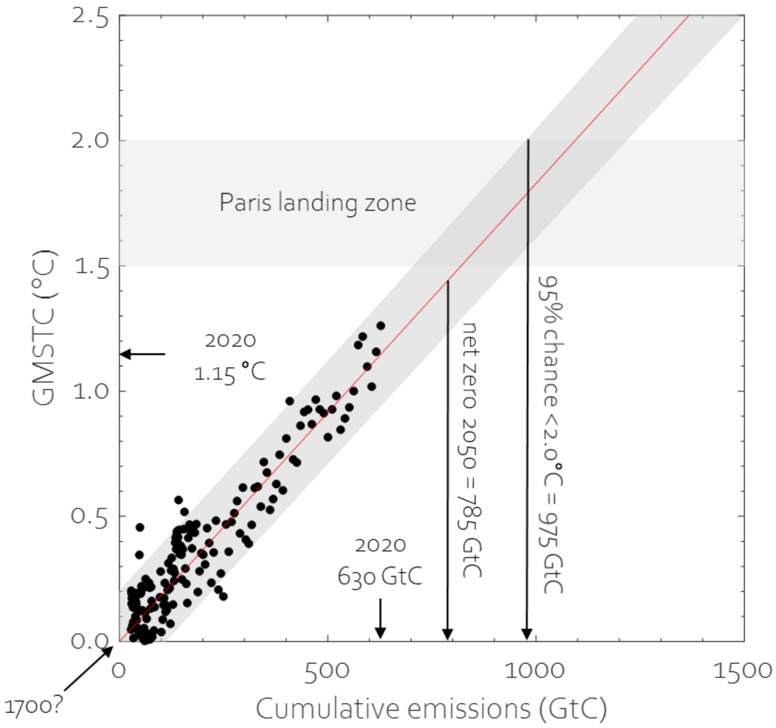

Figure 5. The relationship between cumulative carbon emissions from Figure 2 and HadCRUT4 Global Mean Surface Temperature Change[31] (GMSTC). Regression gives 1.8 °C of warming for every 1 TtC added to the atmosphere[32].

For us, all of this is incredibly convenient because it means the GMSTC response of the climate system to anthropogenic CO_2 emissions can be relatively accurately described by,

$$\Delta T = \frac{1.1}{600} \Sigma u \quad (3)$$

where Σu are the cumulative carbon emissions since the start of the industrial era (in GtC) and ΔT is the GMSTC. The 1.1/600 is the transient climate sensitivity to cumulative emissions, and comes from the fact that our present-day warming of 1.1 ˚C has been produced by some 600 GtC released by human activity since the start of the industrial era (Figure 5). This holds if we adopt CO_2 as a representative for all anthropogenic greenhouse gases. From this we conclude

31 https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html

32 Mathews HD, Zickfeld K, Knutti R, Allen AR (2018) Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets Environmental Research Letters, 13, 1

the the Paris Agreement is synonymous with emitting well below one trillion tonnes of carbon, with Figure 5 indicating that in 2020 we have between 150 and 350 GtC of 'headroom' left to emit to land GMSTC in the 1.5 - 2.0 ˚C range. Again, this is highly relevant to the scenarios we will explore shortly because you will see there are emissions locked into the current stock of capital which will live and hence emit for decades.

It is useful to unpack these global average temperature changes because there is a lot of regional variability sat behind these averages and as a result the impacts will be similarly variable. When this variability maps onto the huge inequalities in income distributions sat behind global aggregate measures such as GWP we see great potential for very significant regional disparities in the impacts of climate change. We could attempt to capture this spatial variability explicitly in our model, but it will immediately lose its simple character. So instead I encourage you to do the regional disaggregations in your head, qualitatively. To help guide this for climate change, there are some useful rules of thumb to appreciate. Firstly, the Earth's surface is 70 % sea, which experiences significant evaporative cooling and has a high thermal inertia. As a result, land warming is approximately twice that of the global average. Secondly, the greenhouse effect is largest at night and at high latitudes, and hence we might double the global mean again when looking at warming over land in high latitudes. Beyond this regional climate change becomes much harder to forecast.

3.7 Damages

In the specification of the coupled climate-society system thus far we have described how the economy drives climate change, but we haven't defined how climate change now feeds-back and drives the economy. Again, orientate yourself using Figure 1. To complete the picture we need to specify what is known as 'the damage function' i.e. how climate change (as represented through GMSTC) affects material losses to the economy.

There are two ways of accounting for climate losses in this framework; by reducing productivity (through equation 1a), or by increasing the rate at which the fabric of the economy decays (through equation 1b). It's a matter of debate which is the 'best' way given climate probably impacts on both. However, ultimately this will amount to the same thing as both productivity and depreciation will impact on growth as detailed in equation (1c). Because of this we will attribute losses to increasing the decay rate of productive structures because there is something thermodynamically defensible about this mode of action where warmer, more energetic climates erode societal structures faster.

The controversy over the climate damages function is not about the mode of operation in an IAM, it is controversial because up until recently we hadn't a clue how to specify the magnitude of damages with climate change, and even now perhaps we will struggle. This is because any anthropogenic damages up until recently were inseparable from the effects of natural climate variability. Allied to this, we have little or no idea how the economy would naturally (endogenously) react/adapt to these experienced losses. As a result, at best this function can be seen as a wild guess, leading some to conclude that any attempt quantify future losses using IAMs is a pointless and misleading exercise[33]. If so, we should disregard all

33 Pindyck R (2017) The Use and Misuse of Models for Climate Policy. Review of Environmental Economics and Policy 11(1):100-114

estimates of climate losses, which not only undermines important IAM findings like those of say Stern (2006), but also our entire understanding of the magnitude of the risks we face. This places us in a very uncomfortable place because the future could then be either far worse or, ironically, far better, than we have imagined.

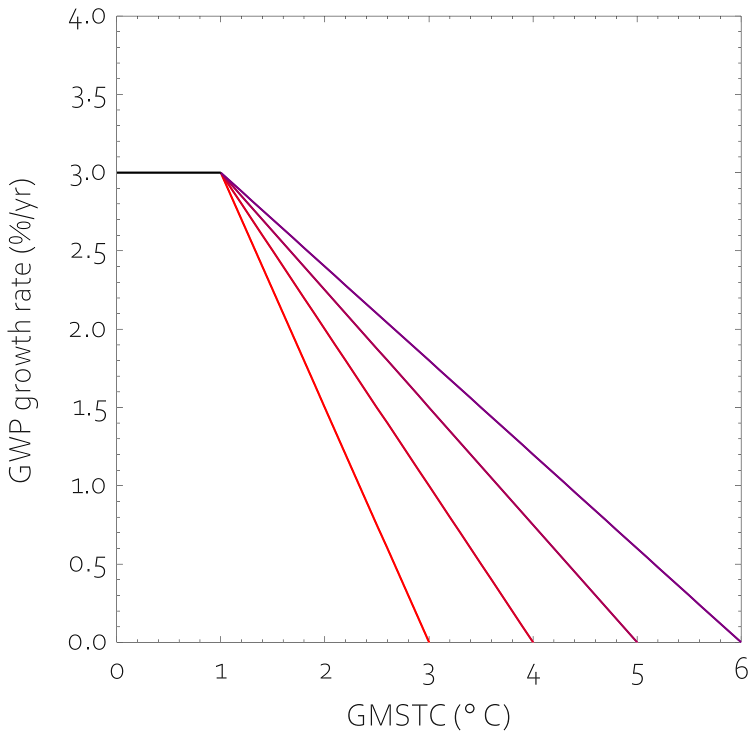

Figure 6. The speculated relationship between Global Mean Surface Temperature Change (GMSTC) and the unadapted growth rate of the global economy as represented by Gross World Output (GWP).

Recently Burke et al., [34] present a very interesting line of evidence which reveals a possible way forward. They correlated deviations in the growth of GDP for 160 countries to deviations in the local weather about a local climatic mean and used this to estimate the sensitivity of national GDP growth rates to weather variations. They found this sensitivity varied with climate in a consistent, albeit nonlinear way, supporting the proposition that climate change is best represented as a growth effect. They also found that globally the winnings approximately cancelled the losings so that the net effect of climate change in the range 0 - 1 ˚C was negligible. However, above 1 ˚C they found the losings started to rapidly outweigh the winnings. This is largely consistent with the shared experience of climate change where, thus far, the approximately 1 ˚C of warming has not really had a drastic impact on the global economy, even if there have been significant regional impacts. It is also consistent with our emerging experience of climate change where it appears the net impacts are starting to be of a globally significant magnitude (think Australian and Californian wild fires).

34 Burke M, Hsiang SM, Miguel E (2015). Global non-linear effect of temperature on economic production. Nature, 527, 235-239

The big question is what form the damage function takes above 1 ˚C? For this we can only take a balance of evidence and perception of risk perspective as this is not a world we have inhabited yet. However, the impacts on growth is a very useful way of trying to build this picture, which is what is attempted in Figure 6. The thinking goes like this. It is hard to envisage a world where the global economy is still prospering enough to grow if GMSTC hits 6 ˚C. After all, this could be 12 ˚C on land, which is simply huge. This feels like it bounds our damage function, as does the observation that not much happens between 0 - 1 ˚C. Another bound is that the synthesis of the climate science suggests that the economy can continue to function relatively well <2 ˚C, hence the terms of the Paris Agreement. But maybe tipping points elicited above 2 ˚C mean a 3 ˚C world can't house a viable economy [35]? Again, although highly uncertain this feels like a reasonable synthesis of the science and the global policy response to the associated risks. I am going to assume that each degree of warming above 1 ˚C wipes one percent off growth per year, so that in the absence of adaptation, all growth is quenched at 4 ˚C. This can be represented most simply as

$$d = max(3, s_d(3 + \Delta T - 1)) \qquad (4),$$

where s_d = 1.0 %/yr and is the climate sensitivity of the global economy. This is probably the most pessimistic damage function out there, although that probably is more a reflection of the over optimistic view generally adopted in the IAM community. It certainly isn't out of line with the results Burke et al., present, or the wider perception of climate risks within the climate science community and beyond.

Perhaps you're a degrowther and think the economy needs to slow down, I do. Letting the climate to do this for you is probably the worst way possible of achieving this ends because of the risk of it affecting those least able to cope. After all, although we have necessarily aggregated to the global scale, we know these losses are wildly unequally and unfairly spread across the planet. We also are now finding that through repairing the effects of climate damages in an emergency, we are amplifying fossil fuel emissions (think flying helicopters to pour flame retardant on the Australian bush). Like many adaptive measures, actions such as these can be viewed as adaptive responses manifest through changing productivity, A, and it is important that we don't lose sight of the plasticity of productivity in the global economy and the way it is driven by innovation. We will give that further consideration in PART 2.

4. Summary

And that is that in terms of model description. In Part 2 we turn equations 1-4 into a working model in Excel and use it to explore doing nothing (BAU), decarbonisation (anticipatory reductions in emissions through investing in the zero carbon economy) and adaptation (innovation on productivity) scenarios. This will not simply be a dry coding exercise, but instead is specifically designed to help us start to explore our normative values around these three very different types of futures. As a result, even if you don't think you are interested in the practical modelling, I believe the read should be rich, as I hope you have found PART 1 to be. We end in Part 3 where we have a go at using SIAM to estimate both the Social Cost of Carbon (SCC) and the Marginal Abatement Cost (MAC).

35 https://www.nature.com/articles/d41586-019-03595-0

5. Acknowledgements

SIAM has evolved over the past six years as a teaching aid for a 3rd year undergraduate module called Climate and Society. Like me, the students have little or no economics training, and this current draft owes a lot to our slowly resolving ignorance. This 2022 revision has also benefited significantly from an ESRC-NISER funded project - Timescales and Investment Dynamics in the Economy (TIDE).