3.9 A 17 minute wicked case study – global warming and climate change

In this unit we will look at a complex problem and study it using the approach and tools we have learnt so far in this chapter.

I found this article entitled “What Most People Don't Understand About Climate Change” on atlantico.com. It is an interview with US President Obama’s top science advisor, John Holdren about the problems people have understanding climate change.

Climate change is a complex problem as it involves a number of social, environmental, economic and technological factors. It is also a classic system problem: it involves observing weather patterns over long periods of time and on a global scale, it involves long delays between causes and effects, the dynamics of the climate are complex a generally misunderstood, many effects of climate change are difficult to attribute to a cause and the climate is a common resource, that suffers from a classic systemic problem called the “tragedy of the commons”.

We will use our studies of feedback from chapter two and accumulations and non-linear relationships from this chapter to improve our understanding of climate change.

We will once again ask our three questions to help organize knowledge about the situation: What is changing? How is it changing? And why is it changing?

Firstly, what is changing? The answer to this question appears obvious: the climate. However, the climate is vast. According to Wikipedia, climate is the statistics of weather in a given region over long periods of time and “is measured by assessing the patterns of variation in temperature, humidity, atmospheric pressure, wind, precipitation, atmospheric particle count and other meteorological variables.” That’s a mouthful! In any case, it’s doesn’t help us focus.

When we use the term “climate change”, we are often referring to changes in the Earth’s average temperature and its related effects. We can narrow our focus to the Earth’s average temperature and seek to understand and work out why and how it has changed over time.

According to data published by NASA, the average global temperature has increased by 0.9° Celsius over the past 134 years. This is the answer to our second question.

Before we go any further, let’s take a closer look at the main engine of global warming and climate change. I have located and read a number of articles in the system dynamics field to improve my operational thinking skills on climate change. As usual, the references are given in the bibliography.

The temperature at the earth’s surface is mainly determined by the balance of the incoming solar radiation, called insolation and the energy that the earth radiates back to space. The difference between solar energy and radiated energy is called the radiative balance.

The Earth’s surface temperature rises slowly as the heat stored at the Earth’s surface accumulates. This in turn leads to more energy being radiated which lowers the radiative balance. This is a negative feedback loop: solar energy heats the earth until it is just warm enough for the energy radiated back into space to balance the solar energy input. The global average net radiation must be close to zero over the span of a year or else the average temperature will rise or fall. We can call this an “Earth’s surface temperature balancing loop”.

The heat energy that is stored at the surface of the Earth is a stock. The surface of the Earth includes all land, the lower atmosphere and the top 50 to 100 meters of the ocean where most sea life exists. Heat energy accumulates with the radiative balance. When the radiative balance is positive, the heat stored increases, and when it is negative the heat stored at the surface of the Earth decreases. We can check that it is a stock by freezing time. Yes, that's right. Imagine that the world is standing still. The heat energy stored at the surface can still be measured, most commonly as the surface temperature. It is a stock, as stocks can be measured when time stands still. Radiative balance, radiated energy and solar energy on the other hand can no longer be measured as they need to be expressed as a number of units over time, such as the number of watts per square meter per month or per year. They are not stocks.

We can convert our causal loop diagram to a stock and flow diagram. We first draw a stock called "Heat stored at surface". What increases this stock? The radiative balance. We add radiative balance as an inflow. As a negative radiative balance also decreases the stock, the same variable is also an outflow. We use a double headed arrow to show that radiative balance is a bi-flow. We then add the other variables in the same balancing loop as before.

If temperature is regulated by a balancing loop, why then is the surface temperature of the Earth increasing?

The short answer is: the greenhouse effect. This happens when the atmosphere captures and recycles energy emitted by Earth's surface. Let's add this effect to our model.

Greenhouse gases present in the atmosphere such as carbon dioxide absorb some of the heat radiated by the earth instead of letting it escape into space. The gases then radiate the heat back downwards towards the Earth. This creates a positive radiative balance which increases the heat stored at the surface and warms the earth. We can add a variable called "GHG in atmosphere" to our model.

We tend to see greenhouse gases as a bad thing, and yet naturally occurring greenhouse gases such as water vapor warm the earth to a comfortable 15 degrees. Did you know that without greenhouse gases in the atmosphere, the mean global temperature would be a very chilly minus 17 degrees?

The problem is that human activity has increased the quantity of greenhouse gases in the atmosphere. Such anthropogenic greenhouse gas emissions have been increasing exponentially since the beginning of the industrial age. As a consequence, atmospheric concentrations of greenhouse gases have also been growing exponentially.

As the IPCC explains:

> "Anthropogenic greenhouse gas emissions have increased since the pre-industrial era driven largely by economic and population growth. From 2000 to 2010 emissions were the highest in history. Historical emissions have driven atmospheric concentrations of carbon dioxide, methane and nitrous oxide to levels that are unprecedented in at least the last 800,000 years, leading to an uptake of energy by the climate system."

According to the IPCC, carbon dioxide (CO_2) was the largest single contributor to radiative forcing over the period 1750–2011. The burning of fossil fuels accounts for 80% of CO_2 emissions. The remainder of CO_2 emissions comes from deforestation and other changes to land use.

Greenhouse gases - carbon dioxide, methane and nitrous oxide - accumulate in the atmosphere. They are a stock. The inflow to this stock is the emission of greenhouse gases and the outflow is the absorption of gases by plants, soils and the ocean waters.

We can add a new variable "fossil fuel consumption" as cause of GHG emissions. Can you see how the arrow points to the tap on the flow? This is because the rate of flow depends at least in part on this variable. As more fossil fuels are consumed, we open the tap a little more on the GHG emissions inflow.

If we had any doubt about greenhouse gases in the atmosphere being stocks, the article hints that accumulations are important in the sixth paragraph when Holdren explains that:

> "the only way to attain [1.5 degrees] is to get very good at technologies and practices that would actually take emissions negative. It wouldn't be enough to get emissions to zero, we would actually have to develop the technologies to be pulling carbon out of the atmosphere"

The article also cites a study in Nature Climate Change from May 2015 in the seventh paragraph that concluded that :

> "carbon emissions would have to go negative sometime this century to stay below 1.5 degrees of warming by 2100. Global carbon emissions would have to peak in the next few years, then decline rapidly, and the world would have to essentially stop emitting greenhouse gases between 2045 and 2060."

The words "emissions" and "pulling" things out of the atmosphere bring to mind inflows and outflows. By picturing greenhouse gases in the atmosphere as a stock we can almost visualize this happening. National Geographic Magazine goes one step further by using a picture of guess what … a bathtub! A link to National Geographic's graphic is provided in the references below the video.

Why do we need technologies to "pull" carbon out of the atmosphere? Why do carbon emissions have to "go negative" and stop?

It's all about bathtub dynamics. About 55% of greenhouse gases emitted over a period are absorbed, the remaining 45% remains airborne and accumulates in the atmosphere. The IPCC estimates that about 40% of anthropogenic CO_2 emissions have remained in the atmosphere since 1750.

The net flow into the greenhouse gases in atmosphere stock is positive and growing. Using bathtub dynamics we know that when the net flow is positive and growing the stock grows parabolically. We can see this happening in these two charts from the 2014 IPCC report on climate change. The top image shows annual greenhouse gas concentrations in the environment rising parabolically since the 1950s and the bottom chart shows anthropogenic CO_2 emissions rising linearly over the same period. Assuming that CO_2 absorption remains relatively stable, the net flow was positive and growing over this 60 year period.

Using our knowledge of bathtub dynamics, we know that the only way to reduce the effect of greenhouse gases on the radiative balance is by reducing the stock of greenhouse gases in the environment. If we simply reduce our greenhouse gas emissions, the stock will still keep growing, albeit at a slower rate. The net flow of greenhouse gases into the environment needs to be zero or negative.

We can see that our bathtub thinking skills greatly help our operational thinking around global warming and climate change. Scholars who have studied the problems that children and adults have understanding climate change dynamics argue that bathtub thinking skills are often more helpful than a scientific or a technical education or even contextual knowledge about the climate.

The article identifies a second problem people have in understanding climate change: **delays**. In the tenth paragraph, John Holdren notes that:

> "I think the aspect of climate change that probably most people don't understand and need to is the long time scales involved […] That is, it takes the climate a long time to adjust completely to what we add to the atmosphere. And as a result of that, we are not even today experiencing the full consequences of what we've already added to the atmosphere. If we stopped adding greenhouse gases today, the global temperature would continue to coast upward to close to 1.5 degrees until it stopped."

The cause and effect relationships in our model are not instantaneous. There are long delays. The earth's temperature does not immediately rise when CO_2 is emitted through human activity. Any change takes time to move through the accumulations. Relationships are most often nonlinear, and stocks must reach threshold levels before any changes significant changes can be observed. Can you picture these boxes filling like bathtubs? We can use double bars to represent these delays.

Delays are also present in the actions we take to address climate change. This is the third main point of the article. In the ninth paragraph of the article Holdren notes that it will take a long time to change the energy system. He explains that the :

> "global energy system represents something over $20 trillion in capital investment, which ordinarily would turn over on a timescale of 30 or 40 years. There is no way to rebuild the energy system overnight—it's too big, too costly to do that."

Let's explore this situation further by adding the economy and the energy system to our model. We build on and extend our existing model by starting at the periphery and identifying direct causes and direct effects on variables that are related to energy and the economy. To make a little room, we will hide the surface temperature balancing loop. This part of our model is based on the work of Thomas Fiddaman that is provided in the reference section.

We will begin with the variable "fossil fuel consumption" and add new variables as we go. Consumption is driven by demand for fossil fuels. As demand increases so too does the extraction and production of fossil fuels which in turn empties natural stocks of these fuels. As more fuels are produced and consumed, revenues increase which are reinvested in marketing actions to continue driving demand. This is a reinforcing loop of marketing driven demand. In our model we assume that all production is sold.

As production increases, so too does investment in capital stocks such as oil wells, refineries, tankers and coal mines. Discards are abandoned investments that represent a proportion of the stock. Investment in energy producing capital improves productivity by alleviating capacity constraints and promoting economies of scale. This lowers costs and prices and further drives demand. There are now two new reinforcing loops.

Did you notice that we added the price variable a second time to our model as a cause of the demand variable? We have done this to avoid cluttering our model. Ideally, we should draw a link between price and demand but, as we will later see this would have involved cutting across other links and variables. Instead we use a "ghost" variable, placing it in brackets and a using a lighter color.

We can add price next to the variable revenues in the same way as we multiply price by production volumes sold to in order to calculate revenues.

Investment in research and development increases the stock of cumulative technical knowledge and leads to the creation of new, productivity improving technology. Productivity improvements again have a negative effect on price and lead to an increase in demand and further investments in R&D. This is a reinforcing loop of R&D driven innovation.

Cumulative production experience contributes to learning and leads to productivity gains, reduced costs and increased demand. This is a reinforcing loop of learning-by-doing in production. Cumulative experience is like knowledge or expertise: it is a stock.

Consumers also benefit from learning-by-doing. The more you use a product, the more adept and familiar you are at using it and end use productivity increases. As people use fossil fuels, they grow familiar with the entire process from sourcing to consumption. We can show this link in our model.

As end-use productivity with fossil fuels increases, new products are developed using the same energy source to benefit end-user familiarity, which increases productivity even more. There is now a new reinforcing loop. This loop is an example of path dependency or lock-in that we saw in chapter 2. It also illustrates the bandwagon effect if companies simply copy others in their use of fossil fuels. The price of fossil fuels may also affect design choices.

The development of new products stimulates investment in complementary fossil fuel infrastructure which has a positive effect on end-user productivity and demand for fossil fuels.

We have labeled eight reinforcing loops in our model. These reinforcing loops are examples of lock-in. According to Thomas Fiddaman :

> “Principal among these positive loops are learning-by-doing, economies of scale, network or bandwagon effects, and the development of complementary infrastructure. In the energy system, this means that dominant technologies may have a self-sustaining advantage by virtue of size alone, even though they may be suboptimal in terms of their energy or carbon intensity. Fossil fuels appear cheaper than renewables in part because they are the dominant source, not because they are inherently superior”

We saw in chapter two that lock-in arises when positive feedback reinforces the position of a dominant firm, product or technology. In the energy sector, the systemic structure acts as a barrier to the necessary change urged by Holdren.

Our model is now complete. Of course we could have added other variables to our model, such as the effect of rising temperatures on sea levels, the albedo effect of solar flux reflection or the impact of changes in the climate to economic activity and populations but this would be outside the scope or boundary of our model.

We should never forget that we construct models to improve our understanding of a given situation. We need to use Occam’s razor and seek efficiency in our explanations. Here, our model is sufficient to explore the misunderstandings many of us have about climate change that were mentioned in the article such as the causal mechanisms behind the rise in global temperatures, the long delays inherent in climate change and the time and effort it will take to change our energy system and address one of the world’s wicked problems.