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Richard Betts My job is to set the scene for the rest of the conference by talking about what 4° climate change actually means regionally across the world and also the potential rate of climate change, when we may get to 4°.

And I'm going to base this on some of the IPCC SRES emissions scenarios which are shown here. So these are scenarios - this is showing the carbon dioxide emission scenarios for several different storylines, so future scenarios of population growth; socioeconomic change; technology change and so on, which have been used in a variety of different climate models to project future climate change over the next century. And I'll focus on two in particular: the A1B scenario here which sometimes is called the median emissions scenario and I'll also focus on the A1FI scenario.

The A1 family of scenarios consider fairly rapid economic growth, which obviously isn't right at the moment, but these scenarios are supposed to be robust to year by year changes in the global economic system. The difference between B and FI is B is a balance of energy sources between fossil fuel and non-fossil fuel sources. FI stands for Fossil Intensive, so that's, essentially, burning all the fossil fuels you can get your hands on.

Now, this is a fairly iconic figure from the last IPCC report in 2007 which put some of these scenarios into climate models to show the projected rates of global warming relative to the pre-industrial state. So the main climate models looked at these three scenarios: B1, A1B and A2. So A2 is sometimes called the medium-high scenario. And also there is a hypothetical scenario or if we fixed CO2 concentrations at the present day and we still get some warming, even if we did that.

But the most extreme scenario looked at in IPCC with the main climate models was the A2 scenario and you can see that looking at the uncertainty and the range of projections from different models just about touched 4° by the end of the century. So that's suggesting that 4° is possible by the end of the century.

But there was other work done for IPCC with simpler models, trying to estimate what these more complex models would've done under a wider range of scenarios and a wider range of feedbacks, and these grey bars here show that. And this is the A1FI scenario there and I'll come back to that later in more detail.

But first of all, how are we doing in terms of our actually emissions compared to these projections? There's a bit of a story going around that actually, recent emissions have been above the high emissions scenario, above the worst case projected by IPCC. That's not exactly right; the paper which said that had a bit of a misunderstanding.

But the actual emissions shown here - this is the 2008 update on actual emissions within the range of scenarios used to drive the climate models for IPCC - this is slightly confusing, because this is the A1B scenario there and the A1FI is there; they, kind of, crossover. You can see this more clearly here; they crossover here. The reason for that is different models were used to produce these different emissions scenarios. So although the underlying assumptions of population and technology and economic growth are the same, the way these translate into emissions is different from different models.

But basically, it's true to say that current emissions are near the upper end of what has been looked at in the IPCC climate models, so therefore it is worth looking at high emissions scenarios.

And I'll talk about a range of different techniques for combing projections of different models and trying to assess the confidence in our projections or the uncertainty in our projections.

Often we tend to use an ensemble technique these days which is using different models, or different versions of models, because we don't know - we have no perfect model; we can only look at what all the different models are giving and try and see what this gives us as our best guess or our plausible range of projections.

So one technique is the multi-model technique at the top, which is what's in the coloured lines in my first IPCC figure I showed earlier, so using all the models from all the different current modelling centres around the world, which are mostly different. Some of them are not different, some of them are very close to each other, but mostly, you have independent models there.

A second approach is to use one model but vary the key parameters within that model and that's been done twice here in the UK. The one many of you may be familiar with is the climateprediction.net project which many of you may even use this on your PCs. So this is using the Hadley Centre model, HadCM3 with one-and-a-half thousand or more variants of that model to see what tweaking the parameters of that model gives you in terms of changing the projections.

Then also internally, within the Met Office Hadley Centre, we have a similar approach called 'Quantifying Uncertainties in Model Projections'. Again, with the HadCM3 model, 17 variants of that were looked at in more detail in storing much more of the data. So together, these two are quite powerful.

Thirdly, because these climate models are so computationally expensive to run you can't cover the whole range of possibilities, so often you need to use simpler climate models which you tune to represent the complex models, so it's the model of the model, if you like. And that's what's used, again in IPCC, to give a likely range of warming, as showed in my earlier slide.

And then finally, you can use a combination of all the above techniques as used in the UKCP09 projections. Again, we produced those with the Hadley Centre model mostly, again, going through a simple model and bringing in some of the IPCC models as well. And I'll use a combination of all these things in my talk today.

So first of all, I'll look at the A1B scenario, which is probably the most widely studied of all the emissions scenarios. And this is what all 23 IPCC models give for global warming relative to the 1860 to 1890 mean under the A1B scenario. What we've picked out here is, in orange, the three simulations which do go above 4° by the end of the century. Most of them do stay below 4° by the end of the century under this scenario, but I'm going to use these to illustrate what the regional patters of climate change are like by just picking on the average of these upper three.

So the red line here is the average of what we're calling the high-end simulation, so those which do achieve 4° warming by the 2090s. So the red line is the average of those. So this shows the pattern of warming averaged over those three high-end IPCC simulations for A1B. So three models and they give a mean global warming of 4.3°C. So you can see that there's quite a wide range of regional variations in warming.

Again, this may be slightly confusing because this is a map of warming relative to 1961 to '90; not relative to pre-industrial. That's because when you're looking at impacts, which Nigel will talk about in the next talk, it's actually more useful to talk about change relative to the present day rather than pre-industrial because that means something. So hopefully that ties in better with Nigel's talk. So this shows you the changes relative to not too long ago in recent history. So you can see a wide range of patterns of warming.

The oceans, on the whole, warm less; it takes longer to warm water than it does the land. Most of the land is warming, say around 4 or 5°C by the end of the century, but some areas, particularly the high latitudes and John Schellnhuber's third pole in the Himalayas, are warming by, perhaps, 8° or more of even, perhaps, 10° in the Arctic. As you're losing the sea ice, the reflective nature of the sea ice is being taken away, you've got the dark underlying ocean which is absorbing more sunlight, more of the sun's radiation and warming the ocean further. So a wide range of patterns of warming for 4°.

Also, arguably what we really want to know if where the rain is going to be and this is changes in the precipitation by the 2090s averaged over the three high-end A1B scenarios from IPCC. On the whole, as you warm the world you increase global average precipitation, so rainfall and snowfall added together. So many areas do get an increase in rainfall, particularly in the high latitudes Eastern Africa there. Now, we're only showing the results here where two-thirds of the models agree, which is two in this case because there's only three models.

(Laughter)

But this is the usual technique started in IPCC to look at likely changes, is about two-thirds of the models. So you can see increases in rainfall in many places so we should, obviously increase the risk of flooding, for example, but also in many regions there's a decrease in rainfall, particularly over the Mediterranean region, Western Africa, Central America, parts of Southern Africa, parts of South America; so again, a very strong regional difference in the response of precipitation to climate change.

Now, as I said, the IPCC model ensemble didn't look at the high emissions scenario but we have looked at that with the Hadley Centre model. But before I go onto that I want to show you how the Hadley Centre model compares to the IPCC ensemble. So we've done our own ensemble of simulations, so using the HadCM3 model, but perturbing various parameters, the input numbers in there, to try and capture the range of uncertainty in the projections. And this shows - it's the equivalent of the IPCC ensemble projection I just showed earlier but with the Met Office Hadley Centre model ensemble.

So again most, under the A1B, most simulations are staying below the 4° line but a good proportion - perhaps more than the IPCC ensemble - are going above 4° by the end of the century.

And again, the pattern of warming there - so this is consistent with the pattern from the average of the high-end IPCC simulations, so much more warming in the Arctic because of feedbacks from sea ice and snowmelt over land. In Amazonia, in the Hadley Centre model, we get more warming - it's a classic features of the Hadley Centre model is to warm Amazonia - and also the warming in Central Asia tends to come more extreme and further south.

Patterns of precipitation change, again broadly agree with the high-end IPCC scenarios. In fact, I should point out that the high-end IPCC scenario do not include the Hadley Centre model actually, which I was surprised about when I looked. So this is not biased by the Hadley Centre model being in the projection I showed earlier. So again, we get more rainfall, more snowfall, high latitudes, an increase in global average precipitation, decreases over the Mediterranean and Central America, more significant decreases over South Africa and significant decreases over Amazonia. So again, some - perhaps up to 20% or more decreases in precipitation in many areas.

So what about the A1FI scenario, the high emissions scenario - so up to the top there - what does that look like? So again, this is now using the Hadley Centre model, HadCM3 and it's the mean of a high-end simulation, so those which go past 4° before the end of the century. This time it's 14 simulations that do that, 14 out of a possible 17 go past 4° by the end of the century. And the mean of the high-end group, mean warming is 5.4°C.

And the patterns of warming are, kind of, similar to what we've already seen but more extreme, so again, more extreme warming in Southern Africa, Amazonia, North America, Northern Asia. Most of the world is warming by 6-7° or so, the Arctic's warming by 12-13-14° or more, again, because of the feedbacks. And again, the precipitation changes: similar to as already seen but, again, more extreme. So an increase in global average precipitation, increased precipitation at high latitudes: Southern Asia, Eastern Africa; but a decrease in precipitation over the Mediterranean, Western Africa, Central America, Amazonia, Southern Africa and Southeast Asia.

What about the timing of reaching 4°? Well, this is, again, the time series of global warming in the A1FI scenario with the Hadley Centre ensemble. You can see that three of the ensemble members don't reach 4° by the end of the century but most do. One of them gets there by 2060 but most of them are, sort of, getting to 4° in the 2070s or so. And this is not inconsistent with the IPCC simple models, which I showed in the first slide.

But there's an important feature which is missing from all these simulations so far and that's feedbacks from the global carbon cycle. These are all based on a translation of the emissions scenario into a scenario of atmospheric CO2 concentrations which ignore the effect of climate change on carbon sinks. Now, it's well known that the rate of change in atmospheric CO2 concentration shown here - again, this is an IPCC figure; this is the year by year change in atmospheric CO2 concentration - is only about 60% of the actual rate of CO2 emissions. And if you include deforestation emissions the atmospheric CO2 concentration is rising at about 40% of total emissions.

So we have the budget for the last 10 years or so, shown from the IPCC, is these emissions of up to seven gigatonnes of carbon per year from fossil fuel burning and `[[SEM 0:15:34]]` production, and about one or so, but with large uncertainty, from deforestation. But that's balanced, to some extent, by a large sink of carbon on the land, plants grow better under higher CO2, draws down CO2 from the atmosphere, pumps carbon into the soil. And there's actually more carbon in the world's soils than actually in the atmosphere.

And there's an even stronger sink in the ocean and CO2's dissolved in the ocean waters, and some of it is taken up by plankton and pumped down to the deep water as the plankton die off. So you get significant sinks which are helping to offset the emissions from fossil fuel burning and deforestation. So we have this free ecosystem service, if you like, which is buffering us from the full effects of our CO2 emissions.

But this ecosystem service may not last. Now, this is a climate and carbon cycle projection of the change in carbon stores in global vegetation in red and global soils in blue. This is work published by Peter Cox and myself and colleagues in 2000, so it's 10 years old now nearly. But it's using, basically the HadCM3 climate model with interactive vegetation soils and oceans as well, so it's the full carbon cycle in there. And over the 20th century you can see the model suggests, as is again agreed by IPCC, that the land should be taking up carbon both in the vegetation and in the soils.

But then if you go into the future, these sinks decrease, the red line is the vegetation carbon soil and you see that flattens-off in the middle of the century and then decreases. This is largely the Amazon Forest failing to survive under an area of drying climate, as you saw in my earlier slides. Not all models show that but we've been unable to rule it out. So it still seems to be a plausible but not a certain future for the Amazon. It may be avoided if we can protect the forest against deforestation but it's still a plausible future in the longer term.

But more seriously, the global carbon store in soil flattens off early and then declines very rapidly and then goes down below the pre-industrial levels. That's because the soil carbon is released to the atmosphere naturally through the process of decay, you get respiration from the microbes in the soil, essentially, but that tends to go up under higher temperatures. So soil respiration increases, the soil carbon store is largely released back to the atmosphere, so we get this enormous loss of carbon from the land in this model.

And then we translated that into the effect on atmospheric CO2 rise and, as I said, this is a 10-year-old study so this is using the older scenarios from IBCC - this one's called IS92A; 'Business as Usual' it was called in those days - and we looked at without CO2 feedbacks, the blue line, and with CO2 climate feedbacks here, the red line.

And if you include these carbon climate cycle feedbacks, instead of the business as usual scenario giving you a CO2 rise of about - CO2 concentration of about 750ppm by the end of the century, the CO2 concentration goes to about 1,000ppm by the end of the century under that scenario. So a significant acceleration of the CO2 rise and that naturally will translate into an acceleration of global warming.

That was only the one model and that's 10 years old now. In the meantime, the same work has been repeated by other modelling groups in an international intercomparison project called C4MIP, stands for Coupled Climate Carbon Cycle Modelled Intercomparison Project, and that looked at almost 20 models of both complex and simple climate models including carbon cycle feedbacks. And what I'm showing here is the difference in the CO2 concentration over time between your pairs of simulations with and without carbon cycle feedbacks. So it's essentially the difference between these two lines but for a whole load of different models.

This is the Hadley Centre model here, the most extreme. So we recognise that we do have the most extreme feedback in our model. Others have less extreme feedbacks but the common thing here is they all have a positive feedback. So there seems to be a consensus that carbon cycle feedbacks are positive and would be expected to accelerate the CO2 rise to some extent.

So what happens if you put that into the climate model projections and try and use a simple model, tuned against the complex models, including the range of uncertainty in the climate system and the carbon cycle feedbacks?

This is a figure from my colleague, Jason Lowe, who is going to be speaking later in the conference, and what we're showing here is the A1FI scenario, so the high emissions scenario, including carbon cycle feedbacks in trying to capture the uncertainty in this. So the median projection, you could call it the 'best guess' if you like, gives a warming of 4° in the 2070s. If you look at the extremes, this is a 10th and 90th percentile, so essentially, we're chopping off the extreme 10% and the least extreme 10%. So the 90th percentile gives you a 4° warming at 2060. So that seems to be a plausible worst case scenario for reaching 4° including high emissions and strong carbon cycle feedbacks.

And finally, a figure from Mark New: this is with the other large climate model ensemble based on HadCM3, the climateprediction.net project, so this is using 1,549 variants of HadCM3 and this is not using carbon cycle feedbacks and it's using the A1B emissions scenario, but what they're showing here is the proportion of the models which go past certain thresholds of global warming. So this is the proportion going past 2°, at different dates, 3° and 4°. So for the 4° line you can see that about 10% of these 1,549 models go past 4° at 2060 under the median emissions scenario and without carbon cycle feedbacks. So again, this backs-up the fact that reaching 4° by 2060 is plausible.

We have not yet combined this with carbon cycle models all at a high emissions scenario, so we don't know what would happen there. But I guess the message is both this and the Hadley Centre work suggests that 4° by 2060 is a plausible worst case scenario. Best case is probably in the 2070s, but we could be as early as 2060.

So to conclude then, the current CO2 emissions are near but not above the upper end of the IPCC emissions scenarios. Four degrees of global warming relative to pre-industrial is possible by the 2090s, especially under the high emissions scenario. And that would mean that many areas could warm by 10° or more. The Arctic could warm by 15° or more and annual precipitation could decrease by 20% or more in many areas, or it could increase by 20% or more in many areas.

With the carbon cycle feedbacks, we're expected to accelerate the warming, so with high emissions the best guess would be that we'd reach 4°C warming, roughly in the 2070s. A worst case scenario could be 4° by 2060.

And I will leave it there, thank you.
