The impacts of climate change across the globe: a multi-sectoral assessment

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Abstract

The overall global-scale consequences of climate change are dependent on the distribution of impacts across regions, and there are multiple dimensions to these impacts. This paper presents an global assessment of the potential impacts of climate change across several sectors, using a harmonised set of impacts models forced by the same climate and socio-economic scenarios. Indicators of impact cover the water resources, river and coastal flooding, agriculture, natural environment and built environment sectors. Impacts are assessed under four SRES socio-economic and emissions scenarios, and the effects of uncertainty in the projected pattern of climate change are incorporated by constructing climate scenarios from 21 global climate models. There is considerable uncertainty in projected regional impacts across the climate models, and coherent assessments of impacts across sectors and regions therefore must be based on each model pattern separately; using ensemble means, for example, reduces variability between sectors and indicators. An example narrative assesment is presented in the paper. Under this narrative approximately 1 billion people would be exposed to increased water resources stress, around 450 million people exposed to increased river flooding, and 1.3 million extra people would be flooded in coastal floods each year. Crop productivity would fall in most regions, and residential energy demands would be reduced in most regions because reduced heating demands would offset higher cooling demands. Most of the global impacts on water stress and flooding would be in Asia, but the proportional impacts in the Middle East North Africa region would be larger. By 2050 there are emerging differences in impact between different emissions and socio-economic scenarios even though the changes in temperature and sea level are similar, and these differences are greater in 2080. However, for all the indicators, the range in projected impacts between different climate models is considerably greater than the range between emissions and socio-economic scenarios.

1.   Introduction

The assessment reports of the Intergovernmental Panel on Climate Change (IPCC) review hundreds of studies into the potential impacts of climate change (e.g. IPCC, 2007; 2014). Key conclusions are firstly that the distribution of impacts across space and between regions is more important in terms of the global-scale impacts of climate change than the global aggregate impact, and secondly that impacts occur across many dimensions and therefore need to be expressed in terms of multiple indicators. However, there have still so far been few consistent studies of the impact of climate change across sectors and the global domain. Most global studies have concentrated on one sector, and different studies have used different climate and socio-economic scenarios. The few multi-sectoral studies (Hayashi et al., 2010; van Vuuren et al., 2011; Piontek et al., 2014) have used few climate models and only a small number of indicators. It has therefore been difficult to produce consistent assessments not only of the global-scale impacts of climate change, but also of the potential for multiple overlaying impacts across several sectors. Such assessments are of value not only to global-scale reviews of the potential consequences of climate change, but also to organisations concerned with the distribution of impacts across space. These include development, disaster management and security agencies, together with businesses or organisations with international coverage or supply chains.

This paper presents for the first time an assessment of the multi-dimensional impacts of climate change across the global domain for a wide range of sectors and indicators, using consistent climate and socio-economic scenarios and a harmonised methodology. Impacts are estimated under four different future world scenarios using up to 21 different climate model patterns to characterise the spatial pattern of climate change. The assessment constructs a set of coherent narratives of impact across regions and sectors, and also includes a representation of some of the major sources of uncertainty in potential regional impacts. It complements other global-scale assessments using the same methodology and models into the relationship between amount of climate forcing and impact (Arnell et al., 2014) and the impacts avoided by climate mitigation policy (Arnell et al., 2013).

2.   Methodology

2.1   Overview of the approach

The assessment involves the application of a suite of spatially-explicit impacts models run with scenarios describing a range of emissions and socio-economic futures. These emissions and socio-economic futures are here represented by the A1b, A2, B1 and B2 SRES storylines (IPCC, 2000). Scenarios characterising the spatial and seasonal distribution of changes in climate and sea level around 2020, 2050 and 2080 are constructed from up to 21 global climate models (Meehl et al., 2007a) in order to assess the climate-driven uncertainty in the projected impacts for a given future. The period 1961-1990 is used as the climate baseline.

The impact sectors and indicators are summarised in Table 1 (see Supplementary Information for details of the impact models). They span a range of the biophysical and socio-economic impacts of climate change, but do not represent a fully comprehensive set covering all impact areas which may be of interest; they represent an 'ensemble of opportunity' based on the availability of models. All

the land-based impact models use the same baseline climatology, and all the indicators relating to socio-economic conditions use the same socio-economic data. The impact assessment is therefore harmonised, because all models use the same baseline climatology and, where relevant, socio-economic data, but is not a fully integrated assessment because different models are used in each sector. Only one impact model is used in each sector, so the uncertainty associated with impact model structure and form is not incorporated.

The socio-economic impacts of climate change in a given year are expressed relative to the situation in that year in the absence of climate change (i.e. assuming that the climate remains the same as over the baseline period 1961-1990). For the 'pure' biophysical indicators – crop productivity, suitability of land for cropping, terrestrial ecosystems and soil organic carbon – impacts are compared with the 1961-1990 baseline. Impacts are presented at the regional scale (Supplementary Table 1).

Most of the indicators represent change in some measurable impact of climate change, such as the average annual number of people flooded in coastal floods or crop productivity. Three of the indicators, however (water scarcity, river flooding and crop suitability), represent change in *exposure* to impact. The extent to which exposure translates into impact depends on the water management and agricultural practices in place, but these are so locally diverse and dependent on local context that it is currently not feasible to represent them numerically in global-scale impacts models. The indicators do not incorporate the effects of adaptation to climate change, with the exception of crop productivity where the crop variety planted varies with climate (see Supplementary Information)

Impacts can be expressed in either absolute or relative terms, and there are advantages and disadvantages in both when comparing impacts across regions. Large percentage impacts in a region may represent small absolute numbers and therefore make a small contribution to the global impact, but may indicate substantial impacts in the region itself. In contrast, a small percentage impact in another region may produce large absolute impact – and thus contribute substantially to the global total – but the implications for the region itself may be smaller.

The distribution of impacts between regions and across sectors varies with between different spatial patterns of change in climate, as represented by different climate models. One possible way of summarising the global and regional impacts of climate change would be to show the ensemble mean (or median) impact for a given sector and region across all climate model patterns, perhaps with some representation of uncertainty through identifying consistency between the different models (as is often done for climatic indicators such as temperature and precipitation). However, this is problematic when the concern is with multiple indicators of impact and comparisons between regions for two main reasons. The calculation of an ensemble mean makes assumptions about the relative plausibility of different climate models, but more importantly the ensemble mean impact does not necessarily represent a plausible future world. Calculating the average reduces the variability between regions and the relationships between sectors and indicators.

An alternative approach is therefore to treat each climate model as the basis for a separate narrative or story, describing a plausible future world with its associations between indicators and regions. Uncertainty in potential impacts is then characterised for each region and indicator by comparing

the range in impacts across different climate models, but recognising that aggregated uncertainty – across regions or indicators – is not equivalent to the sum of the individual uncertainty ranges.

2.2   Climate and sea level rise scenarios

Climate scenarios were constructed (Osborn et al., 2014) by pattern-scaling output from 21 of the climate models in the CMIP3 set (Meehl et al., 2007a: Supplementary Table 2) to match the changes in global mean temperature projected under the four SRES emissions scenarios A1b, A2, B1 and B2. These temperature changes were estimated using the MAGICC4.2 simple climate model with parameters appropriate to each climate model (Meehl et al., 2007b: Supplementary Figure 1a). Pattern-scaling was used rather than simply constructing climate scenarios directly from climate model output partly to better separate out the effects of underlying climate change and inter-annual variability, and partly to allow scenarios to be constructed for all combinations of climate model and emissions scenario. Rescaled changes in mean monthly climate variables (and year to year variability in monthly precipitation) were applied to the CRU TS3.1 0.5x0.5^o 1961-1990 climatology (Harris et al., 2013) using the delta method to create perturbed 30-year time series representing conditions around 2020, 2050 and 2080. The terrestrial ecosystem and soil carbon impact models require transient climate scenarios, and these were produced by repeating the CRU 1961-1990 time series and rescaling to construct time series from 1991 to 2100 using gradually increasing global mean temperatures. Pattern-scaling makes assumptions about the relationship between rate of forcing and the spatial pattern of change, which have been demonstrated to be broadly appropriate for the averaged climate indicators used here (e.g. Tebaldi & Arblaster, 2014), but which do constitute caveats to the quantitative interpretation of results.

Sea level rise scenarios were constructed for 17 climate models, in two ways. Spatial patterns of change in sea level due to thermal expansion were available for 11 of the models. Uniform projections of the contributions of ice melt were added to these patterns, and the patterns were rescaled to correspond to specific global temperature changes using the same methods as applied in Meehl et al. (2007b). Sea level rise scenarios for the other six climate models were constructed by adding the ice melt projections to the globally-uniform sea level rise due to thermal expansion as calculated using MAGICC4.2. Global average sea level rise scenarios are shown in Supplementary Figure 1b; note that the highest change is produced by one model which is considerably higher – by around 20cm in 2100 – than the others. The effects of dynamic components of changes in the Greenland and Antarctic ice sheets are not incorporated, but the range in sea level rise across the models is large compared with the potential magnitude of the dynamic effect.

2.3   Socio-economic scenarios

Future population and gross domestic product at a spatial resolution of 0.5x0.5^o were taken from the IMAGE v2.3 representation of the SRES storylines (van Vuuren et al., 2007). The population living in inland river floodplains was estimated by combining high resolution gridded population data for 2000 (CIESIN, 2004) with flood-prone areas defined in the UN PREVIEW Global Risk Data Platform to estimate the proportions of grid cell population currently living in flood-prone areas. Cropland extent was taken from Ramankutty et al. (2008). It is assumed that river floodplain extent, cropland extent and the proportion of grid cell population living in floodplains do not change over time.

3.   Exposure in the absence of climate change

The impacts of climate change in the future depend on the future state of the world. Table 2 shows the regional exposure to water resources scarcity, river and coastal flooding and residential energy demand in 2050 under the A1b socio-economic scenario, together with (modelled) average regional crop yields and ecosystem indicators, assuming climate and sea level remain at the 1961-1990 level. The table also shows global totals for some of the indicators under the other three socio-economic scenarios, alongside global totals for 2000.

The vast majority of people living in water-stressed watersheds, river floodplains and flooded in coastal floods are in south and east Asia (including India, Bangladesh and China). By 2050 east Asia (predominantly China) accounts, with Europe and North America, for the vast bulk of heating energy requirements. However, the absolute numbers hide regional variations in the proportions of people living in exposed conditions; more than 75% of North African people would be living in water-stressed watersheds in 2050, along with two-thirds of people in west Asia.

4.   The regional impacts of climate change in 2050 in an A1b world

4.1   Introduction

By 2050, global average temperature under A1b emissions would be between 1.4 and 2.9^{o}C above the 1961-1990 mean, with an average increase across climate models of around 1.9^{o}C. Global average sea level would be 12 to 32 cm higher than over the period 1961-1990, with an average increase of 18 cm (note that changes in temperature and sea level under A1b are between changes under RCP6.0 and RCP8.5) . However, the spatial patterns of changes in temperature, precipitation, sea level and other relevant climatic variables vary between climate models, so the projected potential impacts also vary. This section first describes the potential impacts across the world and across sectors under one example plausible climate story, and then assesses the uncertainty in impacts by region and sector.

4.2   A coherent story: impacts under one plausible climate future

Figure 1 and Table 3 show the impacts in 2050 under one climate model; this particular model has an increase in global mean temperature of 2.2^{o}C (relative to 1961-1990) in 2050 under A1b emissions, and a global mean sea level rise of 16cm.

Under this plausible story, approximately 1 billion people are exposed to increased water resources stress due to climate change, relative to the situation in 2050 with no climate change, and almost 450 million people are exposed to a doubling of flood frequency. In contrast, around 1.9 billion water-stressed people see an increase in runoff, and around 75 million flood-prone people are exposed to flooding half as frequently as in the absence of climate change. Approximately 1.3 million

additional people are flooded in coastal floods each year. Around a half of all cropland sees a decline in suitability, but about 15% sees an improvement. Global residential heating energy demands are reduced by 30% (bringing them back to approximately the 2000 level) but cooling demands rise by over 70%. The net effect is a reduction in total heating and cooling energy demands of around 15%. There are, however, considerable regional variations in impact.

Under this story, increases in water scarcity are most apparent in the Middle East, north Africa and western Europe, whilst increases in exposure to river flooding is largest in south and east Asia. The suitability of land for cropping declines in most regions, but increases at the northern boundary of cropland and along some margins in east Asia. Spring wheat yield changes show a mixed pattern of change, maize yields decline everywhere except in parts of north America and eastern China, and soybean yields tend to increase in parts of south and east Asia, north America and small parts of south America, but decrease elsewhere. Increases in coastal flood risk are concentrated in Asia and eastern Africa, whilst wetland losses focus around the Mediterranean and north America. Cooling energy demands increase particularly in regions where there is currently little demand for cooling, but increase only slightly in some warm regions – because the relative change in requirements is smaller. Heating energy demands decrease most in the warmest regions.

Many regions are exposed to multiple overlaying impacts. For example, under this plausible climate story river flood risk increases across much eastern Asia, coastal flood risk increases substantially, and cooling energy demands increase by more than 70%. At the same time, the productivity of the three example crops increases in parts of eastern Asia, but decreases across much of northern China. The suitability for agriculture appears to increase in northern and western China, although soil organic carbon contents decline (in this case because conversion of forest to arable land reduces the inputs of carbon from vegetation).

In southern Asia, crop suitability declines, producivity of maize declines but soybean productivity increases (in some parts). River flood risk increases and some coastal megacities see increased flood risk. Cooling energy demands rise by around 30-40%, but there is little change in heating demands. Water scarcity reduces under this story across many water-scarce parts of southern Asia.

The suitability of cropland for crop cultivation declines across much of sub-Saharan Africa, primarily due to reductions in available moisture; more than 90% of cropland in southern Africa would see a reduction in suitability for crop production; maize yields reduce by 20-40%. River flood risk increases substantially in parts of western Africa, and coastal flood risk increases in particular for many east African coastal cities. Across the Middle East and North Africa crop suitability declines and large populations are exposed to increased water scarcity and increased cooling energy demands; NPP also reduces in many parts of the region.

Within western and central Europe, river flood risk is little affected under this story, but close to 200 million people are exposed to increased water resources stress. Crop suitability increases in the north of the region but declines elsewhere, and spring wheat productivity declines across much of central and eastern Europe. Cooling energy demands are increased very significantly – from close to zero in northern Europe – but heating energy demands fall by at least 40%.

Under this story, the main potential impacts in north America appear to be reductions in crop suitability across much of western and central north America, but increases at the northern margins of agriculture, and mixtures of increases and decreases in crop yields. Cooling energy demands increase very significantly in the eastern parts of north America, where heating energy demands fall. Coastal wetland loss is particularly large along the west coast.

Across south America, maize and soybean yields fall and NPP decreases substantially across the Amazon basin; the suitability for cropping declines in the drier parts of eastern south America, but increases along parts of the west coast.

The impacts plotted in Figure 1 and tabulated in Table 3 would arise under one particular plausible climate future. In principle it is possible to produce similar stories under other climate models. Table 4 shows the global aggregated impacts for each indicator under another six climate models (and they should be compared with the global row in Table 3). Supplementary Figures 2-7 and Tables 3-8 show the regional impacts under six more climate model patterns.

4.3   Uncertainty in projected regional impacts

The uncertainty in regional impacts, by sector, are given in Table 5, which shows the range in estimated impacts across the climate models used (which range from 21 for most indicators to 7 for SOC).

For most impact sectors, the projected ranges are very large. In some cases – specifically the water and river flooding sectors – this is because of very large uncertainty in projected changes in regional rainfall (in south and east Asia, for example). In some other cases, the large uncertainty is because the sector in a region is particularly sensitive to change (for example where the baseline values in the absence of climate change are small – see forest and NPP change in west and central Asia). In other cases, the uncertainty range is dominated by individual anomalous regional changes. For example, the large range in estimated additional people exposed to coastal flooding is due to one particular climate model producing very considerably higher sea level rises in some regions than the others. There is least uncertainty in projected reductions in heating energy requirements and, for most regions, increases in cooling energy requirements; the greatest uncertainty here is in those regions where requirements are currently low – Europe and Canada – but are sensitive to small changes in temperature.

The considerable uncertainty in each region and sector needs to be interpreted carefully. It is not correct simply to add up the extremes of each range across regions and use this to characterise the global range; the global range will be smaller than the sum of the extremes because no one climate model produces the most extreme response in every region. Similarly, it is not appropriate to define the maximum impact across all sectors in a region as the sum of the maximum impacts for each

sector, because again no one single climate model produces the maximum impact in all sectors. Indeed, there are some associations between impacts in different sectors between climate models. For example, models which produce the greatest increase in exposure to water resources stress tend to be those which produce the smallest increase in exposure to river flooding, and the greatest area of cropland with a decline in suitability (see Supplementary Figure 8 for an example).

5. Impacts under different worlds and over time

Figure 2 shows how global impacts vary in 2020, 2050 and 2080 between the four SRES scenarios, across all climate models. There is little difference in impact between either the emissions or socio-economic scenarios in 2020, when temperature differences between the emissions scenarios (Supplementary Figure 1) are very small. By 2050 the differences in temperature between the A1b, A2 and B2 emissions scenarios remain small, but B1 produces a lower increase in temperature so in many sectors impacts are smaller with this scenario. B2 has a lower CO_2 concentration than A1b or A2, so produces a smaller increase in NPP and forest area despite the temperature changes being similar. Socio-economic impacts under A2 are higher than under the other scenarios despite little difference in temperature, and this is because of increased exposure under the A2 world. More people live in water-stressed or flood-prone areas and, in the coastal zone, there is less investment in coastal protection. By 2080 the difference between the emissions and socio-economic scenarios becomes greater. The greatest impacts are under A2, primarily because exposure is greater, and the lowest impacts tend to be under B1 with the lowest increase in temperature. However, for all indicators, the range between climate model patterns is considerably greater than the range between the emissions or socio-economic scenarios.

6. Conclusions

This paper has presented a high-level assessment of the global and regional impacts of climate change across a range of sectors. The assessment used a harmonised set of assumptions and data sets, four scenarios of future socio-economic development and emissions, and climate scenarios constructed from 21 climate models. The distribution of impacts between regions and the relationship between different impact indicators are important, so the assessment first describes impacts under a set of discrete 'stories' based on different climate models, and then considers uncertainty in regional impacts separately. The paper has therefore demonstrated a method for assessing multi-dimensional, regionally-variable impacts of climate change for a global assessment.

With A1b emissions and socio-economics, one plausible climate future (based on one climate model pattern) would result in 2050 in 1 billion people being exposed to increased water resources stress, around 450 million people exposed to increased frequency of river flooding, and an additional 1.3 million people flooded each year in coastal floods. Approximately half of all cropland would see a reduction in suitability for cropping, and the productivity of three major crops – spring wheat, soybean and maize – would be reduced in most regions. Global residential cooling energy requirements would increase by over 70% globally, but heating energy requirements would decrease

so total global heating and cooling energy requirements would reduce globally. The productivity of terrestrial ecosystems would be increased, and soil organic carbon contents would generally increase, leading to improved soil productivity and increased carbon storage. However, there is strong regional variability. Under this one climate model pattern, most of the global impacts on water stress and flooding would be in south, southeast and east Asia, but spring wheat productivity increases across much of Asia. In proportional terms, impacts on water stress and crop productivity are very large in the Middle East and North Africa region, which is exposed to multiple impacts.

There is considerable uncertainty in the projected regional impacts under a given emissions and socio-economic scenario, largely due to differences in the spatial pattern of climate change simulated by different climate models; this uncertainty varies between regions and sectors. Large increases in exposure to water resources stress, for example, are associated with large reductions in crop suitability but small increases in exposure to river flooding. The full richness of relationships between impacts in different places, and in different sectors, can therefore only be understood by comparing narrative stories constructed separately from different climate model scenarios.

There are, of course, a number of caveats with the approach. The climate scenarios used here are based on SRES emissions assumptions, and not on more recent RCP forcings. However, the spatial patterns of change in climate under the latest generation of climate model simulations are broadly similar to those used here (Knutti & Selacek, 2013). The climate scenarios are constructed by pattern scaling, and whilst this allows a direct comparison between different emissions scenarios and time periods, it does assume a particular relationship between the rate of global temperature change and the spatial pattern of change in climate. The indicators used represent an 'ensemble of opportunity', and do not necessarily span the full range of impacts of interest; there are also alternative indicators for many of the sectors considered here. The indicators do not (with the notable exception of crop productivity) explicitly incorporate the effects of adaptation in reducing the consequences of climate change. Comparisons with other single-sector global-scale impact assessments are made difficult by the use of different impact indicators (e.g. in the water sector) and different climate model scenarios. Insofar as it is possible to make comparisons, impacts as estimated in these other assessments are within the ranges presented here, but nevertheless the impacts presented here are best interpreted as indicative only. Finally, the indicators are calculated using only one impact model per sector. It is increasingly recognised that impact model uncertainty may make a substantial contribution to total impact uncertainty in some regions (e.g. Hagemann et al., 2013), and several initiatives are currently under way (for example ISI-MIP: Warszawska et al., 2014) to systematically evaluate the effects of impact model uncertainty.

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Figure 1:   Map of impacts under the A1b 2050 scenario: one plausible model

Figure 2:   Global-scale impacts of climate change in 2020, 2050 and 2080 under A1b, A2, B1 and B2 emissions and socio-economic scenario. The grey bars represent the range across the climate models, the example narrative story is shown by the solid circle.

Table 1:   Impact indicators

Table 2:   Regional and global exposure to impact in the absence of climate change

Table 3:   Regional and global impacts in 2050, under the A1b emissions and socio-economic scenario, under one plausible climate story. The socio-economic impacts are relative to the situation in 2050 in the absence of climate change (Table 2).

Table 4:   Global impacts in 2050, under the A1b emissions and socio-economic scenario, under six plausible stories. Compare with the global impacts in Table 3.

Table 5:   The range in regional and global impacts in 2050, under the A1b emissions and socio-economic scenario, across all climate models

Supplementary Figure 1:   Change in global average temperature (1a) and sea level (1b) under the four SRES emissions scenarios, relative to the 1961-1990 average. The plots show the average for each emissions scenario across all climate models with MAGICC model parameters, together with the maximum and minimum projected changes (dotted lines). The changes with A1b emissions under the individual climate models in 2100 are shown by asterisks.

Supplementary Figures 2-7   Maps of impacts under A1b 2050: six plausible models

Supplementary Figure 8:   Association between increased exposure to water resources stress in south Asia and (a) increased exposure to river flooding and (b) decline in crop suitability, across the 21 climate models. A1b emissions, 2050

Supplementary Table 1:   Regional classification

Supplementary Table 2:   Climate models used in the assessment

Supplementary Tables 3-8:   Regional impacts, by metric, under all climate model patterns: 2050, A1b emissions and socio-economic scenario