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NOTE AND COMMENT

The uncertainty of climate sensitivity and its implication for the Paris negotiation

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Abstract Uncertainty of climate sensitivity is one of the critical issues that may affect climate response strategies. Whereas the equilibrium climate sensitivity (ECS) was specified as 2–4.5 °C with the best estimate of 3 °C in the 4th Assessment Report of IPCC, it was revised to 1.5–4.5 °C in the 5th Assessment Report. The authors examined the impact of a difference in ECS assuming a best estimate of 2.5 °C, instead of 3 °C. The current pledges of several countries including the U.S., EU and China on emission reductions beyond 2020 are not on track for the 2 °C target with an ECS of 3 °C but are compatible with the target with an ECS of 2.5 °C. It is critically important for policymakers in Paris to know that they are in a position to make decisions under large uncertainty of ECS.

Keywords Uncertainty · Equilibrium climate sensitivity · Paris climate conference · Intended nationally determined contributions · 2 °C target

By the end of June, 2015, the United States, the European Union, China and several other countries submitted their intended nationally determined contributions (INDCs) to the UNFCCC secretariat. This is a good start toward the coming Paris climate conference (COP 21). However, according to our estimate based on our global energy systems model DNE21+ (Akimoto 2008) and a simple climate change model MAGICC (Meinshausen et al. 2011), these pledges are nowhere near sufficient to limit the temperature increase to less than 2 °C since pre-industrialization if we apply 3 °C as the best estimate[1] of the equilibrium climate sensitivity (ECS).

ECS is defined as an increase in global mean surface temperature caused by a doubling of the atmospheric CO_2 concentration. The uncertainty of climate sensitivity poses one of the greatest challenges in planning strategies on how and to what extent we should cope with risks of climate change.

Throughout IPCC's 1st to 3rd Assessment Report, the likely range of ECS was estimated as 1.5–4.5 °C with its best estimate at 2.5 °C. The 4th Assessment Report (AR4) specified a likely range (greater than 66 % probability) of ECS as 2–4.5 °C with its "most likely value" or "best estimate" of 3 °C, but the 5th Assessment Report (AR5) lowered the figure to 1.5–4.5 °C. In addition, no best estimate was given by AR5 because of the difference of methodologies of estimating ECS as explained below (IPCC 2013).

According to the estimates of atmosphere–ocean general circulation models (AOGCMs) in the AR5, the mean value of ECS is 3.2 °C and the ranges is 2.0–4.5 °C, close to that in the AR4. Climate sensitivity can also be estimated from observations of surface temperature and climate forcing data. The values of ECS thus estimated are rather lower as pointed out by Rogelj et al. and others (IPCC 2013, Lewis and Curry, 2014, Otto et al. 2013) and Lewis and Curry (2014) estimated the likely range of climate sensitivity as 1.25–2.45 °C with its median estimate at 1.64 °C.

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[1] There is no definition of the word 'best estimate'. Often the word is used in the same meaning as 'most likely value'. Sometimes it is used as the same meaning as 'median' or 'mode'. IPCC (2013) states that best estimate and most likely value are defined in various ways in different studies.

There are several criticisms of the observation-based methods, though, including one arguing that the observed warming is likely biased low (Durack et al. 2014).

We would like to examine the effect of uncertainty of ECS on emissions targets. Rogelj et al. (2014) admitting recent estimates based on the observed warming trends tend to show lower values of climate sensitivity, argues that "[T]here are several climate policy implications that can be drawn from recent ECS estimates. The most important, however, is that they do not change the big picture if all available evidence is taken into account. (…) Even the lowest ECS estimate assumed in this study only results in a delay of less than a decade in the timing of when the 2 °C threshold would be crossed when emission trends from the past 10 years are continued."

This conclusion, what we found, comes from the Supplementary Material of the paper. There, two ECS distributions, among others, were used for comparison; one was named as *IPCC AR4 consistent* and the other as *IPCC AR5 consistent*. By comparing those two, Rogelj et al. concluded that the differences of climate sensitivity 'do not change the picture'. What matters is that the median values of those two were almost the same, i.e., 3 °C for the former and 3.1 °C for the latter, though distribution itself is a little bit flat in *AR5 consistent*.

As pointed out previously, the likely range of ECS was lowered to 1.5–4.5 °C (in AR5) from 2 to 4.5 °C (in AR4), and experts were unable to agree on the value of the best estimate in AR5 though it was agreed as 3 °C in AR4. In addition, the value of 2.5 °C had been used as best estimate (most likely value) throughout IPCC's 1st to 3rd assessment reports where the likely range of climate sensitivity had been 1.5–4.5 °C. Under the above situation, it is only natural to assume the best estimate (median) for AR5 will be lower than 3 °C. Therefore, we chose the best estimate value of 2.5 °C for the purpose of comparison to explore the impact of difference in ECS on climate negotiations. The point at issue here is whether INDCs submitted by major countries are consistent with the 2 °C target under different climate sensitivities. Note that it is not the authors' intention to argue 2.5 °C is the correct value.

Rogelj et al. (2012), Schaeffer et al. (2015) and IPCC (2014) calculated the temperature by MAGICC with the probabilistic mode for climate sensitivity by assuming its probability density function (Table 1). However, as the probabilistic mode of MAGICC is not accessible for

Table 1 Relationship between CO_2 eq. concentrations, emissions reductions and temperature changes

CO_2 eq Concentrations in 2100 [ppm CO_2 eq] category label (concentration range)	Subcategories	Cumulative CO_2 emissions [$GtCO_2$] 2011–2100	Change in CO_2 eq emissions compared to 2010 2050 (%)	Temperature change (relative to 1850–1900)			
				2100 Temperature change [°C]	Likelihood of staying below temperature level over the twenty first century		
					1.5 °C	2.0 °C	3.0 °C
450 (430–480)	Total range	630–1180	−72 to −41	1.5–1.7 °C (1.0–2.8)	More unlikely than likely	Likely	Likely
500 (480–530)	No overshoot of 530 ppm CO_2 eq	960–1430	−57 to −42	1.7–1.9 °C (1.2–2.9)	Unlikely	More likely than not	
	Overshoot of 530 ppm CO_2 eq	990–1550	−55 to −25	1.8–2.0 °C (1.2–3.3)		About as likely as not	
550 (530–580)	No overshoot of 580 ppm CO_2 eq	1240–2240	−47 to −19	2.0–2.2 °C (1.4–3.6)		More unlikely than likely	
	Overshoot of 580 ppm CO_2 eq	1170–2100	−16 to +7	2.1–2.3 °C (1.4–3.6)			

The above table is an extract from Table SPM.1 from AR5 WG3 that shows information including the relationship between CO_2 eq. concentrations and temperature changes in 2100

Temperature change in 2100 is provided for a median estimate of the MAGICC calculations, which illustrates differences between the emissions pathways of the scenarios in each category

The range of temperature change in parentheses includes, in addition, the carbon cycle and climate system uncertainties as represented by the MAGICC model

Note that the above figures are calculated based on a climate sensitivity of 3 °C (most likely value)

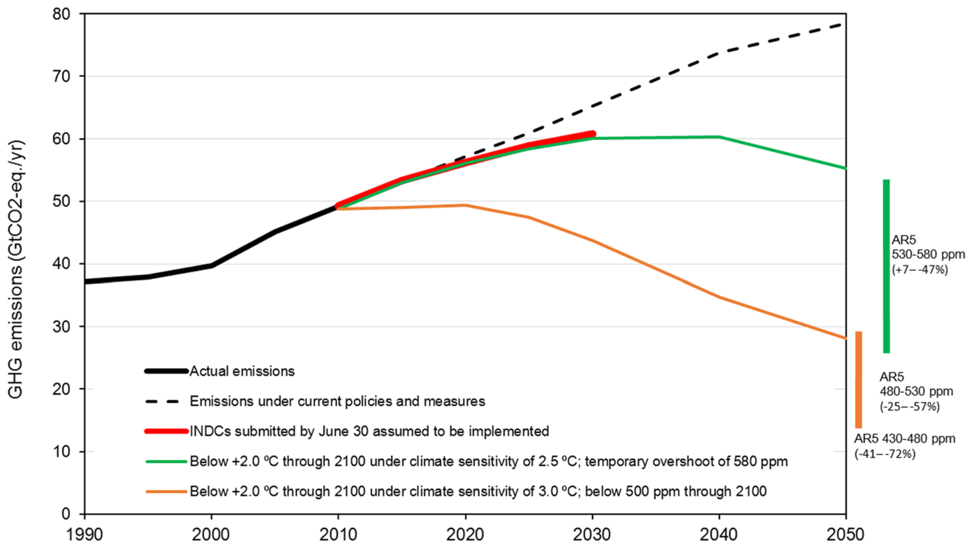

Fig. 1 Estimated emission pathways toward 2050 by the DNE21+ -model (and MAGGC model) which is a global energy system model with 54 disaggregated regions and countries, and seeks cost-effective measures on emission reductions*: Black dotted line* shows the emissions pathway under current policies, *green line* shows the emissions pathway that limits the temperature increase below 2 °C through 2100 under a climate sensitivity of 2.5 °C, which corresponds to the scenario of a slight temporal overshoot of 580ppm CO_2-eq. concentration in AR5. Temperature is expected to stabilize below 2 °C in the long run. *Orange line* shows the emissions pathway that limits the temperature increase to below 2 °C through 2100 under a climate sensitivity of 3 °C, which corresponds to the scenario in which the concentration stays below 500ppmCO_2 eq. through 2100 in AR5. Temperature is expected to stabilize below 2 °C even under a climate sensitivity of 3 °C. The *red line* shows emissions until 2030 based on the assumption that individual country's INDCs submitted at the end of June will be implemented. We assumed China's emissions in 2030 to be 16.7GtCO_2-eq. This almost corresponds to its BAU emissions. The US pledge covers only until 2025 and comprises two targets, i.e., 26 and 28 % emissions reduction relative to 2005. We assumed here that the 28 % emission reduction will be implemented by 2025, thereafter with a linear interpolation to 80 % reduction in 2050. (*Source* Research Institute of Innovative Technology for the Earth)

outsiders, we calculated the temperature for different emission pathways by using our global energy systems model DNE21+ and MAGICC without the probabilistic mode under certain climate sensitivities, i.e., 3.0 and 2.5 °C, instead of the median value under the probabilistic mode assuming the probability density function.

Figure 1 shows three emission pathways of which only figures toward 2050 are shown: The black line shows an emissions pathway with current policies (BAU), the green line shows an emissions pathway that limits temperature increase below 2 °C over the twenty first century under a climate sensitivity of 2.5 °C, which corresponds to the scenario of temporally, though slightly, overshooting 580 ppm CO_2-eq. in AR5, and the orange line shows an emissions pathway that limits temperature increase below 2 °C over the twenty first century with a climate sensitivity of 3 °C, which corresponds to the scenario where concentration stays below 500ppmCO_2 eq. through 2100. The red line shows an emissions pathway until 2030 on the assumption that the INDCs of countries that have been submitted by June 30 will be implemented. We estimated China's emissions will peak out in 2030 at 16.7 GtCO_2-eq. based on its upper range of CO_2/GDP improvement ratio of 65 % with annual GDP growth ratio of 6.2 % through 2015–2030. For the calculation of the 2030 emissions of United States, refer to the legend to Fig. 1.

The outcome of our model shows global total emissions under major countries' INDCs (red line) in 2030 will not be on track to attain the 2 °C target if climate sensitivity is 3 °C (orange line). On the other hand, the red line emissions are in line with the green line that is consistent with the 2 degree target if climate sensitivity is 2.5 °C, and if we allow a temporal overshoot of 580 ppmCO_2-eq. This implies, with ECS equal to 2.5 °C, that the 2 °C target is still within reach.

The authors would like to show, based on DNE21+ model, the difference of marginal abatement cost (MAC) to attain 2 °C target due to the difference of ECS. As shown in Fig. 2, MAC in 2050 is estimated to be as high as \$318/tCO_2 under ECS of 3 °C, but it is merely \$24/tCO_2 if ECS is 2.5 °C. This implies that 2 °C target would still be a feasible target.

It is clear from the above explanations that the impact of a mere 0.5 °C difference in climate sensitivity is of critical significance for policy objectives, which is especially significant given the large uncertainties over climate sensitivity.

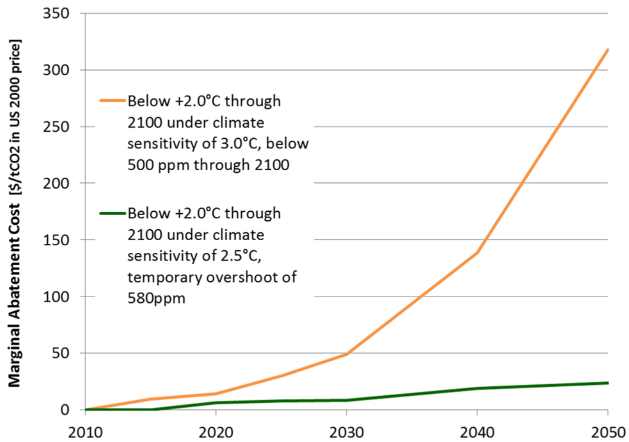

Fig. 2 Difference of Marginal Abatement Cost due to difference of ECS. The figure shows the difference of marginal abatement cost (MAC) due to difference of ECS. Both *orange and green lines* show MAC necessary to achieve 2 °C target (temperature stays below 2 °C since pre-industrialization through 2100). *Orange line* is based on the assumption that ECS would be 3 °C whereas *green line* is drawn on the assumption it would be 2.5 °C. MAC in 2050 in the former case is \$318/tCO_2 and the latter is \$24/tCO_2. (*Source* Research Institute of Innovative Technology for the Earth)

It is scientific community's vital role to narrow the uncertainty range of ECS. At the same time it is critically important for policymakers in Paris to know that they are in a position to make decisions under large uncertainty of ECS.

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