Natural Handling of Uncertainties in Fuzzy Climate Models

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Abstract: The wide range of the IPCC emission scenarios and the corresponding concentrations, forcings and temperature obtained with the use of the Magicc/Scengen Model are substituted by linearly increasing emissions that preserve the ranges of the values for the concentrations forcings and temperatures. In fact IPCC values are comprised within the values of the linear emissions. These allow the identification of simple relationships that are translated to fuzzy rules that in turn conform the fuzzy model. The sources of uncertainty that the model permits to explore are: the uncertainty due to not knowing what the emissions are going to be in the future, the one related to the climate sensitivity of the models (this has to do with different parameterizations of processes used in the models) and the uncertainties in the temperature maps produced by the models. Here we produce maps corresponding to 1, 2, 3, etc., degrees centigrade of temperature increase and discuss the timing of exceeding them. Therefore the argument instead of talking about the uncertainty in temperature at a certain date becomes about the uncertainty in the date certain temperature will be reached. The timing becomes another uncertainty.

1 INTRODUCTION

In a recent publication, Gay et al. (2012) simplified the emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) using linear functions of time that after being fed to the Magicc model (Wigley, 2008), produced the same wide range of concentrations of greenhouse gases (GHG) and aerosols, and the corresponding range of temperatures in 2100. These results show very clearly that higher temperature increases correspond to higher emission of GHG and higher atmospheric concentrations. This fact can be transformed into linguistic rules that in turn are used to build a fuzzy model, which uses concentration values of GHG as input variables and gives, as output, the temperature increase projected for year 2100. Based on the same principles a second fuzzy model is presented that includes a second source of uncertainty: climate sensitivity.

It is our intention to extend these results and produce maps of temperature.

It has been customary to ask what the temperature is going to be in 2030 or in 2050 and proceed to estimate the impacts that the changed temperature would have on social or economic sectors and activities that either may improve or most probably would be affected in a negative way. But in 2030 or in 2050 different models say different things so, what do we do? Use ensembles? Use the averages? Consider the standard deviation? Is the physics consistent? Here we propose to show temperature maps corresponding to global increases of 1, 2, 3, etc., degrees centigrade, give an idea of the uncertainty in timing, in contrast to the uncertainty in temperature for a certain date. This means that depending on the emissions, concentrations etc., the larger these variables, the sooner 1, 2, etc., degrees will be reached and considering other sources of uncertainty like the sensitivity, the pace of change may increase considerably. When we display the information in two dimensions produced by different models then the uncertainty due to different modeling strategies has to be considered.

We think that it is easier to consider a degree by degree strategy than one based on dates. The question of what to do if the temperature increases one degree or what should we be doing right now because the temperature is reaching one degree by 2021 (in the worst of cases) and if we do nothing we will be two degrees warmer by 2039 with grave consequences for all.

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2 METHOD

By using linear and non-intersecting emission trajectories, concentrations of GHG and global mean temperatures increases can be directly related as illustrated in figures 1 and 2 of Gay et al. (2012).

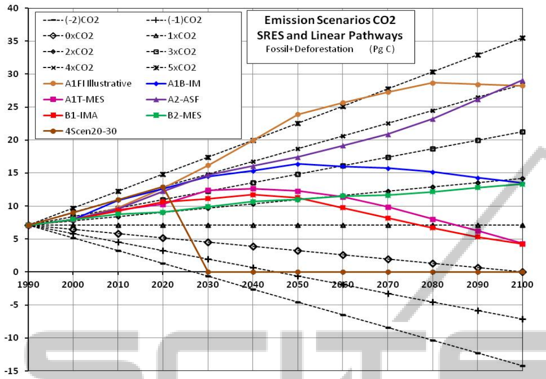

Figure 1: Emissions scenarios CO2, Illustrative SRES (Nakicenovic, et al. 2000) and Linear Pathways. (-2) CO2 means -2 times the emission (fossil + deforestation) of CO2 of 1990 by 2100 and so for -1, 0, 1, to 5 CO2. All the linear pathways contain the emission of non CO2 GHG as those of the A1FI. 4scen20-30 scenario follows the pathway of 4xCO2 but at 2030 all gases drop to 0 emissions or minimum value in CH4, N2O and SO2 cases.

With the linear emission pathways shown in the previous figure, used as input for the Magicc model, Gay et al. (2012) calculated the resulting concentrations (figure 2); radiative forcings (figure 3) and global mean temperature increments (figure 4) that we repeat here for clarity.

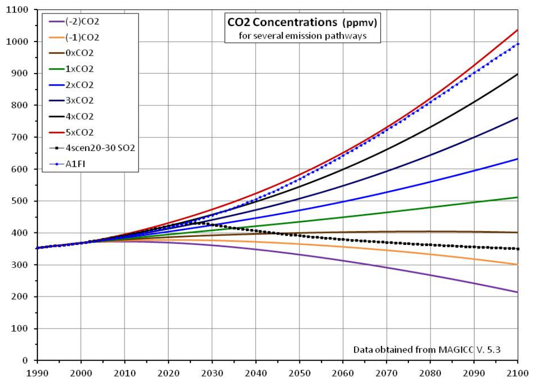

Figure 2: CO2 Concentrations for linear emission pathways (4scen20-30 SO2 and A1FI are shown for reference). Data calculated using Magicc V. 5.3.

We would like to remark a statement made before (that can be directly observed in Fig. 4): if we want to keep temperatures at two degrees or less by the

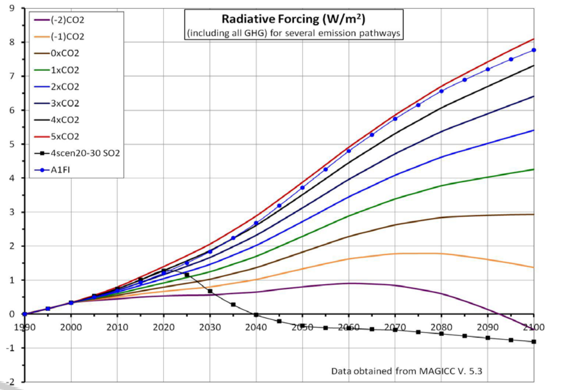

Figure 3: Radiative forcings (all GHG included) for linear emission pathways and A1FI SRES illustrative, the 4scen20-30 SO2 only include SO2. Data calculated using Magicc V. 5.3.

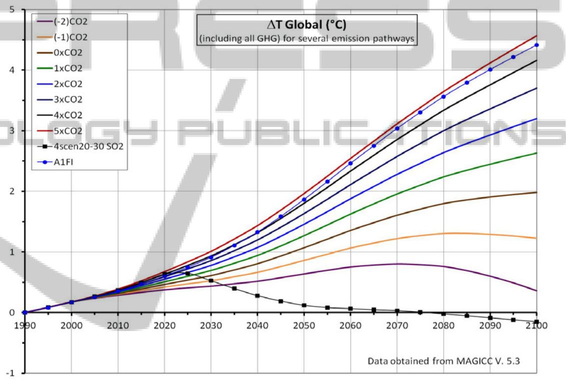

Figure 4: Global mean temperature increments for linear emission pathways, 4scen20-30 SO2 and A1FI; as calculated using Magicc V. 5.3.

year 2100, we should have concentrations in 2100 consistent with the -2CO2, -1CO2 and 0CO2 trajectories. The latter is a trajectory of constant emissions equal to the emissions in 1990 that gives us a temperature of two degrees by year 2100.

From the linear representation, it is easily deduced (as mentioned earlier) that *very high* emissions correspond to *very large* concentrations, *large* radiative forcings and *large* increases of temperature.

These simple observations are basic for the formulation of the fuzzy model, based on linguistic rules of the **IF-THEN** form, capable of estimating increases of temperature. The fuzzy model was built using the results of the Magicc model (Wigley, 2008) as crisp mathematical model, and Zadeh´s extension principle (Zadeh, 1965).

For illustrative purposes (the full rules are reported in Gay et al., 2013) we repeat here the first two rules of the 18 that were developed previously:

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   1. If (concentration is (-2)CO2) and
(sensitivity is low) then (deltaT is
T1) (1)
   2. If (concentration is (-1)CO2) and
(sensitivity is low) then (deltaT is
T2) (1)
   …
```

where the triangular fuzzy sets corresponding to T1 and T2 are (0.07, 0.07, 1.23) and (0.07, 0.61, 1.98) respectively.

The 18 rules were obtained from the combination of 6 concentrations, projected to 2100 and consistent with 6 linear emission trajectories, and 3 fuzzy values for the sensitivity of climate which are 1.5, 3.0 and 6.0 deg C/W/m2, all the values were taken from the data previously generated by successive runs of Magicc software.

Once we have the global temperatures and an idea of the associated uncertainty due to different emission paths and sensitivities we would like to convert this information to a two dimensional display of temperatures. The way to accomplish this is using the same idea for scaling employed in the Magicc/Scengen system (Wigley, 2008). This consists of scaling the value that results from running for a Global Circulation model (GCM) option (one of 20 possible), for example with double CO2 at a certain grid point in the following way:

$$T_{new} = T_{grid}/T_{map} \times T_{magicc} \tag{1}$$

where T_{new} is the scaled temperature, T_{grid} is the value of the temperature given by the GCM at a certain position, T_{map} is the average temperature (global) of the map and T_{magicc} is the temperature given by the simple model

However, emissions and sensitivity introduce uncertainties in the temperature that in turn must be reflected in the scaled temperature.

If we denote the uncertainty by a Δ then we propose:

$$\Delta T_{new} = T_{grid}/T_{map} \times \Delta T_{magicc} \tag{2}$$

where ΔT_{magicc}, is in fact a fuzzy number and consequently ΔT_{new} new also is.

We have to mention that another source of uncertainty is which GCM we use. We will try to illustrate this point too.

From the application of the Magicc/Scengen to the emission trajectories developed in the previous paper (Gay et al., 2012) we can extract the years in which the 1, 2, 3 and 4 degrees centigrade thresholds are reached.

According to the IPCCs Fourth Assessment Report (IPCC-WGI, 2007) the best estimate for the sensitivity is 3.0 however this parameter varies from 1.5 to 6, as mentioned before, so there is a source of uncertainty associated with this parameter. This is shown by the different values in the tables 1 to 5. Dates for emission scenarios B1-IMA and A1FI-MI (Nakicenovic et al. 2000) are shown for reference.

Table 1: Dates to achieve the 1 °C thresholds following linear emission trajectories from -2CO2 to 5CO2.

Emission Trajectory	Sensitivity (deg C/W/m2)		
	1.5	3.0	6.0
-2CO2			2049
-1CO2		2057	2039
0CO2	2079	2048	2033
1CO2	2063	2042	2029
2CO2	2056	2038	2027
3CO2	2051	2035	2024
4CO2	2047	2032	2023
5CO2	2044	2030	2021
B1-IMA	2090	2043	2027
A1FI-MI	2046	2033	2024

Table 2: Dates to achieve the 2 °C thresholds following linear emission trajectories from -2CO2 to 5CO2.

Emission Trajectory	Sensitivity (deg C/W/m2)		
	1.5	3.0	6.0
-2CO2			
-1CO2			2073
0CO2		2100 (1.98°C)	2059
1CO2		2072	2052
2CO2		2064	2048
3CO2	2093	2058	2045
4CO2	2081	2054	2042
5CO2	2053	2051	2039
B1-IMA			2057
A1FI-MI	2076	2053	2042

Table 3: Dates to achieve the 3 °C thresholds following linear emission trajectories from -2CO2 to 5CO2.

Emission Trajectory	Sensitivity (deg C/W/m2)		
	1.5	3.0	6.0
-2CO2			
-1CO2			
0CO2			2087
1CO2			2071
2CO2		2093	2064
3CO2		2081	2059
4CO2		2074	2055
5CO2		2069	2052
B1-IMA			2095
A1FI-MI		2070	2054

Taking into account the opinion of the IPCC that the best estimate for the sensitivity is 3, it can be said that we would be exceeding the one degree threshold by 2030 (sensitivity of 3 and emission trajectory of 5CO2). However due to the values that this

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Table 4: Dates to achieve the 4 °C thresholds following linear emission trajectories from -2CO2 to 5CO2.

Emission Trajectory	Sensitivity (deg C/W/m2)		
	1.5	3.0	6.0
-2CO2			
-1CO2			
0CO2			
1CO2			2095
2CO2			2080
3CO2			2073
4CO2		2097	2068
5CO2		2088	2064
B1-IMA			
A1FI-MI		2090	2065

Table 5: Dates to achieve the 5 °C thresholds following linear emission trajectories from -2CO2 to 5CO2.

Emission Trajectory	Sensitivity (deg C/W/m2)		
	1.5	3.0	6.0
-2CO2			
-1CO2			
0CO2			
1CO2			
2CO2			2100
3CO2			2088
4CO2			2080
5CO2			2075
B1-IMA			
A1FI-MI			2077

parameter may assume (1.5 to 6) this threshold may be delayed to 2044 if the sensitivity is 1.5 or may be advanced to 2021 if the sensitivity is 6. These values for the threshold correspond to our worst emissions scenario 5CO2. If we continue mounted in the same scenario we could be reaching 6 °C by 2087 and almost 7 °C by 2100.

Again for the 3 °C threshold we could be surpassing it as early as 2052 and the "best estimate" would be 2069; if the sensitivity were 1.5 the 3 °C temperature would not be reached.

From these tables we can also learn that if the sensitivity is 6 there is no way of staying at two degrees unless the concentrations of CO2 had followed the -2CO2 trajectory: negative emissions that means very strong subtraction of CO2 from the atmosphere.

If we were lucky and the climate sensitivity had a value of three the concentration would have to be equivalent to the 0CO2 path in 2100 this is about 300 ppmv.

There are obvious messages from the tables: the smaller the emissions the later the thresholds are exceeded, if we want small increases of temperature then we need to impose small emissions or more precisely small concentrations of CO2.

Two sources of uncertainty are illustrated in the tables, the first coming from the emissions: large emissions large temperature changes and the second due to our imprecise knowledge of the climate sensitivity of the models. One uncertainty is for the politicians because emissions depend on policy and the second for the scientists who may narrow the gap in the estimations of climate sensitivity.

3 RESULTS

The results of the fuzzy model that combines six levels of concentrations of CO2, from -2CO2 to 3CO2 in year 2100 (where 1CO2 identifies the concentration associated to the emissions in 1990), and 3 levels of sensitivity: 1.5, 3 and 6 are presented here. The model, that incorporates the uncertainties mentioned above, consisting of 18 fuzzy rules (Gay et al., 2013), is run to obtain global temperatures increases in year 2100 and their corresponding uncertainty intervals. This information is then used to produce two-dimensional maps depicting physically consistent geographical distributions of temperatures which in turn are consistent with global temperatures obtained from our fuzzy model. That the temperatures are physically consistent can be justified by using the results of a physically consistent model, in the same way the Magicc/Scengen does: using the results of runs of different GCMs.

The fuzzy model with the best estimate for the sensitivity is used to get the uncertainty intervals for 1, 2, 3 and 4 °C.

In the fuzzy model the value of the sensitivity is fixed at the best estimate of 3 and varying the concentration we try to get 1, 2, 3, etc degrees. The temperature is a function of the concentration. In this way we obtain:

For an increase of one degree the concentration of CO2 required is 220 ppmv and the uncertainty interval is from 0.08 to 2.17 degrees, based on the fuzzy sets feet presented in Gay et al. (2013) and reproduced here as a graph (see figure 5). Therefore for a one degree global increase the uncertainty extends to more than two degrees, consequently for a 1 °C global increase, maps for one and two degrees (see ahead, figure 7) are to be considered.

If ΔT is 2 degrees the interval is from 0.08 to 3.27 °C; for 3 and 4 degrees the uncertainty intervals are from 1.07 to 5.02 °C and from 1.82 to 6.41 °C respectively (see figure 6). Therefore for a 3 °C global increase the uncertainty extends to 5 °C so, maps corresponding to 3, 4 and 5 degrees should be considered.

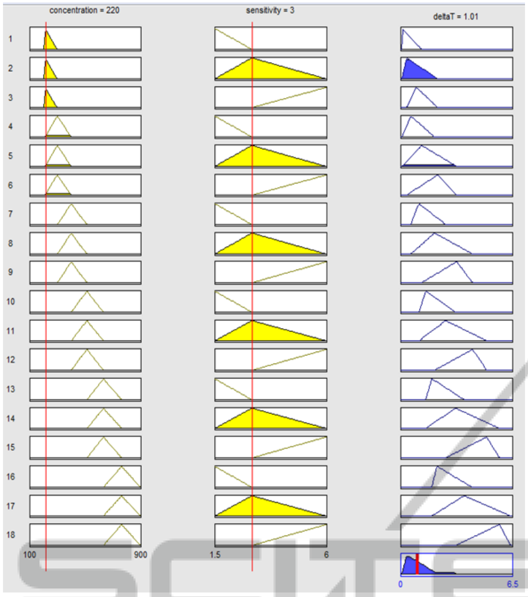

Figure 5: The 18 rules of the fuzzy model for the estimation of global mean temperature increase ΔT, for a concentration of CO2 of 220 ppmv and sensitivity of 3.0 deg C/W/m2. The uncertainty interval is (0.08, 2.17) or (0.08, 3.27) deg C considering the elongated part (calculated with MATLAB).

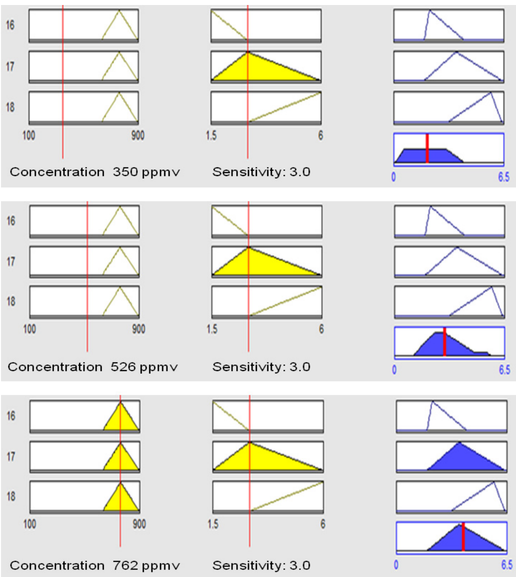

Figure 6: Similar to figure 5, estimation of global mean temperature increase ΔT and its uncertainty intervals (from the feet of the triangular fuzzy sets) for concentrations of CO2 of: 350 ppmv (upper panel) with 2.01 °C (0.08 to 3.27); 526 ppmv (middle panel) with 3 °C (1.07 to 5.02) or (1.07 to 5.75) considering the elongated part and 762 ppmv (lower panel) with 3.98 °C (1.82 to 6.41). Data calculated with MATLAB only the last 3 are shown for simplicity.

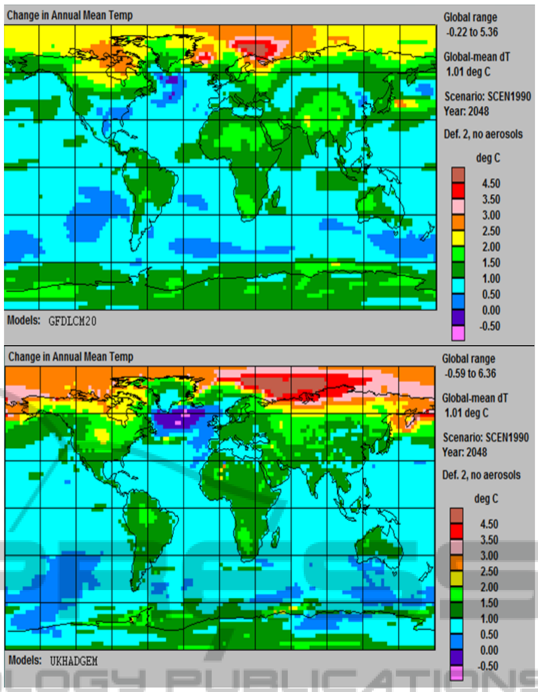

Figure 7: Spatial distribution of ΔT= 1.01 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 0CO2 emission trajectory (SCEN1990 in map). Maps were obtained using Magicc/Scengen V. 5.3.

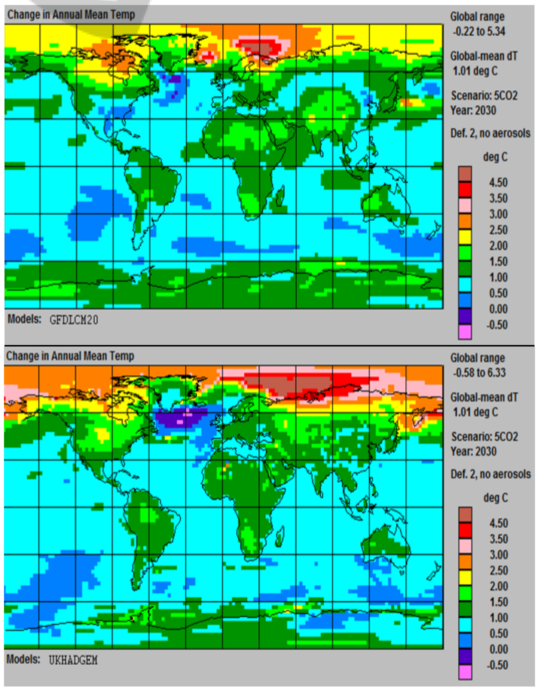

Figure 8: Spatial distribution of ΔT= 1.01 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 5CO2 emission trajectory. Maps were obtained using Magicc/Scengen V. 5.3.

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Now that we have the temperatures and the uncertainty intervals we use the Magicc/Scengen to obtain the maps for the temperatures referred above. This is done next.

As an example the results for the GCMs: (Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.0) GFDL 2.0 and (Hadley Centre Global Environmental Model version 1) HADGEM1 for 1, 2, 3 and 4 °C are shown (figures 7 to 12).

The maps obtained with Magicc/Scengen for the HADGEM1 model for an increase of 1.01 °C (and for ΔT ~ 2 °C) with 5 and 0 CO2, are almost identical, as expected; the same for the GFDL2.0, i. e., they are independent from the emission trajectories.

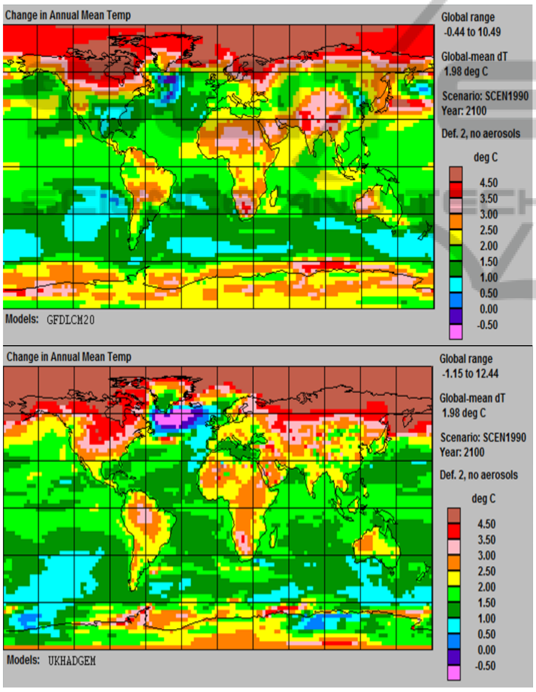

Figure 9: Spatial distribution of ΔT= 1.98 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 0CO2 emission trajectory (SCEN1990 in map). Maps were obtained using Magicc/Scengen V. 5.3.

Once we have temperatures, uncertainty intervals and two dimensional maps we can go back to the original question, but put in different terms. When is the temperature going to be one degree warmer than today? The answer: as soon as 2021 but there is the possibility of a larger increase. A picture of the warming can be imagined between maps of upper and lower panels shown in Figures 7 or 8. Now if the temperature is 2 degrees? The answer is that all the maps shown in the figures would become possible.

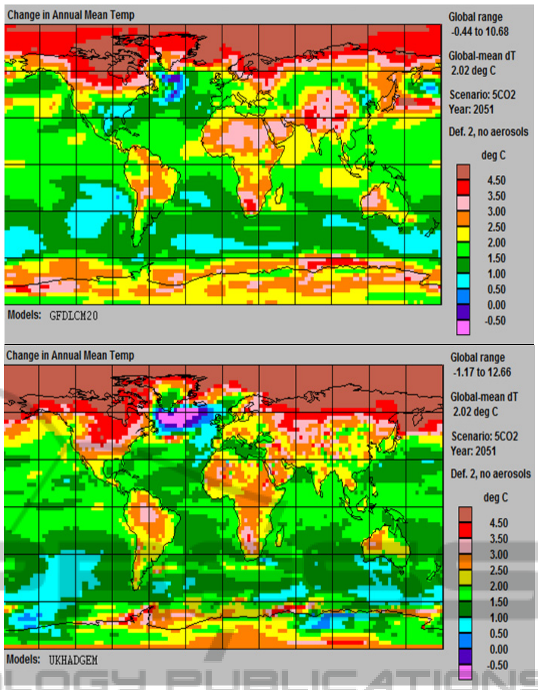

Figure 10: Spatial distribution of ΔT= 2.02 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 5CO2 emission trajectory. Maps were obtained using Magicc/Scengen V. 5.3.

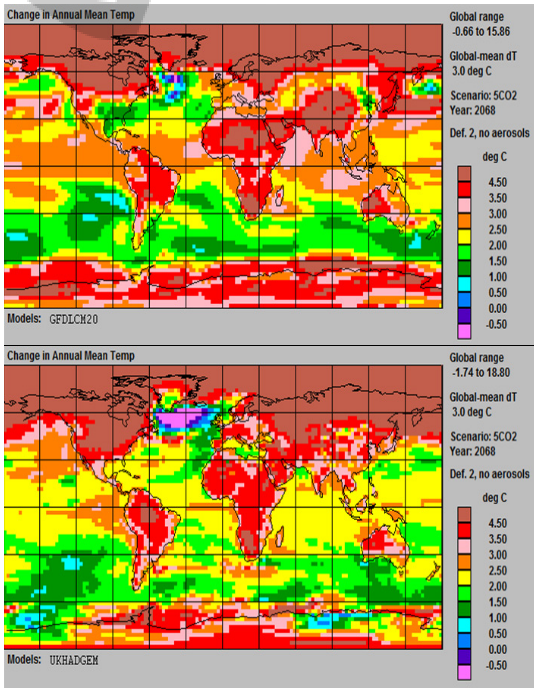

Figure 11: Spatial distribution of ΔT= 3.0 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 5CO2 emission trajectory. Maps were obtained using Magicc/Scengen V. 5.3.

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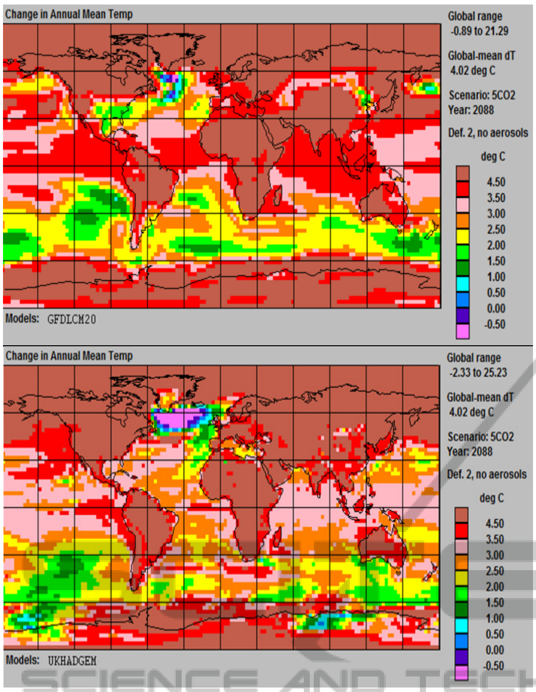

Figure 12: Spatial distribution of ΔT= 4.02 °C according to GFDL 2.0 (upper panel) and HADGEM1 (lower panel) for 5CO2 emission trajectory). Maps obtained using Magicc/Scengen V. 5.3.

4 CONCLUSIONS

Based on the fuzzy model presented by Gay et al. (2013) and the simple climate model contained in Magicc/Scengen we show how the global mean temperature increase is distributed on the globe for the significant thresholds of 1, 2, 3 and 4 °C. The linear emission pathways include all the possibilities mentioned in successive reports of IPCC.

In this work we considered the possibility of analysing the impacts of temperature increase from the perspective of the year in which some temperature is reached. Two sources of uncertainty are taken into account, the emissions of GHG and the climate sensitivity.

The larger concentration and sensitivity the sooner the successive thresholds of temperature will be reached. If the sensitivity is 6 there is no way of staying at two degrees unless the concentrations of CO2 had followed the -2CO2 trajectory: negative emissions that means very strong subtraction of CO2 from the atmosphere. We think that it is easier to consider a degree by degree strategy than one based on dates. For a one degree global increase the uncertainty extends to more than two degrees, then for a 1 °C global increase, maps for one and two degrees are to be considered. For 4 °C and sensitivity 3, uncertainty can extend to 6.41 °C

We construct maps for 2 GCM´s (as an example) with the necessary concentration to reach 1, 2, 3 and 4 °C limits to 2100. The maps show the spatial distribution of the temperature increase over the globe.

Emissions and sensitivity introduce uncertainties in the temperature that in turn must be reflected in the scaled temperature displayed in a map. Other source of uncertainty considered is the GCM. As expected, the map for any limit of temperature depends on the GCM but not on the emission trajectory. The maps constructed for different GCM´s illustrate all possibilities for a region of the globe.

Future work can be done to show how the GCM´s introduce uncertainty in the estimates of temperature increase in a regional scale.

ACKNOWLEDGEMENTS

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