A Simple Fuzzy Model to Estimate Carbon Emissions towards 2100 Consistent with Expected Temperature Increases

Carlos Gay García[1,2] and Oscar Casimiro Sánchez-Meneses[1]
[1]*Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México, Mexico*
[2]*Programa de Investigación en Cambio Climático, Universidad Nacional Autónoma de México, Ciudad Universitaria, Ciudad de México, Mexico*
{cgay@unam.mx, casimiro}@atmosfera.unam.mx

Keywords: Global Temperature Increments, Fuzzy Climate Models, Future Carbon Emissions, Linear Emission Pathways.

Abstract: It is a matter of discussion the magnitude of impacts caused by incremental thresholds of global temperature over the most important socio-economic and natural sectors. The focus is on the 2 °C and 1 °C thresholds. Based on a set of linear emission trajectories of CO2, a simple fuzzy model which estimates CO2 emissions for 2100, starting from the emissions projected for 2030 is shown. An additional fuzzy variable, the year for which the net carbon emissions begin to decrease, is also calculated. For the estimates of future global mean temperature increments, the simple climate model MAGICCv5.3, with moderate climate sensitivity, was used. The uncertainties of values of future emissions are easily included by a convenient selection of fuzzy sets in the input and output variables of the model. The results show that, in order to reach the 2 °C threshold, it will be necessary to require negative net emissions for years as close to 2030 as 2060´s and, even more, for the case of 1 °C. Indeed, 1 °C is, by now, far of the actual mitigation capabilities of the world. This information must be useful for the decision makers. The model developed can be extended for other values of global temperature increments.

1 INTRODUCTION

There are a lot of previous works about the estimation of future emissions of carbon dioxide (CO_2) based on multiple emission scenarios. More recently and widely used, it can be cited the "SRES" emission scenarios (from the Special Report on Emission Scenarios, IPCC, 2000) and the RCP´s (from the Representative Concentration Pathways, Meinshausen, 2011).

In recent years, the interest of climate change scientific community has been directed to the study of the impacts caused by significative incremental thresholds of global temperature, such as 1 °C and 2 °C, over the most important socio-economic and natural sectors. The thresholds represent stabilisation objectives for the emissions of greenhouse gasses beyond 2100. In the COP21 (Conference of the Parties to the United Nations Framework Convention on Climate Change, UNFCCC, December 2015, Paris, FR.) it was stated, among others agreements, the objective of elaborating a "special report on the impacts of global warming of 1.5°C (SR15) above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty" (http://www.ipcc.ch/meetings/session44/l2_adopted _outline_sr15.pdf).

Also in the COP21 another important agreement was reached, synthetized in the Intended Nationally Determined Contributions (INDCs). The INDC´s reflect the "climate actions that largely determine whether the world achieves the long-term goals of the Paris Agreement: to hold the increase in global average temperature to well below 2°C, to pursue efforts to limit the increase to 1.5°C, and to achieve net zero emissions in the second half of this century" (http://www.wri.org/indc-definition).

In this work we build a simple fuzzy model to relate the CO_2 emissions (fossil+deforestation) around year 2030 with the CO_2 emissions for the year 2100 considering the thresholds 1 °C and 2 °C.

The model is based on the linear emission pathways developed in previous works (Gay et al., 2012, Gay et al., 2013, Gay and Sánchez, 2013) and we use the simple climate model MAGICC v5.3 (Wigley, 2008) to estimate global mean temperature increments associated to cumulative emissions.

Fuzzy models of type FIS (Fuzzy Inference System), based on original work on fuzzy sets (Zadeh, 1965); have been used in previous works to estimate the uncertainties in emissions scenarios (Gay et al., 2013, Gay and Sánchez, 2013). It is not necessary to have sharp limits for fuzzy logic; therefore, ranges of uncertainty can be suitably calculated.

The main purpose is to establish a direct relation between emissions around 2030 and the emissions at 2100 through the threshold of global temperature increments.

2 SIMPLE FUZZY MODEL FOR EMISSION DATA FOR 2100

Gay et al. (2012) presented a set of linear, not intersected, emission paths calculated starting from the emissions of 1990, same reference date and value that the SRES (Nakicenovic, et al., 2000), and following paths directed towards emission values for 2100 ranging from 5, 4, 3, …, to -2 times the value for 1990, which is 7.098 petagrams of carbon (Pg C). The linear paths are used as input in MAGICC v5.3 to calculate the corresponding global concentrations, forcings and temperature increments (see figures 1 and 2 taken from Gay et al., 2012).

The linear emission pathways provide a convenient framework to estimate the uncertainties associated with concentrations, forcings and temperature increments, because any other realistic emission pathway (RCP´s as example) lies within the purposed limits 5CO2 and -2CO2.

Even though the value of emissions at 1990 is not actualized (by now the value is 7.53 Pg C) it has been decided to preserve the original emission time series for comparison with previous works but it has been included the actual observed series of CO_2 emissions in our graphs (see figures 5 and 6).

The MAGICC v5.3 contains a fairly detailed carbon cycle box model over ocean and land. Roughly, changes in CO_2 concentrations in the atmosphere with time are calculated in function of direct emissions (fossil and industrial), exchange with terrestrial biosphere, contribution from oxidized methane of fossil fuel origin, and sources of CO_2 derived from others processes, such as flux from the ocean carbon and net carbon uptake or release by the terrestrial biosphere due to CO_2 fertilization and climate feedbacks (Meinshausen et al., 2011 - 1).

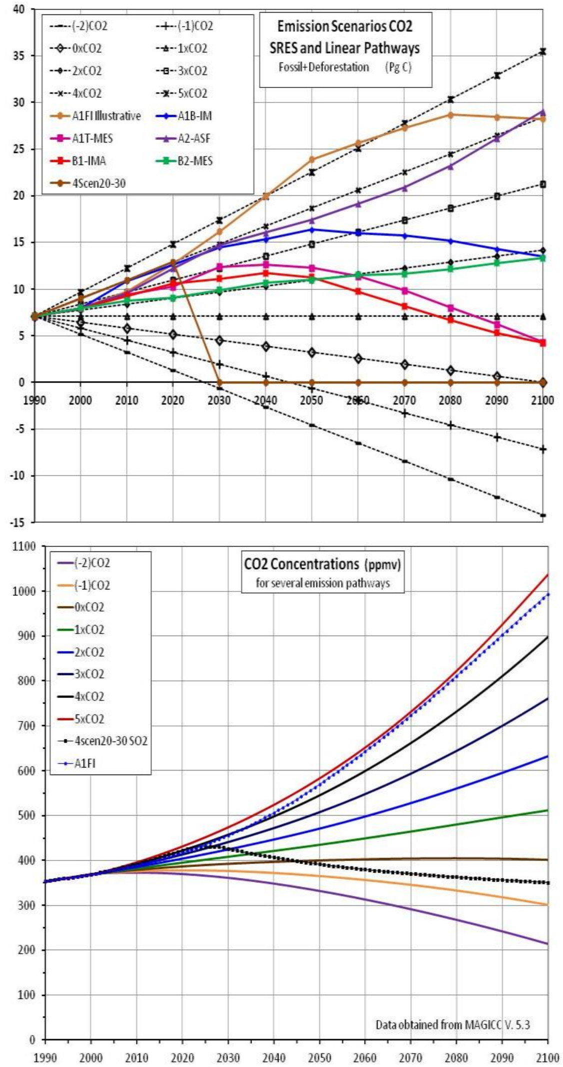

Figure 1: Upper panel: Emissions scenarios CO_2, Illustrative SRES and Linear Pathways. (-2)CO2 means -2 times the emission (fossil + deforestation) of CO_2 of 1990 by 2100 and so for -1, 0, 1, to 5CO2. All the linear pathways contain the emission of non CO_2 greenhouse gasses (GHG) as those of the A1FI (Nakicenovic, et al., 2000). 4scen20-30 scenario follows the pathway of $4xCO_2$ but at 2030 all gases drop to 0 emissions or minimum value in methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2) cases. Lower panel: CO_2 Concentrations for linear emission pathways, 4scen20-30 SO_2 and A1FI are shown for reference. Data calculated using MAGICC v5.3.

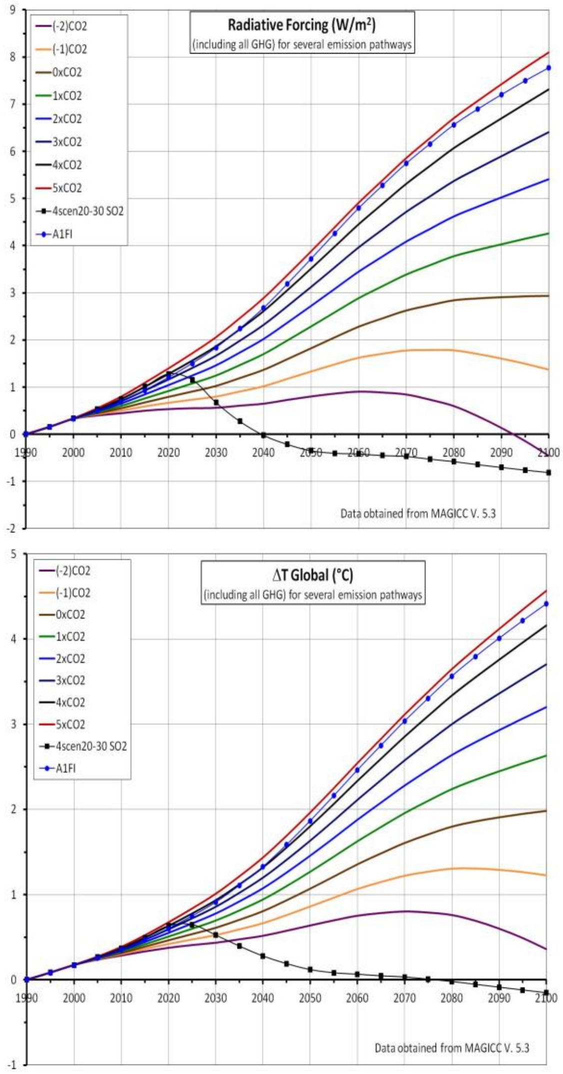

Figure 2: Upper panel: Radiative forcings (all GHG included) for linear emission pathways and A1FI SRES illustrative, the 4scen20-30 SO_2 only include SO_2. Lower panel: Global temperature increments for linear emission pathways, 4scen20-30 SO_2 and A1FI as calculated using MAGICC v5.3.

In a more direct manner, the concentrations for year 2100, from the linear emissions pathways, can be associated with the cumulative emissions for year 2100 (see figure 3).

Similarly, the global mean temperature increments can be associated with cumulative emissions for 2100 (see figure 4).

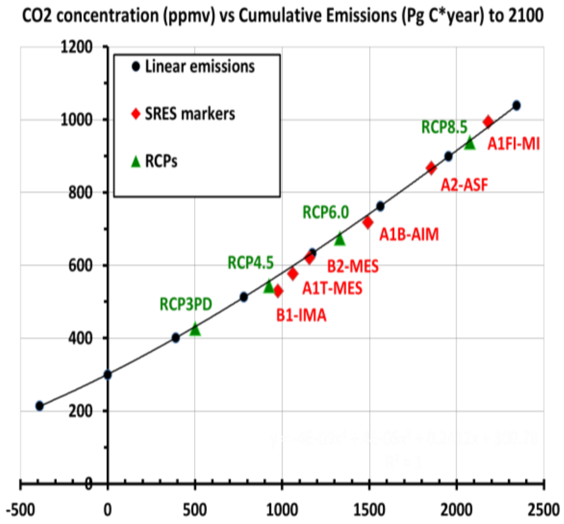

Figure 3: CO_2 concentration vs Cumulative Emissions for 2100. Linear emission pathways are shown as black bullets. RCP´s are taken from MAGICC 6.0 (Meinshausen et al., 2011 - 2) and SRES scenarios from MAGICC v5.3.

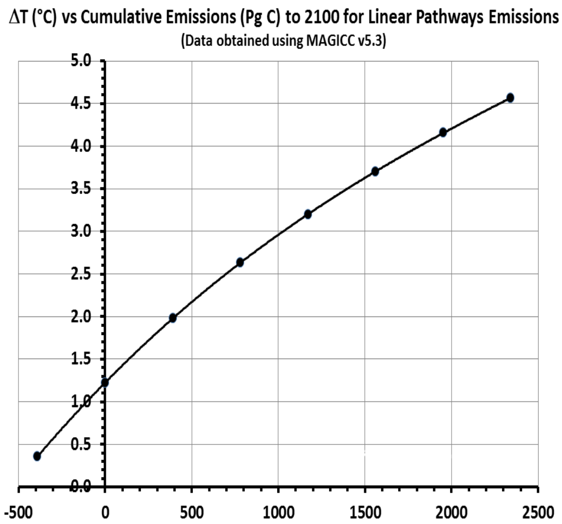

Figure 4: Global mean temperature increment as function of Cumulative Emissions (area under the path of emissions) for 2100.

Therefore, the value of cumulative emissions (the area under any emission pathway) can be calculated in correspondence with any given threshold of temperature increment.

Thus, for an increment of 1 °C the cumulative emission must be -105.39 Pg C and for 2 °C the corresponding value is 390.39 Pg C.

With these data we draw the polygonal emission pathways shown in figures 5 and 6.

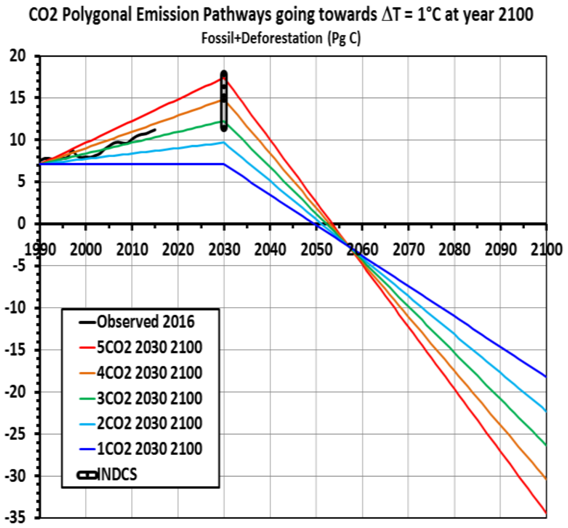

Figure 5: Polygonal emission pathways that lead to global mean temperature increment of 1 °C. Observed data from Global Carbon Project (https://www.co2.earth/global-co2-emissions). The vertical thick bar represents the range of INDC´s global total emissions for 2030 (data taken from Table 3.2 of UNEP (2015).

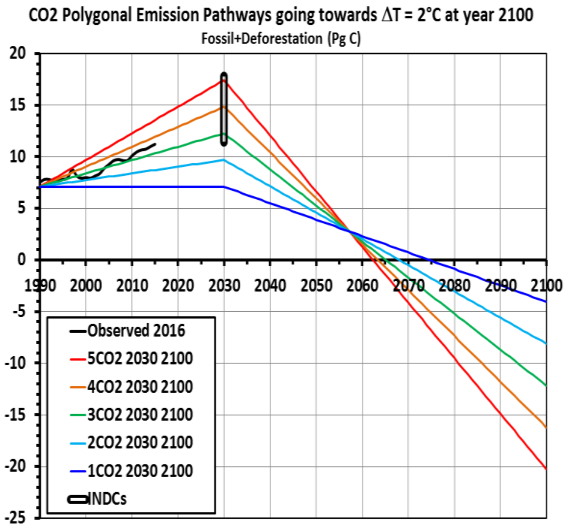

Figure 6: Polygonal emission pathways that lead to global mean temperature increment of 2 °C. Observed data from Global Carbon Project (https://www.co2.earth/global-co2-emissions). The vertical thick bar represents the range of INDC´s global total emissions for 2030 (data taken from Table 3.2 of UNEP (2015).

The figures 5 and 6 show us that the thresholds of 1 °C and 2 °C, require great negative net emissions of CO_2 for 2100.

A simple fuzzy (Mamdani) model can now be constructed, with the input and output fuzzy sets shown in Tables 1 and 2, for both thresholds 1 °C and 2 °C. The Fuzzy Logic Toolbox, coming with a free temporary license of MatLab, was used.

The fuzzy rules, in linguistic form, are:

1. **If** (Emission for 2030 is low) **then** (Emission for 2100 is Less negative)
2. **If** (Emission for 2030 is Med) **then** (Emission for 2100 is Negative)
3. **If** (Emission for 2030 is High) **then** (Emission for 2100 is Far negative).

The same rules are valid for the case of 2 °C.

Table 1: Fuzzy sets for 1 °C simple model Emissions 2030 vs Emissions 2100 (in Pg C).

	Membership value (μ)		
	0	1	0
Emission for 2030 fuzzy set			Input
Low	7.10	9.68	12.26
Med	9.68	12.26	14.84
High	12.26	14.84	17.42
Emission for 2100 fuzzy set			Output
Less negative	-26.33	-22.28	-18.22
Negative	-30.39	-26.33	-22.28
Far negative	-34.45	-30.39	-26.33

Table 2: Fuzzy sets for 2 °C simple model Emissions 2030 vs Emissions 2100 (in Pg C).

	Membership value (μ)		
	0	1	0
Emission for 2030 Fuzzy set			Input
Low	7.10	9.68	12.26
Med	9.68	12.26	14.84
High	12.26	14.84	17.42
Emission for 2100 Fuzzy set			Output
Less negative	-12.17	-8.11	-4.06
Negative	-16.22	-12.17	-8.11
Far negative	-20.28	-16.22	-12.17

The fuzzy model was applied for 2030 and the results are shown in figures 7 and 8.

The lower panels, in the figures 7 and 8, show the entire span of output and input values. For the case of the 1 °C simple fuzzy model the output ranges from -22.3 to -30.4 Pg C while, for 2 °C simple fuzzy model, the output span is less pronounced, from -8.09 to -16.2 Pg C. In both cases, the output is inside the ranges expected.

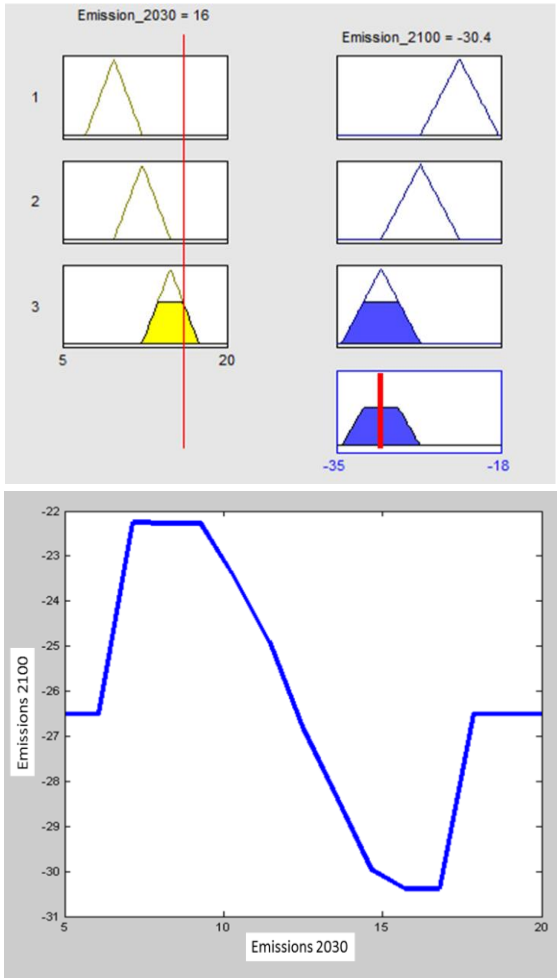

Figure 7: Upper panel: Fuzzy rules for 1 °C simple model (emissions in Pg C). The uncertainty in output is (-34.45, -26.33). Lower panel: Corresponding graph of the output range of the values of the emission for year 2100. The fuzzy sets were calculated with MatLab.

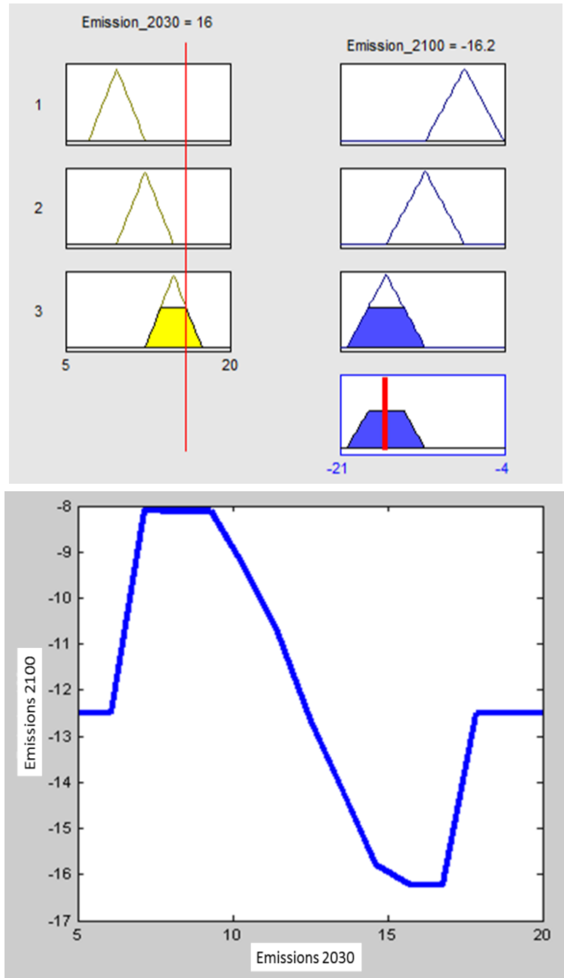

Figure 8: Fuzzy rules for 2 °C simple model (emissions in Pg C). The uncertainty in output is (-20.28, -12.17). Lower panel: Corresponding graph of the output range of the values of the emission for year 2100. The fuzzy sets were calculated with MatLab.

3 WHEN SHOULD WE BEGIN TO TAKE ACTIONS?

A simple fuzzy model to estimate the effect of delaying the taking of actions can be constructed starting from the information obtained in our previous calculations.

First, it can be noted that the actual CO_2 emission path is near the linear emission path 3CO2 (see figures 5 and 6). Then, a set of polygonal emission pathways, on the line of 3CO2, can be used to calculate the emissions for 2100, if actions are taken in 2020, 2030, 2040 or 2050, for both thresholds of temperature increments (see figures 9 and 10).

By the use of the Fuzzy Logic Toolbox of MatLab, in a similar way to the presented in the section before, a simple fuzzy model yields the results shown in figures 11 and 12.

The fuzzy rules applied, for 1 °C and 2 °C, in this case are:

```
   1. If (Date is Soon) then (Emission
for 2100 is Less negative)
   2. If (Date is Late) then (Emission
for 2100 is Far negative)
```

The fuzzy sets and the values of membership are presented in Tables 3 and 4.

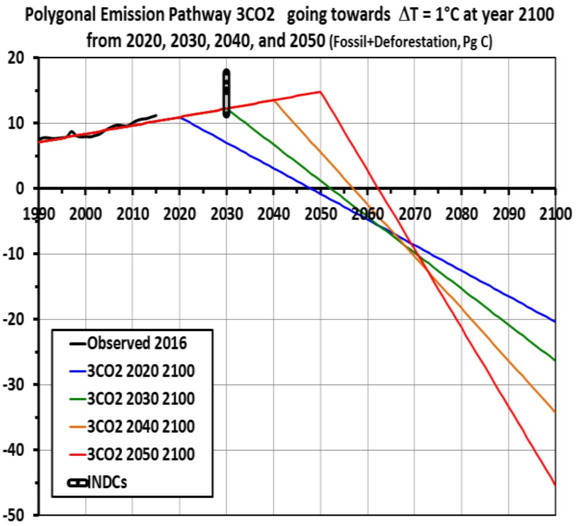

Figure 9: Polygonal emission pathways starting from 3CO2 for years 2020, 2030, 2040 and 2050 for 1 °C (emissions in Pg C). The vertical thick bar represents the range of INDC´s global total emissions for 2030 (data taken from Table 3.2 of UNEP (2015).

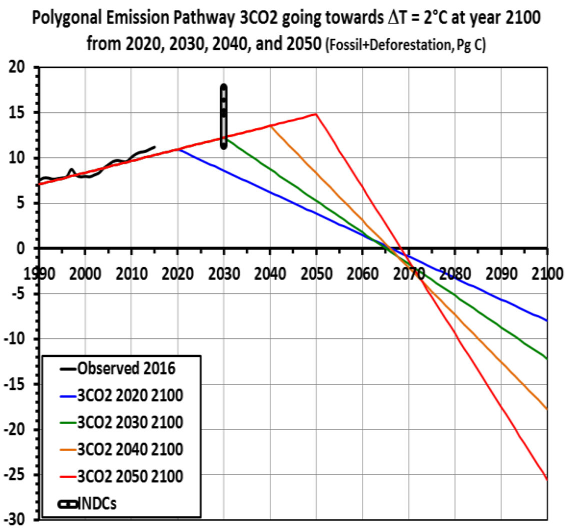

Figure 10: Polygonal emission pathways starting from 3CO2 for years 2020, 2030, 2040 and 2050 for 2 °C (emissions in Pg C). The vertical thick bar represents the range of INDC´s global total emissions for 2030 (data taken from Table 3.2 of UNEP (2015).

Table 3: Fuzzy sets for 1 °C simple model Date vs Emissions 2100 (emissions in Pg C).

	Membership value (μ)		
	0	1	0
Date to take actions fuzzy set			Input
Soon	2020	2030	2040
Late	2030	2040	2050
Emission for 2100 fuzzy set			Output
Less negative	-34.27	-30.39	-20.38
Far negative	-45.38	-34.27	-30.29

Table 4: Fuzzy sets for 2 °C simple model Date vs Emissions 2100 (emissions in Pg C).

	Membership value (μ)		
	0	1	0
Date to take actions fuzzy set			Input
Soon	2020	2030	2040
Late	2030	2040	2050
Emission for 2100 fuzzy set			Output
Less negative	-17.75	-12.17	-7.99
Far negative	-25.55	-17.75	-12.17

In the figures 11 and 12, the lower panels show the span of output and input values. The output range is inside the range expected. The emission for the year 2100 ranges from -27.3 to -37.9 Pg C for the first simple model and, for the second model, it varies from -12.6 to -18.8 Pg C.

4 DISCUSSION AND CONCLUSIONS

The INDC´s included in the figures 5, 6, 9 y 10, as a vertical bar, represent the global total emissions of CO2 equivalent, projected for 2030, in units of Pg C. The data were obtained from The Emissions Gap Report 2015 (UNEP, 2015). In the graphs mentioned, the bar ranges from the value corresponding to the 2 °C scenario (an idealized global scenario consistent with limiting warming to below 2 °C) to the baseline scenario (that assumes that no additional climate policies have been put in place since 2010), i.e., from 11.46 to 17.74 Pg C. Also, the bar shows the cases of conditional and unconditional INDCs (very close in the graphs) with emissions of 14.74 and 15.28 Pg C, and the current policy trajectory of emissions with 16.37 Pg C. With the simple fuzzy models developed in section 2, these values of emission give the results for year 2100 shown in table 5.

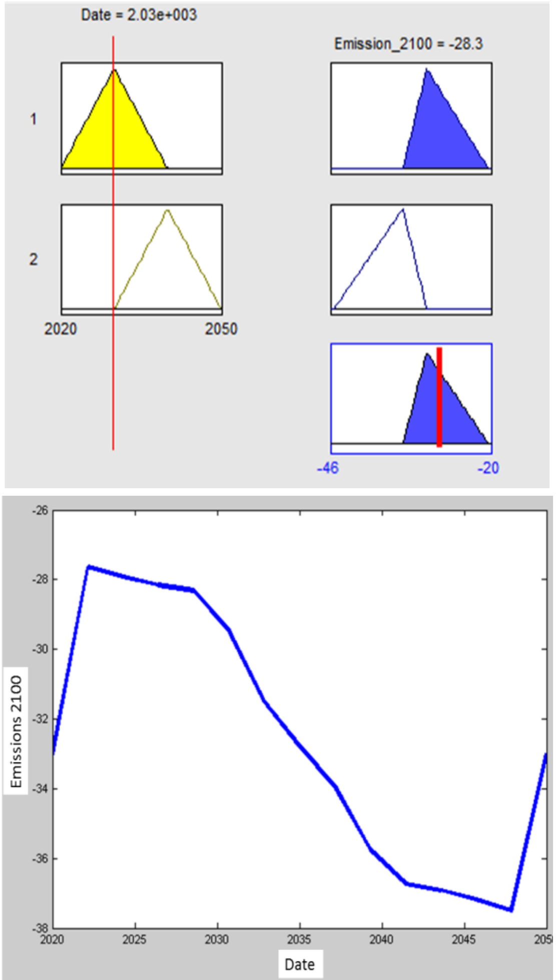

Figure 11: Fuzzy rules for 1 °C simple model (emissions in Pg C). The date in the input fuzzy set is 2030 and the uncertainty in output is (-34.27, -20.38). Lower panel: Graph of the output range of the values of the emission for year 2100. The fuzzy sets were calculated with MatLab.

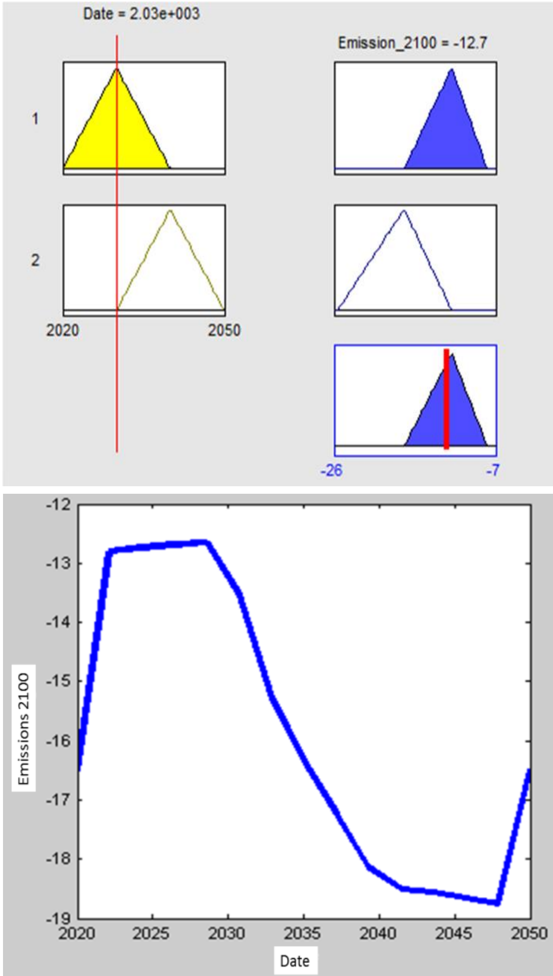

Figure 12: Fuzzy rules for 2 °C simple model (emissions in Pg C). The date in the input fuzzy set is 2030 and the uncertainty in output is (-17.75, -7.99). Lower panel: Graph of the output range of the values of the emission for year 2100. The fuzzy sets were calculated with MatLab.

Table 5: Emissions for year 2100 calculated with the emissions projected by INDCs until 2030 (Pg C).

Emission scenario cases	Projected emission	Fuzzy model for 1 °C	Fuzzy model for 2 °C
2°C pathways	11.46	-24.9	-10.8
Conditional INDC	14.74	-30.2	-16.0
Unconditional INDC	15.28	-30.4	-16.2
Current policy trajectory	16.37	-30.4	-16.2
Baseline 2010	17.74	Out of range	Out of range

The value 17.74 corresponding to baseline scenario of The Emissions Gap Report 2015 is slightly out of the input range, but uncertainty interval is (-34.45, -26.33) for 1 °C and (-20.28, -12.17) for 2 °C.

For the remaining cases, the models calculate adequate values of emissions.

The simple fuzzy models developed in section 3 were applied when the decision of taking actions is delayed until 2040. With the model of 1 °C it is obtained the value -36.7 Pg C for 2100 more negative than the values projected by INDCs scenarios. The same happens with model of 2 °C; the net emissions for 2100 have the value -18.5 Pg C.

For decision-making purposes, we have shown that the expectations of reaching stabilisation global mean incremental temperatures of 1 °C and 2 °C (with respect to 1990) for the year 2100 are not plausible. This is even more difficult if the pre-industrial levels are considered since there is about 0.5 °C additional temperature increment between pre-industrial levels and that of 1990.

There is a need to strongly reduce the emissions, as soon as possible, with the objective of reaching the expected 2 °C.

Reducing very drastically the emissions of CO2, and other greenhouse gases, to go back to levels of emission corresponding to 1 °C will require to have emissions of -28.3 Pg C for 2100, if the actions are taken in 2030. If we wait longer, greater efforts will be necessary.

ACKNOWLEDGEMENTS

This work was supported by the Programa de Investigación en Cambio Climático (PINCC, www.pincc.unam.mx) of the Universidad Nacional Autónoma de México and the Centro de Ciencias de la Atmósfera of the same university.

REFERENCES

Gay, C., Sánchez, O., Martínez-López, B., Nébot, Á., Estrada, F. 2012. Simple Fuzzy Logic Models to Estimate the Global Temperature Change due to GHG Emissions. 2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH). Special Session on Applications of Modeling and Simulation to Climatic Change and Environmental Sciences - MSCCEC 2012. July 28-31. Rome, Italy. Thomson Reuters Conference Proceedings Citation Index (ISI), INSPEC, DBLP and EI (Elsevier Index) http://www.informatik.uni-trier.de/~ley/db/conf/simultech/simultech2012.html.

Gay García, C., O. Sánchez Meneses. 2013. Natural Handling of Uncertainties in Fuzzy Climate Models. 3rd International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH). Special Session on Applications of Modeling and Simulation to Climatic Change and Environmental Sciences - MSCCEC 2013. July 29-31. Reykjavík, Iceland. Thomson Reuters Conference Proceedings Citation Index (ISI), INSPEC, DBLP and EI (Elsevier Index) Abstracts in: http://www.simultech.org/Abstracts/2013/MSCCEC_2013_Abstracts.htm

Gay, C., Sánchez, O., Martínez-López, B., Nébot, Á., Estrada, F. 2013. Fuzzy Models: Easier to Understand and an Easier Way to Handle Uncertainties in Climate Change Research. In: Simulation and Modeling Methodologies, Technologies and Applications. Volume Editor(s): Pina, N., Kacprzyk, J. and Filipe, J. In the series "Advances in Intelligent and Soft Computing". Springer- Verlag GmbH Berlin Heidelberg

Meinshausen, M., S. C. B. Raper and T. M. L. Wigley 2011 - 1. "Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6: Part 1 – Model Description and Calibration." Atmospheric Chemistry and Physics 11: 1417-1456. doi:10.5194/acp-11-1417-2011.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J-F, Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P. 2011 -2. "The RCP greenhouse gas concentrations and their extensions from 1765 to 2300", Climatic Change 109 (1-2): 213–241, doi:10.1007/s10584-011-0156-z

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T. Y. Jung, T. Kram, E. L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi, 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 599 pp.

UNEP (2015). The Emissions Gap Report 2015. United Nations Environment Programme (UNEP), Nairobi. 97 pp.

Wigley T. M. L. 2008. MAGICC/SCENGEN V. 5.3: User Manual (version 2). NCAR, Boulder, CO. 80 pp. (On line: http://www.cgd.ucar.edu/cas/wigley/magicc/)

Zadeh, L.A. 1965. Fuzzy Sets: Information and Control. Vol. 8(3) p. 338-353.