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ESTIMATING THE GLOBAL TEMPERATURE CHANGE BY MEANS OF A FUZZY LOGIC MODEL OBTAINED FROM IPCC PUBLISHED DATA

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ABSTRACT

The long term scenarios (until year 2100) developed by the The Intergovernmental Panel on Climate Change indicate a wide range of future concentration of greenhouse gases and aerosols. It can be inferred from these data that higher temperature increases are directly related with higher emission levels of greenhouse gases and the related increase into the atmosphere. It is also evident that lower temperature increases are related with smaller amounts of emissions and, therefore, with lower greenhouse gases concentrations. In this work simple linguistic rules are extracted from the IPCC reports in a subjective way. These rules describe the relations between the greenhouse gases emissions, their concentrations, the radiative forcing associated with concentrations, and the temperature changes. These rules are used to build a model, based on fuzzy logic, that uses emission and concentration values of greenhouse gases as input variables and gives, as output, the temperature increase projected for the year 2100. Different clustering alternatives are studied for the input and output variables. For instance, if the emissions and the concentrations are discretized into 5 classes, i.e. very low, low, medium, high and very high; and the temperatures increase are discretized in the same classes, a linguistic rule will be: if the greenhouse gas concentrations are very high then the temperature global increment is very high. A second fuzzy model is also built based on temperature values obtained from a determinist climate system model. This kind of fuzzy model is very useful due to its simplicity and to the fact that it includes the uncertainties associated to the input and output variables. A simple model, however, contains all the information of a sophisticated determinist model (or a set of them). These characteristics of the fuzzy model allow not only the understanding but also the discussion of the processes involved in the problem under study.

Key words: Global Warming, IPCC Data, Temperature Modelling, Fuzzy Logic, Extension Principle.

RESUMEN

Los escenarios de largo plazo (hasta el año 2100) desarrollados por el Panel Intergubernamental de Cambio Climático indican un rango muy amplio en los valores de las futuras concentraciones de gases de invernadero y aerosoles. Basándose en estos datos se puede inferir que los mayores incrementos de temperatura están directamente relacionados con una mayor cantidad de emisiones de gases de invernadero y el concomitante incremento de su concentración en la atmósfera. De igual manera, los menores incrementos de temperatura están relacionados con una menor cantidad de emisiones y, por ende, con menores concentraciones de gases de invernadero. En este trabajo se utilizan reglas lingüísticas simples, extraídas de manera subjetiva de los reportes de IPCC, que describen las relaciones entre las emisiones de gases de invernadero, sus concentraciones, los forzamientos radiativos asociados a estas concentraciones y los cambios de temperatura. Estas reglas se usan para construir un modelo, basado en lógica difusa, que utiliza los valores de emisiones y concentraciones de gases de invernadero como entradas y arroja, como salida, el incremento de temperatura proyectado al año 2100. Se analizan diversas formas de categorizar las variables de entrada y de salida. Por ejemplo, si las emisiones y concentraciones son categorizadas como muy bajas, bajas, medias, altas y muy altas; y los incrementos de temperatura son catagorizados de la misma manera, una regla lingüística sería: si las concentraciones de gases de invernadero son muy altas, entonces el incremento global de temperatura es muy alto. Se construye además un segundo modelo difuso basado en datos de temperatura provenientes de un modelo determinista del sistema climático. Este tipo de modelo difuso es muy útil por su simplicidad y por contener las incertidumbres asociadas a las variables de entrada y salida. Un modelo muy simple, en el cual, sin embargo, se encuentra contenida toda la información de un modelo determinista (o un conjunto de ellos) muy sofisticado(s). Estas características del modelo difuso facilitan tanto el entendimiento como la discusión de los procesos involucrados en el problema bajo estudio.

Palabras clave: Calentamiento Global, Datos del IPCC, Modelado del Clima, Lógica difusa, Principio de extensión.

1. INTRODUCTION

There is a growing scientific consensus that increasing emissions of greenhouse gases (GHG) are changing the Earth's climate. The IPCCs Fourth Assessment Report, released in November of 2007, states, Warming of the climate system is unequivocal, as is now evident from observation of increases in average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The report notes that eleven of the last twelve years (1995-2006) rank among the twelve warmest years of recorded temperatures (since 1850). Since the start of the industrial era (about 1750), the overall effect of human activities on climate greatly exceeds that due to known changes in natural processes, such as solar changes and volcanic eruptions (IPCC, 2007). The projections of future global temperature change ranged from 1.4 to 5.8 °C in the case of the IPCCs TAR report (IPCC, 2001). More recently, the projections indicate that temperatures would cover a range spanning from 1.1 to 4 °C but that temperatures of more than 6 °C could not be ruled out (IPCC, 2007). These differences reflect our limitations to perform accurate predictions of future climate change caused by the emissions of GHG. The sources of the uncertainty that prevent us from obtaining a better precision have diverse origins. One cause is related to the computer models that are used to predict future climate change. The global climate is a highly complex system due to many physical, chemical, and biological processes that take place among its subsystems on a wide range of space and time scales. These processes are simulated by global circulation models based on the fundamental laws of physics, which are the principal tool for predicting the response of the climate to increases in GH. In general, all model experiments point to global warming through the coming century. These complex global models, however, are not perfect representations of reality because, among other reasons, they do not include important physical processes (e.g. ocean eddies, gravity waves, atmospheric convection, clouds and small-scale turbulence) which are known to be key aspects of the climate system, but which are too small or fast to be explicitly modelled (WILLIAMS, 2005). Another cause is related to the parametrizations that are used in these models. More complex models implies more parameters that can be different from one model to another and that slightly modified, inside the same model, give different temperature values. Thus, it is important to determine the sensitivity of the simulated climate to the parametrized physics. The most important source of uncertainty is, however, the development of anthropogenic GHG emissions, which are related to the boundary conditions used by the climate models and are of crucial importance in the modelling approach. Future anthropogenic GHG emissions depend on numerous driving forces, including population growth, economic development, energy supply and use, land-use patterns, and a host of other human activities. An obvious (perhaps) observation is that temperatures are organized according to the emission profiles belonging to the four principal story line families A1, A2, B1, and B2 in which all emission paths of the SRES have been classified (NAKICENOVIC et al., 2000). From the point of view of a policy maker the results of the 3rd and 4th IPCCs assessments regarding the projection of global or for that matter regional temperature increases pose a problematic analysis due to the large difference in values, i.e. up to a 600 percent. These differences are the reflection of the uncertainties that have to be dealt with by the scientists and ultimately by the policy makers. Policy makers argue that they need more information than what is provided by the science of climate change. They do not know how to handle the uncertainty because many of them confuse uncertainty with ignorance.

The view of the concept of uncertainty has been changed in science over the years. The traditional view looks to uncertainty as undesirable in science and should be avoided by all possible means. The modern view is tolerant of uncertainty and considers that science should deal with it because it is part of the real world. This is especially relevant when the goal is to construct models. In this case, allowing more uncertainty tends to reduce complexity and increase credibility of the resulting model. The recognition by the researchers of the important role of uncertainty mainly occurs with the first publication of the fuzzy set theory, where the concept of objects that have not precise boundaries (fuzzy sets) is introduced (ZADEH, 1965).

Fuzzy logic, based on fuzzy sets, is a superset of conventional two-valued logic that has been extended to handle the concept of partial truth, i.e. truth values between completely true and completely false. The opportunity that brings fuzzy logic to represent sets as degrees of membership has a broad utility. On the one hand, it provides a meaningful and powerful representation of measurement uncertainties, and, on the other hand, it is able to represent efficiently the vague concepts of natural language. In this study we proposed a simple method based in Fuzzy Logic to estimate temperature increases within certain uncertainty intervals. The model is constructed by visual inspection of data contained in the reports of the IPCC. We use also a simple climate model to reproduce not only a unique, precise temperature but directly the ranges of temperature observed in the TAR (IPCC, 2001) and in the IPCC 4AR (IPCC, 2007). The climate model depends on a small number of parameters, with well-known ranges of variations, which are treated directly as fuzzy logic sets.

2. FUZZY LOGIC MODEL OBTAINED FROM IPCC DATA

The Third Assessment Report of the Intergovernmental Panel on Climate Change shows estimates of emissions, concentrations, forcing, and temperatures through 2100 (see Fig. 1). From these figures, we can conclude that high emissions correspond to high concentrations, high forcing, and finally, high temperatures. Contrarily, low emissions correspond to low concentrations, low forcing and, finally, low temperatures. This simple observation allows us to formulate simple rules that can be converted to a fuzzy model that can be used to estimate temperatures within certain uncertainty intervals. We used in this study the Fuzzy Logic Toolbox of MATLAB, which is a technical computing environment with tools for the design of systems based on fuzzy logic.

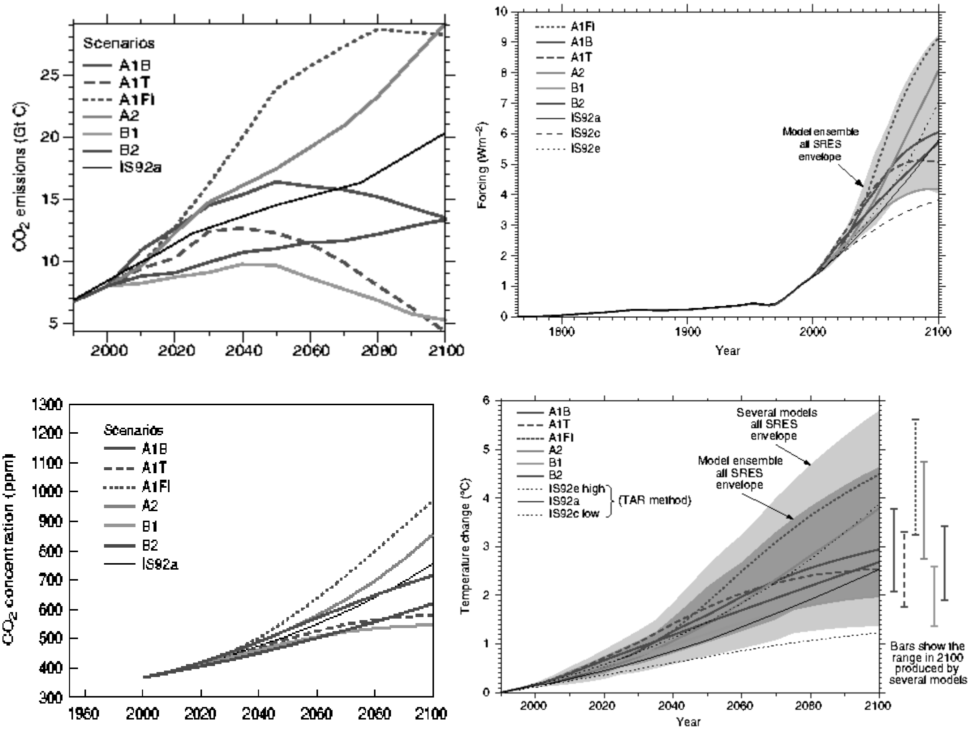
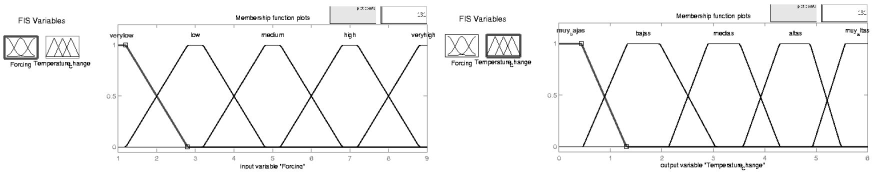


Figure 1: Anthropogenic emission of CO2 for the six illustrative SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T. For comparison the IS92a scenario is also shown (upper-left panel). [Based on IPCC Special Report on Emissions Scenarios.] Atmospheric concentration of CO2 resulting from the six SRES scenarios and from the IS92a scenario computed with current methodology (lower-left panel). Simple model results: estimated historical anthropogenic radiative forcing up to the year 2000 followed by radiative forcing for the six illustrative SRES scenarios. The shading shows the envelope of forcing that encompasses the full set of thirty five SRES scenarios (upper-rigt panel). Simple model results: global mean temperature projections for the six illustrative SRES scenarios using a simple climate model tuned to a number of complex models with a range of climate sensitivities. Also for comparison, following the same method, results are shown for IS92a. The darker shading represents the envelope of the full set of thirty five SRES scenarios using the average of the model results (mean climate sensitivity is 2.8 °C). The lighter shading is the envelope based on all seven model projections (with climate sensitivity in the range 1.7 to 4.2 °C). The bars show, for each of the six illustrative SRES scenarios, the range of simple model results in 2100 for the seven AOGCM model tunings (lower-right panel). Note: Figure adapted from the IPCCs TAR report (IPCC, 2001).

The first thing that we need to do is define the fuzzy discretization for the different variables of interest. For example, the radiative forcing at year 2000 has a value of approximately 1.2 w/m2. From a visual inspection of Fig. 1, we determine that the radiative forcing may vary in a wide range from 4 to 9 W/m2 by the year 2100. Therefore, we use a range from 1 to 9 w/m, which is known as the universe of scope of the linguistic variable forcing. Finally, we need to define for this variable several fuzzy sets which cover its universe of scope. Notice that given the linguistic variable, we can define several linguistic labels that are related each one to a fuzzy set. For example, after some trial-and-error adjustments we choose very low, low, medium, high, and very high for the linguistic variable forcing. The same procedure is repeated for the linguistic variable temperature (using the same linguistic labels).



Rule 1. **If** ***(forcing is very low)*** **then** ***(Temperature change is very small)***

Rule 2. If ***(forcing is low)*** **then** ***(Temperature change is small)***

Rule 3. If ***(forcing is medium)*** **then** ***(Temperature change is medium)***

Rule 4. If ***(forcing is high)*** **then** ***(Temperature change is large)***

Rule 5. If ***(forcing is very high)*** **then** ***(Temperature change is very large)***

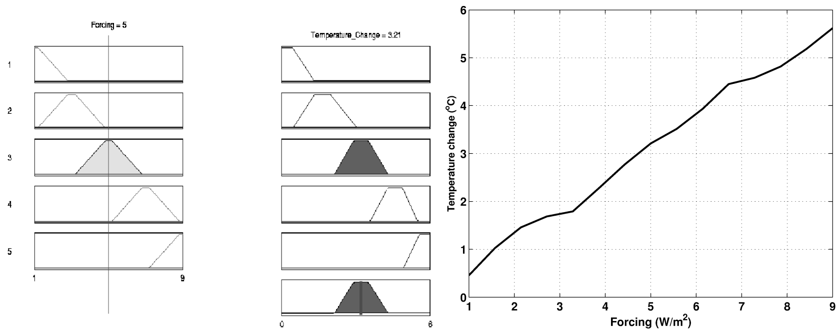


Figure 2: Fuzzy model based on linguistic rules derived by visual inspection of IPCC data. The input variable (Forcing) is discretized by 5 fuzzy sets, which are labelled as Very low, Low, Medium, High, and Very High (upper-left panel). A similar discretization and labelling is used for the output variable (Temperature, upper-right panel). The linguistic rules connecting both fuzzy sets are shown in the middle panel. The defuzzification process and its result are shown in the lower panels.

Now, fuzzy logic provides the means for constructing fuzzy systems, which consist of several rules, extracted from expert knowledge, that explain how the linguistic labels are related (set of linguistic rules in the **IF-THEN** form). For example, **IF** forcing is very low **THEN** temperature is very low, a very simple rule. The selected discretizations of the input/output universes and the linguistic rules are shown in the upper and the left-lower panel of Fig. 2. Notice that the output values (temperature) have the form of a fuzzy set. This fuzzy set is transformed into a numerical value by means of defuzzification. The resulting temperature values are shown in the right-lower panel. It should be noted that the formulation of these linguistic rules and the definition of fuzzy sets have a subjective character. There are some fuzzy inference and defuzzification methods that allow us to compute output values for certain input values. In this paper the Mamdani's fuzzy inference method is used.

3. A SIMPLE CLIMATE MODEL AND ITS CORRESPONDING FUZZY MODEL

In the previous section, we introduced a fuzzy model based entirely on expert judgment rather than on an objective quantitative method. Here, we constructed a fuzzy model, similar to that of the section 2, but based on temperature data obtained from a simple climate model.

3.1 The simple climate model

The climate model used here is identical to that of TAHVONEN et al. (1994). These authors developed a highly simplified time-dependent low-dimensional system to describe conceptually the interaction of climate and economy. They simulated the climate system by just two variables, namely globally averaged near-surface air temperature (T) and globally averaged tropospheric CO_2 concentration (C). T and C are not considered absolute values but anomalies with respect to the pre-industrial values, which are characterized by $C = 0$ and $T = 0$. Our description follows very closely to these authors. The emissions $E(t)$ and the temperature $T(t)$ are related through the concentration of CO_2 and two highly simplified linear differential equations.

$$\frac{dC(t)}{dt} = -\sigma \cdot C(t) + \beta \cdot E(t) \quad (1)$$

$$\frac{dT(t)}{dt} = -\alpha \cdot T(t) + \mu \cdot C(t) \quad (2)$$

In Eqs. 1 and 2 all constants except β are unknown and have to be fitted to data either from observations or from simulations (see Section 3b of TAHVONEN *et al.*, 1994). The conversion rate, β, which relates emission to concentration, is set to 0.47 $ppmGtC^{-1}$ (cf. MAIER-REIMER and HASSELMANN, 1987). The terms $\sigma \cdot C(t)$ and $\alpha \cdot T(t)$ describe feedbacks which force the temperature and CO_2 concentration back to the preindustrial levels ($T = 0$, $C = 0$). A more physical description: these are memory terms that determine the rate of relaxation of the solutions to the equilibrium levels which are determined by the external forcing. The two source terms, $\beta \cdot E(t)$ and $\mu \cdot C(t)$, drive the system away from the preindustrial levels. TAHVONEN et al. (1994) discuss in detail some severe simplifications of the linear system (Eqs. 1 and 2). They, however, found this system sufficient to describe first-order interactions.

Given an emission path $E(t)$, the concentration path $C(t)$ and the temperature path $T(t)$ are completely determined. We performed a set of 11 experiments in which Eqs. 1 and 2 are integrated for 250 years (1850-2100). In all experiments, the model is driven during the first 150 years using available emissions data (source: WRI). In the first experiment, the model is driven using the SRES-A2 emissions scenario for the period 2000-2100 (Fig. 3, upper-left panel). In the following 9 experiments, SRES-A2 emissions are reduced linearly (10 % per model run). Finally, 2000 year emissions are used in the last experiment.

The results (Fig. 3, upper-right and lower-left panels) show that the simulated ranges of concentrations and temperatures are comparable to that reported by the IPCC. Despite its simplicity, the climate model is able to describe the dynamics imposed by the emissions paths projected up the year 2100. The linear relation between emissions and temperatures is evident when we plotted emissions vs. temperature at year 2100. Notice, however, that the nonlinear nature of the climate system implies that its reactions to unexpected perturbations could be different as the expected ones. This issue is beyond the scope of this research.

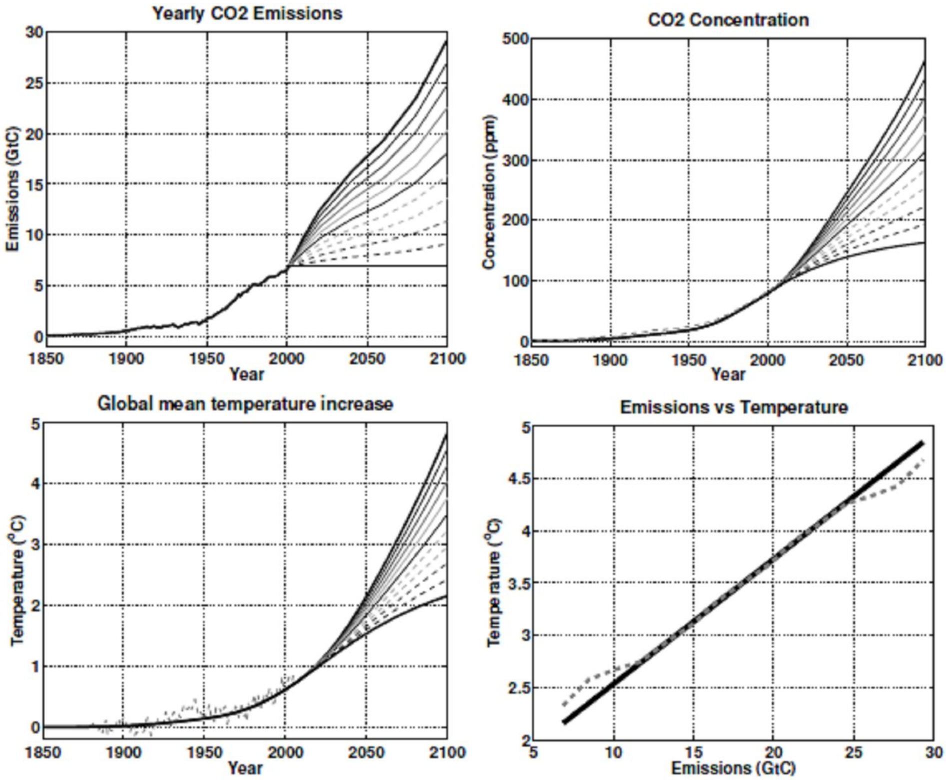


Figure 3: Evolution of: CO2 emissions (upper-left panel), atmospheric concentration (upper-right panel), and temperature (lower-left panel) represented as deviations of the preindustrial levels. The observed values of emissions for the period 1850-2000, and the corresponding concentrations and temperatures computed by the linear model are plotted with tick black lines. Observed values of concentrations and temperatures are also shown (thick grey dashed lines). For the period 2000-2100, SRES-A2 emissions scenario and the 2000 year emissions are used as the upper and lower values of our simulations. See text for details. Linear relation between emissions and temperature at year 2100 (thick black line, lower-right panel). In this panel, the results of a Fuzzy Model derived from the simple climate model are also shown (thick grey dashed line).

3.2 The corresponding Fuzzy Model

From the simple climate model described in section 3.1 it is intended to construct the corresponding fuzzy model by means of the extension principle. The extension principle enables us to extend the domain of a function on fuzzy sets, i.e. it allows us to determine the fuzziness in the output given that the input variables are already fuzzy. The fuzzy input variables and the transformation function are then used by the extension principle to obtain the fuzzy sets of the output variable. In the problem at hand, the input fuzzy sets are defined as explained in section 2, for instance we choose very low, low, medium, medium-high, high, and very high for the linguistic variable emissions; and the transformation function is already given by the function shown at the lower-right panel of Fig. 2. The extension principle is then used to obtain the temperature fuzzy sets, i.e. small, very small, medium, large, and very large by applying the transformation function to each of the emissions fuzzy sets. The selected discretizations of the input/output universes are shown in the Fig. 4. The resulting temperature values are shown in the lower-right panel of Fig. 3. It is evident that the fuzzy model captures very well the implicit relation between emissions and temperature. Despite its simplicity, this kind of model is very useful because it includes the uncertainties associated to the input and output variables.

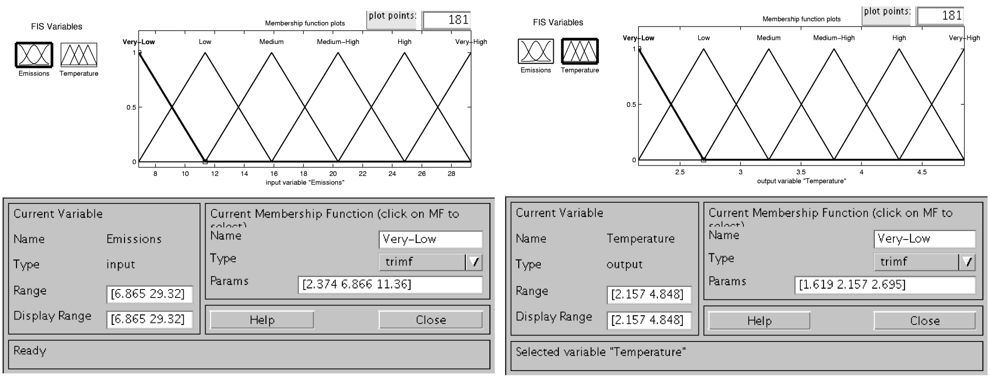


Figure 4: Fuzzy model based on temperature data obtained from a simple climate model. Fuzzy input variable (Emissions) and its selected discretization (left panel). The output variable (Temperature) is discretized in the same way (right panel).

4. DISCUSSION AND CONCLUSIONS

In this work simple linguistic rules are extracted from the IPCC reports in a subjective way and are used to build a fuzzy model. The fuzzy model uses emission and concentration values of GHG as input variables and gives, as output, the temperature increase projected at year 2100. A very simple linear climate model reproduces the wide range of concentrations and temperatures reported by the IPCC. Despite its simplicity, the model describes the dynamics imposed by the emissions paths projected up the year 2100. A second fuzzy model, based on the temperature values obtained from the simple climate model, is constructed. This kind of fuzzy model is very useful due to its simplicity and to the fact that it includes the uncertainties associated to the input and output variables. A simple model, however, could contain all the information necessary for decisions to be made without recurring to highly complex climate models. These characteristics of the fuzzy model allow not only the understanding but also the discussion of the processes involved in the problem under study.

5. REFERENCES

IPCC (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press.

MAIER-REIMER, E. and HASSELMANN, K.F. (1987). Transport and storage of CO2, in the ocean - an inorganic ocean-circulation carbon cycle model. Clim. Dynam. 2: 63-90

NAKICENOVIC, N. et al (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp.

TAHVONEN, O., VON STORCH, H. and VON STORCH, J. (1994). Economic efficiency of CO2 reduction programs. Clim. Res. 4, 127-141.

WILLIAMS, P.D. (2005). Modelling climate change: The role of unresolved processes, Phil. Trans. R. Soc. A, 363, 2931-2946.

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