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2013

Mathematical Contest in Modeling (MCM/ICM) Summary Sheet

(Attach a copy of this page to your solution paper.)

Type a summary of your results on this page. Do not include
the name of your school, advisor, or team members on this page.

Measuring Earth's Health by CO2: a Technology Diffusion Network Approach

We measure Earth's health condition by its Atmosphere CO2 Concentration (ACM) and jointly utilize three interacting models to predict future concentration level. The health measure can be calculated by the combined results of these three models.

The Technology Diffusion Network Model is the core of our solution. (1) The nodes represent individual countries, each with a Technology Index as its ability to produce CO2 emission reduction technology. (2) The links identify the diffusion of technology, and a certain amount of Inspiration passes from one country to another through these links. (3) Self-produced technology and received inspiration make the Accumulated Technology Index (ATI), which determines the amount of Inspiration together with a Closeness index between the two countries. (4) These indicators are estimated by most current data. Together they contribute to individual ATIs and converts into CO2 Reduction Rates.

The CO2 Regression Model uses datasets by country from the last two decades to predict future CO2 emission. It includes many contributing factors like economic growth and structural changes in energy consumption, but excludes the effect of technology advance depicted above.

The CO2 Absorption Model looks at the carbon cycle in terms of nature's ability to absorb CO2. When CO2 level rises, global temperature climbs at the same time. This lowers oceanic absorption and though it facilitates photosynthesis at first, an abnormally elevated temperature makes plants sick and altogether hinders photosynthesis. When plant absorption reaches zero, no more organic matter will be produced, leading to the tipping point.

Our dynamic global model allows us to embrace the complexity of Earth's interrelated systems from a simple focus of technology. It includes the effects of nodal conditions on the whole network and vice versa. As we run our model to predict future Earth health, we find that if emission reduction technology remains under-developed, we will reach the tipping point by the year of 2051. If effective measures are taken, this state shift may very well be postponed. This urges policy makers to invest more in Research & Development expenditure and collaborate to facilitate technology sharing between countries.

The structure analysis shows us that countries with higher economic and technology level are likely to be more critical nodes in this model. Higher economic freedom and shorter distance defines more important links. Sensitivity to missing links or changing relationships relies on the specific condition of the link. Our model also uses feedback loops regarding technology diffusion and CO2-temperature relations. Our model reacts well when adjusting various parameters according to policy changes and would thus help inform planning.

Measuring Earth's Health by CO_2: a Technology Diffusion Network Approach

21581

February 5, 2013

Abstract

We adopt atmospheric CO_2 concentration as earth's health measure. We build a model featured by a global network of technology diffusion to predict future CO_2 concentration.We predict that future CO_2 concentration is the product of three trends: the emission reduction rate led by new technology, an existing rate of emission growth and CO_2 absorption influenced by global temperature. To begin with, we introduce our model and its justification. Next,we run the model and see how it predicts the tipping point. Finally, we assess the sensitivity and structure of the model.

Contents

1 Introduction

Scientific studies have concluded that stress on Earth's biological and environmental systems is increasing. Humans are blamed for much of it and the need for a model to monitor and predict the conditions of such systems is urgent. Despite there are some models available to serve this purpose, most of them constrained their scope of research into a local system and thus failed to address the global connection between different systems. However, the complex interaction between biological and environmental systems all around the globe shouldn't be neglected or oversimplified. Recently, a Nature article written by 22 internationally known scientist suggested that we are approaching a potential state shift, which could be detrimental. And to face such challenge, they called for a better global predictive model.

Rather than attempting to address the vastly complex ecosystem, we focus on one specific aspect of the environment to shed light on the Earths health condition: carbon dioxide. Carbon dioxide is a greenhouse gas, which has caused rises in global temperature. And it's proved that such an increase in temperature has given rise to changes in climate and rises in sea level. Former CO2 predictive models either ignored the global-local interactions or failed to take technology improvements into consideration when estimating CO2 amount. Our Model incorporates a global green-technology network when predicting future CO2 levels. It quantifies the changes that development and diffusion of CO2 emission reducing technology can bring. Also, our model is capable of analyzing the global effect of certain local policies. Therefore it is more instructive and informative than previous models in some ways.

The rest of the essay is organized as follows: Section 2 studies the nature of the issues we are concerned with. By analysing such issues, we set up our model and provide our reasons for doing so. Section 3 validates our model through available data. In section 4, we run our model to see its results, especially its results concerning earth's tipping point. Section 5 looks into the details of the network structure and the sensitivity of our model. Section 6 evaluates our model, pointing out its strengths and weaknesses.

2 Our Model

2.1 Sketch of Model

2.1.1 Health Measure

Earths health is strongly associated with atmospheric CO2 concentration and global temperature. As concentration elevation leads to temperature increase, ocean absorption decreases. Plant absorption increases at first and then decrease eventually. This forms a positive feedback loop and accelerates the rise in concentration level. When plant absorption reaches zero, no more organic matter will be produced, leading to the tipping point or a state shift in Earths biosphere.

We can thus reasonably use atmospheric CO2 concentration as an index to measure earths health and build a model to simulate this index based on the considerations above.

2.1.2 Model

There are three primary methods for reducing the amount of carbon dioxide in the atmosphere: employing energy efficiency and conservation practices; using carbon-free or reduced-carbon energy resources; and capturing and storing carbon either from fossil fuels or from the atmosphere. Basically, they can be categorized into two ways, either (1) a structural shift that substitutes fossil fuels use with carbon-free or reduced-carbon energy sources, or (2) a technological advance that improves energy efficiency and lower emission rate. Of course, there are many conscious ways to reduce energy consumption, taking the bus to work rather than driving your own car for instance, but this is not the purpose of our discussion in this paper.

Here we wish to isolate the technology factor from the compound and take a closer look at it. Technology production and diffusion bring about a fascinating global network where each country is interdependent with another. We predict that future CO_2 concentration is the product of three trends, (1) the emission reduction rate led by new technology, (2) an existing rate of emission growth and (3) CO_2 absorption influenced by global temperature. By using a Technology Diffusion Model, a CO_2 Regression Model and a CO_2 absorption model, we can estimate future CO2 concentration through the following model:

$$Concentration_{predicted} = Emission_{regression} \times (1 - ReductionRate) - Absorption \tag{1}$$

2.2 Network of Technology Diffusion

2.2.1 Overview

Currently, substituting fossil fuels with carbon-free and reduced-carbon energy sources is the most significant measure to reduce carbon emission. Unfortunately, such practices are not without consequences. Difficulties to explore and produce these substitutes not withstanding, examples such as nuclear and solar energy application have encountered barriers, raising questions of nuclear safety and low efficiency.

On the other hand, technology to enhance energy efficiency and reduce carbon emission remains at an under-developed level. As energy demand soars higher still, it is too much to hope that future demand will plunge or substitutes alone will solve the issue. This calls for a dramatic advance in technology, not just regionally centered on developed countries, but in a global setting with all countries alike.

This is why we propose a global network model where emission reduction technology is both produced and diffused.

The nodes in our model represent individual countries. For reasons stated above, we assume that each country's current emission reduction technology (ERT) is at a non-existent level. They each have a Technology Index that indicates its ability (speed) to produce such technology.

The links in our model identify the diffusion of this technology. One country's technological success inspires another in multiple ways. The amount of inspiration is proportional to both the closeness of two countries and the mother country's accumulated technology.

Next,we separately define each parameter.

2.2.2 Technology Index

Technology is an intangible item that is difficult to measure directly, but it can be justified that the speed of new technology creation of a certain field depends on roughly two aspects: (1) In the sense of a stock variable: The current existing level of technology in all other fields; (2) In the sense of a flow variable: The amount of effort invested in a certain year and its efficiency.

Part (1) could be estimated by Essential Science Indicators (ESI) provided by Web of Knowledge, an academic citation indexing and search service. A country ranking of all-fields aggregate citations informs us the number of times a country's ISI-indexed journal articles has been cited by other authors. This gives us a estimation of the existing level of technology a country is at:

Country	US	Japan	China	Germany	UK	Russia	Brazil	Canada
TechIndex	20.53	19.28	16.11	15.80	12/50	12.27	10.94	10.86
Country	India	Australia	Iran	Mexico	South Africa	Indonesia	Saudi Arabia	
TechIndex	10.59	8.69	8.04	8.00	5.73	3.55	3.10	

Figure 1: Chart 1

Part (2) is often estimated by three widely used indirect approaches, according to Keller (2004), approach, indicator, and source are listed below:

Approach	Indicator	Data Source
Inputs (R&D)	Annual R&D expenditures (Research and Development)	OECD (Organization of Economic Cooperation and Development)
Outputs (patents)	Residents' Patent Applications	World Bank
The effect of technology (higher productivity)	TFP growth (Total Factor Productivity)	Conference Board

Figure 2: Chart 2

2.2.3 Closeness

We define the closeness of country A and B to be:

$$C_{AB} = \frac{\alpha F_A F_B}{\sqrt{d_{AB}}} \tag{2}$$

where F_A and F_B are the Economic Freedom Index (EFI) of country A and B respectively, d_{AB} is the distance between country A and country B, and α is the balancing constant.

The Economic Freedom Index by the Heritage Foundation takes into account rule of law, limited government, regulatory efficiency and open markets in order to measure the openness of a certain market. Eaton and Kortum (2002) suggest that there are mainly two channels of international technology diffusion: trade and foreign direct investment. By multiplying the EFI of A and B, we are able to estimate the feasibility of diffusion.

Jaffe et al (1993) showcase that technology spillover is much stronger when the geographical distance is shorter. Here we estimate the distance between country A and B's capital cities to be the geographical distance between A and B. Considering that transport is usually more convenient between capital cities and they are often the science/technology/business centers of the countries, our estimation can be largely justified.

2.2.4 Accumulated Technology Index

The Accumulated Technology Index (ATI) is a function of time. We denote the ATI of country A in year t by $ATI_A(t)$. For simplicity, we assume:

- Time t is a discrete, integer value and its unit is year, year 2013 being year 0. $CTI_k(0) = 0$.
- Each year's increase is the sum of two parts: technology produced by the country itself and the inspiration it receives from all others.
- The amount of inspiration that country i passes to country k in year t is defined as $ATI_i(t-1) \cdot C_{ik}, i, k = 1 \ldots n, i \neq k$.
- Country k's newly produced technology this year is a constant $TechIndex_k$.

Thus for country k in year t we have:

$$ATI_k(t) = ATI_k(t-1) + TechIndex_k + \sum_{i=1, i\neq k}^{n} ATI_i(t-1) \cdot C_{ik} \tag{3}$$

2.2.5 Reduction Rate

The result of the above assumption is that ATI is growing exponentially. However, not all technology can be applied to reducing carbon emission and the marginal return of technology often decreases. ATI is a function of time and so is the Reduction Rate (RR). Hence we convert ATI into RR through the following way. For country k in year t, we have:

$$RR_k(t) = \beta \cdot ln(1 + CTI_k(t)) \tag{4}$$

where β is a constant irrelevant to k and t but relevant to the total number of countries n.

2.2.6 Human Elements

Human behavior and government policy severely affect the parameters of the model.

- More R & D funding would sufficiently increase Technology Index.
- Should governments form stronger ties and find ways to collaborate, closeness would be increased and inspirations larger. However, if governments choose to establish barriers to impede the sharing of knowledge, the country itself suffers too.

2.2.7 Further Explanations

Some may question the possibility that a certain technology may travel from A to B in one year and transfer back to A in another. In fact, what travels along the link of the network is defined as inspiration. It is not necessarily a certain type of knowledge or technology, but a positive effect through the connection. Some take direct returns from it, while others may improve this technology in certain ways and in turn benefit the mother country.

2.3 CO_2 Regression Model

We adopt a CO_2 regression model to predict CO_2 emission in the future. As previously assumed, technology advance was excluded from this model, while many other factors contribute to the CO_2 emission trend. These factors may include economic growth, structural changes in the economy(shifting from heavy industry to service sector), and structural changes in energy consumption(shifting from high-carbon fuels to low-carbon fuels or carbon-free fuels).

Let Y_A denote CO_2 emission of country A, $x_1, x_2, ..., x_m$ denote factors that can affect CO_2 emission respectively. Hence, we have:

$$Y_A = G(x_1, x_2, ..., x_m) + e \tag{5}$$

where e is an error independent of $x_1, x_2, ..., x_m$.

Each of these factors is a function of time t with a random error e independent from t and each other, i.e. $x_i = g_i(t) + e_i, i = 1...m$. Therefore, $Y = f(g_1(t) + e_1, \ldots, g_m(t) + e_m) + e = F(t) + e_0$, where e_0 is a random error and heteroscedasticity may exist.

Using a two-decade dataset from the World Bank, we see that for most countries we selected, the trend can be best reflected through a heteroscedasticity-robust linear regression model. The model is given by:

$$Y = \beta_0 + \beta_1 t + \epsilon \tag{6}$$

Regression results of some countries are shown below.

India: India resembles a typical developing country with r^2 being 0.9271.

The United States: The US resembles some developed countries with r^2 being 0.4785 (from 1992 to 2010), 0.8667 (from 1992 to 2008).

Germany:Germany resembles some developed countries whose emission is already decreasing, with r^2 being 0.6997 (from 1992 to 2010), 0.6802 (from 1992 to 2008).

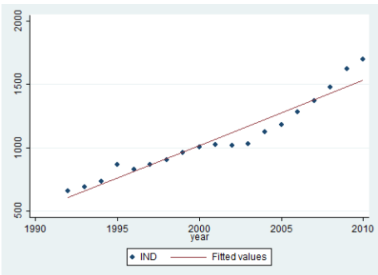

Figure 3: India

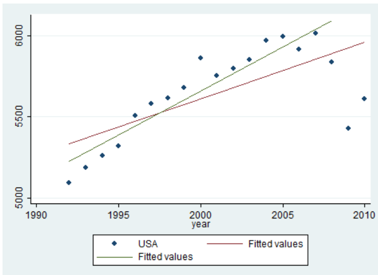

Figure 4: The US

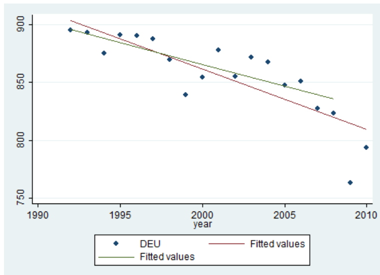

Figure 5: Germany

As we can see, the economic crisis in 09, 10 had an impact on Germany and the US. Since CO_2 emission depends largely on fossil fuel consumption and fossil fuel consumption is closely related to economy, we can attribute such abnormal values to the crisis. However, as the crisis draws to an end now, the original trend will likely resume. We can filter such values out before we perform regression. Although we may find it difficult to explain the reason of this trend and its volatility, using linear model to simulate its change is reasonable.

2.4 CO_2 Absorption Model

A NASA study (2010) examined the nature of Earths greenhouse effect and clarified the role that greenhouse gases and clouds play in absorbing outgoing infrared radiation. The study concludes that the planets temperature ultimately depends on the atmospheric level of carbon dioxide. So far there is no definitive

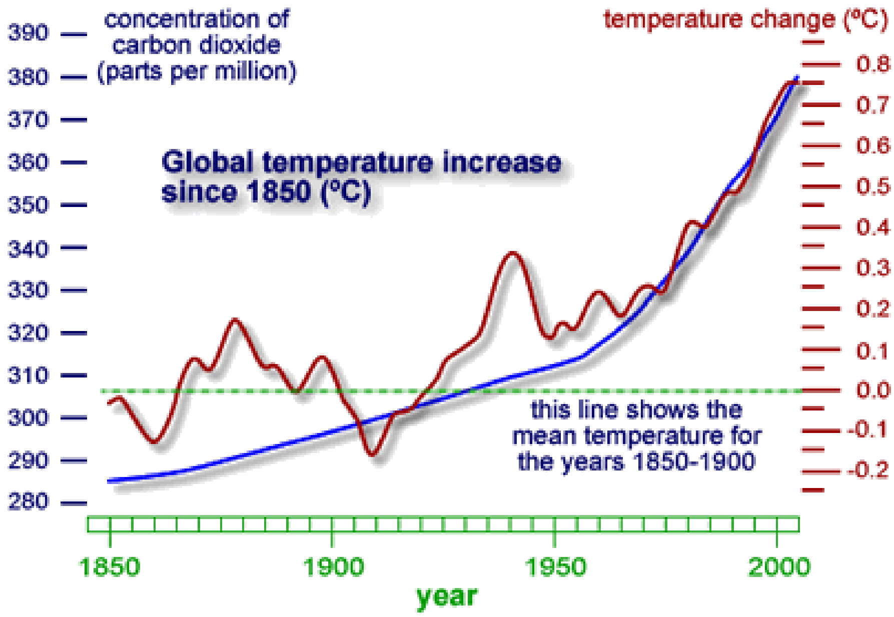

Figure 6: ACC and Global Temperature Increase

formula to determine their relationship, but as the graph shows, they demonstrate a linear relationship especially in the last 25 years.

Let t denote time, T(t) denote the global mean temperature at time t, and C(t) denote the atmospheric CO_2 concentration (ACC) at time t. The model is given by:

$$T(t) = \eta_0 + \eta_1 C(t) \tag{7}$$

where η_1 is a positive parameter.

The carbon cycle is the biogeochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere and atmosphere. Four main carbon storages, in decreasing order of size, are the geological, oceanic, terrestrial and atmospheric reservoirs. Carbon takes form in CO_2 in the atmosphere and mainly travels between the atmosphere, land and ocean. The most important fluxes between the atmospheric and terrestrial reservoirs are photosynthesis, biological respiration and fossil fuel combustion. CO_2 can also dissolve in the ocean and be stored as carbonate carbon through biochemical process.

Currently the mass of carbon in the atmosphere is around 730 Pg (10^{15} g). In other words,

$$m_{CO_2} = \frac{44}{12} m_c \simeq 2700000 MMT (million metric tons) \tag{8}$$

The atmospheric CO_2 concentration (ACC) is 385 PPMV. Since as the graph be-

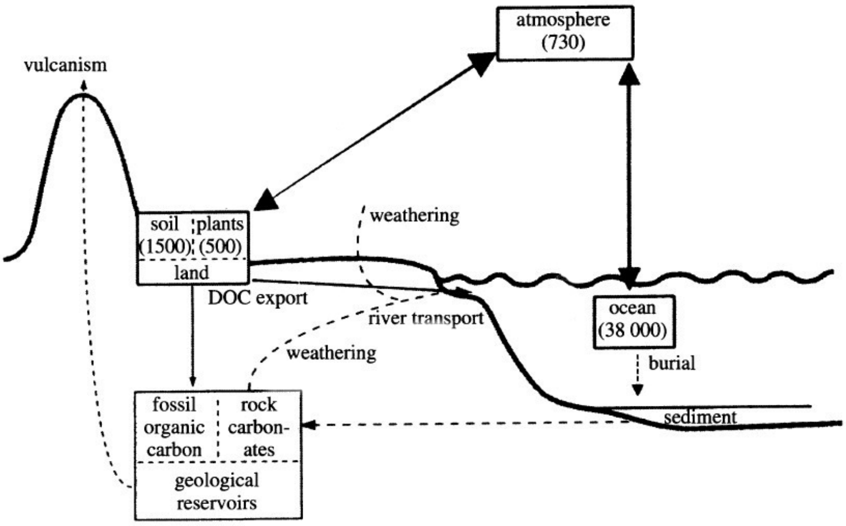

Figure 7: Carbon Cycle

low shows, the range of concentration is within 10ppmv, which is much smaller than the 2008 figure of 384PPMV, we can assume that the CO_2 is distributed evenly throughout the atmosphere.

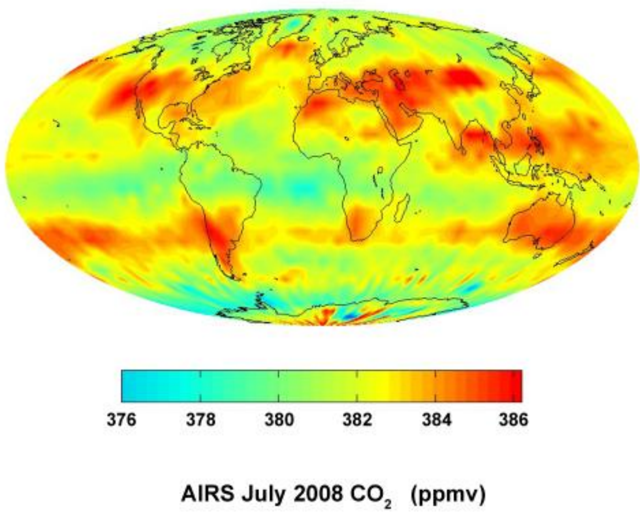

Figure 8: ACC Distribution

We also assume that concentration of atmospheric CO_2 is in direct proportion to its mass:

$$C_{CO_2} = \mu_{CO_2} m_{CO_2} \tag{9}$$

It can be deduced that $\mu_{CO_2} = 1.426 \times 10^{-4} PPMV/MMT$.

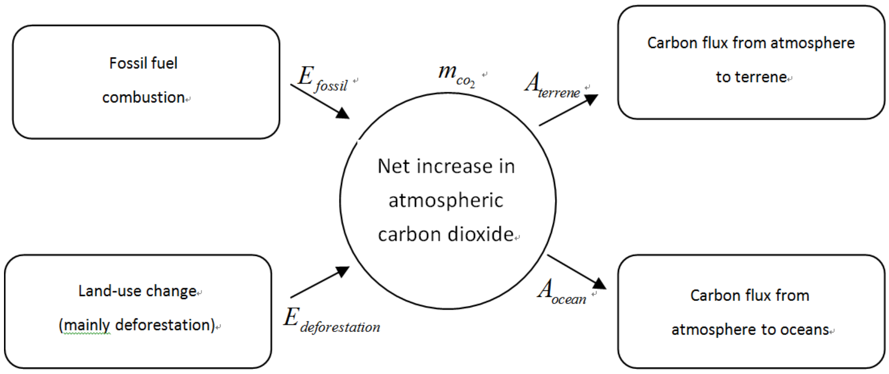

Figure 9: CO_2 Emission and Absorption

The model of the mass of atmospheric CO_2 is given by:

$$m_{CO_2}(t) = m_{CO_2}(t-1) + E(t) - A(t) \tag{10}$$

$E(t)$ denotes emission, $A(t)$ denotes absorption.

Emission: Since forest coverage rate remained steady for the past few years, we assume that emission due to deforestation is non-existent. The total emission is consistent with fossil fuel combustion.

$$E(t) = E_{fossil}(t) \tag{11}$$

Absorption: As is depicted in the graph above, the total absorption

$$A(t) = A_{ocean}(t) + A_{terrene}(t) \tag{12}$$

where $A_{ocean}(t)$ is absorption by ocean that is linear to temperature, $A_{terrene}(t)$ is absorption by terrene that relies on plant photosynthesis. The latter is the result of a complex mix, while the rise in concentration positively affects photosynthesis, an increased temperature caused by it impedes photosynthesis as it tends to make plants sick, according to Yadvinder Malhi (2002).

$$A_{ocean}(t) = \alpha_{ocean} - \beta_{ocean} T(t-1) \tag{13}$$

$$A_{terrene}(t) = (\alpha_{terrene} + \gamma_{terrene} C(t-1) - \beta_{terrene}(T(t-1) - 13.5)^2) Area_{forest} \tag{14}$$

Per World Bank data, in 2008: $m_{CO_2} = 2700000$ MMT, $C_{CO_2} = 385$ PPM, $T = 14.5^oC$, $\eta_0 = 10.65, \eta_1 = 0.01$, $\alpha_{ocean} = 15000, \beta_{ocean} = 500$, $\alpha_{terrene} = 1000, \gamma_{terrene} = 30, \beta_{terrene} = 3000, Area_{forest} = 1$

2.5 Tipping Point

The above is a starting point to predict future concentration level and world temperature. As concentration and temperature increase, ocean absorption decreases. Plant absorption increases at first and then decreases eventually. This forms a positive feedback loop and accelerates the rise in concentration level. When plant absorption reaches zero, no more organic matter will be produced, leading to the tipping point.

3 Validation of Our Model

3.1 Technology Diffusion Network

Since we assume the current emission reduction technology is at a non-existence level, we would not be able to validate this specific type of technology directly. However, the soundness of the model can be verified by tracing the historic data of another type of technology. For example, if we look at the technology of waste disposal, we can track patent/journal publishing and citations to compare the data with the models simulation result.

3.2 CO2 Regression Model

We run this model alone without technology impact and estimated a 47% growth in 25 years. This is very much consistent with the United States Congress Office of Technology Assessment estimation that emissions will likely rise by 50% over the next 25 years, hereby verifying our prediction.

3.3 CO2 Absorption Model

We can use emission, concentration and temperature data from 2004 to 2008 to validate the model. In 2004, the ACC is 378.4 ppmv. In 2005,2006,2007,2008, the worlds CO_2 emission is separately 28292 MMT, 28885 MMT, 29590 MMT, 30318 MMT. Estimation by our model puts the concentration in 2008 at 385.0 ppmv while the real data is 385.2 ppmv in 2008. The error of increase is 2.94%. This error is well within our acceptance range.

4 Earth Health Predictions

We now run our model to see how it predicts future earth health. Since data availability of all countries in the world is very poor, we select a pool of 15 countries to run our model. These 15 countries are: China, United States, India, Russia, Japan, Germany, Iran, Canada, United Kingdom, Saudi Arabia, South Africa, Brazil, Mexico, Australia, and Indonesia.

Our criterion is:

- They rank top 20 in annual CO2 emission chart and so are big players in the network.
- Their geographical distribution is roughly even by continent.
- Ratio of developed and developing country is reasonable.

Figure 10: Selected Countries

We then collected data from the following sources:

- Network of Technology Diffusion Model:www.heritage.org/index
- CO_2 Regression Model:www.eia.gov
- CO_2 Absorption Model:www.worldbank.org

Next, we estimate parameters based on the available data we acquired. As the algorithm is lengthy but rather simple in essence (just a few array operations and iteration), we simply present the result as follows:

- If emission reduction technology is still at a non-existent level, the tipping point defined above is the year of 2051.
- If emission reduction technology follows the proposed model, the tipping point would not be for at least another 60 years, after which we feel our model insufficient to predict.
- If emission reduction technology follows the proposed model, the maximum atmosphere CO2 concentration will be reached in the year of 2062 with the value 465.

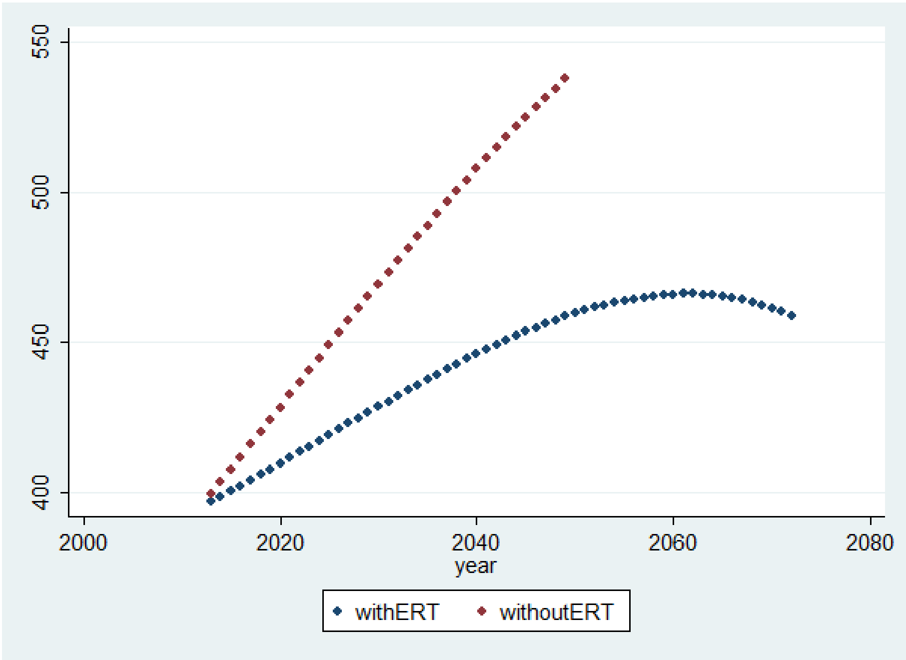

Figure 11: ACC

4.1 Warning for Policy Makers

From the results above, we can conclude that developing emission reduction technology must be taken seriously. If no such measures are taken, the tipping point is just around the corner. Should the tipping point arrive, plants would suffer immensely and so will all other creatures.

4.2 Human Factors and Uncertainties

Human factors are in already investigated in section 4. Uncertainties in the future will also affect the final result.

For example:

- Global or local economic crises may strike again in the future, and thus reduce the CO2 emission and postpone the tipping point.
- Epidemic outbreaks may have similar impacts.
- Price of crude oil may increase dramatically as drilling technology lag behind. This would postpone the tipping point too.

5 Network Structure Analysis and Sensitivity Analysis

We can easily observe from the structure that nodes with higher TechIndex are more important, because they produce new technology faster. By performing a simple sorting algorithm, we get the top-five nodes under this measure:

Table 1: Tech Index

Country	USA	JPN	DEU	GBR	BRA
Index	20.53	19.28	15.80	12.50	10.94

Each nodes has 14 links, the sum of their weight (Closeness) measures the its ability to inspire other countries. Therefore, nodes with higher sum are more critical. The top-five countries are:

Table 2: Weight Sum

Country	CAN	DEU	GBR	USA	JPN
Sum	1.19	1.15	1.14	1.14	0.90

As for links, we determine their sensitivity in the following way. We remove this link from the network and calculate the increase it brings to our Health Measure Index in year 2023. Links that bring higher increases are more important. The top-five are:

Table 3: Edge Sensitivity

Edge	(USA,CAN)	(DEU,GBR)	(USA,DEU)	(USA,GBR)	(USA,MEX)
Increase in Acc	0.15	0.08	0.05	0.05	0.04

As for feedback loops, positive feedback loops are almost everywhere in this network. As countries inspire each other repeatedly, any factor increasing nodal TechIndex and ATI is amplified along time.

The analysis results coincide with our intuition:

- Countries that are more advanced in technology make more important nodes.
- Countries that have higher economic freedom index and better location tend to make more important nodes.
- Links between freer and more developed countries and are shorter geographically tend to make more important links.

6 Strengths and Weaknesses

6.1 Strengths

- **Novelty**
  When addressing the global network, our model takes a rare approach of technology diffusion, while traditional papers tend to focus on physical elements. We stress the importance of technology advance in protecting the Earths health.
- **Rationality**
  Using CO2 as an index of the Earths health measure is rational and can be justified by much literature.

6.2 Weaknesses

- **Quantifying policy influence**
  Although our model provides warnings for policy makers, our model cannot quantify policy influence and actions necessary to avoid undesirable outcomes.

- **Trade-offs**
  Possible trade-off between R & D expenditure and economic growth is not taken into the framework of our model.

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