Climate Change
Sources, Effects and Policy

(Not for publication or Distribution)

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MIT INTEGRATED GLOBAL SYSTEM MODEL Framework (IGSM)

- Designed to analyze interactions between humans and the Earth system
- This comprehensive set of models is used to study the causes, consequences and solutions to problems that arise from global change.
- We define global change broadly and consider the unintended impacts of global economic and population growth on natural resource availability, the climate, and air and water quality.

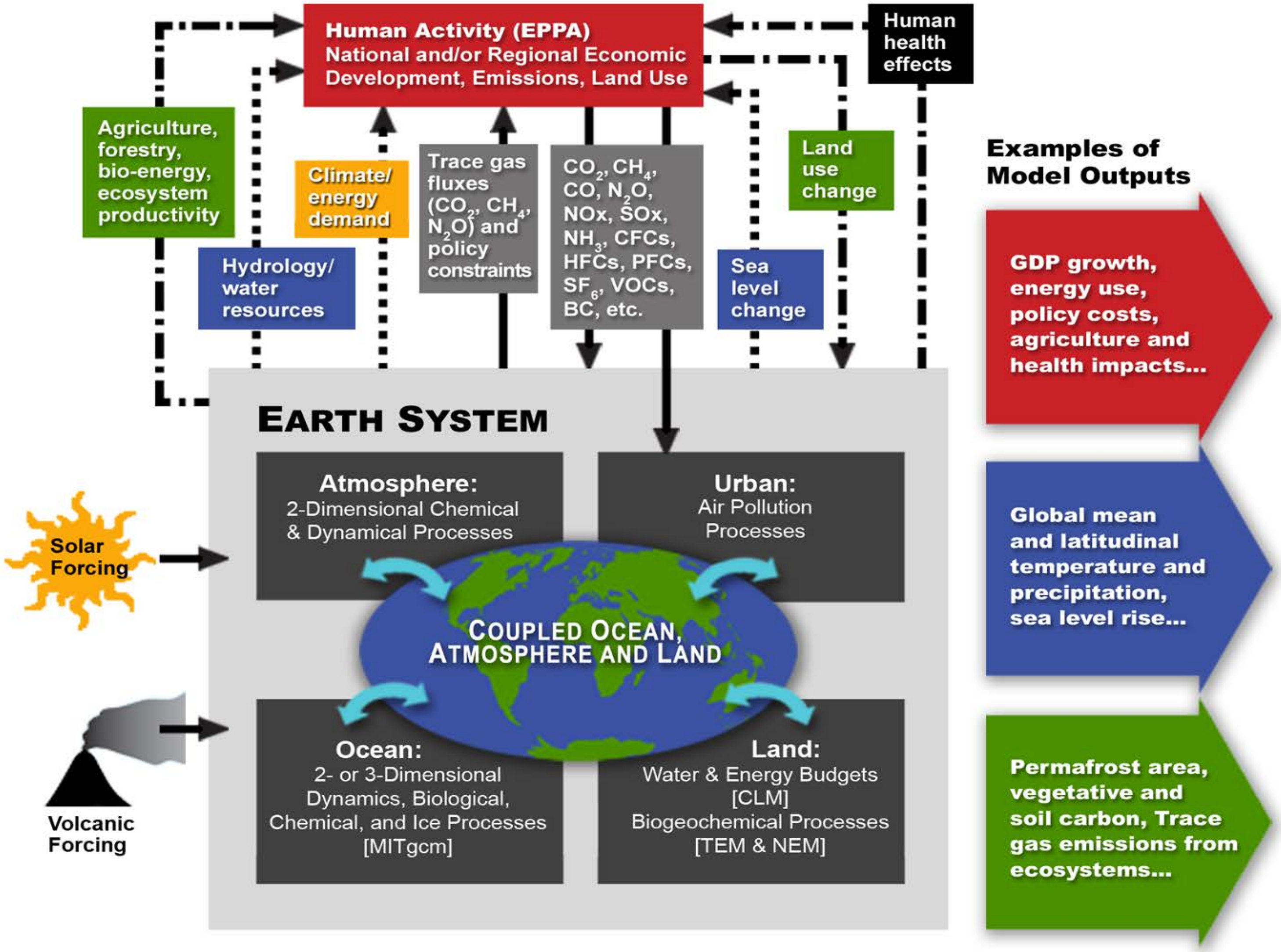
MIT INTEGRATED GLOBAL SYSTEM MODEL Framework (IGSM)

- The IGSM framework consists primarily of two interacting components—the Economic Projection and Policy Analysis (EPPA) model and the MIT Earth System model (MESM)
- EPPA model simulates the evolution of economic, demographic, trade and technological processes involved in activities that affect the environment at multiple scales, from regional to global.
- The result of these activities in terms of greenhouse gas emissions, conventional air and water pollutants, and land-use/land-cover change are input into the MESM.

MIT INTEGRATED GLOBAL SYSTEM MODEL Framework (IGSM)

- MIT Earth System Model comprises coupled sub-models of physical, dynamical and chemical processes in the atmosphere, land and freshwater systems and ocean.
- This allows researchers to calculate the likely ***environmental impacts of human activities*** simulated in the MIT Economic Projection and Policy Analysis (EPPA) model, and feed those impacts back into the EPPA model in order to assess their economic and other implications.

MIT INTEGRATED
GLOBAL SYSTEM MODEL Framework (IGSM)



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Introduction

I am going to talk to you today about climate change.

This is a continuation of a conversation that began about thirty years ago. I was chairman of the Department of Economics at MIT then. One morning, two economists from the Sloan School of Business at MIT came to my office. They told me that they were interested in starting research on global warming. I told them that I was interested in the same thing.

I did not know much about it, but my intuition suggested that it could be very important.

However I knew that we could not do the research as economists alone. We needed to collaborate with of climate scientists. I would call the head of the Department of Earth and Atmospheric Sciences at MIT and arrange a meeting.

The next afternoon we walked over to the Earth Sciences department and met with the head of that department. We came to a quick agreement in principle on collaboration. It took time to raise the money for the research, but we started the Joint Program on the Science and Policy of Climate Change. It has since become perhaps the largest private research program on climate change.

We all meet every Friday for lunch. That has been going on for almost thirty years. That is a lot of lunches. The scientists have learned about the magnitudes of greenhouse gas emissions from the economists and potential reactions to climate change. Economists have learned about magnitudes of climate change and consequences of policies to reduce climate change.

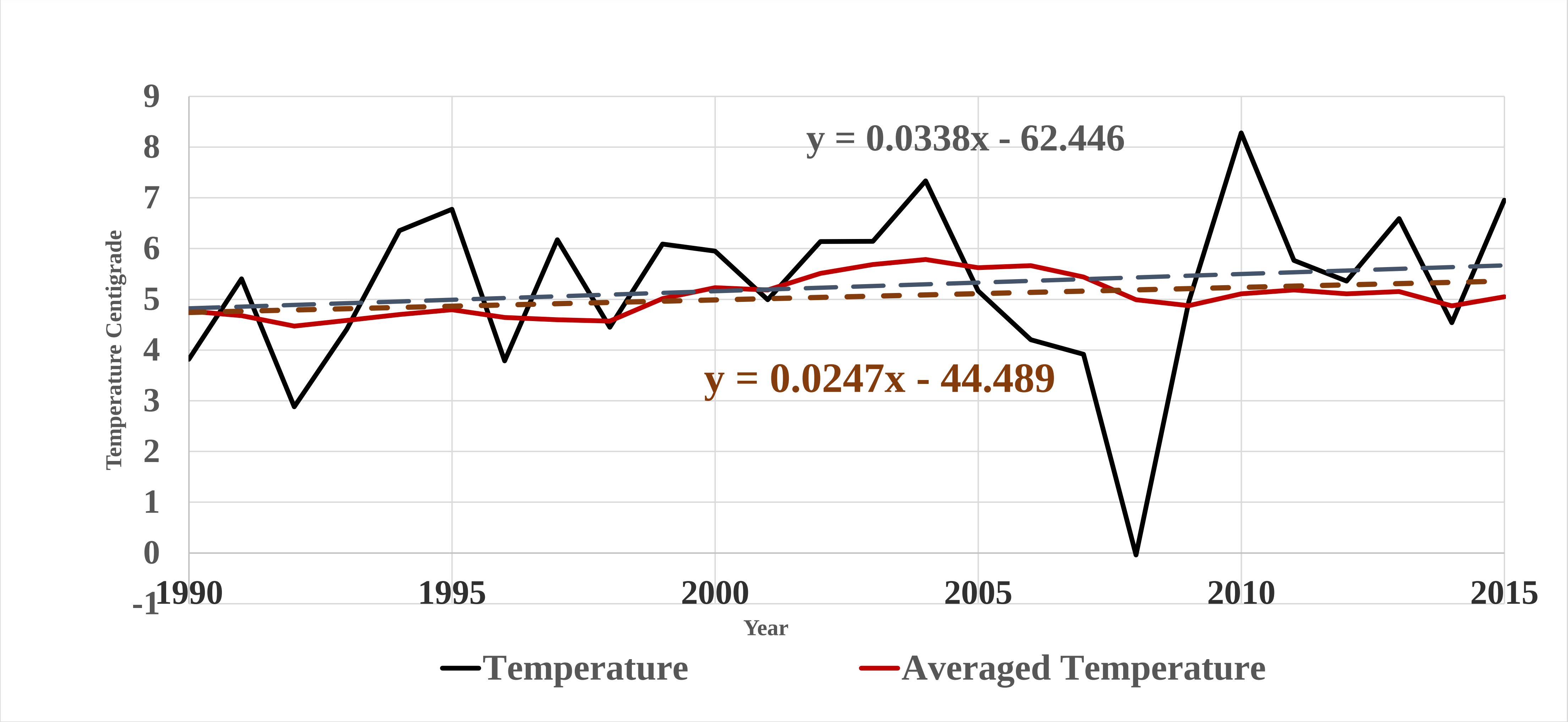
I cannot claim to know deeply the sciences necessary to understand climate change, but I have learned what science and economics can tell us about it. I want to pass on some of that understanding to you.

First I want to show you something that may be surprising. Figure 1 shows the average monthly temperatures in Tehran since 1990, almost 20 years.

The black line shows the actual temperatures. The red line shows the 10 year running average of those actual temperatures. The running average reduces the short term fluctuations. The black and red dashed lines show the trends and their equations are shown in black and red. X stands for year.

Put on a number for x and you will get the temperature change for a single year.

Figure 1
Climate change in Tehran



The temperature change numbers for Tehran do not seem very large, but think of what they mean for the future. If the current rates of emissions of carbon dioxide and the climate processes continue, that implies a two and a half to almost 3 and a half degree temperature increases in 100 years. The grandchildren of some of you would be living in quite a different world: no snow, no indoor heating, much more air conditioning, no gardens and food would be more expensive.

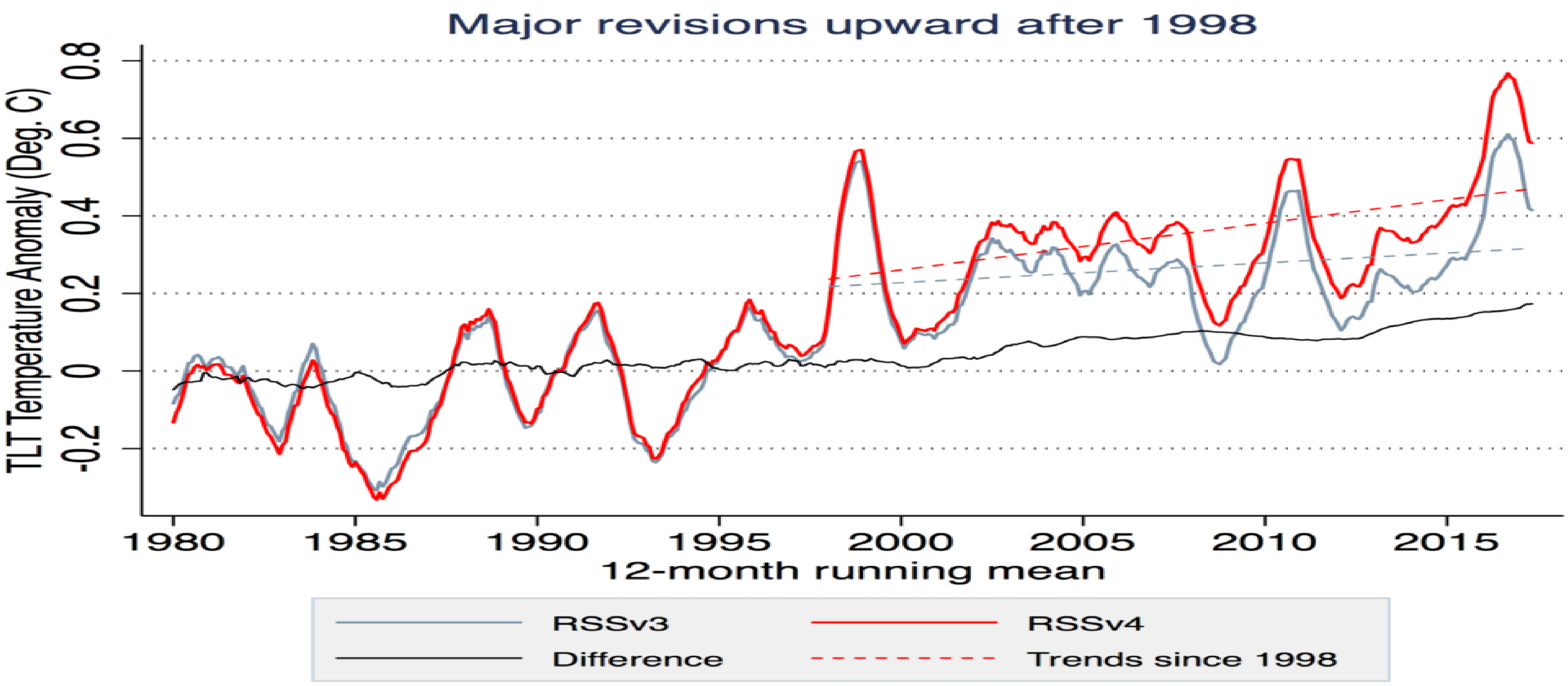
- The evidence of global warming
  - Now I want to turn to a brief examination of the evidence on global warming. This will help in understanding the significance of global warming.

    There are two kinds of evidence. The first is observations of the climate. The second is an

  - analytic approach based on scientific physics.
  - It seems obvious that we can simply look at temperature changes and identify warming. But observations can be unreliable. There are two reasons why the evidence of our eyes can be
  - deceiving. First, our measuring instruments can be faulty. Second it is easy to confuse short
  - term sequences for long term trends.

Measurements of atmospheric temperatures have improved with the development of more sophisticated thermometers. There are also satellite measurements of earth temperatures, but there is disagreement among them. Yet those have improved and the resulting changes in measurements have been substantial. Figure 2 shows results from two different satellite measurements and the difference between them as the black line. The red line shows the recently improved measurements. Both measurements show a distinctive upturn in 1998. The difference between the two sets of measurements, by 2015, is almost .2 degree centigrade, or almost a half degree Fahrenheit, not an inconsiderable difference.

Figure 2



Major revisions upward after 1998
TLT Temperature Anomaly (Deg. C)
0.8
0.6
0.4
0.2
0
-0.2
1980
1985
1990
1995
2000
2005
2010
2015
12-month running mean
RSSv3
RSSv4
Difference
Trends since 1998

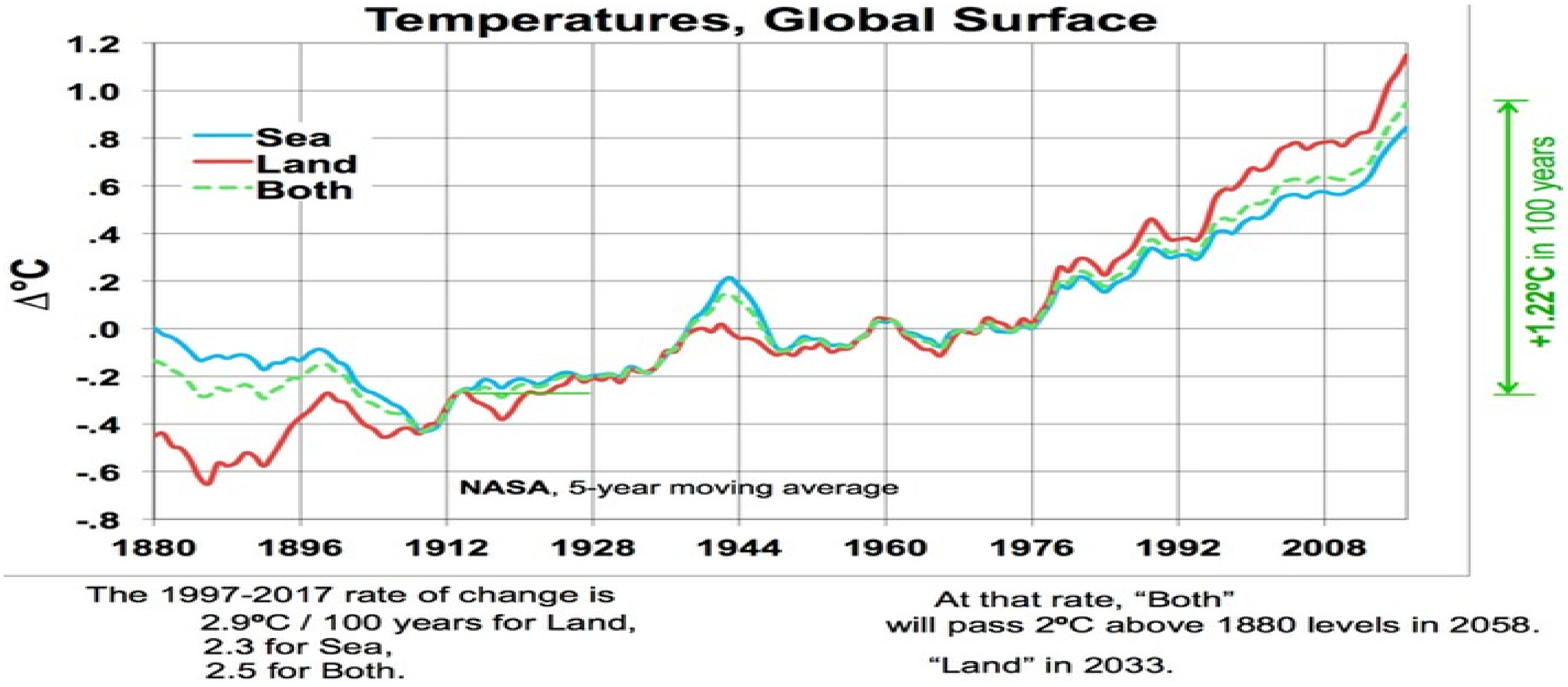
Measurement methods have improved for the ocean as well. Old methods of measuring ocean temperatures were very simple. A bucket was dropped into the ocean from a ship and the water temperature was measured when the bucket was drawn up. Or the temperature of the water intake for the engine was measured.

The old methods have been replaced using ocean buoys. But the ocean buoys are not distributed evenly over the world's oceans. In particular the South Pacific has relatively few buoys. Methods have had to be developed to adjust for that, but there is plenty of room for error.

Then there is the problem of disentangling short and long term changes in atmospheric temperatures. This can be difficult. There are recent as well as historic examples of this. Recently it appeared from the world temperature data that global warming had stopped or slowed down considerably. The evidence was seized upon by some persons to deny that there was, in fact, a climate change trend. But the evidence of slowdown in global warming turned out to be a short term phase. As a result of changes in ocean currents, the oceans had been absorbing more heat from the atmosphere and ocean temperatures had been rising while atmospheric temperature increases had virtually halted.

Turning to the long term upward temperature trend. That goes back far beyond 1998. Figure 3 shows the temperature sequence starting in 1880. The figure shows both the atmospheric temperatures and the ocean temperatures and the mean. By the 1890's the warming effects of carbon in the atmosphere were recognized. Even if the measurements are off by a degree, the long term pattern is clear.

Figure 3


Temperatures, Global Surface
1.2
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
ΔºC
Sea
Land
Both
NASA, 5-year moving average
1880
1896
1912
1928
1944
1960
1976
1992
2008
+1.22ºC in 100 years
The 1997-2017 rate of change is
2.9ºC / 100 years for Land,
2.3 for Sea,
2.5 for Both.
At that rate, "Both"
will pass 2ºC above 1880 levels in 2058.
"Land" in 2033.

Regional Differences in Atmospheric Temperatures

There are also substantial regional differences in climate. These can be very large. There are the topological differences. Mountainous regions are cooler because the higher altitudes are cooler. And there are differences in prevailing wind patterns. There are differences due to tree cover which creates shade. Cities are called, “heat islands.” They are hotter because of lack of shade and absorption of heat by buildings and local populations using energy.

My favorite example of a local climate difference is a small town in the middle of the U.S. called Liberal. While most of the rest of the U.S. has become warmer over time, there has been absolutely no temperature change in Liberal.

The existence of climate change and the regional differences are often not recognized simply because the changes are slow and small. For example, not many people would believe that there has been significant warming in Tehran.

Analytic global warming estimation methods

The second approach to estimating climate change is quite different, involving physics. To a climate scientist the earth is a heat engine. Global temperatures are determined by heat exchanges. The sun heats the atmosphere, which heats the earth and oceans. The earth and oceans, in turn, reflect some of that heat back into the atmosphere. The amount reflected depends on the greenhouse gases in the atmosphere.

Climate scientists are accustomed to modeling heat exchanges. They produce a system of simultaneous differential equations for their model.

The solution to the equations takes the form:

$$temperature = a_1 * r_1 + a_2 * r_2 + \ldots.. + a_n * r_n \quad ,$$

where the r's are root of the equations and the a's are numerical estimates of the weight in the solution of each root. The roots may be positive or negative, real numbers or imaginary numbers. However the models are far too complicated to permit finding a precise solution. So the climate scientists write computer programs which iterate until they come up with a good approximation to the solution When plotted it looks just like the observed chart for the evolution of world temperatures. That is a very important reason why the scientists have confidence in their predictions of global warming.

The modeling results that correspond to the actual temperature changes are obtained when the effects of the greenhouse gases are put into the equations. Without those greenhouse gas effects in the equations, there is no warming.

That implies that the analysis of the effects of greenhouse gases in raising atmospheric temperature is correct and gives the scientists confidence in their analysis.

Someone who denies greenhouse warming cannot argue with the actual temperature changes. But they claim that the changes are not the result of the accumulation of greenhouse gases in the atmosphere. Yet this kind of scientific analysis shows that the temperature changes would not occur, if there were not greenhouse gases.

Estimates of Previous Emissions of Greenhouse Gases

The scientific analysis requires a number of physical parameters including estimates of the amounts of greenhouse gases. That is where economics and technology come in.

Greenhouse gases persist in the atmosphere for long but different periods of time. That implies that we must estimate past emissions. There are again two approaches. The first requires estimating the amount of greenhouse gases that were previously actually emitted. Since carbon dioxide is the most important gas, estimates are made of past production and use of fossil fuels. Methane presents special problems since it has other sources than as a fuel. For example, animals, when they defecate, produce methane. In addition, estimating the methane produced by the rotting of dead plants is especially chancy, The other approach depends on modeling again. Working backward that approach estimates what the temperature would be, if there were no greenhouse gases in the atmosphere. Then it is possible to estimate the quantity of atmospheric greenhouse gases which is necessary to produce the temperatures actually observed. Methane, again, presents a special problem. A lot of it comes from leaks in gas pipelines, for which precise estimates are not possible.

The Kinds of Greenhouse Gases

Table 1 lists the kinds of greenhouse gases and compares them to carbon dioxide, which is the most common. Like other greenhouse gases, carbon dioxide decomposes in the atmosphere and is transmuted by other gases into a less harmful form.

Greenhouse Gas	Chemical Formula	Anthropogenic Sources	Atmospheric Lifetime[1](years)	GWP[2] (100 Year Time Horizon)
Carbon Dioxide	CO_2	Fossil-fuel combustion, Land-use conversion, Cement Production	~100[1]	1
Methane	CH_4	Fossil fuels, Rice paddies, Waste dumps	12[1]	25
Nitrous Oxide	N_2O	Fertilizer, Industrial processes, Combustion	114[1]	298
Tropospheric Ozone	O_3	Fossil fuel combustion, Industrial emissions, Chemical solvents	hours-days	N.A.
CFC-12	CCL_2F_2	Liquid coolants, Foams	100	10,900
HCFC-22	CCl_2F_2	Refrigerants	12	1,810
Sulfur Hexaflouride	SF_6	Dielectric fluid	3,200	22,800

Aerosol Cooling

A partial offset to greenhouse warming is the atmospheric cooling effect created by the very small particles that come from natural sources as well as modern activities. These aerosols exist in dust, smoke and many types of gases. Dust from the Gobi desert creates smog in Beijing, but it also cools it. Trees and other plants emit gaseous aerosols and the effects are not completely understood.

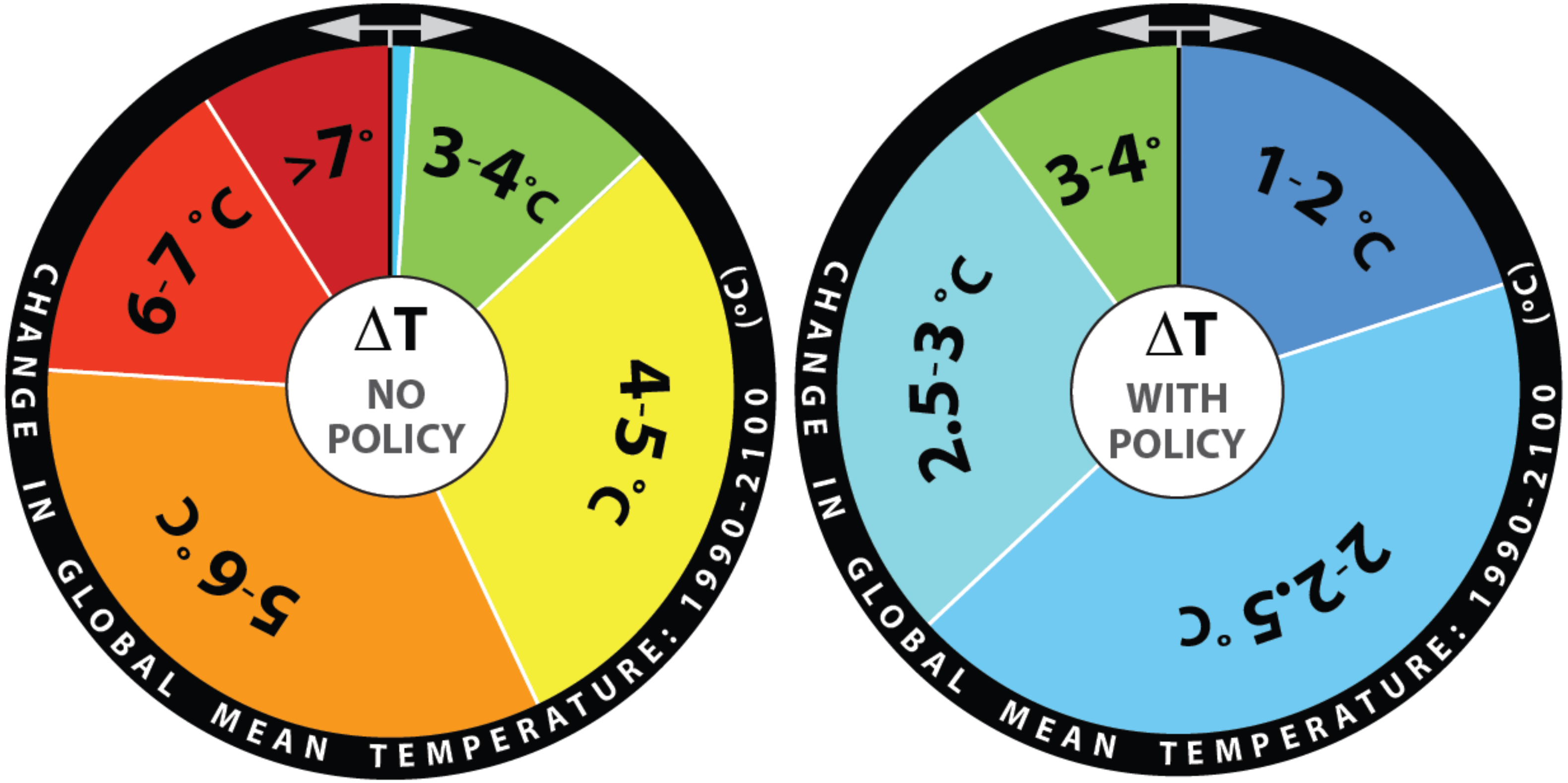
But the effects are substantial. An extreme example was the so-called, Year Without Summer, in 1816. That was the result of a great eruption of a large volcano in Indonesia. The result was the circulation of atmospheric dust, smoke and other aerosols around the globe. Average global temperatures fell by about a half degree centigrade resulting in agricultural damages and in real food shortages in some parts of the world.

Uncertainties

We have estimates of future greenhouse gas concentrations and physical equations to estimate their warming effects. But there are also other numbers that go into the equations. These numbers cannot be measured with experiments and precise measurements. So there is uncertainty in future global warming estimates. That is why climate scientists project a range of global warming for the future, not a single number.

In the MIT project on Global Change we have created what is called a, "wheel of fortune," shown in Figure 4. That illustrates estimates of the probability of different levels of changes in world temperatures from now to 2100. Spin the wheel and find a warming estimate for the future.

THE GREENHOUSE GAMBLE



Take a spin at http://globalchange.mit.edu

The MIT Joint Program on the Science and Policy of Global Change

- The web site for the Wheels of Fortune has been changed. It is now
- https://globalchange.mit.edu/media/greenhouse-gamble-spin

- Try some spins.

The costs of greenhouse gas emissions and gobal warming

There are simply no good estimates of the costs of global warming.

Estimates do exist for the costs of additional air conditioning and some of the effects on agricultural production, for example, but even these are rough approximations at best.

There are no reasonably good estimates for other measurable costs. There are, other important costs which are not measurable. How is one to estimate all the costs of increased sickness, which go far beyond hospitalization and medicines. Important areas will be lost to agriculture and people will have to move. Populations in coral islands inundated by rising ocean waters will also have to move. The costs cannot be measured but cannot be ignored.

Amelioration of climate change

It is not possible now to give a precise summary balance of the positive and negative effects of climate change. However, we know that the negatives will be life changing in much of the world. That is why considerable attention is being given to reducing the potential effects of climate change.

The most commonly suggested policy to ameliorate climate change and which would be most effective is simply to reduce the amounts of greenhouse gases going into the atmosphere. That is the objective of the Paris agreement, which I will come to later.

Reduction of greenhouse gases focuses on the reduction in the use of fossil fuels. Those include coal, natural gas, gasoline and diesel.

Electric power production, which has been primarily from coal, is the major source of carbon dioxide. China and India are now the major sources. That was true for the U.S. but is changing as electric power plants and industry shift to natural gas and solar and wind power. Gasoline and diesel fuels are also major sources of carbon dioxide as their use in transportation is so significant. With all of its cars, the U.S. is the major source of greenhouse gases from gasoline.

The development of solar power and wind power to are the result of policies to reduce emissions of carbon dioxide from the use of fossil fuels to produce electricity. The cost of the electricity they produce is still usually somewhat higher than the electricity from natural gas plants, but the costs have been coming down rapidly. They will never completely replace fossil fuel electricity because of what is called the, “intermittency,” problem. The sun does not shine at night and is sometimes covered by clouds. And the wind does not always blow hard enough to generate the desired amounts of electric power. That requires two types of adjustment. First, the networks providing electric power must be configured so that intermittent electric power can be moved to where it is needed most. And second, there must be backup sources of electric power when the wind and solar power are not available.

The backup sources must be instantly available or some areas will be blacked out. If there are hydroelectric sources, those might be kept on line indefinitely if the water can be restored. Or some fossil fuel plants can be kept running all the time so that their power can be switched into the electric grid instantly.

Finally electric power batteries can potentially be used. That requires a new type of battery capable of producing large amounts of power for relatively long periods. That type of battery is just now being developed and being put on line.

Another type of action to reduce greenhouse warming is, “climate engineering.” This is being investigated, but has not yet been tried on a substantial scale.

There are two types of climate engineering: reduction in heat coming from the sun and actual removal of carbon dioxide from the atmosphere. Reduction in solar warming could be achieved rapidly by sending sulfur aerosols or other aerosols into the atmosphere. There has even been a suggestion to put mirrors into space to reflect sunlight.

The other method, called, “carbon capture and removal,” would take the carbon dioxide from the smoke and gases generated by electric power plants. The removed carbon dioxide would then be piped to underground storage, using old oil wells, or used in other production. The only commercial experiment to do this in the U.S. has just been abandoned due to high costs.

Estimates of greenhouse gas emissions and costs of amelioration

Projecting future temperatures requires projecting future emissions. There are, again, two approaches. The first, called, “Bottom Up,” attempts to track each source of emissions. Usually it starts with an estimate of future Gross Domestic Product. Then, for example, it makes an estimate of the ratio of the total mileage of automobiles and trucks and the miles per gallon to GDP. Then the resulting carbon dioxide emissions also projected. If there are reasons to think there will be less or more use of autos and trucks and higher or lower gas mileages, those can be built in.

The disadvantages of the Bottom Up method is that the numbers are usually ideal engineering ratios and the interrelationships of the separate sources are not taken into account. It is also difficult to be comprehensive.

The other method of projecting future emissions is called, “Top Down,” and is based on computable general equilibrium models. These models divide the economy into separate sectors with the relationships among the sectors specified with linear or nonlinear relationships. That leads to a system of simultaneous equations. If there are even only a few sectors, it was difficult to actually find a solution until high speed computers came along.
I will take some credit, along with three colleagues, for the first such calculation, done for the Indian economy.

But by now it has become commonplace. The method can be used dynamically to project future outputs of the sectors and their resulting emissions.

In the MIT project, those projected emissions are handed off to the climate scientists and used in their model to project future climates.

Costs of Adjustment

Yet there are simply no good estimates of the costs of adjustment to future climate change. One can make estimates for the U.S. and other advanced countries on the costs of adjusting industrial production and consumption. But how is one to estimate the costs of increased sickness and death. Even worse, how does one estimate the costs of moving the population of the Marshall Islands to, say, Guam, when they are flooded out by the rising seas. And how does one estimate the social costs of losing the sight of snow on the mountains at sunrise.

So we are left with the possibility of knowing some costs and the impossibility of knowing other, perhaps much larger costs

Climate Policy

Turning now to the issues of climate policy, there are, again, two approaches: regulations and taxes. Regulation is a simple idea with practical difficulties. It just imposes limits on the greenhouse gases that can be omitted. It is natural that business firms would try to avoid the costs of such limits. To make the regulations work detailed reporting by the firms and regular inspections are required. It is not an impossible process, however. The EPA, the Environmental Protection Agency, in the U.S. regulates by law emissions of a number of types of emissions that are believed to harm the environment. There are regular inspections of potential emitters to make sure that the regulations are observed.

An extension of programs of simple regulatory limits are the so-called cap and trade schemes. These plans start with the imposition of specific, quantitative limits for individual emitters. For some emitters the costs of adjustment are relatively low and others have higher costs, Emitters with low costs of meeting the limits are allowed to sell a proportion of their limits to other higher cost emitters, who buy them in order to reduce their overall costs of meeting their own emission limits. In the process, the total costs of the regulations are reduced.

These schemes have been used in a number of instances, perhaps most notably in Europe for a time, but given up because of the difficulties of assigning the original limits.

International Agreements

Effective limits to emissions require international policies to avoid ,“free riding,” by countries that rely on others to take on the burdens of limitations. It took until 2015 to reach an international treaty, called the Paris Agreement.

The United States, after participating in the negotiations withdrew from the agreement. It is not customary to criticize one’s own country while in a foreign country. But I will not hide my belief that the withdrawal was a mistake.

Figure 5 shows the amounts of emissions of each country and suggests the task which each country would face in reducing its emissions.

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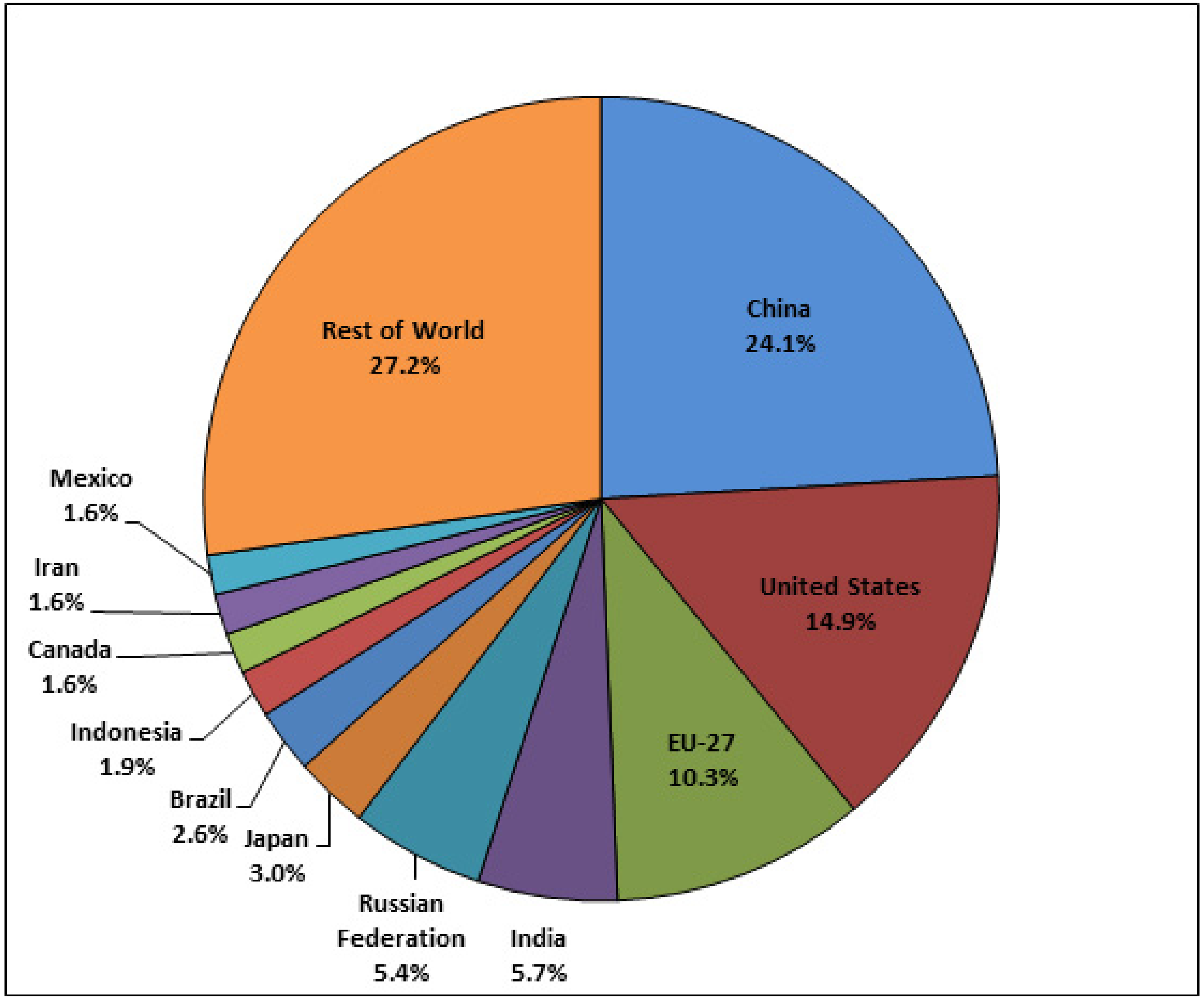
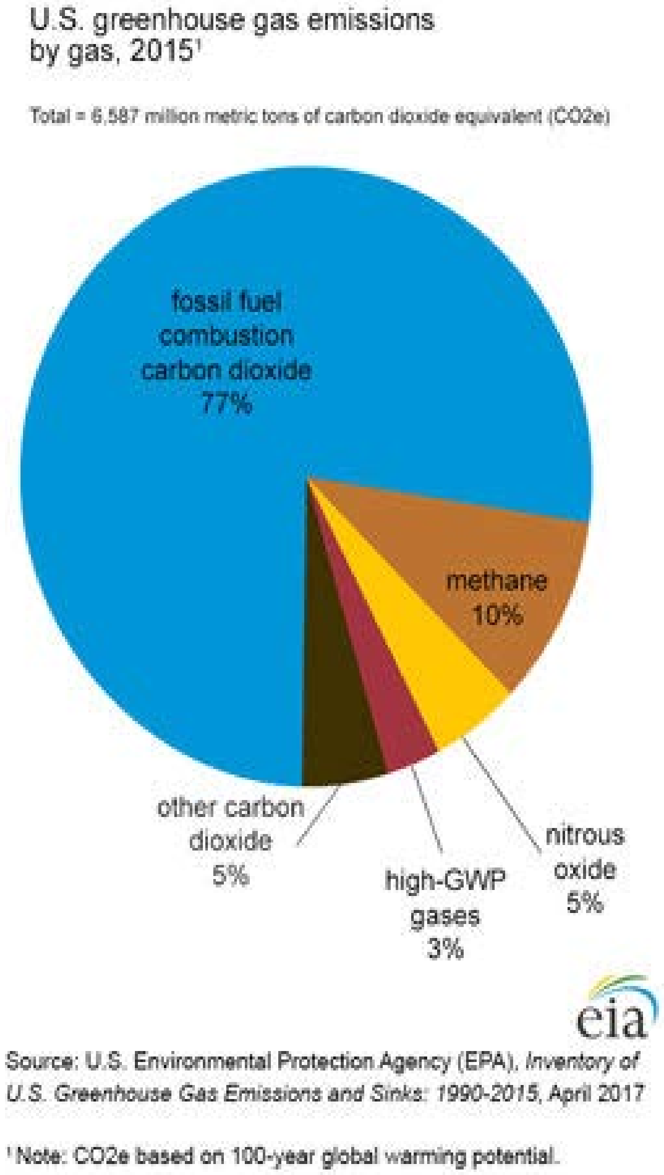


China
24.1%
United States
14.9%
EU-27
10.3%
India
5.7%
Russian Federation
5.4%
Japan
3.0%
Brazil
2.6%
Indonesia
1.9%
Canada
1.6%
Iran
1.6%
Mexico
1.6%
Rest of World
27.2%

GHG Emissions by Sector Sources	Unit	Available Years	Latest Value	Per Capita	Absolute Change from Earliest to Latest Value
Energy	$MtCO_2e$	1990-2013	620.21	8.04 tCO_2e	205.14%
Industrial Processes	$MtCO_2e$	1990-2013	39.78	0.52 tCO_2e	438.22%
Agriculture	$MtCO_2e$	1990-2013	34.70	0.45 tCO_2e	8.00%
Waste	$MtCO_2e$	1990-2013	22.13	0.29 tCO_2e	183.21%
Land-Use Change and Forestry	$MtCO_2$	1990-2013	67.08	0.87 tCO_2	-42,198.28%
Bunker Fuels	$MtCO_2$	1990-2013	13.30	0.17 tCO_2	380.14%

GHG Emissions - Energy Sub-Sector Sources	Unit	Available Years	Latest Value	Per Capita	Absolute Change from Earliest to Latest Value
Electricity/Heat	$MtCO_2$	1990-2013	187.29	2.43 tCO_2	347.42%
Manufacturing/Construction	$MtCO_2$	1990-2013	86.76	1.12 tCO_2	132.41%
Transportation	$MtCO_2$	1990-2013	125.94	1.63 tCO_2	221.77%
Other Fuel Combustion	$MtCO_2e$	1990-2013	142.48	1.85 tCO_2e	152.43%
Fugitive Emissions	$MtCO_2e$	1990-2013	77.75	1.01 tCO_2e	172.96%

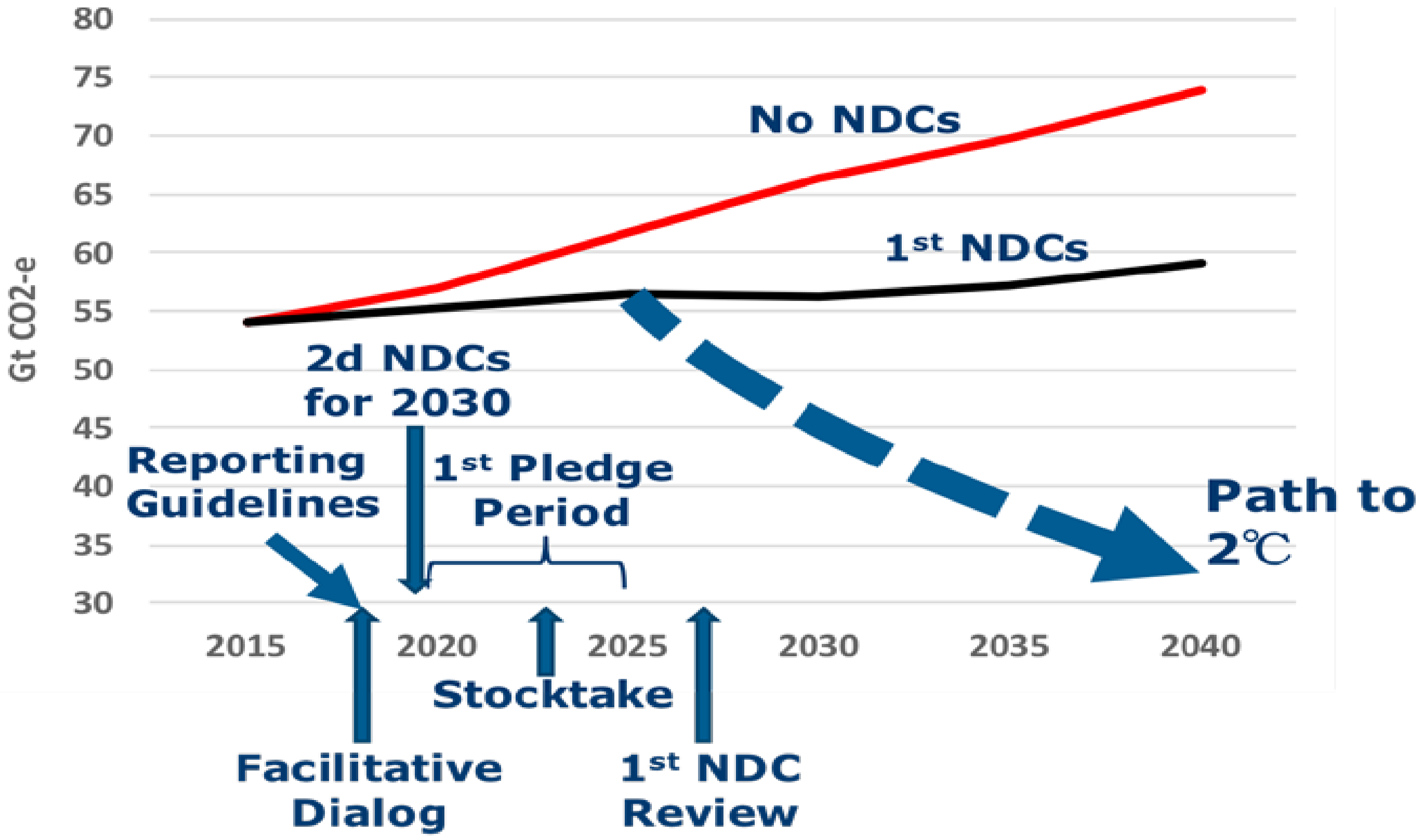
Types and Relative Quantities of Greenhous Gas Emissions



But the Paris Agreement would not be successful, with or without the U.S. participation The outcome of the agreement is illustrated in Figure 5. The vertical axis measures gigatons of carbon dioxide emissions. The, “NDC,” initials stand for the Nationally Determined Contribution by each country to emissions reductions. The horizontal axis shows the dates on which reviews of progress, called, “stocktaking,” would take place. Although the goal for emissions was set to limit temperature change to a maximum of 2 degrees centigrade, the figure also shows that the Paris agreement could not possibly achieve that.

Figure 5

Paris Agreement: Timing and Prospects



Conclusion

I am, by nature, an optimist.

But I find it almost impossible to be optimistic about the future of global warming.

Perhaps, as the warming becomes more intense, countries will agree to take the actions necessary to reduce emissions drastically. Perhaps, facing global warming there will be an agreement on some kind of climate engineering that will take carbon dioxide out of the atmosphere.

There are possibilities.

But it requires a lot of optimism to believe that the possibilities will be realized.